AN ANALYSIS OF COORDINATED OPERATION OF LAKES POWELL & MEAD UNDER LOWER RESERVOIR CONDITIONS

by

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An Analysis of Coordinated Operation of Lakes Powell & Mead under Low Reservoir Conditions

Thesis directed by Edith Zagona and Terry Fulp

Like most river systems, the Colorado River system is operated to meet multiple, frequently conflicting objectives. Reservoir operation on the Colorado River, managed by the U.S. Bureau of Reclamation (Reclamation), is governed strictly according to the *Law of the River,* a collection of documents dating as early as 1922. The hydrology of the Colorado River is highly variable and water managers are faced with the additional challenge of balancing the multiple objectives of users under these conditions. The occurrence of drought, most recently experienced in the river basin in 2000 through 2004, exacerbates these operational challenges. One primary reason is the absence of operational guidelines for low reservoir conditions in the *Law of the River*.

Operating Lakes Powell and Mead according to the operating criteria contained in the *Law* under low reservoir conditions results in an imbalanced reservoir system that increases the Upper and Lower Basin vulnerability to shortage and unprotected power pools. This thesis explores coordinated operation of these reservoirs, which aims to maintain a balanced system, as an alternative operational procedure under low reservoir conditions.

Two coordinated operation strategies developed by the Basin States and Reclamation are explored using CRSS-Lite, a computer model of the Colorado River Basin implemented in the river modeling software RiverWare. CRSS-Lite was developed as part of this thesis and is based closely on Reclamation's official long-term planning model CRSS. Results are presented and analyzed in terms of the impacts on reservoir levels (extended to the protection of minimum power pool and reservoir-based recreation), Lower Basin and Mexico shortage frequency and magnitude and basin-wide evaporation.

Acknowledgements

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Introduction

Water resource managers on the Colorado River are faced with the problem of meeting water demands for a body of stakeholders comprised of state agencies, Native American tribal groups, irrigation districts, municipalities and other non-governmental organizations with often conflicting interests such as municipal, industrial, and agricultural supply, hydropower production, recreation, endangered species and other environmental concerns. This problem is intensified by the extreme hydrologic variability that is characteristic of the Colorado River.

This year, 2005, the Colorado River Basin will most likely receive about average runoff. This will be a dramatic change from the previous five years in which the basin has experienced drought, the likes of which have not been encountered in roughly a century of recorded history. The result was decreased reservoir levels such that Lakes Powell and Mead stand at 33 and 60 percent capacity, respectively, as of April 2005.

Overuse and litigation have been synonymous with the Colorado River since the signing of the Colorado River Compact in 1922, negotiated during a period of relatively higher flows. Since then, the basin has continuously developed. A long history of litigation combined with increasing demands and hydrologic variability have driven the U.S. Bureau of Reclamation (Reclamation) and the Colorado River stakeholders to enter negotiations with the intent of adopting official shortage guidelines for the Lower Basin. Computer modeling will play a central role in developing shortage policy alternatives.

Computer models that are capable of representing the diverse nature and complexities of the basin become critical and powerful tools to facilitate effective planning of reservoir operation and diversions throughout the system. Reclamation uses modeling extensively; their official planning model, the Colorado River Simulation System (CRSS), is a necessary component for long-term planning and policy studies. The exploration of alternative reservoir operating polices and the assessment and review of those in place using modeling is essential to ensure that operations can respond to the changing hydrologic conditions and management objectives on the river.

Using a modeling tool to explore various shortage strategies increases the number of alternatives that can be investigated and encourages the investigation of innovative alternatives. Two such strategies are explored in this research that involve the coordinated operation of Lakes Powell and Mead under low reservoir conditions. This is done using a modeling tool that was developed in the modeling software RiverWare, for the purpose of this research.

1.1 Research Motivation

The complexity of interactions between constraints and operating objectives within a river basin generates the need for a decision support system that can assist water resource managers in organizing and trading off conflicting river and reservoir uses. The Colorado River exemplifies this necessity as it serves as a source of water for irrigation, hydropower, municipal, industrial, recreational and other uses for seven states and Mexico. Each state is apportioned a certain amount for which the distribution and administration is done by the federal government, consistent with a collection of documents known as the *Law of the River*, that includes two interstate compacts that have the status of being both federal and state law, operating criteria, and an international treaty. Increasing development and demand combined with a significantly varying climate magnify these complexities.

Uncertainties and ambiguities exist in the *Law of the River* as to how the river basin is to be operated during drought conditions. The result is an ongoing debate among state water agencies, the federal government and other stakeholders on how to define and provide the appropriate delivery of water through the river's complex allocation system during a shortage while considering other important objectives such as the protection and enhancement of the basin's environmental resources, recreation and power generation needs.

Thus, a computer model that accurately represents the current operating policies on the river and can be easily modified to represent alternative policies would be a highly effective means to explore alternative reservoir operation strategies and communicate their outcomes. Such a model, provided to stakeholders and tailored to meet their needs, would enhance their analysis capability during shortage policy negotiations.

As a shortage policy, coordinated operation is an appealing approach as it aims to balance the contents of Lakes Powell and Mead as the system enters and recovers from drought conditions. The Severe Sustained Drought Study, published in 1995, examined coordinated operation of Powell and Mead as an alternative operation during severe shortage. There is value in revisiting the notion of coordinated reservoir operation because the restoration of a balanced reservoir system reduces risk incurred from low reservoir conditions by providing protection of minimum power pools and potentially reducing shortage levels.

1.2 Physical Description of the Colorado River Basin

The Colorado River begins along the Continental Divide in Rocky Mountain National Park, Colorado. Approximately 1400 miles in length, the river descends 12,000 ft to its discharge point at the Gulf of California. The river drains about 243,000 square miles, roughly 1/12 of the continental U.S., and includes portions of seven states and Mexico. The basin is divided, both physically and politically, into the Upper and Lower Basins at Lee Ferry, Arizona the Colorado River Compact point, a result of the 1922 Colorado River Compact (Compact). Lee Ferry is located at a point on the Colorado River mainstem about thirty river miles south of the Utah-Arizona border and just one mile below the mouth of the Paria River. The Upper Division states include Wyoming, Utah, Colorado and New Mexico. California, Arizona and Nevada are considered to Lower Division states.

A semi-arid watershed, the majority of the southern region of the basin is comprised of desert receiving on the average less than ten inches of annual precipitation. To the north, mountain rich areas with elevations reaching 14,000 feet receive, on average, over four times the precipitation of the desert. Presented in Figure 1-1 is a map of the Colorado River Basin. The Lees Ferry streamflow gaging station, installed in 1921, is located about one mile upstream of the Compact point. Measurements taken at the Lees Ferry stream gage are adjusted for reservoir regulation and depletions to determine the natural flow for planning purposes.

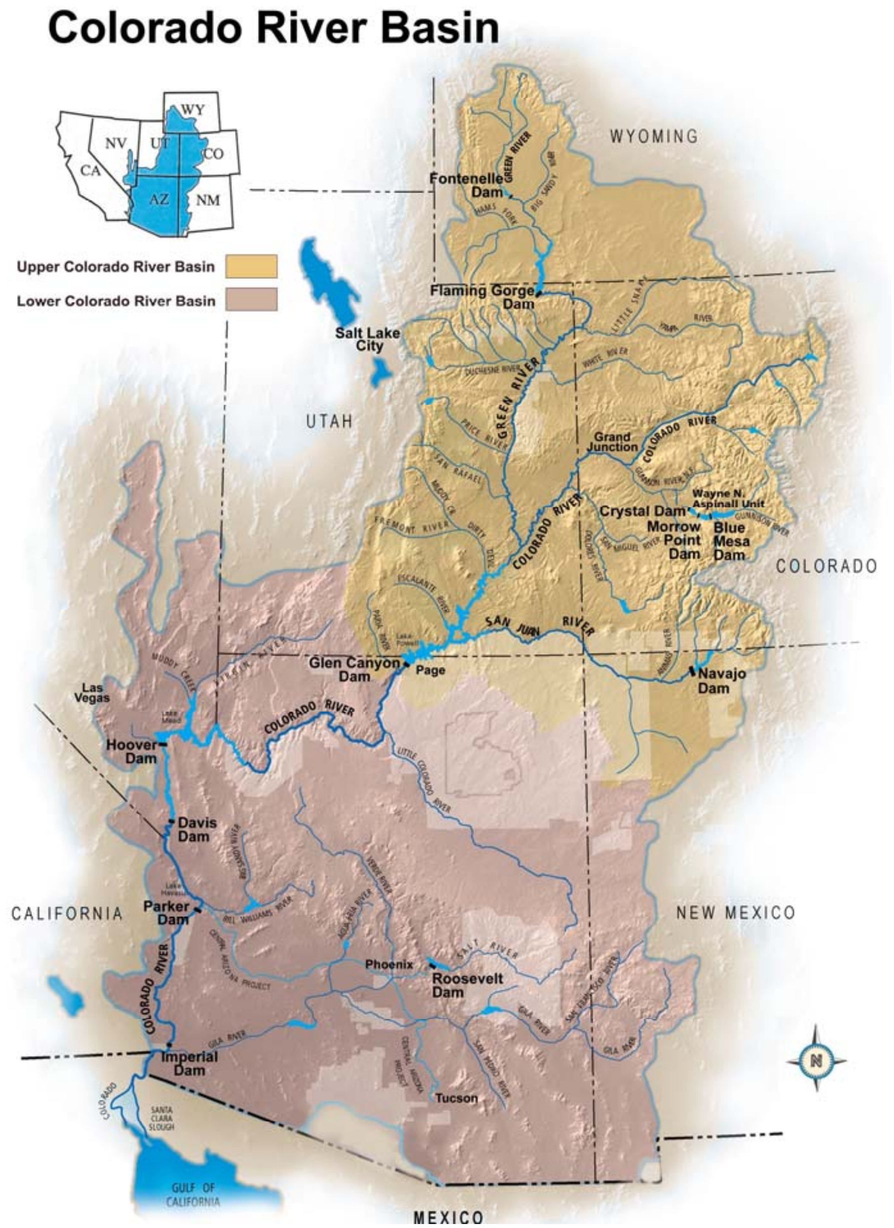


Figure 1-1 Colorado River Basin

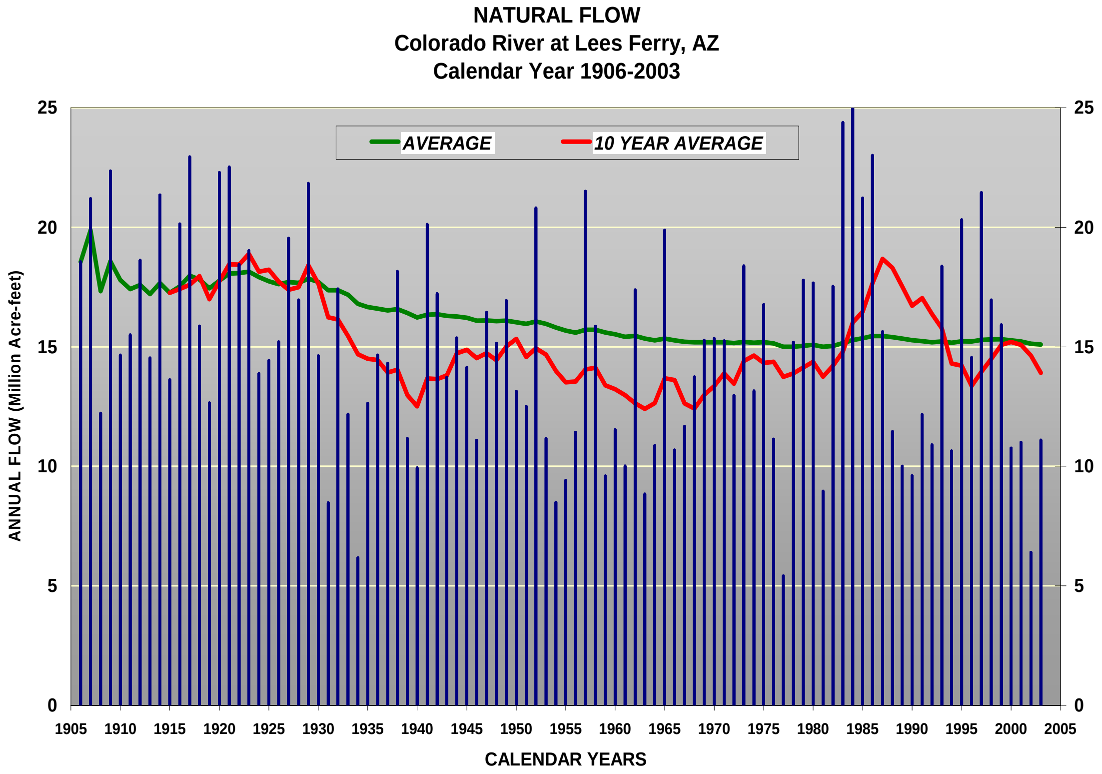
(USBR, 2000b)

1.2.1 Hydrology

The heterogeneity in the basin's natural landscape results in a significant spatial variability in the natural streamflow. Seventy percent of the annual runoff is attributed to snow pack in the high elevation Rocky Mountains. An average of 90 percent of the river's annual streamflow is generated in the Upper Basin. The remaining streamflow is generated by tributary inflows and inflows from rainstorm events in the Lower Basin. The Lower Colorado River Basin's mean annual tributary inflow is about 1.38 MAF, excluding the intermittent flow from the Gila River. The seasonal runoff pattern is characterized by heavy winter snowpack that dominates spring runoff (Christensen et al., 2004). Two key factors in forecasting the spring runoff, critical for reservoir operations, are the accumulated snowpack on April 1, and the antecedent conditions relating to the soil moisture (Pulwarty and Melis, 2001).

The streamflow is also characterized by a large temporal variation illustrated in Figure 1-2. The natural flow at Lees Ferry has varied annually from 5.3 million acre-feet (MAF) to 23.0 MAF during the historical record of 1906 through 2003. The record averages about 15.1 MAF. However, tree-ring reconstructions that have dated as early as 1512 indicate that the average annual streamflow may be nearer to 13.5 MAF (Stockton and Jacoby, 1976). Meko et al. (2005) are currently revisiting the reconstructed flows; their preliminary results indicate a long-term average since 1536 closer to 14.7 MAF. The historical record is a crucial part of planning and used to estimate the probability and frequency of shortages given the occurrence in the past. Figure 1-2 indicates that rarely since the signing of the Colorado River Compact in

1922 has the 10-year average flow been equal to the 16 MAF apportioned between the Upper and Lower Basins.



1996 to 2003: Provisional data, subject to change.

Figure 1-2 Annual Streamflow of the Colorado River, Lees Ferry Gaging Station

(USBR, 2005c)

1.2.2 Environmental Characteristics

The Colorado River Basin is renowned for its natural and distinctive beauty which fuels impassioned environmental crusades and increases tensions further on the already heavily litigated river. It is home to an immense array of species of plants, wildlife and fish that create a rich biodiversity thriving in a fragile habitat. Displaced by habitat loss and alteration due to the construction and operation of mainstem dams and competition with non-native species, four “big river” species are federally listed as endangered. These include the humpback, bonytail, Colorado pikeminnow and the razorback sucker.

Even during a period of drought on the river the urgency of environmental concerns has become apparent. The Lower Colorado Multi-Conservation Agreement was officially launched in April 2005. During November and December of 2004, high experimental flows were released from Glen Canyon. These operations aimed to improve the future of endangered fishes, specifically the humpback chub, sediment restoration along beaches for habitat for young native fish and increasing quantities of non-native fish in sport fisheries (USBR, 2004a).

1.3 Description of Colorado River Facilities & Uses

There are over 90 reservoirs situated along the river and its tributaries boasting an aggregate storage of over 60 MAF, approximately four times the annual average flow. However, 85 percent of the total storage is contained in two reservoirs, Lake Mead and Lake Powell. As shown in Figure 1-1, these reservoirs, formed by Hoover and Glen Canyon Dams, respectively, are at the nexus of the elaborate water transfer system comprised of reservoirs, canals and transbasin diversions. The semi-arid climate of the region results in total evaporative losses from basin reservoirs of about 2 MAF per year (USBR, 2000a). The construction of such massive storage facilities such as Hoover Dam in 1936 indicates that the early river users had the foresight that drought was inevitably part of the basin’s future (MacDonnell et al., 1995).

The management objectives of the Colorado River are to provide water for consumptive use while providing flood control and river regulation; protect and recover endangered species by enhancing and maintaining the ecosystem habitat; provide reliable recreation and generate hydropower (USBR, 2000b). The ultimate goal sought by Reclamation in the operation of these structures is to find an equitable balance of the often competing management objectives in an environment constrained legally and politically (Fulp and Harkins, 2001).

1.3.1 System Reservoirs

Upper Basin reservoirs, including Powell and reservoirs located upstream, provide approximately 31.2 MAF of storage of which 24.3 MAF is contained in Powell. They are operated to provide Upper Basin users with a reliable supply of water and deliver water to Powell such that the minimum objective release, the required delivery to the Lower Basin specified in the Long Range Operating Criteria, can be met. Glen Canyon Dam contains seven generating units with a maximum operating capacity of approximately 1200 MW. In 1996, a record of decision (ROD) was issued that officially adopted an operational regime called Modified Low Fluctuating Flows (MLFF) to enhance downstream resources. One feature of the MLFF criteria is a maximum limit on the release from Glen Canyon of 25,000 cfs except during emergency high flow occurrences. Although the power produced under MLFF remains the same on a monthly and annual scale, the daily and hourly operations are constrained by restrictions on generation during on-peak periods (USBR, 1996). Under a maximum release of 25,000 cfs, the maximum operating capacity is limited to 1048 MW (USBR, 2000b). Power generation at Glen Canyon Powerplant requires the elevation at Powell to be above 3490 ft. This elevation marks the top of the minimum power pool.

Lower Basin reservoirs are primarily operated to facilitate the delivery of water demands in the Lower Basin and to regulate streamflow. Davis Dam and Parker Dam form Lakes Mohave and Havasu, respectively. Davis Dam re-regulates releases from Hoover Dam and assists in the annual delivery obligation to Mexico of 1.5 MAF set forth in the 1944 Mexican Water Treaty. Parker Dam re-regulates releases from Davis Dam and from the U.S. Army Corps of Engineers' (USACE) Alamo Dam on the Bill Williams River and in turn releases water for Mexico. The Metropolitan Water District of Southern California (MWD) and the Central Arizona Project (CAP) pump water from Lake Havasu. The governing operations of Hoover Dam include flood control and to provide releases to meet downstream demands. The Hoover Dam Powerplant has a maximum operating capacity of 2074 MW through seventeen generating units. The minimum power pool at Mead is 1083 ft (USBR, 2000b).

Hoover power is marketed and delivered to Arizona, Nevada and California by Western Area Power Administration (WAPA). Together, Glen Canyon and Hoover powerplant contribute about 3.6 percent of the total generating capability of the seven basin states (USBR, 2000b). WAPA's biggest costumer is MWD, which is allocated 28.5 percent of firm energy from Hoover (ADWR, 1998).

1.3.2 Consumptive Use

The Compact, discussed further in Chapter 3, apportioned 7.5 MAF for "beneficial consumptive use" to each of the Lower and Upper Basin. Due to the geographic location of the basins, the Upper Basin is responsible for not depleting flows at Lees Ferry such that the Lower Basin can utilize their full apportionment.

What constitutes “beneficial consumptive use” is well understood, qualitatively. Beneficial consumptive use is water consumed by human activities and includes water consumed for municipal, industrial, agricultural, power generation, export, recreation and fish and wildlife. A difference of opinion exists, however, on how these uses are quantified (USBR, 2000a). If a state can salvage water that would otherwise be lost by natural causes (evaporation, seepage, groundwater or evapotranspiration) without it counting towards that state’s apportionment, more water can be put to use. If beneficial consumptive use is computed as diversions less return flows, natural losses are charged to that state’s apportionment. Computed as net depletions, the amount by which the natural flow is depleted by human activities, water that would have been lost by natural causes can be put to use without it being counted as “consumed.” In allocating water among Lower Basin states, consumptive use is computed as “diversions less returns to the river.” The Upper Basin computes its states’ respective shares based on the “inflow-outflow” method, i.e., depletions, not including natural losses, to the natural flow at Lee Ferry (Getches, 1985).

Table 1-1 shows the amount of Colorado River water apportioned to each basin state and Mexico for beneficial consumptive use. There is not a secure amount of water available for consumptive use in the Upper Basin; the actual available amount depends on the current storage and hydrology conditions. Thus, the apportionment for the Upper Basin states is based on a percentage of the total water available for consumptive use. Section 1.4 describes the political reasoning behind these apportionments.

Wyoming	14.00 %	California	4.4 MAF
Utah	23.00 %	Arizona	2.8 MAF
Colorado	51.75 %	Nevada	0.3 MAF
New Mexico	11.25 %	Mexico	1.5 MAF

Table 1-1 Basin States & Mexico Apportionment

1.3.2.1 Upper Basin

The Upper Division states (Wyoming, Utah, New Mexico and Colorado) have been slower to develop and use the full apportionment of 7.5 MAF allocated under the Compact. According to the Consumptive Use and Losses Report 1996-2000, the average annual use for the Upper Basin was approximately 4.4 MAF, just over half of its apportionment. Sixty percent was used for agriculture and livestock production, mainly sheep and cattle. Mineral production is also important to the Upper Basin as the Upper mainstem is the country’s primary source of molybdenum. Oil and natural gas extraction is the primary industry along the Green River. An average of four percent of Upper Basin total use is put towards the generation of thermal electric power (USBR, 2000a).

Transbasin exports, that bring water for supplemental irrigation and municipal uses to Colorado’s Front Range, accounted for 16 percent of the total use, the second largest Upper Basin use. There are considerably more diversions in the Upper Basin than in the Lower Basin, however, Upper Basin diversions are much smaller in size. Major cities that receive water from these diversions include Denver, Colorado Springs, Salt Lake City and Albuquerque; the three Upper Colorado River reporting areas (Green River, Upper Main Stem and San Juan–Colorado) serve more than eight million people (USBR, 2000a).

The Upper Basin is legally bound to provide 75 MAF over 10 years to the Lower Basin and, as shown in Figure 1-3, has been slow to develop their full apportionment. Increasing Upper Basin demand coupled with hydrologic variability has forced the Upper Basin to recognize that under the current interpretation of the Law of the River, they will carry a disproportionate share of system-wide drought (MacDonnell et al., 1995). This recognition has motivated the Upper Basin states to contest the uncertainties and ambiguities in the *Law of the River* in which they are unfavored. This will be discussed further in Chapter 3.

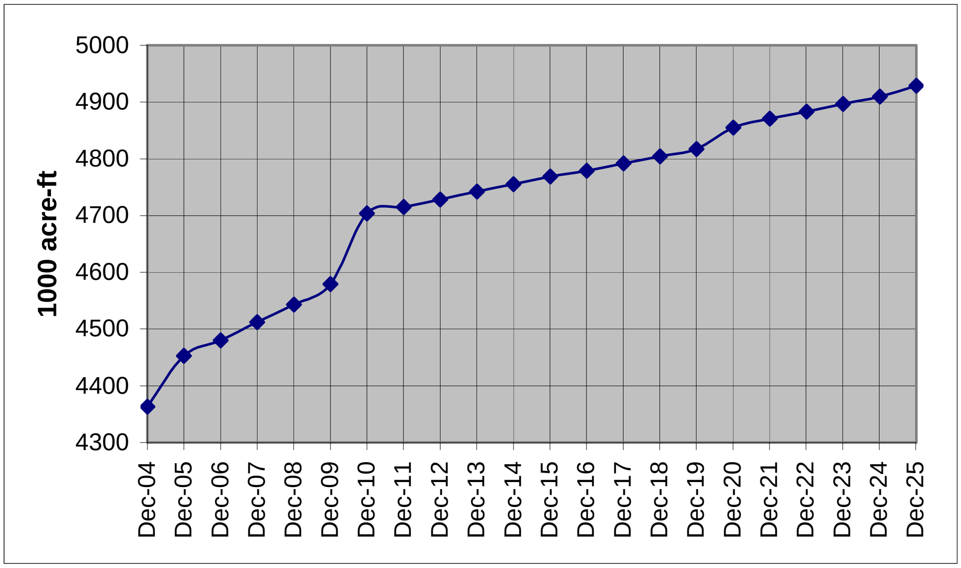


Figure 1-3 Projected Upper Basin Consumptive Use

Source: Upper Colorado River Commission

1.3.2.2 Lower Basin

The Lower Division states' (Nevada, Arizona and California) total consumptive use of the mainstem Colorado River water varied between 7.6 and 8.2 MAF during the period 1996 through 2000. Of this use, 75 percent goes to transbasin diversions, which serve major water agencies and municipalities such as Southern

Nevada Water Authority (SNWA) serving Las Vegas, the Central Arizona Project (CAP) serving Phoenix and Tucson, and Metropolitan Water District (MWD) serving Los Angeles. In addition to supplying water for approximately 2.1 million irrigated acres, the Colorado River and its tributaries serve over 19 million people in the Lower Basin (Pontius, 1997). Lower Basin tributaries consumptive use averaged 2.5 MAF per year from 1996 through 2000. Main Lower Basin tributaries include the Gila, Little Colorado, Bill Williams, Virgin and Muddy Rivers, most of which are located in Arizona. Tributary use is in addition to the states' total consumptive use and does count toward the Lower Basin's 7.5 MAF apportionment. The apportionment of mainstem water was established by the 1964 Supreme Court decision in Arizona vs. California, discussed further in Section 1.4.1.7. Over half of the consumptive use of the tributaries was used for the irrigation of crops (USBR, 2000a).

Ninety percent of Nevada's apportionment is diverted from Lake Mead by the SNWA pumping facilities. Nevada has been using its full apportionment since 2000, however, current conditions have encouraged SNWA to implement conservation measures that have resulted in a savings of 55,000 acre-ft between 2002 and 2004 despite 170,000 new residents to the Las Vegas area (USBR, 2000a and SNWA, 2005). In 2004 SNWA and MWD signed an agreement in which, beginning in 2006, intentionally created unused apportionment" of SNWA could be stored in MWD facilities and paid back by exchange when needed. The amount Nevada can recover per year is limited to 0.30 MAF per year (USBR, 2002).

Arizona diverts from the river at several points, beginning with a diversion point above Lee Ferry and ending at Imperial Dam where water is diverted into the

Gila Gravity Main Canal. Between these diversion points irrigation water is provided for the Fort Mohave and Colorado River Indian Reservations. The largest diversion, the intake for the CAP consisting of a system of pumping plants and aqueducts, occurs at the pumping plant on Lake Havasu. The CAP transports water more than 300 miles to Phoenix and Tucson.

In 1996, the Arizona Water Banking Authority (AWBA) was created and provided Arizona the means to use all of its 2.8 MAF share of the river by 2000. It is estimated that without the AWBA, Arizona would not have used its full allocation until 2030 (AWBA, 1997). Conversely, California at this time had been using more than its 4.4 MAF share. In 1996 California consumed about 5.2 MAF made possible by Arizona's under-use (USBR, 2000a). Motivated by concern that California would continue its reliability on Arizona's unused entitlement, the AWBA put into place a banking mechanism whereby Arizona would utilize the delivery capacity of the CAP's 1.5 MAF per year and recharge the state's groundwater system with excess water not put directly to beneficial consumptive use elsewhere. The AWBA recharged almost 0.294 MAF of CAP water in 2000. Average annual consumptive use of mainstem water by Arizona for 1996 through 2000 was approximately 2.6 MAF. Tributary use for this period averaged 2.2 MAF (USBR, 2000a).

Six large public agencies in Southern California have major water rights to the Colorado River. These are Palo Verde Irrigation District (PVID), Imperial Irrigation District (IID), Coachella Valley Water District (CVWD), Metropolitan Water District of Southern California (MWD), Los Angeles' Department of Water and Power and San Diego County Water Authority (SDCWA). These agencies are responsible for delivering water and power to nearly 15 million people and for the irrigation of approximately 1.2 million acres. The crops grown in Southern California provide a considerable percent of the nations produce and include fruits such as cantaloupes, dates, grapes, oranges, lemons and avocadoes; vegetables such as lettuce, tomatoes, onions and carrots; and alfalfa, wheat, grasses and other forage crops (CRWUA, 2001).

California is entitled to 4.4 MAF of Colorado River water. Those rights have been exceeded since the 1950’s, reaching an all-time high in 1974 of 5.4 MAF, and have continued to be exceeded through 2003 (USBR, 2000a). Most of this water is received at MWD’s pumping plant on Lake Havasu, through the All American Canal diversion at Imperial Dam and through PVID’s diversion at Palo Verde Diversion Dam (USBR, 2000b). It was not until 2001 with the adoption of the California 4.4 Plan and the enactment of the Quantification Settlement Agreement did California begin to work towards cutting back to its 4.4 MAF entitlement. Consumptive use in 2004 totaled approximately 4.3 MAF and is projected to be about the same for 2005 (USBR, 2005d).

Ten Native American Indian tribes have reservations in the Colorado River Basin. Most tribes’ water rights pre-date the Boulder Canyon Project Act of 1928 and therefore have seniority, although some remain undeveloped and even unquantified. The effect and consequences on the allocation of the river that the development of these rights will have is uncertain, although surely considerable (Pontius, 1997). Interestingly, most of these water rights are in Arizona of which the CAP component carries the lowest priority the Lower Basin states.

1.4 Law of the River and Current Operating Policies

This section discusses the policy guiding the operation of the river in terms of allocations and actual reservoir operation. It includes descriptions of portions of the Law of the River that are relevant to the issue of shortage, followed by a discussion about the ambiguous and likely contested areas of the Law. Next is an overview of the Long Range Operating Criteria for Glen Canyon and Hoover Dams, followed by a look at how these operations affect reservoir levels when confronted with drought conditions.

1.4.1 Review of the Law of the River

The management of the mainstem waters of the Colorado River must be consistent with a wide variety of documents collectively referred to as the *Law of the River*. The *Law of the River* is comprised of federal and state laws and regulations resulting from court decisions and decrees, an international treaty with Mexico, contracts with the Secretary, and also includes most operating criteria. It is vital to maintain a sense of how these documents dictate river operations and their history to understand the positions of the Basin States regarding operational policy in anticipation of or during shortage conditions. Portions of the *Law of the River* that are of particular relevance to discussions and negotiations regarding the river operations during shortage are discussed in the following sections. These include: the Colorado River Compact of 1922, the Boulder Canyon Project Act of 1928, the California Seven Party Water Agreement of 1931, the U.S. – Mexico Water Treaty of 1944, the Upper Colorado River Basin Compact of 1948, the Colorado River Storage Project

Act of 1956, the 1964 U.S. Supreme Court Decree, Arizona v. California and the Colorado River Basin Project Act of 1968.

Additional federal laws such as the Colorado River Basin Salinity Control Act, the National Environmental Policy Act, the Endangered Species Act and the Grand Canyon Protection Act recognize the importance of other aspects and interests associated with river operations. The significance of these acts is recognized, however their influences are more indirect on reservoir operation, a main theme of this research, and for that reason receive only this brief mention.

1.4.1.1 The Colorado River Compact of 1922 (Compact)

Negotiated in 1922 by representatives of the seven basin states, the Compact divided the Colorado River Basin into two sub-basins, the Upper and Lower Basins. Furthermore, it determined the initial apportionment of water between the Upper and Lower Basins. The Upper Basin, the area above Lee Ferry from which the water drains naturally into the Colorado River includes the states of Colorado, Wyoming, Utah and parts of Arizona and New Mexico. The Lower Basin is defined as the area below Lee Ferry from which the water drains naturally into the Colorado River system. It includes the states of Nevada, California and parts of Arizona, New Mexico, and Utah. The Compact divided the basin states into two divisions. The Upper Division consists of the states of Colorado, Wyoming, Utah and New Mexico, and the Lower Division includes California, Nevada and Arizona. Throughout this writing Lower Basin and Lower Basin states are used interchangeably and refer to the Lower Division, similarly, Upper Basin and Upper Basin states are meant to mean the Upper Division.

The Compact was negotiated during what turned out to be a period of abnormally high flow with the limited period of record available at the time. The determination of the amount of water allocated was based on the calculation of the average annual flow at Lees Ferry of about 18 MAF (Lochhead, 2001). The actual average annual flow at Lees Ferry since 1922 has been about 15 MAF.

Implying that 2.0 MAF would eventually be delivered to Mexico, there was 16 MAF remaining to apportion within the U.S. To each basin, Article III(a) of the Compact apportioned 7.5 MAF of water per year, in perpetuity, to be put towards beneficial consumptive use. Article III(b) gave the Lower Basin the right to increase this use by 1.0 MAF. This additional water for the Lower Basin was an attempt to placate Arizona's obstinate demands that tributary water be kept separate from the 7.5 MAF apportionment. The Compact deliberately left the division of the 7.5 MAF within each basin to be decided on by that basin (Wilbur and Ely, 1948). Anticipating a future allocation to Mexico, Article III(c) set aside surplus water to meet this need. This article also prescribed both basins to share equally the burden of a deficiency in meeting a future obligation to Mexico. Under Article III(d), the Upper Basin must not cause the measured flow at Lees Ferry to be reduced to below 75 MAF for any 10-year period.

By 1929, the Compact was ratified by each state in the basin with the exception of Arizona. Arizona introduced a resolution in the U.S. House of Representatives stating that it was unwilling to ratify the Compact unless, most significantly, the Gila River "be not included, considered or involved in anyway with the so-called Colorado River Compact." (Wilbur and Ely, 1948) In Arizona's view, the 7.5 MAF apportionment should be taken from the mainstem of the Colorado and not include the Lower Basin tributaries. The resolution was not passed, and it was not until 1944 when, realizing they lacked the political influence to push for the construction of the CAP, Arizona ratified the Compact (Wilbur and Ely, 1948).

1.4.1.2 The Boulder Canyon Project Act of 1928 (BCPA)

The principal purpose of this Congressional Act was to authorize the construction of Hoover Dam and the All-American Canal. It also gives the responsibilities of directing and managing the operation of the dams on the Lower Colorado River to the Secretary of the Interior (Secretary).

Hoover Dam, built for river regulation and flood control purposes, provided California with a secure supply to satisfy present perfected rights. Present perfected rights, for the purpose of the BCPA, are defined as water rights that pre-date the Compact, of which most were held by the irrigators of the Imperial Valley of California. The 1964 U.S. Supreme Court Decree later defined present perfected rights as those that predate the BCPA. The significance of these rights and tribal reserved rights is that they are to be satisfied first in any year in which less than 7.5 MAF of Colorado River water is available (MacDonnell et al., 1995).

California and Utah ratified the Compact immediately following the passage of this act, as anticipated. Arizona, however, still adamantly refused, despite the agreement by California to limit its consumptive use 4.4 MAF each year. The primary reason for refusal being that the Gila River was still subject to apportionment by the Compact (Sparks, 2000).

The BCPA also authorized the Lower Basin states to enter into negotiations regarding the division of the annual 7.5 MAF apportionment. The Act suggested the state apportionments that were later made official in the Supreme Court decision in the case of Arizona v. California.

The Upper Basin states were also given the congressional approval to negotiate a compact regarding the division of their 7.5 MAF apportionment among the states. This was done in the Upper Colorado River Basin Compact of 1948.

1.4.1.3 The California Seven Party Water Agreement of 1931

This agreement required that California provide the Secretary with recommendations about how to allocate the 4.4 MAF of water provided to the state in the BCPA. It also allocated priorities to the agricultural agencies. The first three priorities, totaling 3.85 MAF in which 2.8 MAF are present perfected rights, were given to the Imperial, Coachella and Palo Verde areas for agricultural purposes and to the Yuma Project. Fourth in priority is MWD for 0.662 MAF. In the event of a surplus, meaning water is available for California above 4.4 MAF, MWD has first priority to 0.662 MAF.

1.4.1.4 The U.S. – Mexico Water Treaty of 1944 (Treaty)

The 1944 Treaty with Mexico had long been anticipated by the Compact negotiators. Article III(c) of the Compact set aside surplus water for Mexico and granted the equal burden of supplying any deficiency in Mexico’s delivery to both basins. The Treaty requires that the U.S. deliver 1.5 MAF per year plus up to an additional 200,000 acre-ft in surplus conditions. Mexico’s delivery obligation is viewed as the senior priority on the Colorado River under normal conditions (Lochhead, 2001). The Treaty addresses the possibility of shortage conditions through specifying that the delivery to Mexico be reduced in proportion to the reduction of consumptive uses in the U.S. during “extraordinary drought.” Differing views exist regarding the interpretation of this provision and are discussed further in Section 1.4.2.1.

1.4.1.5 The Upper Colorado River Basin Compact of 1948 (Upper Basin Compact)

Twenty-six years after the signing of the Compact, the Upper Basin states devised a compact that allocated their respective shares of the river. First allocated was 50,000 acre-ft to the portion of Arizona that lies within the Upper Basin. The Upper Basin was uncertain of the amount of water that they were able to allocate given their obligation, under Article III(d) of the Compact, to not deplete the flow of the Colorado River at Lee Ferry below 75 MAF every ten years (Lochhead, 2001). Thus, state allocations were based on the percentages of the available 7.5 MAF apportionment: Colorado – 51.75%; New Mexico – 11.25%; Utah – 23.00%; Wyoming – 14.00%.

The Upper Basin Compact also established and granted the Upper Basin Commission the arduous responsibility to order curtailments to the Upper Basin if necessary to meet downstream delivery obligations.

1.4.1.6 The Colorado River Storage Project Act of 1956

Considering the Compact’s Article III(d) delivery obligation of the Upper Basin, the states were especially aware of their dependence on the Colorado River’s hydrologic variability. They understood that securing storage in the basin was necessary to make the delivery requirement while securing future supplies and maintaining a buffer for shortage times. The Colorado River Storage Act was enacted for this purpose (MacDonnell et al., 1995). It authorizes the construction of nearly 30 MAF of storage space throughout the Upper Basin including Flaming Gorge, Navajo, and Glen Canyon Dams along with the Curecanti Unit (now the Aspinall Unit) on the Gunnison River.

Also created by this Act was the Upper Basin Fund to draw power revenues to be used by the states if financial assistance was required for development of their apportionments. The state allocations of revenues are as follows: Colorado – 46.0%; New Mexico – 17.0%; Utah – 21.5%; Wyoming – 15.5%.

1.4.1.7 The 1964 U.S. Supreme Court Decree, Arizona v. California (The Decree)

By 1946, the Lower Basin states had still not agreed upon how to apportion the water amongst them. Arizona had ratified the Compact only two years earlier realizing it had no political clout to push for other projects without signing (Sparks, 2000). It was at this time that Arizona pushed Congress for the construction of the CAP. The issue of the Lower Basin tributary ownership remained unresolved causing Congress to be reluctant to approve the project. Congress feared the approval would create more uncertainty in allocation issues among the Lower Basin. Arizona sued California in 1952 with the intent of obtaining certainty regarding the allocation issue (Wilbur and Ely, 1948).

The suit, lasting approximately ten years, requested a settlement between Arizona and California as the individual state’s allocation and the ownership of the tributaries. The apportionment between Arizona and California pursuant to the BCPA is ambiguous in that it does not specify whether the 7.5 MAF to be apportioned in the Lower Basin is from mainstem water only or if it includes tributaries, namely the Gila River. Arizona argued that it was to be from the mainstem Colorado River only, thus keeping the water of the Gila for use within Arizona and limiting California to 4.4 MAF of the 7.5 MAF. California argued that the water was to include the tributaries and therefore it would be entitled to water in excess of 7.5 MAF. At the crux of California's position was the extra annual 1.0 MAF apportioned to the Lower Basin and the right to the first 0.662 MAF of surplus waters pursuant to the Seven Party Agreement of 1931 (Lochhead, 2001).

In 1964, the Court, through interpreting the BCPA to apply only to mainstem water, ruled in favor of Arizona and only mainstem Colorado River water was apportioned. Despite the ruling of the Court, antagonism still exists today between the Upper and Lower Basin. The Upper Basin argues that the BCPA references the Compact and the Compact clearly includes the tributaries as it apportions the "Colorado River System." Article II(a) defines the Colorado River System as "that portion of the Colorado River and its tributaries" (Sparks, 2000).

Also resulting from the interpretation of the BCPA was the allocation of 4.4 MAF to California, 2.8 MAF to Arizona and 0.3 MAF to Nevada. The Supreme Court decision also stated that if water apportioned to a Lower Basin state is not used, it may be made available by the Secretary to any other state in that division. The Decree defined present perfected rights as those pre-dating the BCPA, June 25, 1929, that are first to be satisfied in a shortage. In addition, the Decree delegated the Secretary the authority to declare normal, surplus or shortage conditions and to make allocations accordingly. The Decree also specifies that a surplus be divided 50 percent to California, 46 percent to Arizona and the remaining 4 percent to Nevada.

The Decree emphasized that there are limitations to the Secretary's discretion and that any contracts held are subject to the Compact and can "therefore do nothing to upset or encroach upon the Compact's allocation of Colorado River water between the Upper and Lower Basins" (Lochhead, 2001). Furthermore, it enforces that the Secretary's release of water to valid contract holders be dependent on declaration of year as normal, shortage or surplus.

The Decree, essentially the "Lower Basin Compact," had monumental ramifications. One being that the Decree solidified interpretations of the Compact by using the Compact as a backdrop for which its decisions were based. It provides the Secretary with the power to exercise his/her discretion in declaring the circumstances (normal, surplus, shortage) under which water is to be released. However, it also emphasizes the limitations on this discretion in that allocation schemes and other decisions must strictly adhere to the Compact. Also, present perfected rights must be satisfied. The apportionment of shortages then, becomes the only true discretionary act since there are no real guidelines (Lochhead, 2001).

1.4.1.8 The Colorado River Basin Project Act of 1968

There are two key provisions of this act. The first granted Arizona the authority to begin construction of the CAP, but not without a price. The fulfillment of California's 4.4 MAF apportionment was given priority over the CAP in the event of shortage. In other words, the delivery to the CAP could be cut to zero to assure the availability of 4.4 MAF to California for that year.

Second, the Secretary was given several directives for the operation of the two major federal reservoirs, namely Lakes Powell and Mead. To meet the objective of coordinated long-range operation of these reservoirs, the Secretary is to prepare, in consultation with the states of both basins, criteria to use for guidance. These criteria are to be reviewed at a minimum every five years and include projections every year for the operation of the upcoming year. The latter is known as the Annual Operating Plan (AOP).

Concerning reservoir operation, the Act specifies that the Secretary, through the operating criteria, meet these specific requirements in the order listed below regarding releases from Lake Powell.

1. If a deficiency exists regarding the delivery obligation to Mexico, that deficiency is chargeable to the Upper Basin and the release from Powell should satisfy one-half of that deficiency.
2. The release must satisfy Article III(d) of the Compact, i.e., 75 MAF every 10 years.
3. If an annual determined amount of storage can meet the delivery obligations in items 1 and 2 without impairment to annual consumptive uses in the Upper Basin and the storage in Powell is greater than that in Mead, the release shall maintain equal storage in these reservoirs and avoid anticipated spills from Powell.

Because these provisions are from Section 602(a) of the Act, the determined amount of storage in 3 is known as the 602(a) storage. The Act directs the Secretary to take into consideration all relevant factors, specifically historic streamflows, the most critical period of record and probabilities of water supply, in computing this storage quantity.

The following section, which discusses operational policy for reservoir operation, describes in detail how the Criteria for Coordinated Long-Range Operation of Colorado River Reservoirs guide the operation of Lakes Powell and Mead and its interpretation of requirements set forth by the Act and other portions of the *Law of the River*.

1.4.2 Long Range Operating Criteria for Glen Canyon & Hoover Dams

As a response to the directive of the 1968 Act, in 1970 the Criteria for Coordinated Long-Range Operation of Colorado River Reservoirs (LROC) were developed. Powell and Mead are operated according to the guidelines set forth in the LROC, which is reviewed on a five-year basis. In addition to meeting delivery obligations, these operations attempt to meet several other management objectives that range from dependable hydropower generation to habitat restoration can be obtained.

1.4.2.1 Powell Operation

There are three main operational policies that govern the annual release from Powell. The first, of highest priority and stated in the Operating Criteria is to make a minimum objective release of 8.23 MAF over the water year. The water year starts October 1 of each year and ends at September 30 of the following year. The volume 8.23 MAF was determined by adding the Upper Basin’s Compact delivery requirement of 7.5 MAF and half of the delivery obligation of the Mexican Treaty, 0.75 MAF. Next, the gains from the Paria River, which enter the Colorado River mainstem just above Lee Ferry and average 20,000 acre–ft per year (using the historical record 1906 through 1990) are subtracted.

The objective of the second operational strategy is to equalize the storages of Powell and Mead by the end of the water year. The act of making release to meet this objective is referred to as equalization. This objective is based on the provisions set forth in the 1968 Act and also reflects Article III(e) of the Compact. Article III(e) states that the Upper Basin may not withhold water that cannot be reasonably applied domestic and agricultural use. Essentially, equalization is a mechanism to transfer surplus water to the Lower Basin.

Equalization releases are made if 1) the end of the water year storage forecast for Powell is greater than that of Mead and 2) the storage forecast for the end of the water year in the Upper Basin Reservoirs is greater than the quantity of 602(a) storage for that same date.

The 602(a) storage quantity is the storage in the Upper Basin necessary to assure Lower Basin delivery obligations without impairing consumptive use requirements in the Upper Basin. The LROC offers factors to be considered to determine 602(a) storage but does not present a set formula. The factors to be considered include the historic streamflows, the most critical period of record, probability of available waters and estimated future depletions in the Upper Basin.

In 2003, Reclamation adopted an interim 602(a) storage guideline in effect through 2016 per the Final Environmental Assessment (EA) Adoption of an Interim Storage Guideline. This guideline was proposed by the Lower Basin in 2000 during the development of the Interim Surplus Guidelines (see Section 1.4.2.3), also to be in effect through 2016, but was determined by Reclamation at that time to be outside the scope of proposed surplus guidelines. Under the 602(a) storage guideline, in addition to the aforementioned requirements, Powell’s elevation must be above 3630 ft which corresponds to storage of approximately 14.85 MAF, for equalization releases to occur (USBR, 2004b).

The third operations policy is spill avoidance. The definition of spill is water released that cannot be utilized for “project purposes” which includes, but is not limited to power generation.

1.4.2.2 Mead Operation

Two policies govern releases from Lake Mead. The first mode is flood control where the release is determined by a rigid rule developed by Reclamation and the Army Corps of Engineers in 1982, known as the Field Working Agreement. Under this rule, given a maximum probable spring inflow forecast to Mead, flood control releases are computed. The release from Mead then becomes the larger of the release required to meet downstream demands or the flood control release. The objective of the flood control release is to maintain an exclusive flood control space in Mead of 1.5 MAF.

The release required to meet downstream demands considers the consumptive use schedules of the Lower Basin diversions along with the delivery obligation to Mexico. It also includes the reservoir regulation of Lakes Mohave and Havasu, and system gains and losses such as tributary inflow and reservoir evaporation. The consumptive use deliveries may be more under surplus (according to the Interim Surplus Guidelines) or less under shortage (yet to be defined) conditions.

1.4.2.3 Interim Surplus Guidelines

In 1990, California's consumption, for several years, had exceeded its 4.4 MAF apportionment. Even with this excess use, total consumptive use had not exceeded 7.5 MAF in the Lower Basin as California had been able to use the unused apportionments of Arizona and Nevada. However, projected use for 1991 was 7.8 MAF. This projection called for the Secretary to make a decision under both the Decree and LROC as to whether the year would be declared normal or surplus. The declaration of a surplus would allow California to continue its overuse whereas the declaration of normal conditions would require California to limit its use such that Lower Basin consumptive uses total 7.5 MAF. California was also experiencing the effects of a multiple year drought, which increased the importance of the Secretary's decision (Lochhead, 2003).

In 1991 the Secretary issued a normal declaration but gave California the permission to use the unused Nevada and Arizona apportionments. The Basin States recognized the basin-wide risk of California's dependence on unused apportionments as Lower Basin states were within reach of using these full apportionments. The Upper Basin concern was that surplus releases are essentially provided to the Lower Basin via equalization releases from Powell. It was during this time that negotiations begun among the Basin States of how to provide California relief but also create a precedent that would not entitle California to unlimited surplus water (Lochhead, 2003).

The Interim Surplus Guidelines, adopted in 2001, do precisely that. During an interim period of 15 years, the Secretary is provided guidelines that assert the authority to declare “non-hydrological” surplus conditions for the purpose of providing relief to California. The guidelines consist of three elevation tiers on Lake Mead fixed to stipulations that determine the use of surplus water from that range (UBSR, 2000b). The limited timeframe during which the Secretary is to make these essentially political declarations was reason for the Secretary to push California to come to an agreement pledging their commitment to reduce to 4.4 MAF by the end of this period. A grueling negotiation process resulted in the adoption of the Quantification Settlement Agreement in 2003, an agreement between major California water agencies that quantifies use and provides a framework for implementing major conservation measures.

1.4.3 Key Issues & Unresolved Questions Regarding Shortage Policy

The *Law of the River* addresses shortage policy indirectly through the various priorities embedded in the Compacts, Decrees, Acts and Treaty. The Compact places the ultimate burden of shortage on the Upper Basin with the Lee Ferry delivery obligation of 75 MAF over 10 years. The Treaty, places the United States at a junior priority to Mexico. Present perfected rights, defined in the Decree, are senior rights in the Lower Basin. The Colorado River Basin Project Act of 1968 places Arizona’s CAP at a junior priority to California. Although these priorities delineate delivery requirements during shortage, prescribed guidelines for actual operations have not been determined.

The LROC contains factors for the Secretary of the Interior to consider in determining if insufficient water is available to meet the delivery requirements set forth in the Compact. These factors would be examined before the declaration of a shortage; however the ultimate decision and the extent of curtailed deliveries are at the discretion of the Secretary.

1.4.3.1 Delivery to Mexico

The obligation to Mexico during drought conditions is not unambiguously prescribed (Hundley, 1966). Both the Compact and the Treaty address this obligation. The Treaty reads:

> In the event of extraordinary drought or serious accident to the irrigation system in the United States, thereby making it difficult for the United States to deliver the guaranteed quantity of 1.5 MAF a year, the water allocated to Mexico under subparagraph (a) of the Article will be reduced in the same proportion as consumptive uses in the United States are reduced.

The definition of “extraordinary drought” and to what constitutes a situation in which the delivery is made “difficult” has yet to be determined. Extraordinary drought could be defined as the availability of a specified quantity of mainstem water or could be said to exist when shortages are incurred in the United States. It is also unclear how consumptive uses “reduced in the same proportion” are to be computed. A proportional reduction could be interpreted to mean a reduction shared 50 percent between the U.S. and Mexico. The proportional reduction could also be computed based on the shortages incurred by separate entities within the U.S (USBR, 2005c).

At the time the Compact was negotiated, predating the Treaty, the certainty of a obligation to deliver to Mexico was recognized; however, the specific amount was undetermined. Article III(c) of the Compact states:

> If, as a matter of international comity, the United States of America shall hereafter recognize in the United States of Mexico any right to the use of any waters of the Colorado River System, such waters shall be supplied first from the waters which are surplus over and above the aggregate of the quantities specified in paragraphs (a) and (b); and if such surplus shall prove insufficient

> for this purpose, then, the burden of such deficiency shall be equally borne by the Upper Basin and the Lower Basin, and whenever necessary the States of the Upper Division shall deliver at Lee Ferry water to supply one-half of the deficiency so recognized in addition to that provided in paragraph (d).

The Compact states that the first source from which the Mexico delivery should come is “surplus” water, defined as water in excess of “the aggregate of the quantities specified in paragraphs (a) and (b),” or 16 MAF. If water less than this amount exists, both basins are to contribute towards supplying the deficiency equally. The Upper Basin asserts that since their current annual consumptive use does not total 7.5 MAF per year while the Lower Basin has available surplus water, the Upper Basin should not be required to provide additional releases or curtail uses in order to supply water towards the Mexico delivery obligation (Lochhead, 2001). Furthermore, the Upper Basin contests the annual minimum objective release of 8.23 MAF, which includes an implied obligation to supply one-half of the Mexican delivery obligation while there are surplus waters available in the Lower Basin.

1.4.3.2 Upper Basin Issues

After a series of low flow years befell the Colorado River basin in 1924 through 1926, just two years after the creation of the Compact, the Upper Basin realized that 7.5 MAF, allocated by the Compact and based on a limited record during a period of abnormally high flows, was subject to variable hydrology.

The Upper Basin recognized this vulnerability, and the 1948 Upper Basin Compact allocates the water available to the Upper Basin each year according to a percentage for each state. As the Upper Basin was slower to develop, the reliance by the Lower Basin on the resulting excess water increased. It was in 2003 when that reliance was curbed with the signing of the Quantification Settlement Agreement, an agreement between California water agencies to bring down uses within the state to the 4.4 MAF apportionment. With a rigid delivery obligation at Lee Ferry and under the current reservoir levels the Upper Basin is even more pressed to secure an entitlement out of hydrologic leftovers (Lochhead, 2001).

In Article III(d) of the Compact, the Upper Basin is provided a 10-year window to meet the 75 MAF delivery obligation to the Lower Basin, and is thus afforded more leeway in responding to hydrologic variability. For example, assuming low runoff in early years of the 10-year period, reduced releases could be made and then made up for during the occurrence a wet cycle in the latter part of the 10 years, thus meeting the 10-year delivery obligation.

The minimum objective release set forth in the LROC does not afford the Upper Basin the ability to take advantage of the 10-year average. By requiring that the Upper Basin meet the minimum objective release each year, they do not receive credit for equalization releases made during the 10-year period. The Upper Basin asserts that the Article III(d) delivery obligation should not pose a requirement for a minimum annual delivery as specified in the LROC. They believe that the minimum objective release of 8.23 MAF per year overrides the Compact.

1.4.4 Need to Establish Lower Basin Shortage Guidelines

To date, there has never been a shortage declared and the Secretary has no explicit guidelines to use in determining a shortage situation in the Lower Basin. Although no provisions are contained within the *Law of the River* regarding operational procedures, certain provisions addressing shortage allocation indicate that early negotiators did not deem the occurrence of shortage as unfathomable.

It is predicted that non-consumptive uses such as hydropower generation, endangered species, water quality and recreation would feel the worst effects of a prolonged shortage since the *Law of the River* deals predominately with consumptive uses (MacDonnell et al., 1995). Operation schedules that are favorable to hydropower generation would be constrained as they would be in conflict with minimum and seasonal flow needs to prevent endangered species' extirpation and salinity concentrations affecting water quality. Furthermore, salinity standards would certainly be threatened during shortage if the apportionments by the *Law of the River* remained utilized in full. Conflict would arise between the Endangered Species Act and the Secretary's obligation to protect listed species and the consumptive use commitments under the Law (MacDonnell et al., 1995).

In the absence of shortage criteria, the provisions addressing shortage in the *Law of the River* will be called upon and will ultimately govern the reservoir operation during a shortage situation. High tensions between river users during these times will bring any uncertainties in these provisions to the forefront. Therein lies the need for established shortage guidelines that provide direction for the Secretary, aim to mitigate conflicts between consumptive and non-consumptive uses and help stakeholders to plan better by providing a systematic method to shortage declaration.

1.5 Proposed Research

The *Law of the River* will be looked to for guidance for reservoir operations both in response to and in preparation of drought conditions on the Colorado River

Basin. However, the *Law of the River* uses general and ambiguous language regarding water allocation procedures during shortage that is interpreted differently by major users, mainly the Upper and Lower Basins. In addition, the *Law of the River* does not specify operational procedures for Colorado River facilities during shortage years. This reason and the latter render the *Law of the River* inadequate in addressing drought conditions and the need for shortage policy consistent with the *Law of the River* essential.

The Severe Sustained Drought Study, published in 1995, investigated alternative reservoir operating policies in response to severe drought conditions. An operational policy known as “reverse equalization” showed potential in drought conditions by reducing the magnitude of shortages incurred throughout the Basin and delaying the onset of Upper Basin shortages. One reason to revisit the results of the SSD Study is that reverse equalization was found to be the most effective in mitigating the effects of drought when violating the delivery obligation to the Lower Basin pursuant to Article III(d) of the Compact.

Under reverse equalization, Powell and Mead are operated in a coordinated manner. Regardless of reservoir starting conditions, releases are made from Powell to equalize the contents by the end of the year. The coordinated approach to the operation of Lakes Powell and Mead is appealing because it aims to restore the imbalance that is the effect of the normal operations of Powell and Mead at the onset and coming out of drought conditions. This coordinated approach to reservoir operation is both innovative and timely.

Key characteristics of coordinated operation are reduced releases from Powell below the minimum objective and equalization releases at a level below the 602(a) storage level. These features relax operational guidelines set forth by the LROC but are not in direct conflict as the LROC is open to formal review at a minimum of five years to address any shift in management objectives on the river.

This research proposes to further the ideas of the SSD Study by investigating and evaluating the performance of two alternative operating policies that are centered on coordinated operation for Lakes Powell and Mead. To perform the analysis, a modeling tool was needed that would both effectively capture the complex *Law of the River* and accurately represent the physical constraints of the system. In addition, the tool needed to possess the capability of being easily and quickly modified to enable the implementation of the proposed coordinated operation strategies. Additional requirements were that the tool be both fast and accurate. CRSS-Lite, a policy evaluation model implemented in the modeling system RiverWare and based closely on Reclamation's official planning and operations model CRSS, was developed to meet these needs.

Using the CRSS-Lite model, two coordinated operational procedures are explored. The coordinated operation strategies are combined with two sets of pre-existing shortage criteria to form six different scenarios. The shortage criteria are used to determine when a shortage is to be declared and to what extent deliveries are to be curtailed. The results of the coordinated operation strategies are examined in terms of reservoir levels and the frequency and magnitude of shortages to the Lower

Basin and Mexico. The results are discussed in terms of the potential benefits and other implications from an Upper Basin and Lower Basin perspective.

Using Modeling for Policy Evaluation on the Colorado River

This chapter begins with a description of the state of modeling on the Colorado River. In the second section, the modeling tool used in this research, CRSS-Lite, is presented and key aspects are described including the development process, data requirements and representation of current policies. The purpose of this section is to describe 1) how CRSS-Lite mimics the physical components of the Colorado River basin and 2) the ruleset containing the policy to operate those components.

1.6 Current Modeling on the Colorado River

The long history of litigation on the Colorado River over the limited water supply and conflicting views on how those supplies are to be effectively allocated and managed renders the use of a computer model for planning and investigating management alternatives essential. In addition to performing planning studies, a model facilitates communication and understanding of the policies between stakeholders and water managers. A variety of modeling systems are available to water management agencies and stakeholders although often they do not offer the flexibility required to mimic the changing multiple objectives of water projects and require significant effort and expense to maintain and update (Zagona et al., 2001).

1.6.1 Official River Operations Model CRSS

Reclamation utilizes RiverWare that overcomes these shortcomings by its flexible policy expression and the extensive library of physical processes algorithms (Zagona et al., 2001). The Colorado River Simulation System (CRSS) is Reclamation’s designated monthly timestep model used to simulate reservoir and river operations in the Colorado River Basin. It was originally developed in the 1970’s and 80’s as a FORTRAN program. In the mid-1990’s, Reclamation re-implemented CRSS in RiverWare, with involvement of interested stakeholders. The Law of the River and other operating criteria are expressed as logical rules in RiverWare’s rule language that can be understood and modified to meet changing objectives in the basin and are isolated from the physical process model. The RiverWare version of CRSS is now the officially accepted version of the model. The process of implementing CRSS in RiverWare clarified many policies not documented in the FORTRAN version and was crucial in providing the foundation upon which new policies can be added. The flexibility of the RiverWare version of CRSS has made possible model studies for long-term planning, mid-term forecasting and short-term scheduling.

1.6.1.1 RiverWare

RiverWare is a computer software package developed by the University of Colorado Center for Advanced Decision Support for Water and Environmental Systems (CU-CADSWES). It is a generalized river basin modeling tool than can be applied to a river basin of interest for operations and planning purposes (Zagona et al., 2001).

RiverWare is visually oriented and displays and represents the physical river system using a series of predefined objects such as reservoirs, river reaches, canals, etc. These objects are linked together and information is propagated between them via the links when a simulation is performed.

A RiverWare model can be run in three different modes. These are pure simulation, rule-based simulation and optimization. Both CRSS and CRSS-Lite are run in rulebased simulation mode. Rulebased simulation is driven by a set of specified operating policies, i.e., a ruleset. The RiverWare Policy Language (RPL), viewed and modified outside of compiled code, allows the specification of logical statements (i.e. "if-then-else" or "while" statements) and other customized functions to represent policy. The policy contained within the ruleset drives the simulation by setting values on variables within objects on the workspace. The objects then solve their hydrologic equations according to the values the stored values.

1.6.1.2 Long-Term Planning Studies

Long-term planning studies examine the effects of changes on the river system – new or modified structures, change in hydrology or climate, changes in water use and demands, and changes in operating procedures. Examples of long-term planning studies include the Interim Surplus Criteria EIS, Lower Colorado Multi-Species Conservation Plan and the formal review of the LROC (Fulp and Harkins, 2001).

Since the National Environmental Policy Act (NEPA) became a law in 1969, significant federal actions affecting the river system must undergo analysis for environmental compliance and benefits. These studies, involved with Environmental Impact Statements (EIS) pursuant to NEPA require long-term planning model runs that compare several operating policy alternatives. At the initiation of the NEPA process, a public scoping process is conducted to inform the public and formulate potential policy alternatives. From this process, policy alternatives are chosen and modeled in CRSS to assess potential impacts (Fulp and Harkins, 2001).

Due to the wide-ranging effects of these impacts, the time-horizon over which the model is run is on the order of decades. Different operating policies are implemented in separate rulesets, which are interpreted by RiverWare when the model is run. Model output is managed and presented using a Graphical Policy Analysis Tool (GPAT) jointly developed by CU-CADSWES and Reclamation. GPAT presents the output from several RiverWare simulations in graphical comparative figures allowing the impacts of policy alternatives to be fully explored (Wheeler et al., 2002). GPAT was used extensively to display the results of the policy alternatives modeled in this research.

To represent hydrologic uncertainties during long-term policy studies, CRSS uses a technique known as the index sequential method (ISM). Under this technique cycling through the historical hydrologic record, dating 1906 through 1995, generates a future inflow scenario. The result is 90 different hydrologic sequences, referred to as “traces” for each policy alternative. Each inflow scenario can be any number of years in length; however, an inflow scenario of greater than 90 years will result in a portion of the historical record being repeated in each trace (Ouarda et al., 1997). This technique is described in more detail in section 4.3.

ISM continues to be the accepted technique for policy on the Basin despite its shortcomings. The most obvious of these is that the hydrologic sequences generated are limited to what has been seen historically. Using the historical record, the 2000-2004 hydrologic situation could not have been predicted. The need to both develop unique sequences and extend the hydrologic period of record to better represent present day conditions has been stressed (Weatherford and Brown, 1986). Reclamation is making strides towards this concern. They are currently in collaboration with the University of Colorado and Colorado State University to develop stochastic hydrology using both parametric and non-parametric approaches to allow for consideration of hydrologic sequences that are consistent with the statistical characteristics of the period of record, but have not actually occurred.

One option available for water managers to extend the hydrologic period of record for policy decision-making is to incorporate tree-ring reconstructed data of years prior to the first year in the historical period of record. It is an ongoing effort to tailor data of this type to fit the forecasting needs of water managers. The actual use of this data in decision-making, however, represents a challenge that is well understood but not easily overcome between water managers, scientists and public perception. Water managers must frequently operate in environments with multiple players and constrained by regulatory and institutional contexts. The main objective of a water manager is to reach an operating procedure that is optimal under multiple conditions and minimizes risk. From a scientist's perspective, the understanding and explanation of the natural environment are primary goals (Jacobs and Pulwarty, 2003). To a water manager, new information sources can represent risk and the repercussions of management error, especially regarding water shortage, can be substantial in terms of liability (Rayner et al., 2005).

1.6.1.3 Mid-Term Planning & Forecasting Models

Mid-term studies, done on a forecasting horizon of one to two years, include the development of the Annual Operating Plan (AOP) and the "24-Month Study." The AOP is based on a monthly planning model developed each year in consultation with the seven Basin States to determine the projected operation of the river for the following year. It uses forecasts provided by the National Weather Service's Colorado River Forecast Center. The AOP is the basis for decisions such as whether demands will be met under normal, surplus or shortage conditions; the amounts of end-of-water-year storage in the Upper Basin reservoirs; and the availability of river water for delivery to Mexico. The "24 Month Study" model is updated monthly to reflect changes in hydrology and demand and projects reservoir operations for the next two years (USBR, 2005a).

1.6.1.4 Short-Term Scheduling Models

Short-term scheduling for consumptive use and power generation for the Lower Basin is managed through the short-term scheduling model "BHOPS." This model projects the elevations for the lakes Mead, Mohave and Havasu on a daily basis over a time-horizon of four to six weeks. As in the 24 Month Study model, BHOPS is updated to reflect changes in demand, hydrology and system constraints.

1.7 CRSS-Lite - Policy Modeling Evaluation Tool

CRSS-Lite (Lite) was designed to provide a faster, less complex alternative to CRSS for the purpose of screening policy alternatives, policy evaluation and comparing the results of different operations in the Lower Basin. Lite was developed as part of this research at the University of Colorado Center for Advanced Decision Support for Water and Environmental Systems (CU-CADSWES) in collaboration with Reclamation using the modeling tool RiverWare. The representation of the physical system and operational policies in Lite directly mimic those of the Lower Basin in CRSS. Although many computations and operations are made within Lite at a monthly time series, the model runs on an annual basis. Due to ongoing assessments and adjustments made pertaining to the operation of the reservoirs in the Upper Basin above Lake Powell, Lite does not model the river basin above Powell. Variations in Upper Basin demand schedules and hydrology must still be modeled in CRSS. Future work includes the incorporation of the Upper Basin above Powell into Lite.

Although testing of Lite indicates that the results are within 10^{-4} percent of CRSS, the detailed monthly timestep model would still be used to provide the final model results for the final evaluation of selected alternatives used for subsequent resource analyses (i.e., analyses for EIS). Studies of this sort require analyses of monthly data such as flows in reaches for environmental considerations of which Lite does not provide Lite. Lite requires a run-time of approximately fifteen minutes for 90 traces. The coordinated operation strategies investigated as part of this research are modeled in Lite.

1.7.1 Motivation

In addition to being developed to evaluate policy scenarios for the sake of this research, Lite was developed as a potential replacement of CRSSez. CRSSez is a simplified Visual Basic model that was developed by Reclamation in the early 1990’s, based on the old FORTRAN version of CRSS. The greatest benefit of

CRSSez is its speed; it is capable of performing a 90-trace simulation on the order of minutes. It does, however, have the same limitation as the old FORTRAN model: the operating policies cannot be explicitly seen (they are hidden in the code) nor can the policies be modified by the user to investigate new alternatives. Thus, its use is limited to investigating only previously developed polices, alternative demands, or hydrologic inputs.

One reason for the fast run-time of CRSSez is that the reservoirs in the Upper Basin above Powell are aggregated and represented as a single virtual reservoir. This virtual reservoir is operated by applying linear regression equations that predict the inflow to Powell based on historical hydrology, Upper Basin demands and a shortage coefficient derived from CRSS data (USBR, 1998). Also, in CRSSez the operation of the Upper Basin virtual reservoir is dependent on Powell's capacity, which is consistent with the FORTRAN version of CRSS but is not consistent with the current version of CRSS or real operational procedures.

This does not meet the current need for investigating new alternative policies for re-allocation of water or reservoir operations. CRSS-Lite, developed in RiverWare meets this need. RiverWare was developed with the intention of meeting the needs of water management agencies in replacing obsolete site-specific models. RiverWare provides a RiverWare-specific rule language, a rich programming language kept separate from the compiled code that is easily modified and viewed by the user (Zagona et al., 2001). The ability of this language to capture significant detail is demonstrated by its ability to capture the complexity of the operational policies in CRSS.

From the perspective that the primary purpose of CRSS-Lite is the investigation and evaluation of policy alternatives, a language that presents a clear representation of the policy that can be viewed explicitly, and communicated to and shared with various bodies of stakeholders is absolutely essential. CRSS-Lite provides a replacement to CRSSez, built with the modeling paradigm of the prior-generation of hard-wired models and allows users to view and understand the details of the policies participate in the exploring of new alternatives.

1.7.2 Design Objectives

Objectives that governed the design of Lite pertained mainly to performance and ease of use. Regarding performance, the model was to be fast and accurate, both measured in comparison to CRSS. Objectives concerning ease of use were that the management of the model output be less extensive and the model possess the flexibility to easily investigate not just alternative policies but various hydrologic conditions, demand schedules, additional gains and losses, etc. The objective of model flexibility was achieved by implementing the model in RiverWare, which provides maximum flexibility to the models it supports.

Execution of an entire suite of planning runs in CRSS can take up to four hours with extensive data input and output routines that consist largely of disaggregation or aggregation procedures to convert annual data to monthly or vice versa as necessary. For the reason of improving run-time and making the model output more manageable, Lite was implemented on an annual timestep.

The greatest challenge in developing Lite was reconciling the objective of a fast run-time with that of a high level of accuracy. There were two main issues leading to this challenge. First, the operating policies of Lakes Powell and Mead are inherently monthly and require monthly data, yet Lite was to run on an annual timestep. Second, because the Upper Basin reservoirs above Powell are operated independently of Powell and below, not modeling the Upper Basin above Powell would result in significant run-time being saved. However, monthly values are required from the Upper Basin, i.e. reservoir storages and the inflow to Powell, for operating policies of Powell and Mead. These issues and how they were resolved is discussed in more detail in the following sections.

1.7.2.1 Critical Issue 1 – Monthly Rules for Powell & Mead

For speed and simplicity, the CRSS-Lite model was designed to operate on an annual timestep. However, certain operational policies for Powell and Mead such as Mead flood control, equalization and Powell’s minimum objective release are inherently monthly in their logic and execution. Both equalization and the minimum objective release cannot be run in an annual (calendar year) timestep model because their logic executes on a water year basis. If equalization is to occur, it must be completed by the end of the water year. Likewise, Powell's minimum objective release must be satisfied by the end of the water year. Furthermore, monthly storage values of Mead and Powell are needed to determine the end of the water year storage for both, one of two key criteria for equalization. Also, Mead's flood control policy cannot be run annually because it executes different operations during runoff season, January - July, than in drawdown season, August – December, that could not be duplicated in an aggregated annual model. This policy also uses monthly storages of

Powell and other Upper Bain reservoirs to determine the amount of available flood control space in the basin.

The approach taken to resolve this issue was to run the model on an annual timestep, but develop new rules for Powell and Mead that iterate through the months at each annual timestep to come up with accurate results. This approach combines an annual timestep with monthly policy in a way that does not overly simplify the rules. However, this requires monthly values, specifically, inflows to Powell, storages of some Upper Basin reservoirs, and gains between Powell and Mead.

Some of the more computationally intense rules that would require significant run-time if monthly iterations were performed in RiverWare's policy language, RPL, were implemented in C++. Code executed in compiled C++ is much faster than interpretation and execution of RPL, a Flex-Bison based language. The drawback of this is that the code in C++ is not accessible for inspection and modification. Some of the rules, e.g., equalization, were viewed as likely candidates for policy evaluation and modification and were therefore not implemented in C++. However, it is highly unlikely that Mead's flood control algorithm would be modified and was therefore implemented in C++.

1.7.2.2 Critical Issue 2 – Representation of Upper Basin Above Powell

Tests were conducted to evaluate where in the detailed monthly model CRSS the most run-time was being used. The results of these tests showed that if the Upper Basin above Powell was removed from the model and the Lower Basin and Powell simulated with imported monthly inflows to Powell and Upper Basin reservoir storages, a 30% savings of run-time would result. This was identified as a significant potential source for performance gains.

The consideration of the removal of the Upper Basin above Powell was possible only because the same hydrology and depletions in the Upper Basin always result in the same inflow to Powell. This has been true in the past, i.e., all previous conditions and hydrologic scenarios under which CRSS was run did not require the reservoirs above Lake Powell to make releases based on Powell's storage level. In fact, when the CRSS rules were redeveloped in 1996-97, the Upper Basin dependency on Powell's storage was not maintained in the policy in keeping with operational experience. However, it is possible that future conditions and analysis of extreme hydrology could necessitate the Upper Basin reservoirs above Lake Powell making releases based on Powell's storage. To this end, Reclamation's CRSS modeling team is currently working on an enhanced operational policy set for the detailed CRSS model that provides for Upper Basin operational dependency on Powell's storage during dry hydrology sequences.

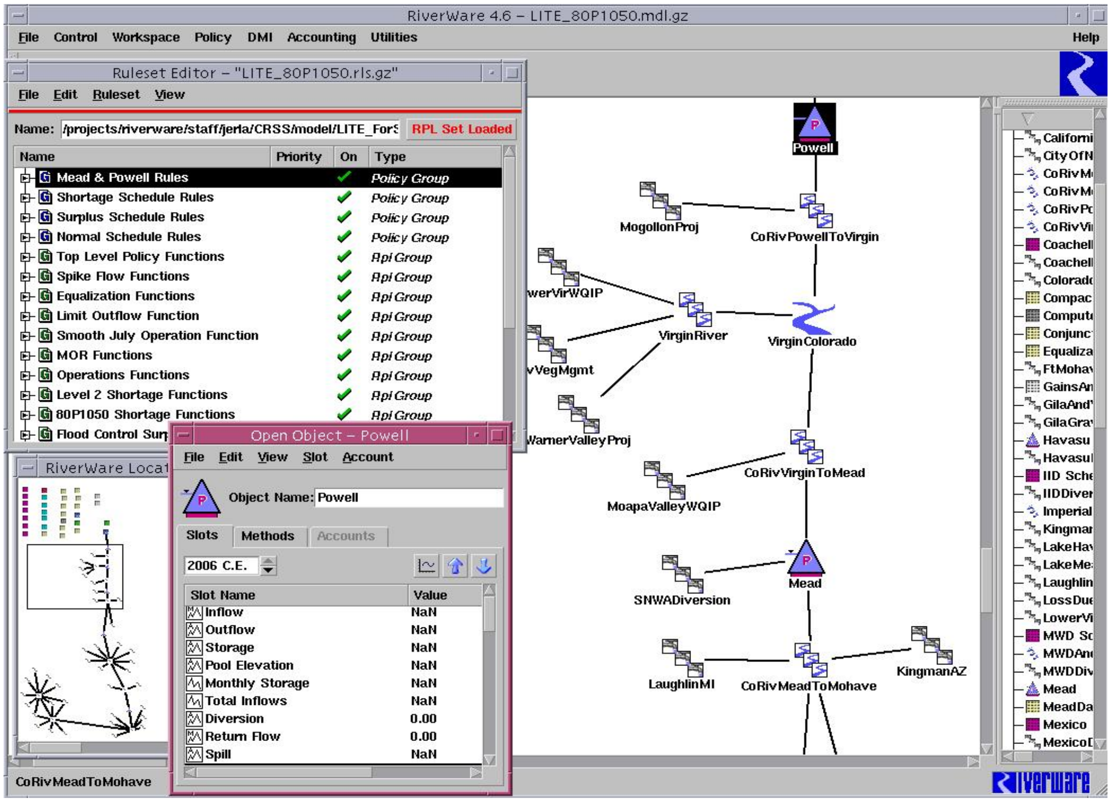
There were two main problems encountered with omitting the Upper Basin above Powell. First and foremost, omitting the Upper Basin assumes that there will always be enough water in the system such that Powell can make the minimum objective release and that a "Compact call" will not be made to Upper Basin by the Lower Basin. Powell was able to release 8.23 MAF during the five consecutive years of drought beginning in 2000, which stands as the worst drought in the period of record. Based on this fact, it was determined that unless the drought worsened, Powell would be able to release 8.23 MAF and the Upper Basin above Powell could be omitted.

Second was the fact that the operating policies for Mead and Powell require monthly values generated in the Upper Basin. An alternative modeling approach that involves simplifying the Upper Basin above Powell as to operate on an annual timestep (thereby reducing run-time and generating annual data for the Powell and Mead rules) was considered but eliminated. Because monthly data is required for the Powell and Mead rules, a disaggregation scheme would need to be applied to the annual output of the Upper Basin. This would introduce inaccuracies that were determined to be unacceptable as the performance of the Powell and Mead rules were capable of being 100% accurate if given accurate data.

The Upper Basin above Powell was ultimately omitted from CRSS-Lite and required monthly Powell inflows and specific reservoir storages are imported from the output of the detailed monthly CRSS model. This approach further improves runtimes and eliminates all inaccuracies from the Powell monthly inflows and reservoir storages. This approach does have the drawback, however, that it assumes that the Upper Basin will always in the future operate without regard to Powell’s storage. Meaningful changes to Upper Basin depletions, hydrology, or operating policies are done in the detailed model from which modified outputs (Powell inflows and reservoir storages) are extracted. As a way to approximate the effects of altered Upper Basin depletions, Lite provides the capability to modify Powell’s inflow in a simplified manner to reflect the modified depletions.

1.7.3 Model Description

Lite is comprised of simulation objects and links that account for system gains and losses and represent the physical operation and transfer of water throughout the system. Another major component of the model is a ruleset containing the policy that dictates the operation of the major reservoirs and diversions in the system. An example of the CRSS-Lite workspace is pictured in Figure 2-1. Figure 2-1 shows the ruleset containing the operational policy that drives the rulebased simulation of the model, the Powell reservoir object, and the Locator View. Towards the right of the figure are the objects that comprise the river reach between Powell and Mead. The Locator view, at the bottom left-hand corner of the figure, is an entire schematic of the model. The white highlighted area is a locator view of the model’s current position. To the left of the Locator view is the open-object view of the Powell reservoir object. All data required for the physical operation of Powell is located within the slots in the object.



Name: /projects/riverware/staff/jerla/CRSS/model/LITE_ForS

Name	Priority	On	Type
Mead & Powell Rules		✓	Policy Group
Shortage Schedule Rules		✓	Policy Group
Surplus Schedule Rules		✓	Policy Group
Normal Schedule Rules		✓	Policy Group
Top Level Policy Functions		✓	Rpl Group
Spike Flow Functions		✓	Rpl Group
Equalization Functions		✓	Rpl Group
Limit Outflow Function		✓	Rpl Group
Smooth July Operation Function		✓	Rpl Group
MOR Functions		✓	Rpl Group
Operations Functions		✓	Rpl Group
Level 2 Shortage Functions		✓	Rpl Group
80P1050 Shortage Functions		✓	Rpl Group
Flood Control Sur			

Object Name: Powell

2006 C.E.

Slot Name	Value
Inflow	NaN
Outflow	NaN
Storage	NaN
Pool Elevation	NaN
Monthly Storage	NaN
Total Inflows	NaN
Diversion	0.00
Return Flow	0.00
Spill	NaN

Figure 2-1 Snapshot of the CRSS-Lite Workspace from Lakes Powell to Mead

Four reservoirs (Powell, Mead, Mohave, Havasu) and 46 diversions are modeled (demands and return flows) throughout the Lower Basin. Appendix A lists these diversions. There are hydrologic "natural" inflows (flows corrected for upstream regulation and consumptive uses and losses) at nine inflow points throughout the Lower Basin. The nine natural inflow points are among reach objects throughout the workspace.

Requested and actual diversions and depletions are stored in diversion objects. These objects are linked to reaches with the exception of SNWA’s diversion is linked to the Mead reservoir object. The amount of water that can be diverted depends on the amount available in that diversion or reservoir object. Unless the total available water is less than the requested diversion, the requested diversion and thus requested depletion is met. The resulting return flow, the difference between the actual diversion and depletion, is linked back to the object (reservoir or reach) supplying the water.

The reservoirs in Lite compute both evaporation and bank storage but do not model either power production or sedimentation. The evaporation is modeled as a function of monthly evaporation rates or coefficients and reservoir surface area. Storages are converted to pool elevations and then to surface areas. The evaporation is computed by multiplying the average surface area over the month by the monthly coefficient. Each monthly value is summed together resulting in an annual evaporation or the total volume lost to evaporation during the year. The evaporation coefficients for Powell, Mead, Mohave and Havasu are listed in the next section in Table 2-1.

The bank storage is modeled as a function of reservoir storage. The change in bank storage is computed as a percentage of the change in reservoir contents over a month. Bank storage coefficients for each reservoir are listed in the next section in Table 2-2.

1.7.3.1 Data Requirements

The data requirements for Lite fall into three categories: consumptive use, hydrologic, and that pertaining to reservoir operation or the data required for the historic ruleset. Consumptive use and hydrologic data are required on both a monthly and annual basis.

1.7.3.1.1 Consumptive Use & Hydrologic Data

Consumptive use requirements consist of annual depletion and diversion schedules and percents to disaggregate schedules of the major diversions (CAP, SNWP, IID, MWD, Mexico, and Coachella) into monthly schedules. The major diversions of the Lower Basin schedules' are adjusted by rules depending on whether normal, surplus or shortage conditions exist. Section 1.2.3.2 describes these scheduling rules. The other Lower Basin diversion schedules are user-input and are unchanged during the simulation. Appendix B includes the consumptive use schedules for the Lower Basin totaled by state.

Hydrologic data requirements include a combination of annual and monthly natural flows. Natural flows are flows corrected for upstream regulation and consumptive uses and losses. Annual flows are input to reach objects that dispatch during the simulation while monthly flows are required for to run the Mead Flood Control method.

1.7.3.1.2 Upper Basin Data

Lite requires the monthly inflow to Powell and the monthly storages for the Upper Basin reservoirs Fontenelle, Flaming Gorge, Blue Mesa and Navajo. These reservoir storages are used to compute the runoff forecast to Powell a main variable in the computation of Powell's monthly storage. These reservoir storages are also used as part of Mead's flood control operation. Under the flood control algorithm, a system space requirement exists each month and may be met by combining Mead's space with existing space in the Upper Basin Creditable storage Reservoirs (Powell, Navajo, Flaming Gorge, Fontenelle and Blue Mesa). For this reason, the monthly storages of these reservoirs are required to perform Mead's flood control algorithm. This algorithm is explained in more detail in Appendix D.

Powell's monthly inflow is a required known for computing Powell's monthly outflow. The monthly outflow from Powell is needed to compute Mead's monthly inflow, which is used in the mass balance equation to solve for Mead's monthly storage once the required release is computed.

1.7.3.1.3 Reservoir Operation Data

Data requirements for all reservoirs are an initial pool elevation, monthly evaporation coefficients and bank storage coefficients. In addition, Mohave and Havasu are operated according to their respective guide curves. Evaporation and bank storage coefficients reflect what is currently used in CRSS and were determined in various studies of historical data (USBR, 1985). This data is listed in Tables 2-1, 2-2 and 2-3.

	Powell	Mead	Mohave	Havasu
January	0.198	0.360	0.360	0.340
February	0.186	0.330	0.360	0.410
March	0.233	0.370	0.480	0.480
April	0.265	0.460	0.610	0.590
May	0.359	0.530	0.810	0.700
June	0.411	0.640	0.930	0.810
July	0.466	0.800	0.930	0.900
August	0.478	0.850	0.840	0.890
September	0.415	0.700	0.680	0.810
October	0.375	0.510	0.560	0.650
November	0.312	0.510	0.400	0.460
December	0.261	0.440	0.350	0.350

Table 2-1 Reservoir Evaporation Coefficients (ft/month)

Powell	Mead	Mohave	Havasu
0.080	0.065	0.000	0.000

Table 2-2 Reservoir Bank Storage Coefficients

	Mohave	Havasu
January	1666	539
February	1666	543
March	1688	555
April	1699	594
May	1699	611
June	1671	611
July	1658	580
August	1658	570
September	1564	557
October	1371	548
November	1460	543
December	1583	539

Table 2-3 Mohave and Havasu Rule Curve (Storage in 1000 acre-ft)

1.7.3.2 Historical Ruleset

The Lite ruleset contains rules that mimic the operation of Powell and Mead in addition to the scheduling determination of the major diversions in the Lower Basin. These rules are essentially identical to those in CRSS, the primary difference being that, within a given year, the rules in Lite are evaluated once per timestep whereas in CRSS many rules execute twelve times per year, or once per month. The operation of Mead and Powell is inherently monthly, specifically with regard to equalization and Mead’s flood control algorithm, and cannot be approximated on an annual basis while yielding accurate results. Lite maintains the monthly operations within rules that are executed annually by performing twelve monthly iterations within a single execution.

The purpose of this section below is to provide a general overview and description of how Powell and Mead operations are replicated in Lite. The operations described reflect the baseline, i.e., current operating conditions. Because Lite simulates at an annual timestep and Powell and Mead are operated on a monthly timestep, these operations cannot be contained in separate rules as seen in CRSS. Instead they must be represented through several functions that are contained in one rule. The rule is executed annually, once for every simulation timestep. However, functions referred to as operational functions contained within the rule execute a minimum of twelve times, in some cases more if additional iterations are required.

A detailed description of the ruleset and operational functions can be found in the CRSS-Lite Overview and Users Manual. Appendices C and D provide a conceptual description of the baseline operating policies.

At the beginning of each year several rules are executed to compute information that is required to determine Powell and Mead’s operation. Because these variables do not depend on the monthly contents at Powell or Mead, they can be computed in separate rules. Examples of these variables include 602(a) storage and the spring runoff forecast into Powell. Also determined at the beginning of each year are whether normal, surplus or shortage conditions exist in the Basin and how the depletion schedules of Lower Basin users (SNWA, MWD, Coachella, IID, CAP) and Mexico will be adjusted accordingly. Normal conditions exist when neither surplus nor shortage conditions exist. No adjustments are made to requested demand schedules under normal conditions. The determination of shortage conditions is based on shortage criteria designed to protect specific elevations at Mead. These criteria and the how shortage allocations are made are discussed in detail in Chapter 3.

Surplus determination is made pursuant to the Record of Decision for Interim Surplus Guidelines through 2016. After 2016, surplus determination is made in a rule that represents the 70R Strategy. This strategy was established from an analysis conducted by Reclamation in 1986 that developed an operating strategy for distributing surplus water to avoid spills (USBR, 2000b). This rule determines a surplus condition to exist if, assuming a 70th percentile historical runoff (thus, “70R”) and normal Lower Basin demands, the combined space available in Powell and Mead at the end of year is less than the space requirement for flood control.

In the event of a surplus, the schedules of entities to receive surplus waters are adjusted to surplus schedules set forth in the Final Environmental Impact Statement for the Secretarial Implementation Agreement (SIA-FEIS).

Once demand schedules have been set, the rule that computes the monthly storages for both Powell and Mead is executed. Operations for both reservoirs are modeled in a single rule because for a given month, Powell must look to the previous month’s storage at Mead in order to determine whether or not equalization is to occur. In turn, Mead must look to the storage at Powell in a given month in determining the system space available, a key decision point for Mead’s flood control operation.

At each monthly computation within this rule, the first step is determining Powell’s storage. Next, Mead’s storage for that month is computed based on Powell’s storage for that month. After Mead’s storage is computed the next month’s computation begins in which Powell’s storage is computed based on the previous month’s storage at Mead.

Operational functions used to determine Powell’s storage represent the operating priorities set forth in the LROC and the SIA-FEIS. The SIA-FEIS established the criteria for the triggering of Beach/Habitat Building Flows or spike flows, which are high releases of short duration for the purpose of distributing sediment and nutrients to provide and restore the dynamics of the natural system (USBR, 2000b). The model criteria for a spike flow release are described in Appendix C.

To determine Mead's monthly storage a pre-defined (hard-coded) function is called that both computes the release needed to meet downstream demands and the release required by the flood control algorithm. The storage returned from the function is the storage corresponding to the greater of the two releases. In the event of a flood control release, the Lower Basin and Mexico schedules are adjusted to reflect surplus conditions. Both the flood control algorithm and the computation of the demand driven release are documented in Appendix D.

Coordinated Reservoir Operation & Shortage Criteria

The *Law of the River* contains a framework for shortage conditions, however, the LROC which contains the current operating criteria for Lakes Powell and Mead, does not define shortage nor does is contain shortage policy that provides a plan of operations for these reservoirs during drought conditions. The need for this policy is elevated as annual inflows to Powell compete with record lows. Furthermore, a difference of opinion exists regarding the interpretation of provisions within the *Law of the River* that would be governing under shortage conditions. In December of 2004, the Secretary announced that Reclamation would initiate a process to develop official shortage guidelines for the Lower Basin and that the guidelines would be developed and in effect by the end of her term.

This chapter will discuss coordinated operation of Lakes Powell and Mead under low reservoir conditions as a proposed reservoir operational procedure to mitigate the system impact of drought, the specific coordinated operation strategies modeled and analyzed in this research and the model implementation of these strategies. Also discussed are the shortage criteria assumptions made in absence of official criteria that used in the analysis to determine when shortage conditions exist and how allocations are to be reduced. These assumptions were necessary to measure the impact of coordinated operation on reservoir levels and shortage magnitudes.

Also discussed is the Severe Sustained Drought study, which was published a decade ago but has recently provoked renewed interest. This study is also relevant because it explores the concept of coordinated reservoir operation. The final section of this chapter discusses the possibility of risk from coordinated operation in terms of hydropower, recreational uses and consumptive uses.

1.8 Shortage Criteria

In the absence of official shortage criteria, under the current legal framework the declaration of shortage conditions is at the discretion of the Secretary. From a modeling standpoint, established shortage criteria are essential because the modeling software must have a way of knowing 1) whether or not the model is in shortage conditions and 2) how to respond if shortage conditions exist. Thus, shortage criteria were developed for modeling purposes to serve two purposes: first, to determine when shortage conditions exist and second, to determine which users and are to be shorted, in what order and by how much. Although there are no established criteria in the *Law of the River*, most provisions regarding allocation priorities during shortage are explicit and are reflected in the criteria used for modeling purposes.

Shortage criteria in the model also serve as a basis for analysis. By governing when and how shortage is administered, the shortage criteria provides a way to measure the outcome of an operational policy in terms of shortage probability and magnitude. Shortage probability and magnitudes are critical model results that are used to assess the benefits and drawbacks of a policy and examine any tradeoffs.

Shortage criteria were included in the earliest versions of CRSS to address concerns related to low water levels at Mead. During the development of the ISG Reclamation selected three critical Mead elevations to protect based on known economic and socioeconomic impacts that would occur if Mead were to drop below these levels (USBR, 2000b). These critical elevations and their significance are presented in Table 3-1 (USBR, 2005c).

Lake Mead Elevation (ft)	Significance
1083	Estimated minimum elevation for efficient power generation at the Hoover Powerplant[1]
1050	Minimum elevation for operation of SNWA's upper intake structure
1000	Minimum elevation for operation of SNWA's lower intake structure
[1] In 2004 Reclamation engineers reevaluated the minimum elevation for power generation to be 1050 ft.	

Table 3-1 Protected Lake Mead Elevations

A two-tiered approach taken by the ISG allocates first and second level shortages to the Lower Basin and Mexico to protect these critical elevations. First level shortages use protection lines to protect either 1083ft or 1050 ft. Protection lines consist of a set of Mead trigger elevations that were developed to prevent Mead from declining below 1050 ft (1083 ft) with an 80 percent assurance probability. The elevation triggers are referred to either 80P1050 or 80P1083 depending on the protection elevation. The 80P1050 elevation triggers are used in the simulations for this research and are plotted below in Figure 3-1.

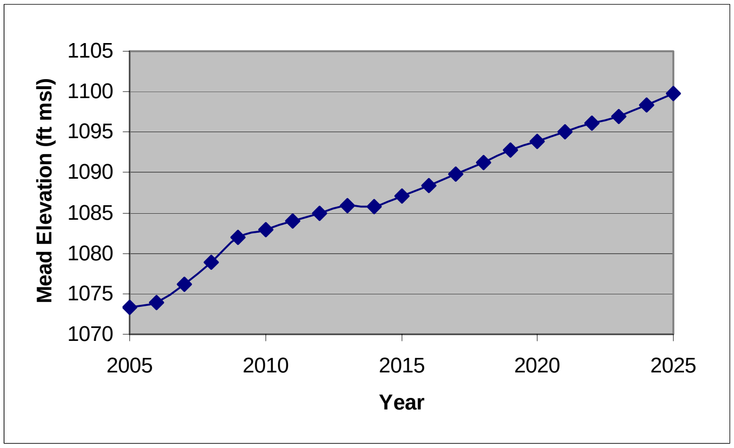


Figure 3-1 Mead 80P1050 Protection Line

The 80P1050 protection line increases because the triggers are a function of Upper Basin demand, which is projected to increase through 2025. The increased level at which a shortage is triggered indicates the expectation of decreasing inflows to Mead. The elevation triggers were developed by Reclamation using forecasted Upper Basin depletion schedules and stochastically generated natural inflows above Powell (USBR, 1998).

At the beginning of each year Mead's elevation is compared to the trigger elevation. If Mead's level is less than the trigger, shortages are administered to both CAP and SNWA, both of lower priority than California in the Lower Basin. The CAP is the lowest priority and is initially shorted the greatest. The CAP shorted depletion is set to a given amount, currently 1.0 MAF, and SNWA is reduced by four percent of the total reduction taken by the CAP. Four percent represents the percentage of Nevada's apportionment to the 7.5 MAF of the Lower Basin. Other Lower Basin diversions such as MWD, IID, Coachella and Mexico do not take a first level shortage.

If the reductions imposed by the first level shortage are not sufficient to prevent Mead from declining below 1000 ft, further shortages are imposed under a second level shortage. Under the second level shortage, probabilistic protection lines are not used. Instead, the EOWY storage of Mead is forecasted assuming a first level shortage is in place. Second level shortages are administered if the forecasted EOWY storage is below the storage corresponding to 1000 ft.

Under the second level shortage, CAP and SNWA consumptive use is reduced as needed to keep Mead at 1000 ft. If CAP and SNWA are reduced to zero and reductions are still needed to maintain 1000 ft, shortages to MWD and Mexico are imposed. It is assumed that a shortage of this magnitude constitutes "extraordinary drought" per the Mexican Treaty. According to the Treaty, under these conditions when the 1.5 MAF delivery to Mexico becomes "difficult," the delivery to Mexico can be reduced by the same proportion as consumptive uses in the U.S. Because the additional shortages still needed must be taken by MWD and Mexico, each takes 50 percent of the remaining reduction (USBR, 2000b).

This approach to determining shortage conditions and the level of curtailed delivery has been the official shortage criteria used in CRSS since introduced in the ISG. Lite uses this same approach and represents the two-tiered shortage policy through a combination of two rules referred to collectively as "Level2" for the purpose of this research. The first level shortage attempts to protect Mead at 1050 ft and uses the 80P1050 elevation triggers displayed above in Figure 3-1. Lite also contains another set of criteria, referred to as "AbsPro." Under the AbsPro criteria, no first level shortages are taken as in the Level2 policy. Shortages are administered when meeting the full schedules of CAP and SNWA would cause Mead to decline below 1000 ft. When shortages are necessary to keep Mead about 1000 ft, they are administered in the same manner as the second level shortage the Level2 policy, described in the previous paragraph.

1.9 Coordinated Operation of Powell & Mead at Low Reservoir Levels

The political boundary at Lees Ferry that divides the basin also serves as the division point for the operation of Lakes Powell and Mead. Powell is operated according to Upper Basin criteria, the minimum objective release and the 602(a) storage requirement that sends surplus storage to the Lower Basin. Mead operations are governed by downstream demands and flood control. Except for considering the capacity of Mead and Upper Basin storage as conditions for equalization, the operating policies of these reservoirs do not consider the hydrologic state of the system as a whole.

An effect of this limitation of the operating policies is an oscillating relationship between the two reservoirs during the onset and offset of drought. This relationship is depicted in Figure 3-2, which plots the storages of Powell and Mead in 1986 through 2005. Note that in 1986 both reservoirs are at approximately the same capacity. The hydrology of this period includes periods of below average runoff from about 1987 to 1994 (excluding 1993), above average from about 1995 to 1999 (excluding 1996) and average or below runoff from 2000 through 2005.

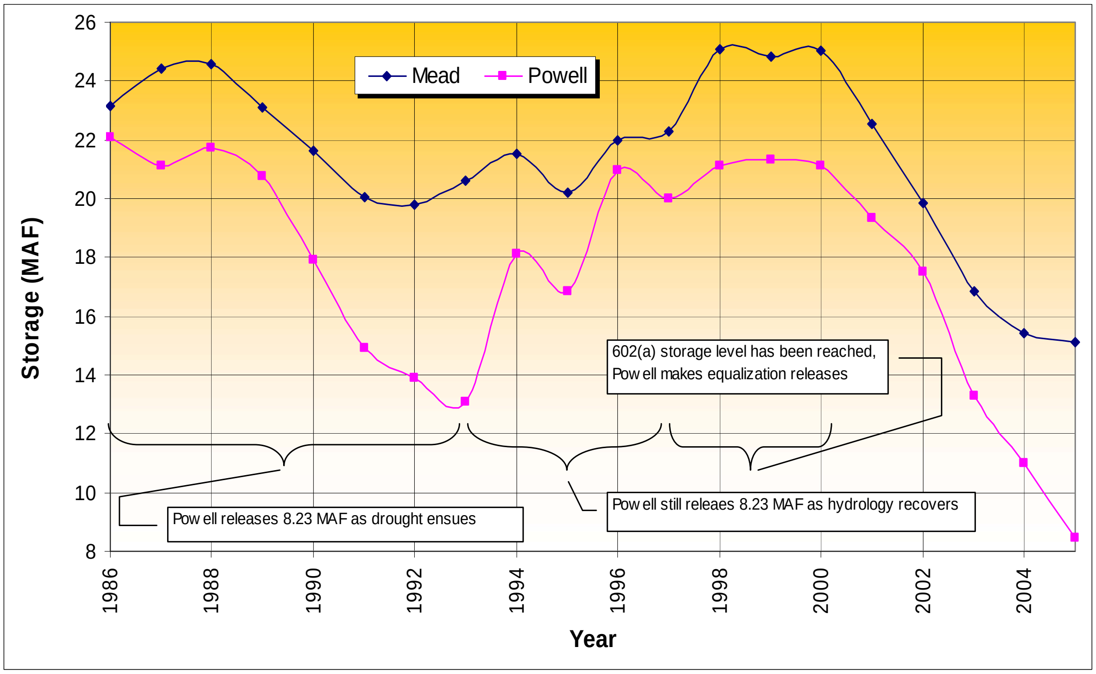


Figure 3-2 Actual Storage Capacity at Powell & Mead 1986 – 2005

At the onset of drought, as the Upper Basin storage falls below the 602(a) storage level, equalization is halted and Powell makes minimum objective releases. During drought, Powell's inflow is likely exceeded by the mandatory of 8.23 MAF annual release into Mead, thus Powell is drawn down at a rapid rate. Under this scenario, Mead declines, but at a slower rate than Powell. This is illustrated in Figure 3-2 by the steepness of the slope at which Powell declines compared to that of Mead.

As hydrologic conditions start to recover in 1993, the reservoir levels in the Upper Basin recover earlier than in the Lower Basin. Because the Upper Basin storage is below the 602(a) requirement, Powell continues to release the minimum objective release. As Powell's inflow exceeds its release, Powell recovers faster than Mead as Mead continues to release to meet downstream delivery requirements.

Notice the quick recovery of Powell (indicated by the steepness of the slope) compared to that of Mead from 1993 – 1996.

Increased consumptive use in the Upper Basin exacerbates this imbalance by increasing the 602(a) storage level. Large equalization releases that will help to raise Mead's elevation are not made from Powell until the 602(a) storage level has been met and the storage in Powell is greater than the storage in Mead. Powell makes equalization releases from 1997 – 2000 resulting in an increased storage at Mead.

Coordinated operation aims to maintain a a more consistent balance of the contents between Powell and Mead. Under coordinated operation, the objective of Powell's release during low flow times is to more evenly distribute risk to both basins. This can be accomplished by incorporating the storage capacity of Mead into the release decision of Powell at all times (rather than only during Upper Basin surplus situations as under the current policy). Given the recent animosity between the Upper and Lower Basins regarding the operation of Powell, coordinated operation is a compelling approach in that it challenges the political boundary dividing the basins by requiring that the conditions in the Lower Basin be a factor in determining the release from Powell.

This research examines the coordinated operation of Powell and Mead by modeling two separate strategies. The Severe Sustained Drought study of 1995 also considered an operational procedure similar to the coordinated operation of Mead and Powell, but as a policy alternative under severe drought conditions. The study and the outcomes are discussed in the following section.

1.9.1 Previous Modeling Studies: Severe Sustained Drought Study

The Severe Sustained Drought (SSD) study was completed in 1995 and conducted by an inter-disciplinary team from the Universities of Arizona, California, Colorado, Nevada, and Wyoming, Colorado State and Utah State Universities and Hydrosphere Resource Consultants, a consulting firm based in Boulder, Colorado. One objective of the study was to assess the ability to cope with drought under the current institutional arrangements (the *Law of the River*) and alternative arrangements. The alternative arrangements considered were built upon points of institutional flexibility that would likely be tested during the course of a severe sustained drought (MacDonnell et al., 1995). The success of the response was measured by evaluating economic, social and environmental impacts (Young, 1995).

1.9.1.1 Inflow Hydrology

The representative severe sustained drought was patterned after the most severe and prolonged period of dryness revealed by Lees Ferry tree-ring reconstructed streamflows. This period was estimated to have occurred in the period 1579 through 1600 (Tarboton, 1994). To build the representative drought used for the modeling exercise, the reconstructed streamflows from 1579-1600 were arranged in decreasing order so that the lowest flows of the sequence would be experienced when the reservoirs are already dry. These flows were followed by the reconstructed flow from 1601 through 1616 as the recovery period to form the 38-year period used for analysis. The recovery period includes a period of high flows such that the mean annual flow is equivalent to the long-term average. The drought is characterized by a 16-year mean flow of 9.6 MAF, compared to the observed historical record mean of 15.1 MAF. The return period of this drought, 2,000 to 10,000 years, is also an indicator of the uncertainty of occurrence. A drought of this magnitude is therefore extremely rare and perhaps unrealistic (Tarboton, 1995).

1.9.1.2 Alternative Shortage Policy Options

A series of simulations were formed in the AZCOL model, built in the STELLA II modeling system. These simulations considered alternative shortage policy options such as compensated and uncompensated shorting of the Mexican Treaty delivery obligation, modification of the Mead shortage elevation trigger and corresponding shorted CAP delivery. In an uncompensated shortage to Mexico, a shortage amount would be determined and would result in a savings divided among the states. In a compensated shortage, a pay-back amount would be determined and the cost would be distributed among the states and federal government. Also considered was the revision of the operating criteria for Glen Canyon Dam through alteration of the equalization rule. In addition to normal equalization, releases would be reduced, even to levels below the minimum objective release to maintain equal contents of Powell and Mead in the event that Powell is at less capacity than Mead. The need for this so-called “reverse equalization” rule was discovered when, during the first simulation, Powell’s contents were dropping at a much faster rate while Mead was staying unexpectedly high (Henderson and Lord, 1995). Elevations in Powell declined enough that, during some years, there was physically not enough water available in the Upper Basin to meet demands, thus resulting in Upper Basin shortage.

The addition of the reverse equalization rule to normal operations was determined through the AZCOL simulations to be a valuable drought coping mechanism and was explored further and in more detail using the Colorado River Model (CRM). CRM, a monthly timestep model, was developed by Hydrosphere Resource Consultants and imitates Reclamation's CRSS representation of the physical system and the policies of the Law of the River (Sangoyomi and Harding, 1995).

Three model simulations were performed in CRM to investigate the effects of reverse equalization. The first simulation followed the current operational procedures to establish a baseline run. The second simulation, Scenario 1, used the drought coping responses that included specific provisions such that the Compact requirements were met, i.e., 75 MAF over ten years delivered at Lees Ferry. The third run, Scenario 2, included the drought responses but suspended the requirements set forth in the Compact. For each model run the same 38-year sustained severe drought inflow hydrology described above was used.

The execution of the reverse equalization rule, with the fifth condition suspended for Scenario 2, was dependent on the following conditions (Sangoyomiand Harding, 1995):

1. The forecasted end of the water year (EOWY) storage in Powell was less than the forecasted EOWY storage in Mead.

2. The forecasted EOWY storage in Powell was less than maximum capacity.

3. The Upper Basin storage was less than the 602(a) storage.

4. Powell was capable of releasing a minimum of 34,000 acre-feet for the current month.

5. With the reverse equalization release, the 10-year moving average release from Powell would be greater than 7.5 MAF as to satisfy the Compact.

The criteria used to determine at what point Lower Basin allocations were to be shorted consisted of a shortage declaration level at Mead and the release available from Mead to meet four levels of shorted allocations (MacDonnell et al., 1995).

1.9.1.3 Results & Discussion

The general finding of these simulations was that reverse equalization and the suspension of the Compact (Scenario 2) mitigated Upper Basin drought effects on consumptive uses with only slight shortages to the Lower Basin. Reverse equalization and adherence to the Compact (Scenario 1) only temporarily relieved the Upper Basin from shortfalls. Once the releases required to meet the Compact overrode the reverse equalization rule, major shortfalls, larger than in the baseline, were undergone in the Upper Basin because no shortages had occurred since reverse equalization was successful in keeping Powell's elevation high. No shortages were taken in the Lower Basin even although Powell had remained at dead storage for five consecutive years.

Scenario 2 best protected Upper Basin consumptive uses. Minor shortages were taken by the Lower Basin because Powell was no longer required to release 75 MAF over 10 years and caused Mead to drop below the shortage declaration level. The power pool at Powell was better protected under both scenarios in comparison to the baseline. Because Upper Basin depletions were not as great under Scenario 1, the protection of Powell's power pool improved over Scenario 2. The SSD Study assessed the effects of reverse equalization during normal and wet years and found the effects to be inconsequential (Sangoyomi and Harding, 1995).

The SSD Study demonstrated the value of coordinated operation through its ability to reduce Upper Basin shortages and protect the power pool during severe sustained drought. Although the SSD Study showed greater Upper Basin shortage reductions from suspending the Compact, from the perspective of water resource management, for coordinated operation to be considered a viable operational option it must be in compliance with the Compact. This research looks at coordinated operation from this point of view. Other significant differences are that initial reservoir contents are much lower while consumptive use is much higher than assumed in the SSD StudySSD Study (Sangoyomi and Harding, 1995).

The depletions used in the SSD StudySSD Study began with 1992 levels and used demand growth data from Reclamation to project out to 2030. While Upper Basin demand projections used are consistent with current levels, Lower Basin demand is substantially higher than the levels used in the study. The SSD StudySSD Study made the assumption that Arizona would reduce the demand for water due to the high cost of pumping water through the CAP. The demand by the CAP averaged annually 0.519 MAF, whereas the current projection for CAP averages 1.4 MAF annually during 2005 through 2025. The shortage criteria did not impose shortages on the Lower Basin unless Mead fell below the shortage declaration level (corresponding to 10.762 MAF), even in the event that Powell was emptied. Even with the Compact suspended, very little shortage was experienced in the Lower Basin (Sangoyomi and

Harding, 1995). Thus, because the Lower Basin demand was underestimated, there were found to be no shortage reductions in the Lower Basin resulting from coordinated operation.

1.9.2 Coordinated Operation within the Current Legal Context

The notion of coordinated operation does not violate any requirements or constraints within the legal context of the *Law of River*. By allowing the minimum objective release be less than 8.23 MAF during years when Powell has less storage than Mead and making equalization releases from Powell at a level less than the 602(a) storage, some guidelines set forth in the LROC are relaxed. However, the LROC could be envisioned as being devised for this purpose. The early negotiators of the river although arguably did not appropriately address the prospect of shortage had anticipated that the managing of the river would be in a state of continuous change in order to reflect the converging and conflicting objectives of users. With this recognition, the LROC can be seen as flexibility within the legal context of the Law intended to be a place where operational changes could be made without disrupting the legal foundation.

An objective of the SSD Study was to identify operating options that showed promise for mitigating drought impacts and could potentially be implemented without Congressional action. An alternative similar to coordinated operation was one of the options identified (Henderson and Lord, 1995)

1.10 Description of Coordinated Operation Strategies

As demonstrated by the SSD Study, coordinated operation is a promising option as it was successful in mitigating the impacts of drought on consumptive uses and is within the legal context of the *Law of the River*. It provides relief to the Upper Basin at the onset of drought by allowing Powell to make reduced releases. Whereas under normal operations Powell would be drawn down at a fast rate meeting the 8.23 MAF minimum objective release, under coordinated operation that rate is decreased, providing a storage buffer to the Upper Basin. As the drought recovers, water is released to the Lower Basin at a level less than the 602(a) storage level thus promoting Mead's early recovery.

Both coordinated operation strategies analyzed in this research were developed in a collaborative effort between Reclamation and the Basin States. In both strategies the release from Powell is reduced below the 8.23 MAF minimum objective release under certain conditions. The first strategy (C1*"Relaxed MOR & EQ"*) allows this to happen when Powell is below a trigger elevation and Mead is above a trigger elevation. Equalization occurs, but only temporarily, at a level that is below 602(a) storage. The second strategy (C2*"Balance Contents"*) is more similar to the coordinated operation strategy in the SSD Study. In this strategy, the objective is to keep Powell and Mead at equal capacity, essentially operating them as a single reservoir. Releases are reduced as necessary from Powell if the storage at Mead is higher. Conversely, if the storage at Mead is lower, larger releases will be made from Powell. In both strategies there is no constraint in place that protects the minimum power pool at Powell.

Each simulation run begins in 2005 and ends in 2025; runs are performed with each strategy in place through 2025 and with each strategy in place through 2016, the interim period defined by the ISG. The interim period is viewed as a transitional period and alternative operating policies are frequently modeled by Reclamation as being in effect only during this period. Baseline or normal operations are in effect 2017 through 2025. The operations for Mead were not modified. The presentation of the strategies first includes a general description followed by a step through of the model logic during each month so as to further clarify the algorithm. Appendices E and F provide detailed descriptions of the strategy implementation in the Lite ruleset.

1.10.1 Coordinated Operation Strategy – C1 *"Relaxed MOR & EQ"*

Two main features of this strategy are the reduction of releases from Powell below 8.23 MAF and temporary equalization that occurs at a level below 602(a) storage. Three elevation triggers are used to determine when equalization or reduced objective minimum (ROM) releases are to occur. The elevation triggers and a description of each are listed in Table 3-2.

Trigger Name	**Elevation (*ft*)**	**Significance**
Lake Powell Trigger (LPT)	3560	Powell elevation trigger for reducing annual releases from Powell
Lake Mead Water Supply Trigger (WST)	1050	Mead elevation trigger for returning back to a minimum objective release of 8.23 MAF
Lake Powell Temporary Equalization Level (TEL)	3606	Powell elevation for activating temporary equalization releases at a level less than the 602(a) storage, 3630 ft.

Table 3-2 Elevation Triggers for Coordinated Operation Strategy C1

The annual ROM release is 7.48 MAF. This was determined by subtracting the average gains from the Paria River from the Upper Basin delivery obligation of 7.5 MAF per year. A ROM release is triggered and will only be made when Powell is below the Lake Powell Trigger (LPT) elevation and Mead is above the Lake Mead

Water Supply Trigger (WST) elevation. If Mead drops below the WST elevation, releases from Powell return to a minimum of 8.23 MAF, even if Powell is below the LPT elevation.

The LPT elevation of 3560 ft is the median elevation between the top of the minimum power pool at 3490 ft and the minimum level for equalization at 3630 ft. The minimum elevation of 3630 ft for equalization releases was established by the 2003 Adoption of an Interim 602(a) Storage Guideline, discussed in Section 1.4.2.1 Powell Operation. This level above minimum power pool was determined to be high enough such that if Powell experienced an extremely low runoff year at an elevation just above the LPT, the minimum objective release could be made without the elevation declining below 3490 ft. The lowest recorded annual runoff at Lees Ferry was 5.3 MAF. Assuming this as worst case as runoff into Powell, with a storage capacity at 4.3 MAF above minimum power pool, Powell could potentially release the 8.23 MAF and still maintain minimum power pool.

Temporary equalization releases are made from Powell at the TEL, which is both higher than the LPT elevation and less than the 602(a) storage level of 3630 ft. Under no circumstances are equalization releases made if the EOWY storage at Powell is less than the EOWY storage at Mead. For the temporary equalization releases to be made, Powell must have made a ROM release at some point in the model run. Equalization releases continue until Upper Basin storage exceeds 602(a) storage on the end of the water year, September 30. After temporary equalization is inactivated it can only be activated again if Powell makes another ROM release.

The TEL was determined by Reclamation using an iterative method and represents an elevation whereby the sum of all water released from Powell, for all traces, under the C1 strategy is equal to the sum of all water released from Powell, for all traces, under the baseline model through year 2025. The baseline model uses the AbsPro shortage criteria.

1.10.2 Coordinated Operation Strategy – C2 *“Balance Contents”*

This strategy is more similar to the “reverse equalization” concept used in the SSD Study. The objective of the strategy is to maintain, as practical as possible, Powell and Mead at the same capacity. No protection is provided for the minimum power pool at Powell.

Equalization releases are made from Powell when the EOWY forecasted storage is both higher and lower than the EOWY forecasted storage at Mead. However, if the forecasted EOWY storage for Powell is less than the minimum power pool, Powell’s release is set to the monthly release corresponding to the minimum objective release of 8.23 MAF. The equalization releases from Powell are constrained to be greater than 6500 cfs and less than 25,000 cfs. These minimum and maximum releases reflect restricted releases from Powell implemented in the 1996 Operation of Glen Canyon Record of Decision.

1.11 Risk Associated with Coordinated Operation

This section discusses the some of the potential impacts associated with coordinated operation in terms of hydropower generation, recreation, environmental concerns and consumptive uses. Although of considerable importance, the analysis of non-consumptive uses, i.e., hydropower generation, water-based recreation, and the protection of water quality and endangered species, is outside the scope of this research. A broad discussion of how these uses may be impacted under coordinated reservoir operation is presented as more of an afterthought.

1.11.1 Hydropower Generation

Together Glen Canyon and Hoover Dams contribute about 3.6 percent of the total hydropower generation capacity of the Rocky Mountain, Arizona-New Mexico-Southern Nevada and California-Mexico areas of the Western Systems Coordinating Council. These areas include all of the seven basin states. The maximum operating capacity of Glen Canyon Dam is approximately 1200 MW but is limited to 1048 MW due to maximum outflow constraints. The maximum operating capacity of Hoover Dam is 2074 MW (USBR, 2000b).

Assuming the capability of the machinery is adequate, there are generally two factors affecting hydropower generation. These are the change in momentum of the water exerting a dynamic force on the rotating elements of the turbines and the net effective head on the generating units. The momentum of the water is a function of pool elevation, as is the net effective head. The net effective head is the difference between the top of the forebay behind the dam and the top of the tailwater below the dam. As the pool elevation of the upstream reservoir decreases as does the net effective head, thus resulting in decreased power output of the turbine and electrical capacity of the generator attached to the turbine (Linsley et al., 1992). Below the minimum power elevation, 3490 ft for Lake Powell and 1050 ft for Lake Mead, the turbines cannot be operated efficiently or safely.

The SSD Study found that minimum power pools were better protected with coordinated operation because Powell was able to make smaller releases at lower elevations than under normal operations. The coordinated operation strategies modeled in this research do not protect minimum power pool at Powell, however, it is still expected that the minimum power pool protection will improve due to reduced releases at lower elevations.

Management to preserve power interests becomes a tradeoff of foregoing consumptive uses. The SSD Study found that by adding a constraint to maintain minimum power pools at all times, the damages to consumptive uses more than doubled during the two years of the critical drought phase (Booker, 1995). This result however, is not a clear-cut argument to favor management for consumptive uses as values for uses ranging from agricultural to urban vary by factors of ten or more within the Basin (Booker and Colby, 1995).

1.11.2 Recreation

A multitude of recreational activities are provided by the Colorado River system. Lakes Powell and Mead are parts of National Recreation Areas, administered by the National Park Service; the 360-mile stretch just between Glen Canyon and Hoover Dam winds through Grand Canyon National Park. Glen Canyon and Lake Mead National Recreational Areas average three million and ten million annual visitors, respectively. From the headwaters to the mouth, sport fishing, white-water rafting, boating, camping and sightseeing are abundant.

Many adjustments have been made to facilities along the Lake Powell and Mead shorelines to accommodate visitors as elevations began decreasing in 2000.

Marinas have increased access to low-water levels by extending boat ramps, as long as 300 ft at Bullfrog along Lake Powell, constructed by attaching elongated concrete surfaces to existing facilities.

There is an obvious correlation with the availability of these activities and the availability of water in the system. Under coordinated operation releases of a greater magnitude will be more frequent because equalization releases are made at a level below the 602(a) storage. These frequent large releases will provide more water in the river between Powell and Mead. On the other side, as Powell releases below the minimum objective release, recreational uses at Lake Powell will benefit from the higher elevation yet recreational uses between Powell and Mead may suffer from reduced flows.

1.11.3 Environmental Impacts

It is a considerable challenge to assess the impacts of reservoir operations on environmental resources or to incorporate environmental concerns into reservoir operations. One reason for this difficulty is that, due to the large special and temporal variability associated with the organisms in the Colorado River Basin, it is hard to know how these impacts will resonate throughout the basin. Tyus et al. (1982) found that throughout the Upper Colorado River Basin, river reaches contained over fifty species of fish. Forty species were found to inhabit the major reservoirs in the Upper Basin. In the Lower Basin, forty species were discovered. Each grouping consists of native and non-native species, both of which are highly dependent on the localized environment, which varies from river reach to reservoir.

Varied flow patterns and temperature regimes are necessary for each stage of life and these requirements differ by species. For example, spawning represents a crucial life stage where, depending on the species, the critical flow is required during a period of a few weeks to an entire season. It is largely unknown how the timing, duration and magnitude of flows will inhibit certain species while benefiting another (Hardy, 1995).

Results from the SSD Study indicate that reverse equalization caters to consumptive uses and attempts to increase reservoir storages for a longer duration. Higher reservoir storages during dry periods correspond to a slight decrease in streamflows. However, the study also showed that minimum flow requirements were complied with nearly all of the time at all locations (Sangoyomi and Harding, 1995).

1.11.4 Consumptive Uses

Results from the SSD Study indicate that the reverse equalization policy with adherence to the Article III(d) of the Compact suspended provided noticeable relief to consumptive uses during severe drought. In particular, operating Powell and Mead conjunctively and thereby reducing the minimum objective release shifted the burden of drought from the Upper Basin and distributed it more equally. However, this relief was temporary and when confronted with the Compact delivery obligation, the contents of the Powell dropped quickly (Sangoyomi and Harding, 1995).

Consumptive uses are expected to fare well under coordinated operation. Reservoir contents were kept highest in the scenario involving reverse equalization with Compact compliance. The reservoirs on the Colorado River were designed with such a substantial storage amount for the purpose of protecting the consumptive uses of the basin during dry years. However, the safeguard of consumptive uses is at the expense of non-consumptive uses such as hydropower generation, recreation, water quality and instream minimum flow requirements. The constant struggle to balance non-consumptive uses and even the relinquishing of certain uses has been a pervasive problem in the management of the river and reflects the preoccupation with rights allocation and consumption (Getches, 1997).

1.12 Model Runs

The two coordinated operation strategies (C1 *“Relaxed MOR and EQ”)* and C2 “*Balance Contents”*) are combined with both shortage policies (Level2 and AbsPro) to form four combination scenarios. Two baselines are established by simulating baseline operations with each shortage policy. Thus, six model simulations are performed and are referred to as: Baseline-AbsPro, Baseline-Level2, C1-AbsPro, C1-Level2, C2-AbsPro, and C2-Level2.

Each of the six simulations is performed 90 times, each time using a different hydrologic sequence (trace) from the historical period of record. This is done using the ISM technique, described further in Chapter 4. The result is a range of probabilistic output for each scenario.

Model Results & Analysis

This chapter begins by outlining the modeling assumptions common to the four coordinated operation and two baseline scenarios. Results of these six scenarios are then presented through a graphical analysis in terms of reservoir levels, releases and shortages. The final section of this chapter provides a summary of the detailed analysis.

1.13 Assumptions Common to All Scenarios

The modeling of river system operations requires that certain assumptions are made regarding the delivery of water and system operations. Common to all scenarios are those assumptions listed below.

- The Upper Basin reservoirs above Powell operate under equivalent rules for all alternatives. These reservoirs are operated to make the greater of the release required to meet downstream demands or to meet their respective guide curves. Monthly storages for the five Upper Basin reservoirs needed for Powell and Mead rules were generated using CRSS and are input to CRSS-Lite along with Powell's monthly inflow. Because these Upper Basin reservoirs are operated independently of Powell and Mead, their operations are not necessary in CRSS-Lite.
- Upper Basin consumptive use increases by approximately 0.5 MAF from 2005 through 2025. This projection is depicted in Chapter 1, Figure 1-3.
- There is no protection of minimum power pool at Powell.
- All alternatives use the same logic for computing Lake Mead's release – the greater of the flood control release and the downstream demands. Mead's flood

control rules are always in effect and are the same logic for all alternatives. The flood control release depends on downstream demands, which vary according to surplus or shortage conditions.

- The initial conditions of the reservoirs for each simulation are the historical elevations on December 31, 2004. These elevations are shown in Table 4-1. (Upper Basin Effective reservoirs and Lower Basin reservoirs), listed below, reflect real conditions and were used as starting conditions for each simulation.

Reservoir	**December 2004 Pool Elevation *(ft msl)***
Fontenelle	6489.78
Flaming Gorge	6013.09
Blue Mesa	7477.99
Navajo	6028.28
Powell	3564.42
Mead	1130.01
Mohave	640.56
Havasu	446.96

Table 4-1 Reservoir Starting Conditions

- Normal demands for the Lower Basin users can be found in Appendix B. In all years the requested depletions for Arizona and Nevada are 2.8 and 0.3 MAF, respectively. California reaches 4.4 MAF in 2018 and requests up to 0.2 MAF less in the previous years.

- Water deliveries to Mexico are pursuant to the Mexican Treaty. For all years of the simulation, the annual depletion schedule for Mexico is 1.572 MAF. The additional 0.72 MAF reflects the average over-delivery to Mexico for the period 1964-2003. During years that flood control releases are made at Mead, Mexico’s depletion is increased to 1.7 MAF.

- The Yuma Desalting Plant is not in operation. As a result, Welton-Mohawk Irrigation and Drainage District agricultural return flows of 0.109 MAF per year are bypassed to the Cienega de Santa Clara in Mexico, reflecting the 1990-2003 average bypass. The bypass is not counted towards the Treaty delivery to Mexico.
- Lakes Mohave and Havasu are operated in accordance with their respective guide curves. These can be found in Table 2-3 in Chapter 2.

1.14 Baseline Single Trace Analysis

Figure 4-1 illustrates the differences in the Level2 and AbsPro shortage criteria under baseline operations for a single-trace run. The run begins in 2005 and ends in 2065 and uses hydrology from 1906 to 1966. The simulated dates are indicated on the plot, i.e. 2005-2065. The figure shows storages for Powell and Mead, the sum of the Upper Basin storage, and the 602(a) storage under both shortage criteria. The 602(a) storage is a function of Upper Basin demand. Reflected in the increasing 602(a) storage is the increase in Upper Basin demand over this period. Through 2016 Powell must be above 3630 ft, corresponding to a storage of 14.85 MAF for equalization to occur per the Final EA Adoption of an Interim 602(a) Storage Guideline. See Appendix C for the equation used to compute 602(a) storage.

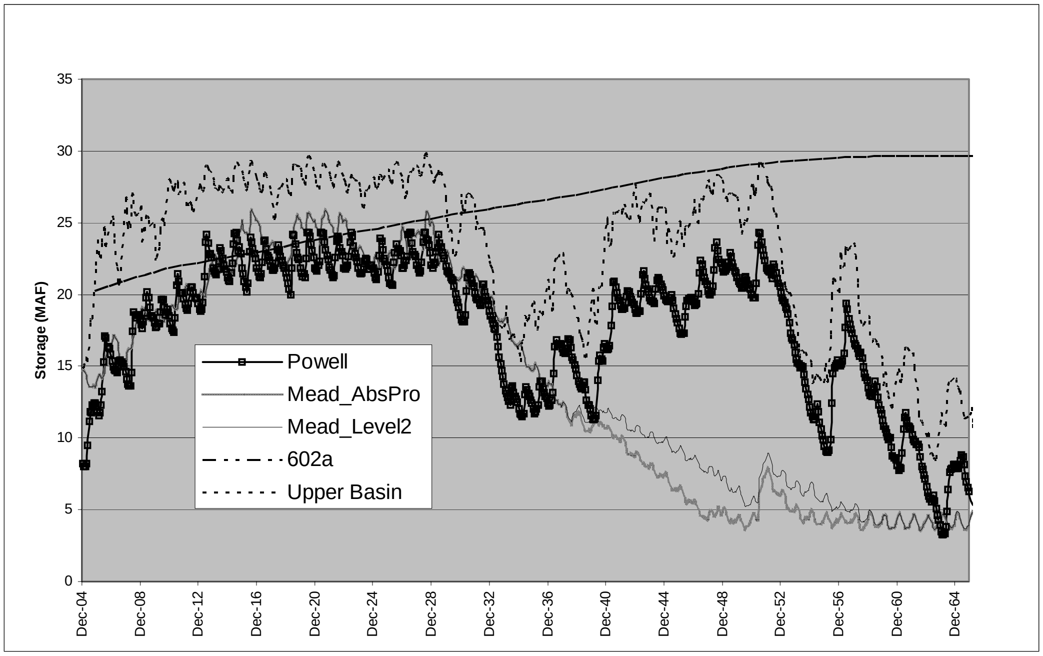


Figure 4-1 Trace 1 Baseline Analysis

Only the storage of Mead varies with different shortage criteria. The reason for this is that Powell's releases depend on Mead's storage only during years when conditions for equalization are met, i.e., when Powell's storage is greater than Mead's and the Upper Basin storage is greater than the 602(a) storage. As shown in the graph, beginning in 2006, these conditions are met and equalization occurs. Equalization releases are not made after 2022 because the Upper Basin storage has dropped below the 602(a) storage level. A combination of the dry hydrology of the 1930's and increasing 602(a) storage results in Powell releasing the only the minimum objective release. Meanwhile, Mead continues to meet the same downstream demands, hence the rapid drawdown of Mead.

Starting in 2038, Mead's storage depends on the shortage policy used in the simulation. Powell, however, is unaffected because it continues to release the minimum objective release, regardless of Mead's storage. As Powell continues to release the minimum objective into Mead, that inflow is exceeded by the release required from Mead to satisfy normal downstream demands that totals 9.0 MAF (7.5 MAF to the Lower Basin and 1.5 MAF to Mexico) not including system losses.

Under the AbsPro policy, larger shortages are imposed on the Lower Basin less frequently; the opposite is true under Level2. Fewer large shortages have the effect of reducing Mead's storage more rapidly because Mead must continue to release for full downstream depletion schedules. Conversely, more frequent smaller shortages have the effect of keeping Mead higher.

Also reflected in the declining Mead storage is the effect of increased Upper Basin depletions. As the Upper Basin states continue to increase their consumptive use, due to the 602(a) storage requirement, less frequent equalization releases will be made. Under the average hydrology of the historical period of record, Mead will continue to decline.

1.15 Index Sequential Method

The ISM, discussed in Chapter 2, is used in CRSS-Lite to generate the range of possible inflows throughout the Basin. The future inflow scenarios are generated by cycling through the historical natural flow record from 1906-1990. For example, the first simulation assumes that the inflows for 2005 through 2025 will be the 1906 through 1926 record. The second simulation will use the 1907 through 1927 record. When the end year of the record, 1995, is reached, the record "wraps around" and reverts back to 1906. Each inflow scenario is referred to as “trace” with a number corresponding to the number of rotations the historical record has undergone. Trace 2, for example, would begin with 1907.

The result of ISM is 90 possible inflow scenarios. Thus, a range of probabilistic output is generated for each reservoir elevation or any other model results, for each year in the simulation. This output is managed and displayed graphically by GPAT, an Excel-based tool developed by CADSWES specifically to analyze RiverWare model outputs. Described below are the calculations done in GPAT to generate the figures presented in this section.

1.16 Presentation of Results & Probabilistic Output

The following sections present the simulation results by comparing C1 *“Relaxed MOR & EQ”* with the Baseline, C2 *“Balance Contents”* with the Baseline, and C1 with C2. For each comparison, first presented are the end-of-the-calendar-year (EOCY) percentile outcomes of Powell and Mead elevations, followed by an analysis of the trends and behavior exhibited in the plots. Following the analysis of the elevation percentiles are analyses of Lower Basin and Mexico shortages and Powell releases for each comparison. Throughout each analysis figures are referenced that are included in different sections. These figures are referenced by the figure number followed by the page number of that figure.

Statistics used to present results of elevations, shortages and releases are percentiles, exceedance and non-exceedance probabilities and maximum values. Percentile analysis is a statistical method used to view the results of the hydrologic traces in a compact manner yet maintain the fluctuations at high and low reservoir levels that would be lost by averaging the results of the 90 traces. The general method to compute percentiles is to rank the total number of values (N), in this case N = 90, and to determine the index (n) that corresponds to a percentile of interest. The value that corresponds to index (n) represents the value at which a certain percent of values fall below. The method used in GPAT was chosen by developers because it works well for small sample sizes. To compute the index (n), the method can sometimes result in an index that is not a whole number. In this case, the percentile value becomes a weighted average of the next highest and lowest values, i.e. the percentile value was not directly produced in the model simulation. Below is an example of the GPAT calculation of Powell's 10th percentile elevation.

Total number of values $N = 90$

Percentile of interest $\%tile = 10$

Index for percentile $n = \dfrac{N * \%tile + 50}{100} = \dfrac{90 * 10 + 50}{100} = 9.5$

Powell elevations $N_9 = 3573$ and $N_{10} = 3580$

10th Percentile elevation = $\dfrac{N_9 + N_{10}}{2} = \dfrac{3573 + 3580}{2} = 3576.5$

The 10th percentile is an indication of the behavior at lower reservoir levels. The 50th percentile represents the median, i.e. half of the values are below and half are above the median value. The median can be thought of as the most likely outcome. The 90th percentile indicates the behavior at high reservoir elevations. Because coordinated operation concerns low reservoir levels, the 90th percentile elevations are unaffected by the C1 and C2 strategies and are therefore not presented in this analysis.

Exceedance probabilities, such as the probability of Lower Basin and Mexico shortage, are generated by counting the number of times a value was exceeded (or not exceeded) throughout the 90 traces. For example, in each year the model reports the total amount of Lower Basin and Mexico shortage. The shortage probability for each year is computed by summing the number of times that the total shortage exceeded zero during that year for any trace. The number of occurrences is then divided by the number of traces, i.e., 90. This is the same method used to compute all probabilities, such as the probability of a certain release from Powell or the probability of Mead being below minimum power pool. Figures reporting the probability of shortage represent the probability of incurring *any* amount of shortage in the Lower Basin and Mexico. Also presented is the probability of incurring a more severe shortage, defined as a shortage that exceeds 0.5 MAF. Figures showing maximum shortage values report the maximum value in that year for all traces.

1.17 C1 "*Relaxed MOR & EQ*" & Baseline Comparison

This section presents the results of the strategy C1 coupled with each of the two shortage criteria, and compares the C1 results with the baseline results. As explained above, Powell's normal operations are unchanged under either Lower Basin shortage criteria. Other relevant graphs referenced throughout this analysis immediately follow this section.

1.17.1 Powell & Mead Percentile Elevations

Figures 4-2 and 4-3 show the 10th and 50th percentiles for Powell and Mead EOCY elevations. The following sections examine the trends and behaviors of each.

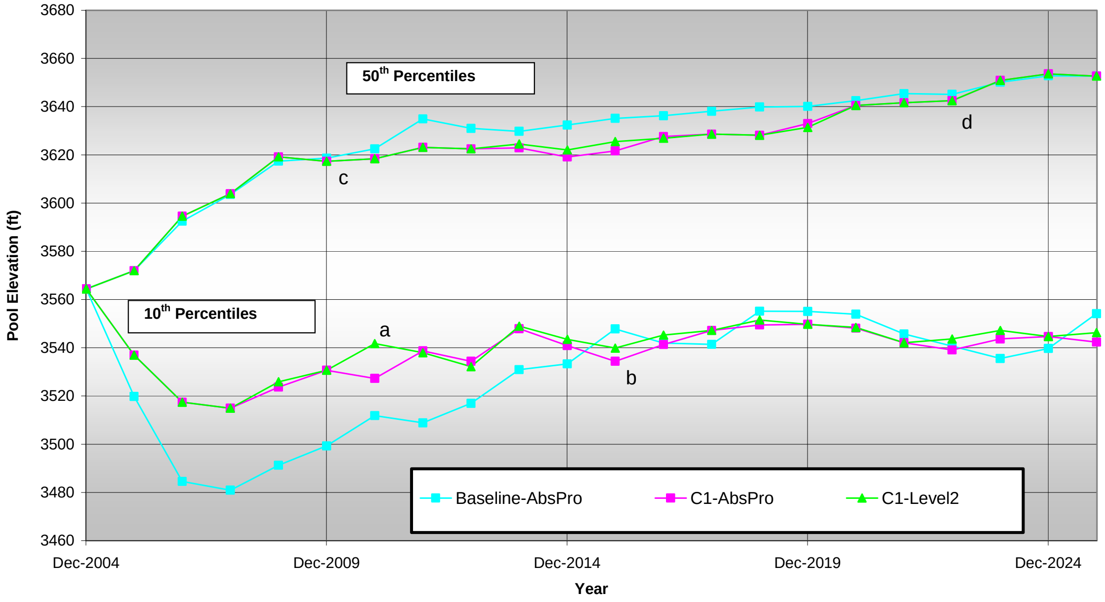


Figure 4-2 Powell EOCY Percentile Elevations – C1 & Baselines

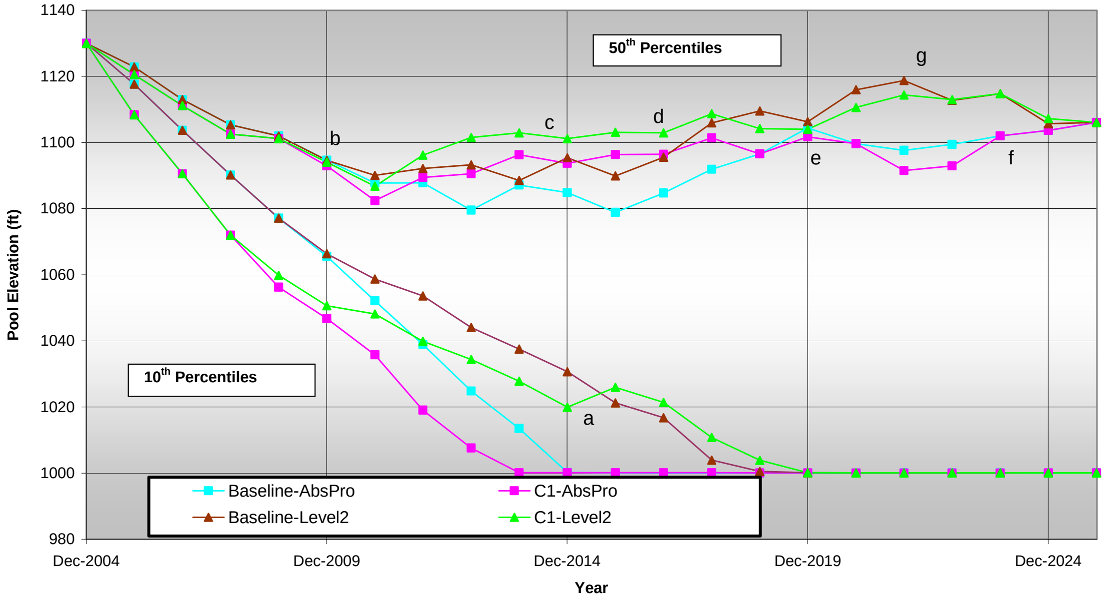


Figure 4-3 Mead EOCY Percentile Elevations – C1 & Baselines

1.17.1.1 Powell EOCY Elevation: 10th Percentile

From 2005 through 2014 the 10th percentile of Powell’s EOCY elevation is substantially lower under the Baseline scenarios than the C1 scenarios. This is because the minimum that can be released under the Baseline is 8.23 MAF whereas under the C1 strategy ROM releases are made when Powell is below 3560 and Mead is above 1050. This behavior is especially dominating during the early year of the run because the initial conditions of Powell and Mead at 3564 ft and 1050 ft, respectively, meet the requirements for a ROM release. Years 2005 through 2014 have the largest probability of Powell releasing below 8.23 MAF (Figure 4-12, 107) due to the initial conditions meeting the requirements for a ROM release.

The 10th percentile is highest under the C1 strategy until 2014. Both C1 scenarios stay within 5 ft of each other with the exception of 2010 where C1-AbsPro is about 15 ft higher, point *a*. The divergence between C1-AbsPro and C1-Level2 at point *a* is due to the difference in the shortage criteria governing Mead’s release. At this point under the Level2 criteria, a 40% probability of shortage (Figure 4-8, 102) exists. There is no probability of shortage for AbsPro. This high shortage probability under Level2 results in an increased Mead elevation thus increasing the probability that Mead will stay above the WST elevation. Powell can release the ROM as Mead is above the WST elevation, which results in an increased Powell elevation. The ROM release causes Mead to decline below the WST trigger and 8.23 MAF is released in 2011. The 10th percentile of Powell’s release (Figure 4-11, 106) at 2010 is 7.48 MAF and 7.89 MAF under the Level2 and AbsPro criteria, respectively. At

2011, both percentile releases return to 8.23 MAF explaining the re-convergence in the 10th percentile elevations at 2011.

At 2014, the C1 scenarios drop below the Baseline for a few years, then rise above for a few years. At 2015, point *b*, both C1 scenarios drop below the Baseline. This occurs due to the higher probability (about 50%) of equalization releases under C1 during this year (Figure 4-13, 108). There is higher probability because as Mead drops below 1050 (Mead's median elevation is 1079 in 2014) Powell must release either 8.23 MAF or equalize below the 602a storage level if the TEL is reached. A slightly higher 10th percentile elevation occurs under C1-Level2 at point *b* than under C1-AbsPro. Mead's elevations at this point are lower under C1-AbsPro, resulting in larger equalization releases from Powell.

After 2016, Powell's operations return to baseline under C1 and the 10th percentiles stay close with a maximum of 4 ft difference occurring in 2023. The Baseline intertwines with the C1 percentiles from 2016 through the end of the simulation and ends about 12 to 15 ft higher. Because the minimum release under all strategies is 8.23 MAF from 2016 through the run end and the baseline conditions apply for equalization, divergences in the percentiles are results of "feeling the effects" of earlier years. This is a result of the more frequent larger releases that were made under C1 through 2016. This effect is illustrated in Figure 4-4 that examines the storages and corresponding releases from Trace 61. Because the results of C1-Level2 and C1-AbsPro are very similar for this trace, the average storage and release between them is depicted in Figure 4-4.

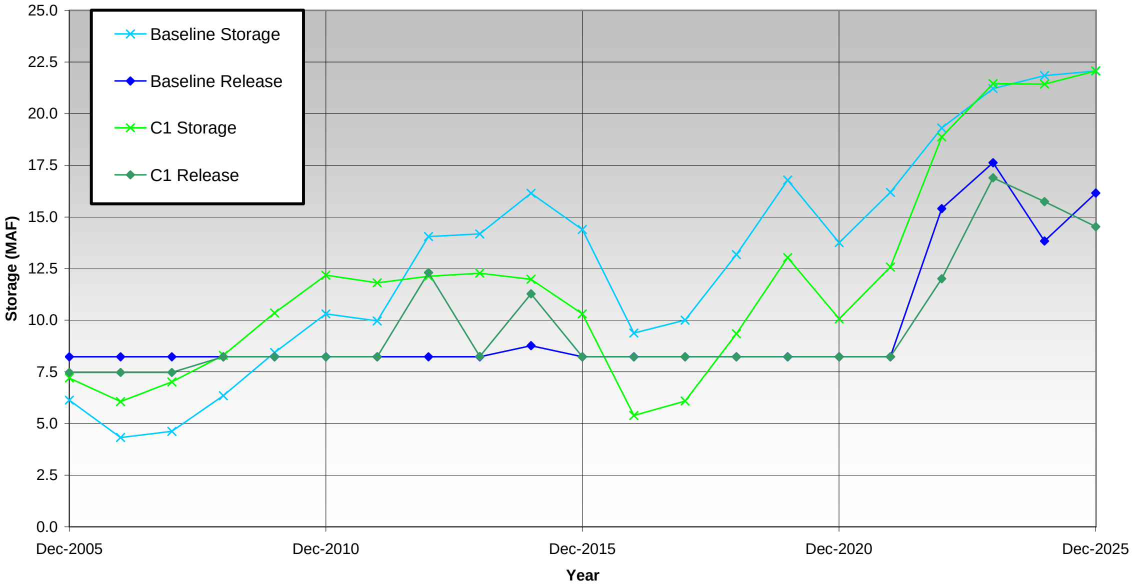


Figure 4-4 Trace 61 Powell Storage & Release – C1 & Baselines

Trace 61 was chosen because, for all traces, the largest difference in Powell's elevation at year 2017 between the Baseline and the C1 strategies occurs. In this trace, in 2012 and 2014, under C1, equalization releases are made at the TEL, while 8.23 MAF is released in the Baseline. From 2015 through 2017, under both scenarios 8.23 MAF, is released. However, due to the large releases made in earlier years under C1, the storage at 2017 is about 3.9 MAF or 53 ft less. This effect also results in the 10th percentile about 12 ft higher at the run end under the Baseline.

1.17.1.2 Powell EOCY Elevation: Median (50th Percentile)

Powell's median elevation is generally higher for the Baseline during the interim period (2005 – 2016) due to the higher probability of equalization releases under C1 (Figure 4-13, 108). Under C1, Powell is able to equalize more often because the 602(a) storage level is relaxed when Powell is above TEL. The convergence of the medians for all scenarios at point *c* and *d* is due to operations being driven by the

ROM and minimum objective release, prior to point *c* and after point *d*, respectively. These operations affect more the lower elevations and can be seen more clearly in the 10th percentile. The Baseline median continues to be greater after 2016 until Powell's storage recovers under C1. Both strategies end at the same median elevation, about 110 ft higher than Powell's initial elevation of 3564 ft.

1.17.1.3 Mead EOCY Elevation: 10th Percentile

Mead's 10th percentile elevations are heavily influenced by the shortage criteria in place. During years when Powell releases 8.23 MAF or less, the release required from Mead to meet downstream demands, under normal conditions, exceeds the inflow. Further, the only way Mead can address this deficit is to short downstream deliveries. The only increase in the 10th percentile occurs under C1-Level2 at point *a* from 2014 to 2015. This increase occurs due to the high shortage probability of almost 40% (Figure 4-8, 102) and the high probability of equalization releases of 50% (Figure 4-13, 108) under C1-Level2.

Scenarios under the Level2 criteria, exhibit a flatter slope from the simulation start date to until reaching 1000 ft in 2019. This is due to the fact that under Level2 the probability for Lower Basin and Mexico shortages are higher than AbsPro for all years of the run, but especially during the first ten years. During these years the probability for shortage under the Level2 criteria is an average of 40% greater than under AbsPro (Figure 4-8, 102). By 2019 the percentile reaches 1000 for all strategies and remains there. This behavior reflects the improbability of Mead recovery under average hydrology and increasing Upper Basin demands.

1.17.1.4 Mead EOCY Elevation: Median (50th Percentile)

Median elevations for all strategies remain almost identical until 2012 when Baseline-AbsPro and C1-Level2 diverge with Baseline-AbsPro staying an average of 20 ft lower until point *e* where they meet. After point *e* they again diverge until coming together at the end of the run. The divergence at point *b* is due to the different shortage criteria and the increased probability of equalization releases (Figure 4-13, 108) under C1-Level2. The shortage probability graph shows that after 2011, the probability of shortage under Level2 does not drop below 45% (Figure 4-8, 102). Recall that the 80P1050 shortage triggers ramp up from 1073 to 1100 during the run length. The trigger at 2012 is 1085, high enough to affect median elevations. This high probability of shortage, results in a higher median elevation at Mead. The higher the shortage probability, the smaller the release Mead has to make to meet downstream demands, the higher Mead's elevation stays. There is no probability of shortage under Baseline-AbsPro until 2014, longer than any other scenario. This explains why the median is lower under Baseline-AbsPro at 2012.

The large divergence beginning in 2020 (just after point *e*) between C1-Level 2 and Baseline-AbsPro is not immediately intuitive especially given that normal operations have resumed under C1 since 2016. This behavior is a reflection of the different shortage criteria and the influence of traces containing dry periods that occur in years prior to 2019. This behavior was verified by plotting Mead’s elevation at 2020 for each trace, which revealed that 24 traces exhibit the same divergence under C1-Level2 and Baseline-AbsPro at 2020. A handful of these traces (Trace 26, 27, 28, 59, 60, 61) were then analyzed further and it was found that they each exhibit similar behavior in the years preceding 2020. This led to the deduction that the behavior exhibited by these traces largely contributes to the divergence occurring after point *e*. The behavior of Trace 27 is presented in Figure 4-5, 4-6 and 4-7 to explain this divergence because it exhibits the largest difference in Mead’s elevation at 2020, for all traces, between the strategies under the Level2 and AbsPro shortage criteria.

Trace 27 represents the period of record hydrology of 1932 – 1952. At the simulation year 2016 the ten-year natural flow average is about 13.7 MAF; at 2007 the annual natural flow at Lees Ferry is about 6.1 MAF. Shown in Figure 4-6, under both Baselines, the minimum objective release is made 2005 – 2016 resulting in a low elevation at Mead in 2016, shown in Figure 4-5, because Mead’s releases exceed the inflow during this time. The minimum objective release is also made during these years in Baseline-Level2, however the elevation at 2016 is 30 ft higher than in Baseline-AbsPro because of shortages being imposed starting in 2008, shown in Figure 4-7. Under C1-Level2 and C1-AbsPro, Powell makes a ROM release in 2007 and 2008. As Mead drops below 1050 in 2009, Powell returns to releasing 8.23 MAF until 2015 when a 13.5 MAF equalization release is made because Powell has reached the TEL.

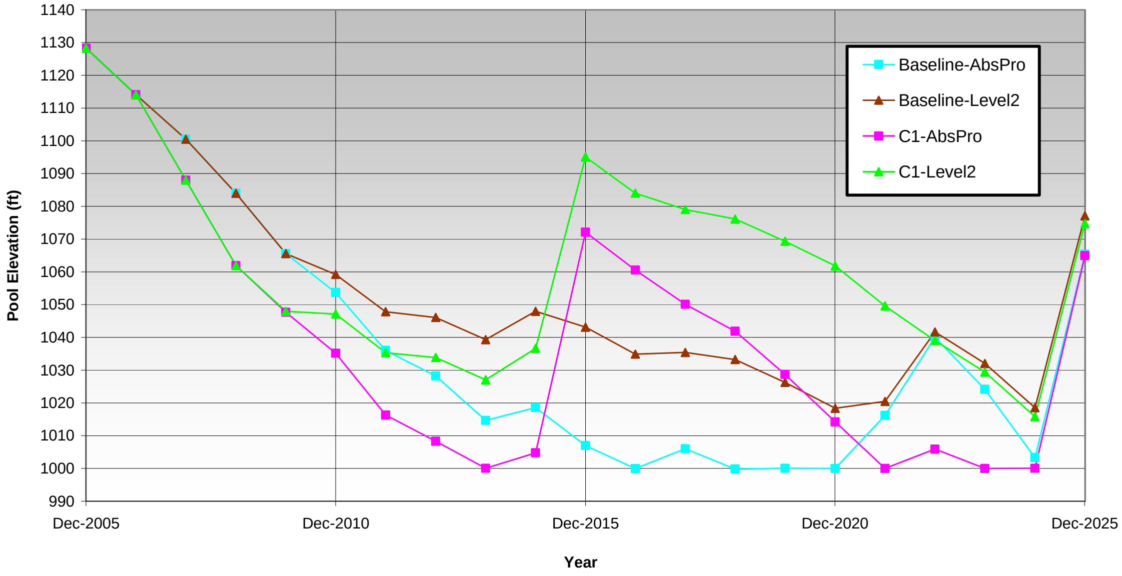


Figure 4-5 Trace 27 Mead Elevation – C1 & Baselines

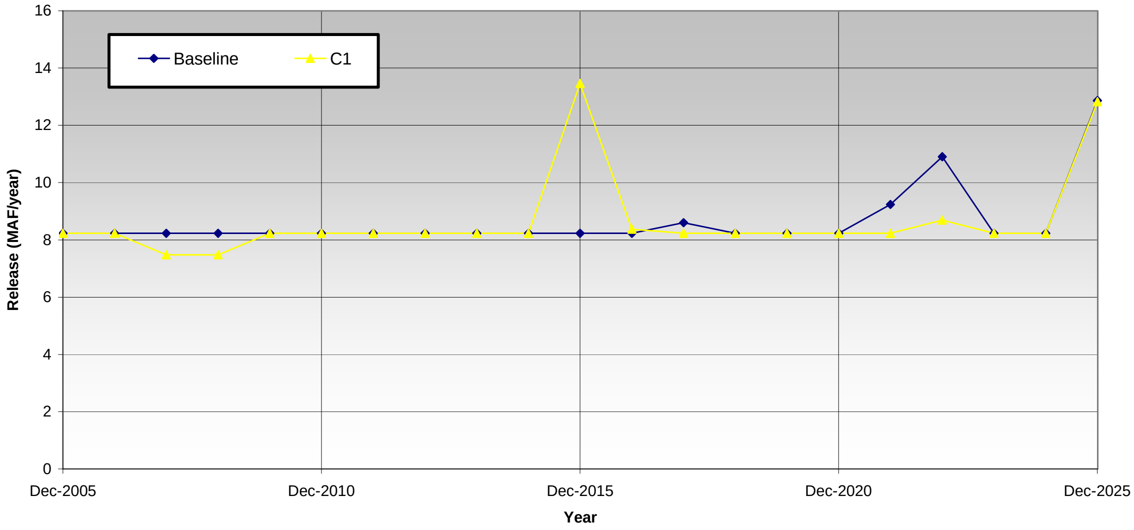


Figure 4-6 Trace 27 Powell Release – C1 & Baselines

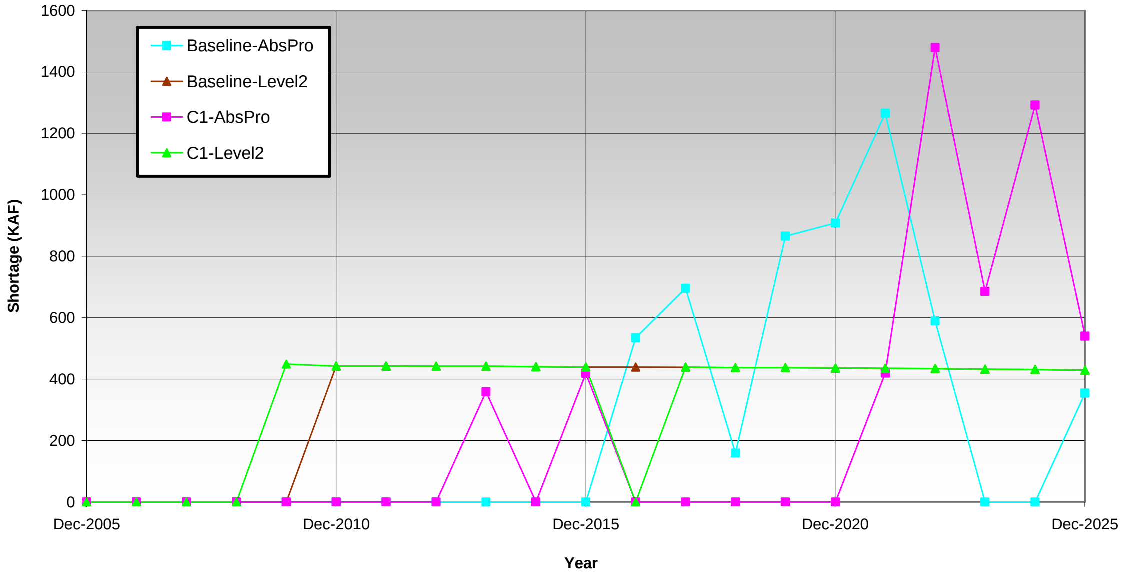


Figure 4-7 Trace 27 Lower Basin & Mexico Shortage – C1 & Baselines

The result of this large equalization release in 2015 is that Mead's elevation in 2016 is 1084 ft under C1-Level2 and 1060 ft under C1-AbsPro. In 2016 Mead is significantly lower under both Baselines. C1-Level2 is 24 ft higher than C1-AbsPro due to shortages imposed 4 years earlier in C1-Level2. In the following years the shortage criteria and previously imposed shortages drive the trend because Powell's release remains the same for C1 and the Baseline for both shortage criteria. Both Level2 strategies end in 2020 with higher elevations than the AbsPro strategies because under the Level2 strategies, shortages were taken earlier.

The reason for the divergence between C1-Level2 and Baseline-Level2 with Baseline-Level2 higher at point *g* is due to the higher probability equalization releases being made in C1-Level2 (Figure 4-13, 108) that result in postponing shortage declaration. Likewise, at point *f*, C1-AbsPro falls below Baseline-AbsPro due to shortage postponement in C1-AbsPro. It should be noted that no significant reason for the median being the same under all strategies at point *e* could be found. This may just be coincidence.

Until the divergence after point *e*, the trends of C1-Level2 and Baseline-Level2 are very similar. During the period 2011 through 2019 when C1-Level2 is slightly higher can be attributed to Powell's increased equalization probability (Figure 4-13, 108) given that the shortage probability of both scenarios are within 5% (Figure 4-8, 102).

Another interesting relationship between median elevations is that of C1-AbsPro and Baseline-Level2 from 2011 through 2019. The relationship takes on the pattern of the two scenarios mirroring one another during 2013, 2015 and 2018. However, in 2018, Baseline-Level2 is above C1-AbsPro whereas it was below during 2013 and 2015. During 2012, 2014, 2016 and 2019 the medians are within 1-2 ft.

1.17.2 Lower Basin & Mexico Shortage

Three figures are presented in this section. The first shows the probability of Lower Basin & Mexico shortage. This is followed by figures that display the probability of a shortage above 0.5 MAF in the Lower Basin and Mexico. Lastly, the maximum Lower Basin and Mexico shortage is presented.

1.17.2.1 Probability of Lower Basin & Mexico Shortage

Figure 4-8 shows the probability that any Lower Basin entity or Mexico will be shorted for all traces in each year. The entities that can incur a shortage in Lite are CAP, SNWA, MWD and Mexico. Both CAP and SNWA will be shorted completely, i.e. receive no water, before a shortage is incurred by Mexico or MWD. The combined normal depletions requested by the CAP and SNWA average approximately 1.7 MAF each year. Appendix B contains the depletion schedule for each major water user in Lite. If CAP and SNWA are shorted completely, the remaining shortage required to keep Mead from falling below 1000 ft is shared equally by MWD and Mexico.

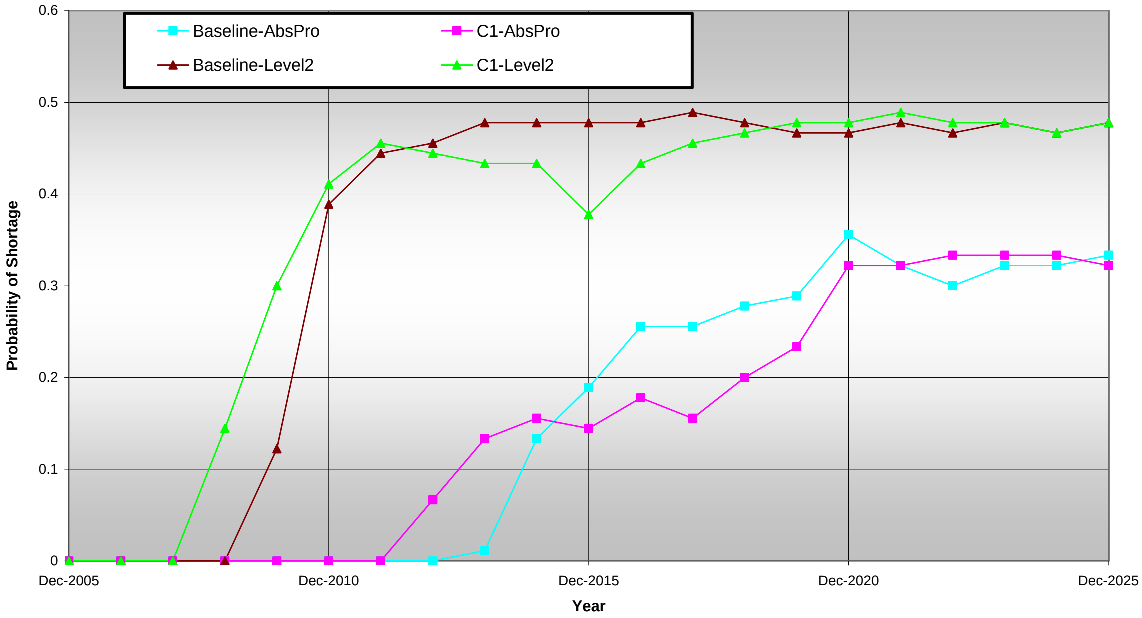


Figure 4-8 Probability of Lower Basin & Mexico Shortage: C1 & Baselines

The probability of shortages under the AbsPro shortage criteria is significantly less than under the Level2 criteria. This is due to the Mead trigger elevations in the Level2 criteria that have the effect of triggering shortages at an earlier date than the AbsPro criteria. The AbsPro criteria require that Mead will drop below 1000 if satisfying the normal depletion schedules of CAP and SNWA before issuing a shortage.

The coordinated operation strategies experience a shortage about one year earlier compared to the Baseline with the same shortage criteria. This is due to the smaller releases from Powell in the earlier years of the simulation under C1 (Figure 4-12, 107). Powell begins the simulation above the LPT elevation, with Mead above the WST trigger, and thus has a high probability of releasing the ROM for the first few years, under average hydrology.

The sudden drop under C1-Level2 at 2015 correlates with the higher probability of equalization releases from Powell during this time (Figure 4-13, 108). This is also the reason for the flatter slope at this time under C1-AbsPro compared to Baseline-AbsPro.

All probabilities, in both Figures 4-8 and 4-9, seem to reach a maximum near 2022 and stabilize at that percentage. This can be attributed to increased Upper Basin demands, thus decreasing the frequency of equalization releases. As Upper Basin depletions increase, as does the 602(a) storage level which governs when an equalization release can occur. As Powell releases the minimum objective release of 8.23 MAF, Mead's release for downstream demands exceed the inflow thus maintaining a high probability of shortage.

Figure 4-9 illustrates the tradeoff between taking shortages earlier or later. Although the probability of any amount of shortage is less under the AbsPro criteria, the probability for shortages exceeding 0.5 MAF are much higher. Thus the performance of the strategies in terms of shortage becomes a question of whether it is best to be precautionary and impose shortages at an earlier time or delay them at the expense of an increased risk of much larger reductions.

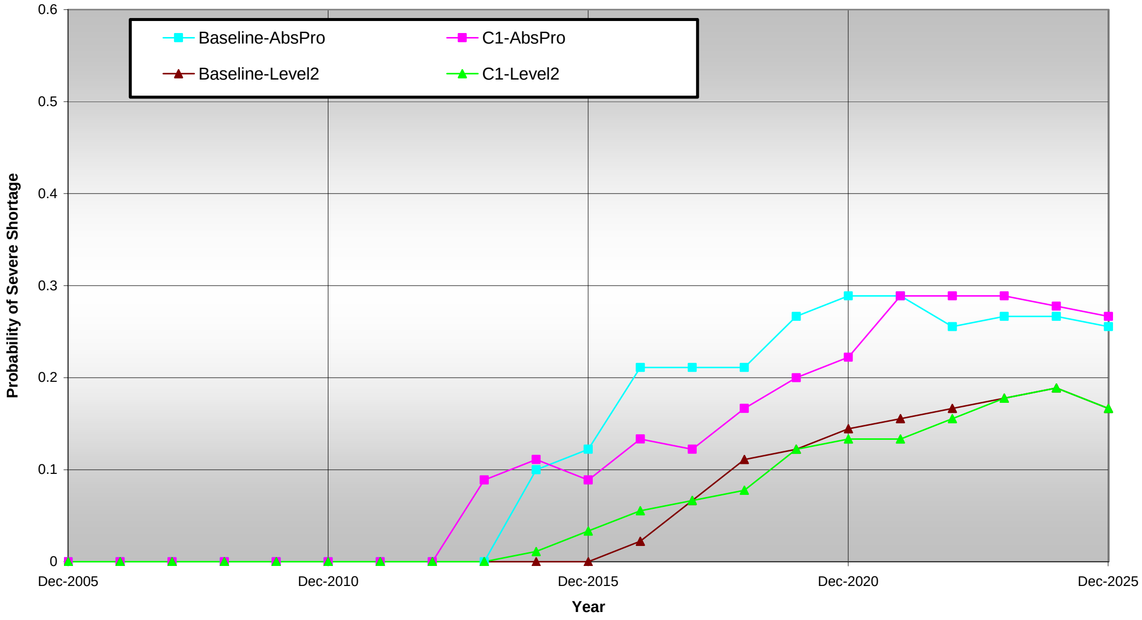


Figure 4-9 Probability of Shortage Above 0.5 MAF – C1 & Baselines

1.17.2.2 Maximum Lower Basin & Mexico Shortage

Figure 4-10 reports the maximum of the total shortage to the Lower Basin and Mexico of all 90 traces for each year. The figure represents the shortage amount required to keep Mead above 1000 under below average hydrology. These values are generated during the traces that contain the years that make up the “critical period” of record, 1953 through 1964, in which the natural flow at Lees Ferry averages 12.2 MAF with five years having flows less than 10 MAF. Under the C1 scenarios, Powell releases 7.48 MAF until Mead drops below 1050 in which Powell returns to releasing 8.23 MAF. Under the Baseline scenarios, the minimum Powell can release, unless it is physically impossible, is 8.23 MAF.

Trace 48 represents the hydrologically driest trace and is most similar to the sequence used in the Severe Sustained Drought study in that the critical period is experienced during the first twelve simulation years. During this trace Powell is emptied to the top of dead storage (3370 ft) for three years under the Baseline scenarios. Although Powell does go below minimum power pool, it never goes below 3400 ft under the C1 scenarios.

The difference in the onset of the maximum shortages between the scenarios under the same shortage criteria is a result of Powell making smaller releases in the early part of the simulation with C1 (Figure 4-12, 107). Scenarios under the AbsPro criteria see greater maximum shortages because the issuing of shortages is delayed in comparison to the Level2 criteria.

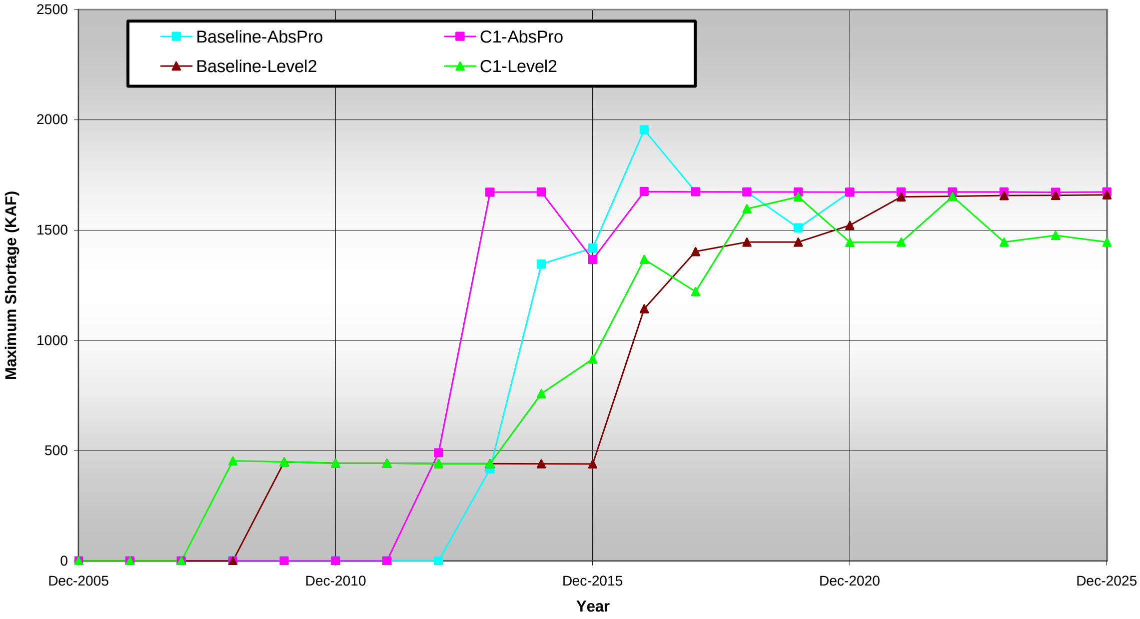


Figure 4-10 Maximum Lower Basin & Mexico Shortage – C1 & Baselines

A shortage greater than about 1.7 MAF would result in a shortage to both MWD and Mexico. For all scenarios, the probability of shortage to Mexico in any year is never above about 1%.

1.17.3 Powell Release

Three figures are presented in this section and include the 10th, 50th and 90th percentiles of the release from Powell, the probability that Powell's release is below the minimum objective release and the probability that equalization releases are made from Powell.

Figure 4-11 shows the percentiles for Powell's release. For all scenarios, the median release is 8.23 MAF. Through 2008, the 10th percentile release for the C2 strategies is 7.48 MAF. At 2009 the 10th percentile release for C1-AbsPro increases to 7.86 MAF while the C1-Level2 percentile remains at 7.48 MAF for an extra year. This is due to shortages being imposed under C1-Level2 at this time allowing Mead to stay above 1050 and permitting a ROM release.

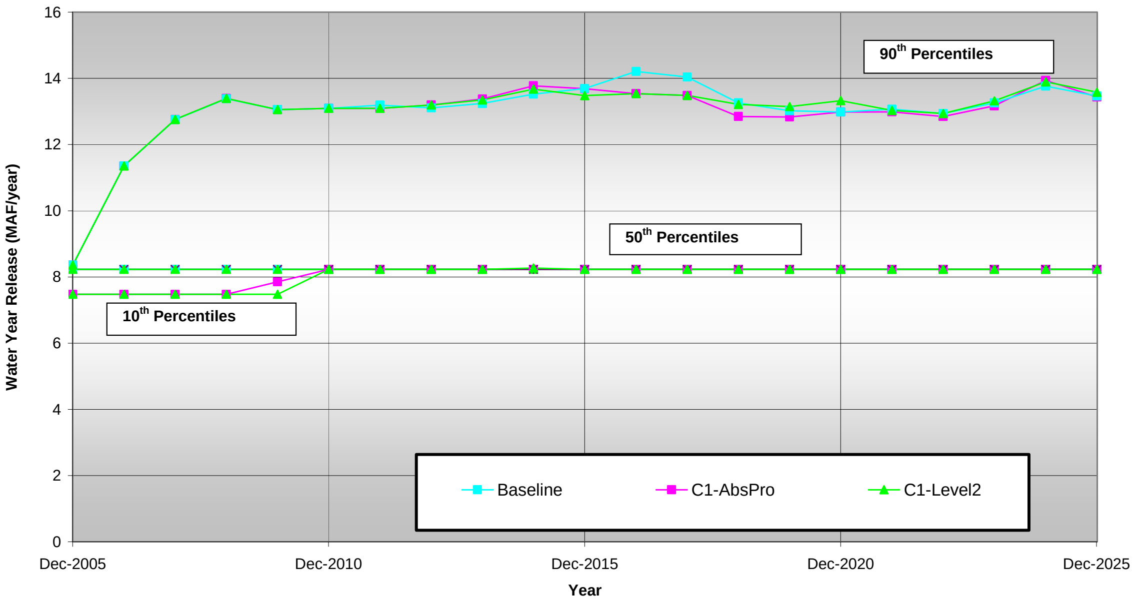


Figure 4-11: Powell Water Year Release – C1 & Baselines

The high 90th percentile of Powell's release at 2016 and 2017 under the Baseline is due to a combination of the wet hydrology of the 1980's being experienced during this period at Traces 67-71 and low elevations at Mead (average median 1084 at 2015 for both Baselines, see Figure 4-3, 91) in the year prior to the high runoff years. These large releases still occur under C1, but because Mead is not as low, not as large of a release is required from Powell for equalization.

Figure 4-12 shows the probability that Powell will release below the minimum objective release. Through 2017 Powell has a higher probability of releasing less than 8.23 MAF under C1. There is a greater chance in the beginning of releasing below 8.23 MAF under C1 because Powell begins the simulation just above the LPT elevation and while Mead is 80 ft greater than the WST trigger. The small probability of Powell releasing less than 8.23 MAF under the Baseline results from dry traces when Powell is emptied and physically cannot release 8.23 MAF.

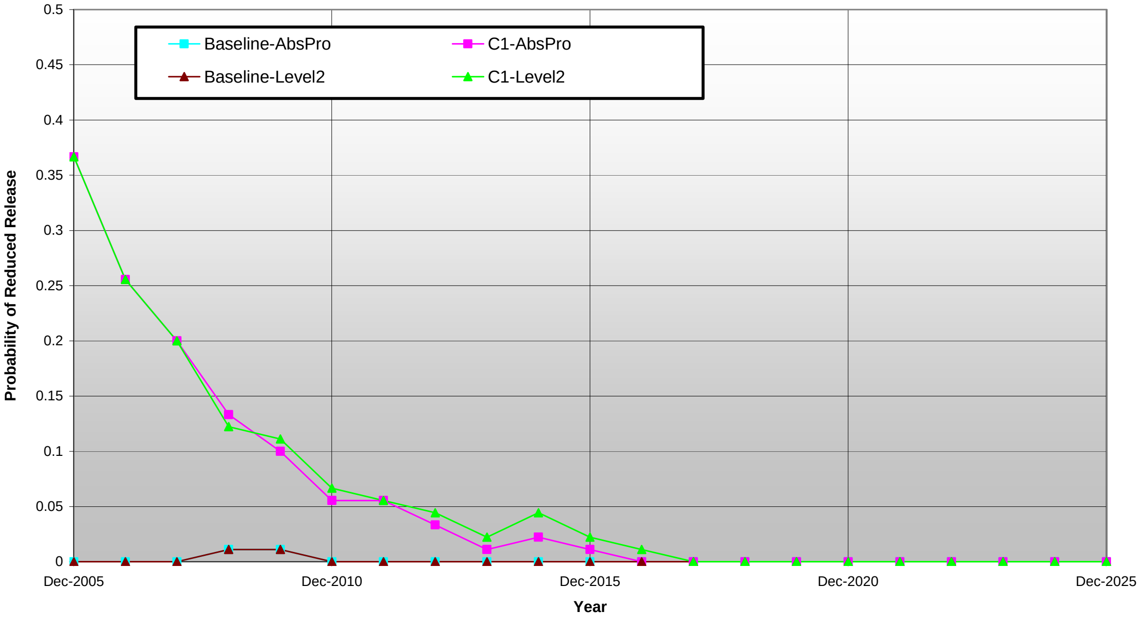


Figure 4-12 Probability of Reduced Release – C1 & Baselines

Figure 4-13 shows the probability of equalization releases being made from Powell. These were assumed to be releases of greater than 8.25 MAF. The C1 strategies increase the probability an average of 7% from 2007 through 2016. The increased probability is because temporary equalization releases are made at a level below the 602(a) storage if during a previous year ROM releases were made. Figure 4-12 shows the increased probability of ROM releases prior to 2007. From 2017 through the end of the simulation, the minimum objective release drives Powell's operation. During this period, the probability of releasing less than 8.23 MAF is 0% while the probability of releasing greater than 8.25 MAF is just below 40%.

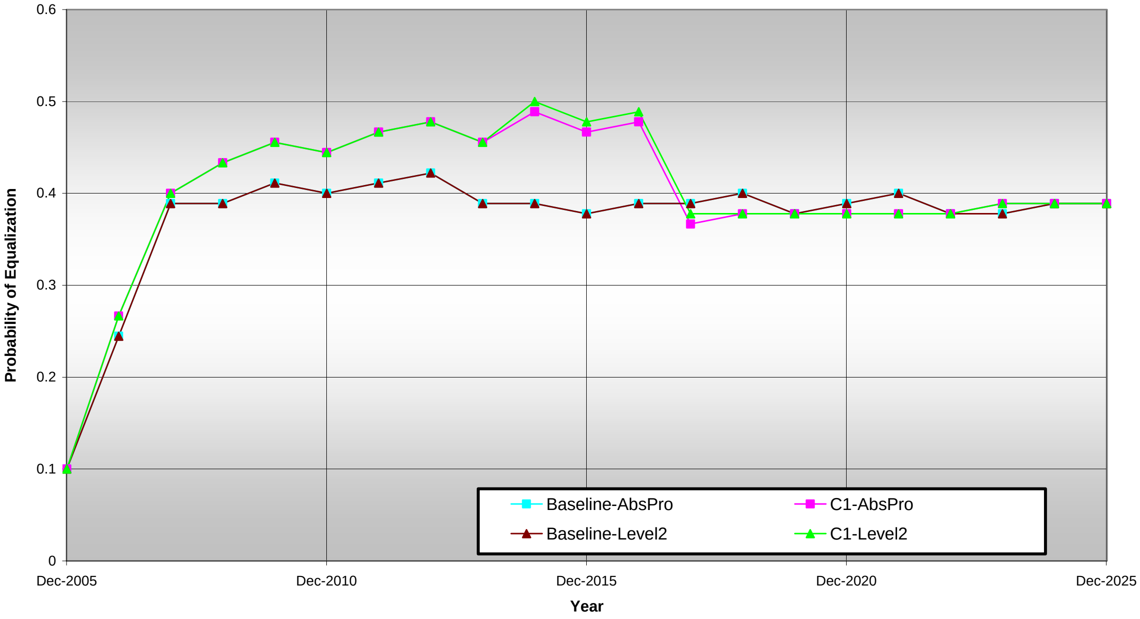


Figure 4-13 Probability of Equalization Releases – C1 & Baselines

1.17.3.1 Compact Delivery

Under the hydrologic sequences generated with the ISM the Upper Basin delivery obligation, as specified by the Compact, of 75 MAF over 10 years is always satisfied. The minimum 10-year volume under the Baseline, C1-AbsPro and C1-Level2 is 81.3 MAF, 78.6 MAF and 76.9 MAF, respectively.

1.18 C2 *Balance Contents* & Baseline Comparison

This section presents the results of the strategy C2 coupled with both sets of shortage criteria. For the reasons explained in Section 1.2, Powell's normal operations are unchanged under either Lower Basin shortage criteria. Graphs that are referred to throughout this analysis can be found immediately following this section.

1.18.1 Powell & Mead Percentile Elevations

Figures 4-14 and 4-15 show the 10th, 50th and 90th percentiles for Powell and Mead EOCY elevations. The following sections examine in detail the trends and behaviors exhibited under each strategy.

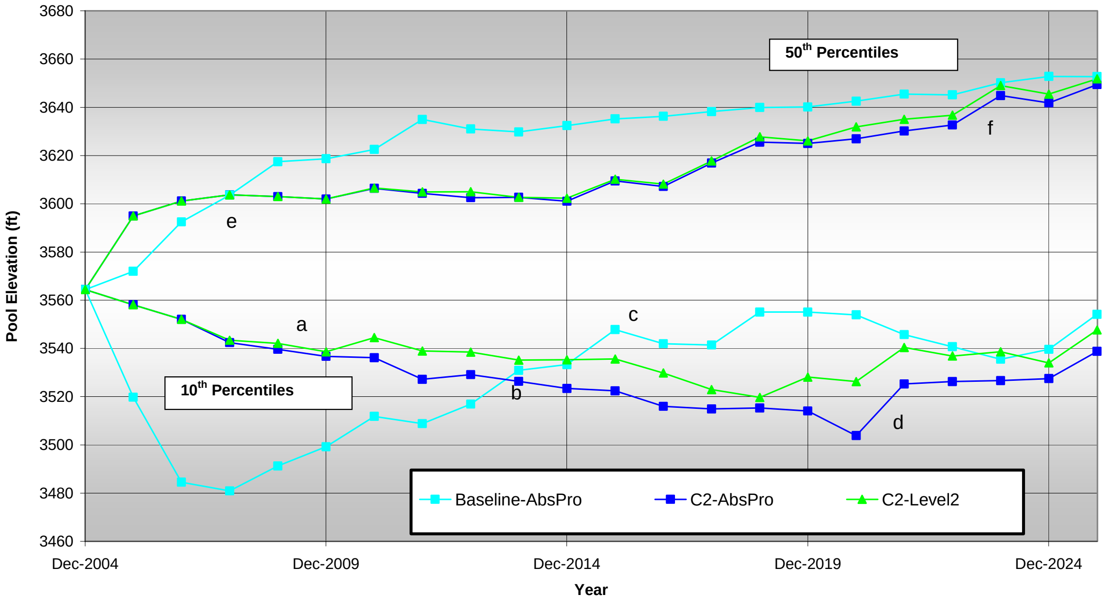


Figure 4-14 Powell EOCY Percentile Elevations – C2 & Baselines

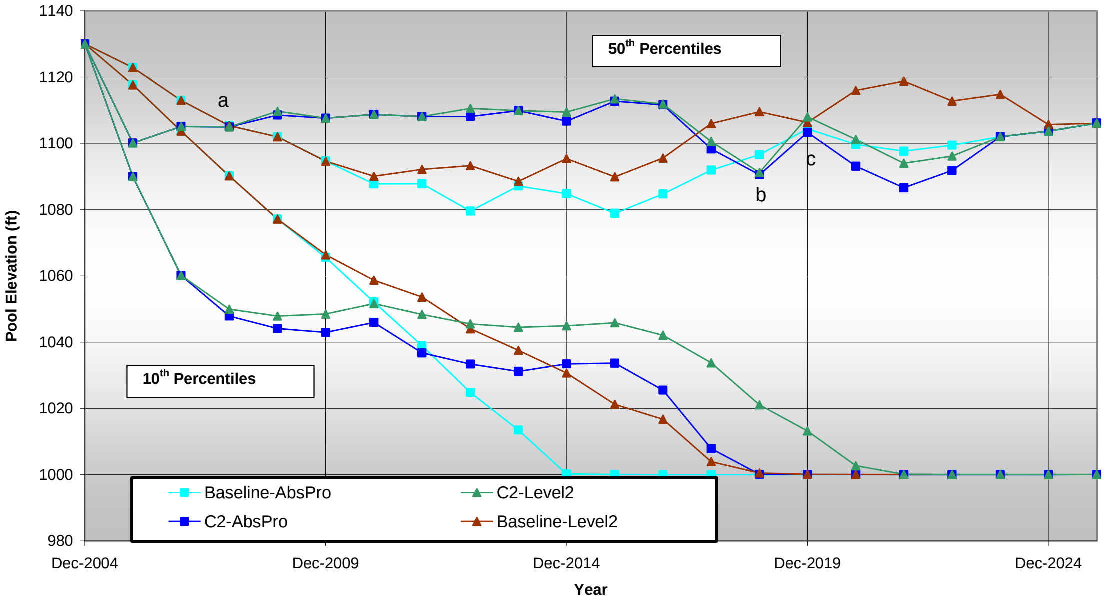


Figure 4-15 Mead EOCY Percentile Elevations – C2 & Baselines

1.18.1.1 Powell EOCY Elevation: 10th Percentile

The 10th percentiles for the C2 strategies are an average of 50 ft higher than the Baseline until 2013, point *b*. In 2009 at point *a*, C2-AbsPro drops below C2-Level2 and remains about 15 ft lower for the remainder of the simulation. From point *b* until a few years before the end of the run the C2 strategies stay significantly lower than the Baseline, reaching a maximum difference of 50 ft at 2020 (point *c*) between the Baseline and C2-AbsPro.

The higher percentile under the C2 strategies during the first 8 years is attributed to Powell releasing below the minimum objective release during this time so as to equalize with Mead. Powell begins the simulation with approximately 5.7 MAF less storage than Mead. Note the significantly higher probability of releasing below the minimum objective release under the C2 strategies through 2009 (Figure 4-20, 121) and the corresponding higher probability of equalization releases during this time under the Baseline (Figure 4-21, 121).

The fact that C2-Level2 stays higher after point *a* is because shortages have already began to be incurred at this point. The probability of shortage in 2009 is over 20% for C2-Level2 and zero under the AbsPro strategies (Figure 4-16, 117). The maximum shortage at this time is 0.5 MAF under C2-Level2 (Figure 4-18, 119). The probability for shortage under C2-AbsPro does not reach 10% under 2018. While Powell is above minimum power pool its release is dependent on Mead's elevation. Thus, the frequency and magnitude of Lower Basin and Mexico shortages, dramatically affect Powell's elevation.

At point *b*, the probability of equalization releases (greater than 8.25 MAF) is about 70% (Figure 4-21, 121). Under the Baseline, this probability is 40%. The probability for equalization releases under C2 stays around 70% beginning in 2006 through 2016, until normal operations are restored. The probability under Baseline never goes below 40%. The larger probability of releasing larger releases is responsible for the decline of Powell's 10th percentile elevation through 2020.

At point *c*, the Baseline percentile is significantly higher and stays higher through 2021. The reason for this is the greater volume released until this time under the C2 strategies. The total volume released from 2005 – 2014 is on the average of 4.0 MAF greater under both C2 strategies compared to the Baseline for roughly half of the traces. A possible reason for this is that even though Powell can release less that 8.23 MAF in some years to equalize if Mead is higher, it is required to make larger releases more often to equalize when the Upper Basin storage is below the 602(a) level.

The large difference between C2-Level2, C2-AbsPro and the Baseline at point *d*, is a result of "feeling the effects" of the high probability of large equalization releases under the C2 strategies. Powell has not been required to equalize below the 602(a) storage level since 2017 and has instead made the 8.23 MAF release at this level since 2017, however, a deficit still exists from earlier equalization releases. The difference between C2-AbsPro and C2-Level2 is due to Mead being shorted more prior to 2017 under C2-Level2 thus requiring equalization releases of less magnitude (Figure 4-16, 117).

From point *d* to the end of the run, the minimum objective release dominates as Mead continues to decline. The 10th percentiles for all strategies converge at 1000 ft.

1.18.1.2 Powell EOCY Elevation: Median (50th Percentile)

The Baseline median is the lowest during the first few years of the run until it crosses and surpasses the C2 strategies at 2007, point *e*. This is due to the same behavior seen in the 10th percentile at this time; Powell begins low and for the first few years and releases below 8.23 MAF whereas under the Baseline, the minimum release is 8.23 MAF.

From point *e* through the end of the run, the Baseline median stays an average of 15 ft higher, doubling difference that in 2011. This occurs due to the high frequency of equalization releases that occurs under the C2 strategies (Figure 4-21, 121). Also during this time, the median release from Powell is approximately 9.7 MAF under the C2 strategies versus 8.23 MAF under the Baseline (Figure 4-19, 120).

The medians begin to converge in the last 4 years, at point *f*. This is the effect of the minimum objective release dominating operations in the later years, with a 60% probability, thereby reducing the differences seen in the earlier years (Figure 4-20, 121). The slight dip of C1-AbsPro below C1-Level2 at point *f*, is an effect resulting from performance of the shortage strategies in the years prior to 2017. This is the same effect seen at point *d* in the 10th percentile. The Level2 shortage criteria impose shortages in the Lower Basin earlier than AbsPro. Thus, equalization releases of less magnitude were required under the Level2 shortage criteria because Mead's required release was not as great.

1.18.1.3 Powell EOCY Elevation: Median (90th Percentile)

Similar to the C1 strategy, there are no significant differences in the 90th percentile. This is due to the fact that the coordinated operation and shortage criteria are not designed to govern operations at higher elevations.

1.18.1.4 Mead EOCY Elevation: 10th Percentile

The C2 strategies delay Mead reaching the 1000 ft 10th percentile by 2 years under Level2 and 4 years under AbsPro. This is due to the increased probability of large equalization release from Powell because under C2 Powell equalizes at a level less than the 602(a) storage so long as the elevation is above 3490 ft. The C2 strategies drop quickly in the first 3 years due to Powell making smaller releases, below 8.23 MAF, so as to equalize. Powell begins the run with approximately 5.7 MAF less storage than Mead.

From 2020 to the end of the run all strategies remain at 1000 ft. This behavior indicates that under the average hydrology of the historical record and increasing consumptive uses in the Upper Basin, increasing 10th percentiles under normal operations is unlikely.

1.18.1.5 Mead EOCY Elevation: Median (50th Percentile)

The C2 strategies exhibit a higher median elevation for most of the simulation and for all years under coordinated operation with the exception of the first 3 years, at point *a,* when Powell makes significantly lower releases. The 10th percentile for Powell’s release averages 6.6 MAF for the first 3 years under C2 (Figure 4-19, 120). The higher median elevation under C2 is a result of the high probability, 70%, of equalization releases (Figure 4-21, 121) and a median release from Powell of 9.6 MAF (Figure 4-19, 120).

The C2 strategies drop below the Baseline-Level2 median at point *b* and are at the same level as the Baseline-AbsPro median. Also at point *b*, the Baseline-Level2 median rises above the median for all other strategies. All converge in 2019 at point *c*. Starting in 2017, Powell returns to releasing a minimum of 8.23 MAF and equalizing only at the 602(a) storage level. The probability of equalization drastically drops from 73% in 2016 to 36% in 2017 (Figure 4-21, 121). From 2017 through 2025, the probability of equalization releases averages 30%. It is because of this one-year transition from a high to low probability of equalization releases that the median storages under C2 drop suddenly at point *b*. Notice that neither Baseline scenario experience this decline; under these scenarios Mead has not grown accustomed to the frequent equalization releases characteristic of C2.

The C2 median increase from points *b* to *c* is a result of increased shortage probability under these strategies (Figure 4-16, 117). From 2018 to 2019 the probability of shortage under C2-Level2 increases from 40% to 50%. Under C2-AbsPro, the probability increases less, from 13% to 18%, however, the maximum shortage is at 1.5 MAF (Figure 4-18, 119) and the probability of shortage greater than 0.5 MAF more than doubles.

The ability of Baseline-Level2 to remain higher during the last 5 years of the simulation, averaging 20 ft above the other scenarios, is due to the shortages that were imposed earlier (Figure 4-16, 117). By 2010 there was a 40% chance of Lower Basin and Mexico shortage. C2-Level2 was the only other scenario to reach a shortage probability of 40% and this did not happen until 2019. The early shortage is also the reason the Baseline-Level2 strategy keeps the median above Baseline-AbsPro starting in 2011.

1.18.1.6 Mead EOCY Elevation: 90th Percentile

Similar to the C1 strategy, there are no significant differences in the 90th percentile. This is due to the fact that the coordinated operation and shortage criteria are not designed to govern operations at higher elevations.

1.18.2 Lower Basin & Mexico Shortage

The coordinated operation strategy C2 has the result of reducing shortage probability in the Lower Basin and Mexico through 2017. This is due to the increased frequency of equalization releases from Powell (Figure 4-21, 121). Under both C2 strategies a shortage is imposed slightly earlier in comparison to the Baseline under the same shortage criteria. This is because there is also in increased probability of releases below 8.23 MAF (Figure 4-20, 121) and a significantly lower 10th percentile release from Powell under C2 (Figure 4-19, 120). Again, the eventual stabilization of shortage probability is a result of increasing Upper Basin depletions that reduce the frequency of equalization releases under normal operating conditions.

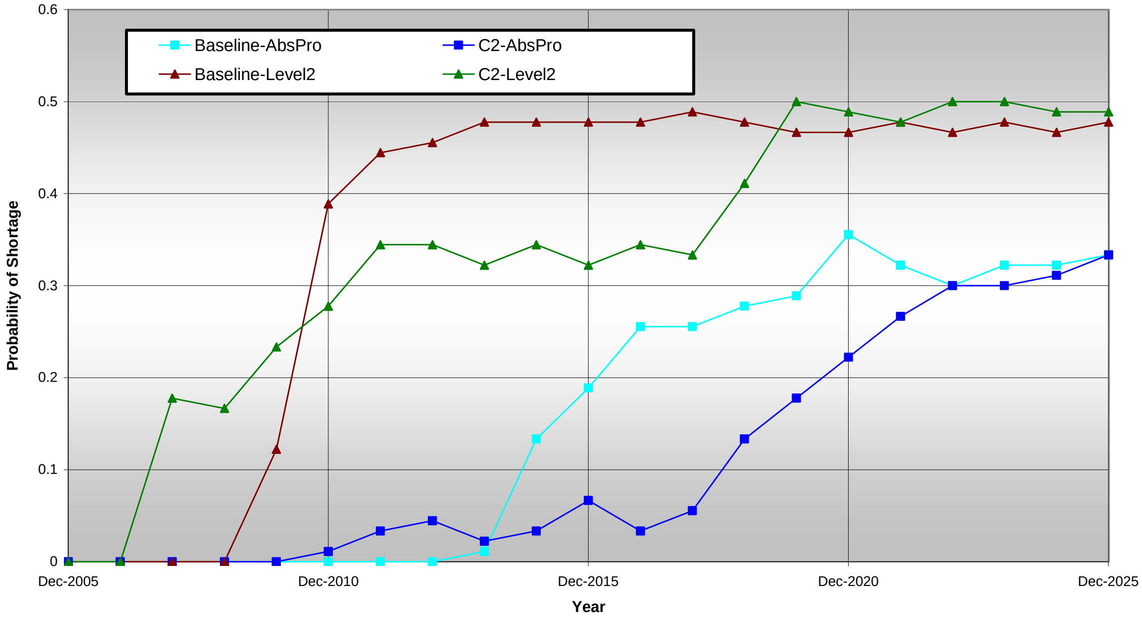


Figure 4-16 Probability of Lower Basin & Mexico Shortage – C2 & Baselines

Figure 4-17 illustrates that even though the probability of any shortage under the AbsPro shortage criteria is less, the probability of severe shortages is significantly higher.

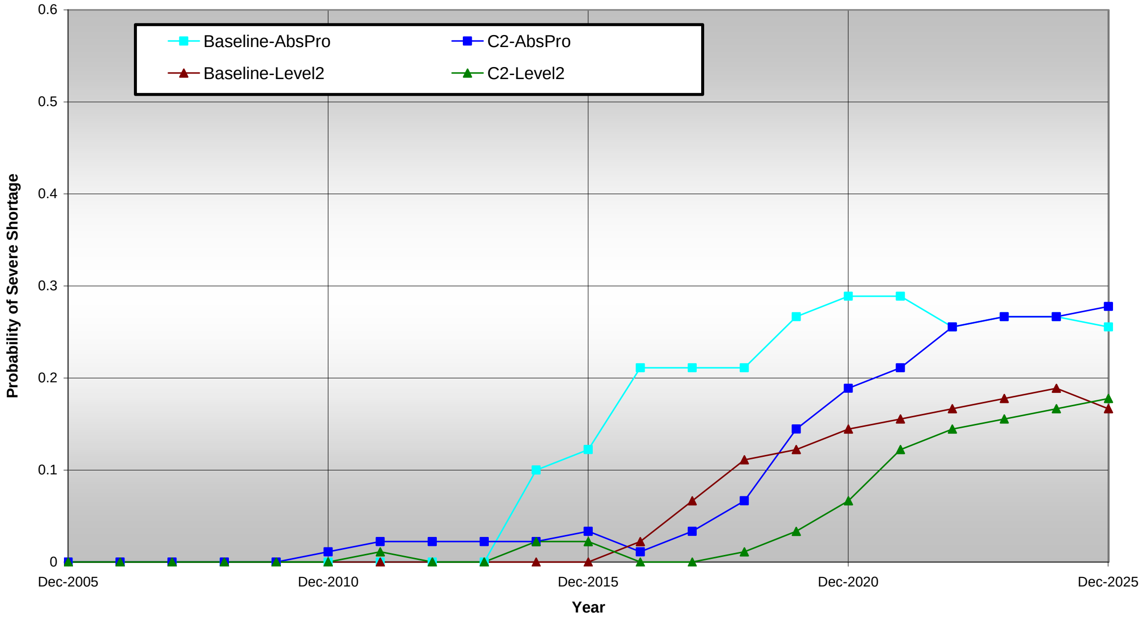


Figure 4-17 Probability of Shortage Above 0.5 MAF – C1 & Baseline

While the C2 strategies are in effect, the probability of a shortage greater than 0.5 MAF is less than 2.5%. It is also this small under Baseline-Level2 due to imposing more frequent shortages of less magnitude. However, as normal operations are restored and Upper Basin consumptive use increases, the probabilities stabilize at 25% and 17% under the AbsPro and Level2 shortage criteria, respectively.

Figure 4-18 depicts the maximum total shortage in the Lower Basin and Mexico. Under the C2 strategies, the highest probability of a shortage to Mexico is 2% in 2015 under C2-Level2. With C2, a maximum shortage of about 1.5 MAF is incurred in 2011, four and eight years earlier than a maximum shortage of equal magnitude under the Baseline-AbsPro and Baseline-Level2, respectively. However, under Baseline-Level2, the probability of any shortage reached 50% by 2010 and stayed that high through the end of the simulation. The probability of shortage with C2-Level2 did not reach this high until 2019. Similarly, a higher probability of shortage was reached at an earlier year under Baseline-AbsPro than C2-AbsPro. As in the C1 vs. Baseline comparisons, these figures demonstrate the fact that more severe shortages are eventually experienced as a result of delaying the onset of any level of shortage.

The reason for the early high maximums and highest maximums at 2015 under the C2 strategies is that during the dry traces, Powell releases a minimum of 5.5 MAF. Powell releases this amount until its elevation falls below minimum power pool, in which the release returns to 8.23 MAF. During Trace 48, Powell reaches the top dead storage in one year for both C2 strategies.

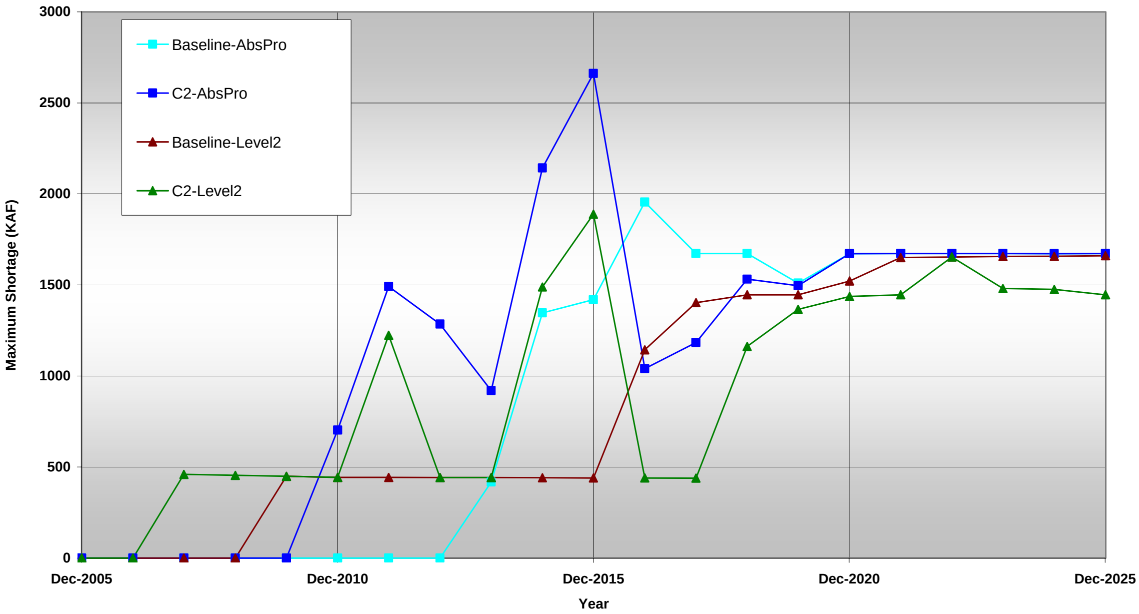


Figure 4-18 Maximum Lower Basin & Mexico Shortage – C2 & Baseline

1.18.3 Powell Release

Figure 4-19 shows the 10th, 50th and 90th percentile water releases from Powell. Other than the slightly lower 10th percentile of C2-Level2 from 2013 to 2016, there are no significant differences between the C2-AbsPro and C2-Level2 strategies.

The reason for this difference is that the earlier issuing of shortages characteristic of the Level2 shortage criteria has the effect of extending the time that Powell is above minimum power pool. Above minimum power pool, Powell’s minimum release is 5.5 MAF, whereas below it is 8.23 MAF.

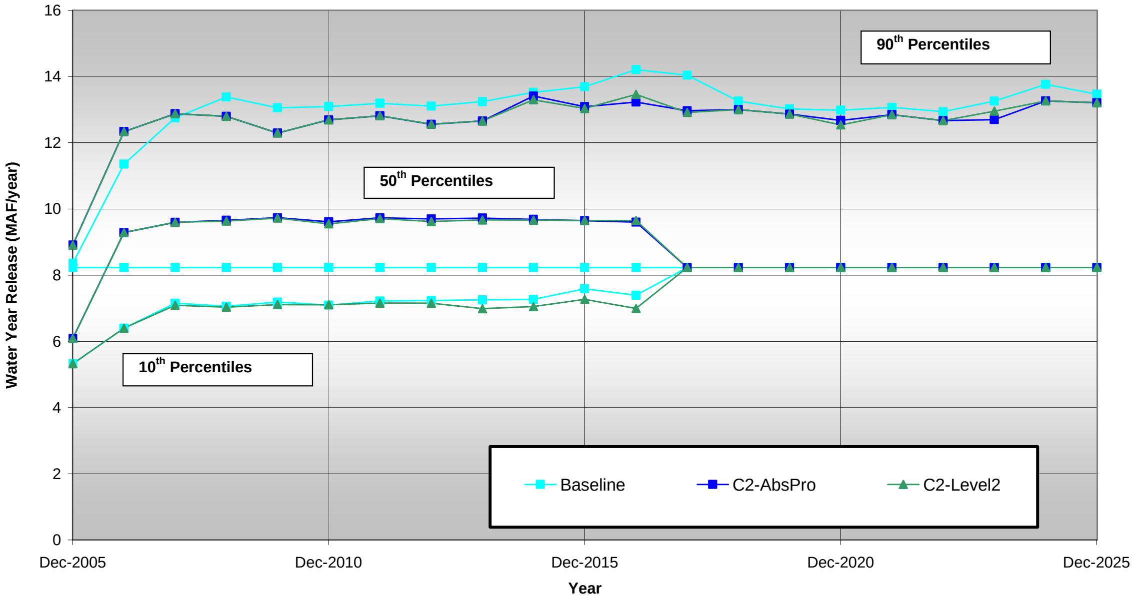


Figure 4-19 Powell Water Year Release Percentiles – C2 & Baselines

The significantly higher median release under C2 is the effect of frequent high equalization releases below the 602(a) storage level (Figure 4-21, 121). The 90th percentile is highest under the Baseline scenario because such high releases are made at lower elevation under C2, reflected in the C2 median release.

Figure 4-20 shows the probability of release below the minimum objective release. The extremely high probability of releases below 8.23 MAF in the first two years of the simulation is because Powell begins with 40% less storage capacity than Mead. After equalization occurs, the probability of the reduced releases drops to below 30%. The small probability of releases under the Baseline being below 8.23 MAF occurs during dry traces in which Powell is drawn down to dead pool and cannot physically release 8.23 MAF.

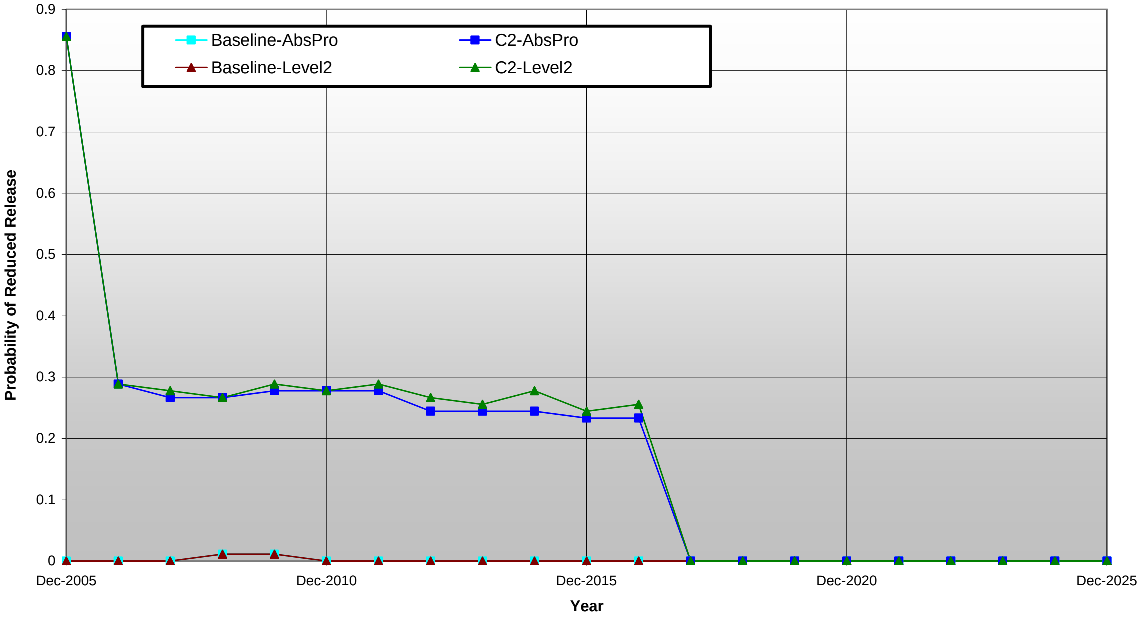


Figure 4-20 Probability of Reduced Release – C2 & Baselines

Figure 4-21 depicts the probability of releases greater than 8.25 MAF. This probability is obviously higher under the C2 strategies compared to the Baseline because Powell makes equalization releases below the 602(a) storage level under C2.

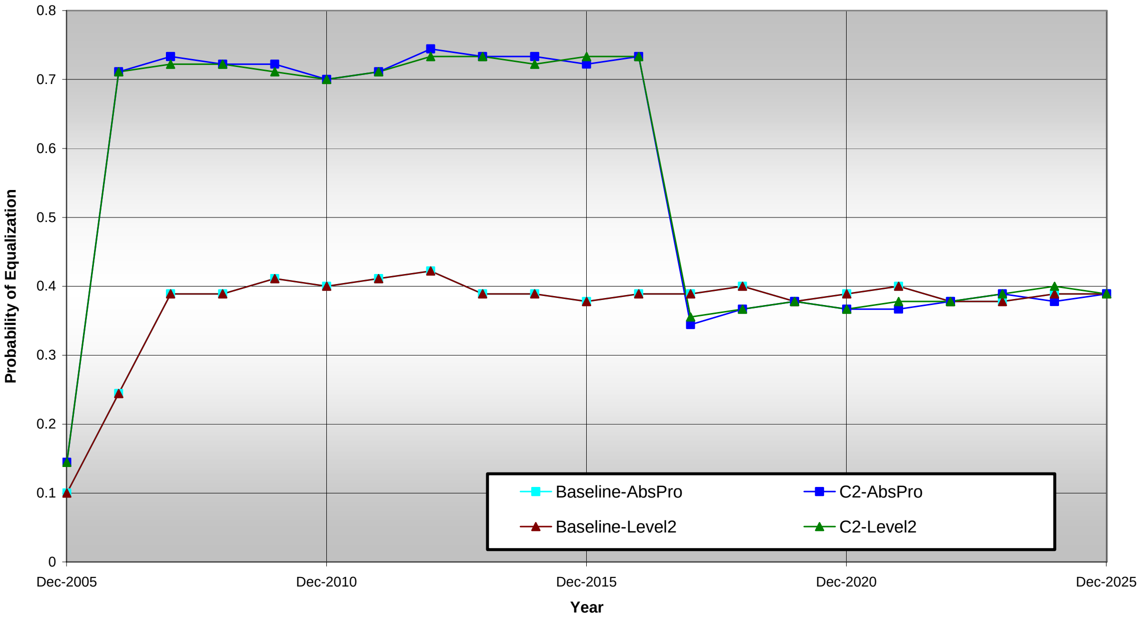


Figure 4-21 Probability of Equalization Release – C2 & Baselines

The probability for equalization releases during the period coordinated operation is in effect is greater than the probability for releases less than the minimum objective release during this time. This indicates that Powell is more often at a storage level less than that of Mead under C2. After 2017, the minimum objective release is the most probable release, due to increased Upper Basin demands that reduce the frequency of equalization releases.

1.18.3.1 Compact Delivery

Under the hydrologic sequences generated with the ISM the Upper Basin delivery obligation, as specified by the Compact, of 75 MAF over 10 years is always satisfied. The minimum 10-year volume under C2-AbsPro and C2-Level2 is 77.0 MAF, 76.0 MAF, respectively.

1.19 Comparison of Coordinated Operation Strategies (C1 & C2)

This section compares the results of the four coordinated operation scenarios. The figures presented are EOCY percentile elevations of Powell and Mead along with the probability of and maximum Lower Basin and Mexico shortage.

1.19.1 Powell & Mead Percentile Elevations

The following page contains two figures comparing the percentile elevations of Powell and Mead. The percentiles are the results of both coordinated operation strategies coupled with the each set of shortage criteria to form four scenarios.

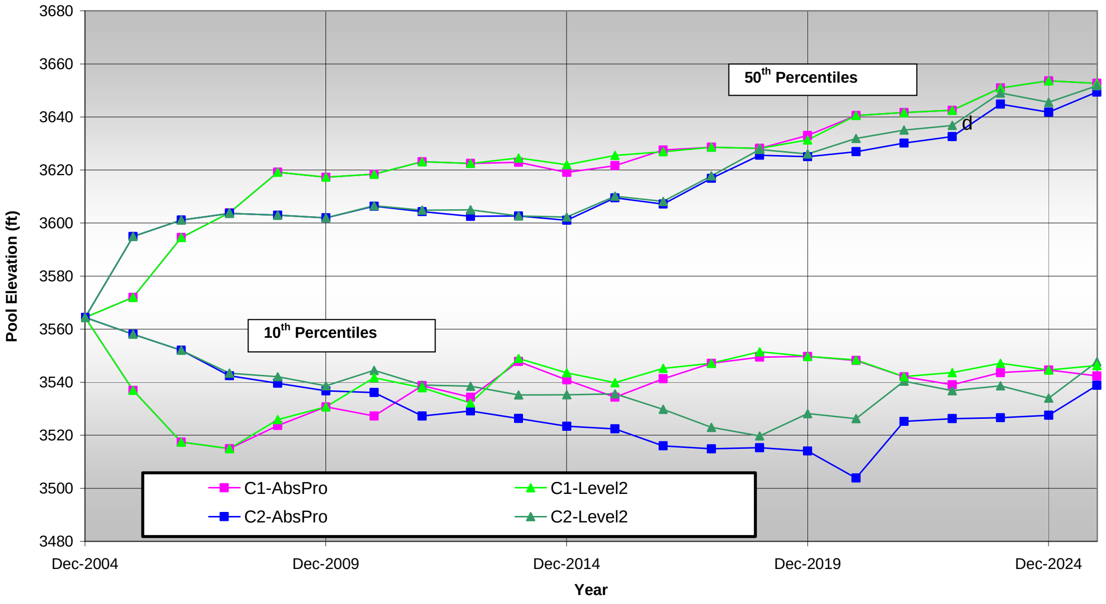


Figure 4-22 Powell EOCY Elevation Percentiles – C1 & C2

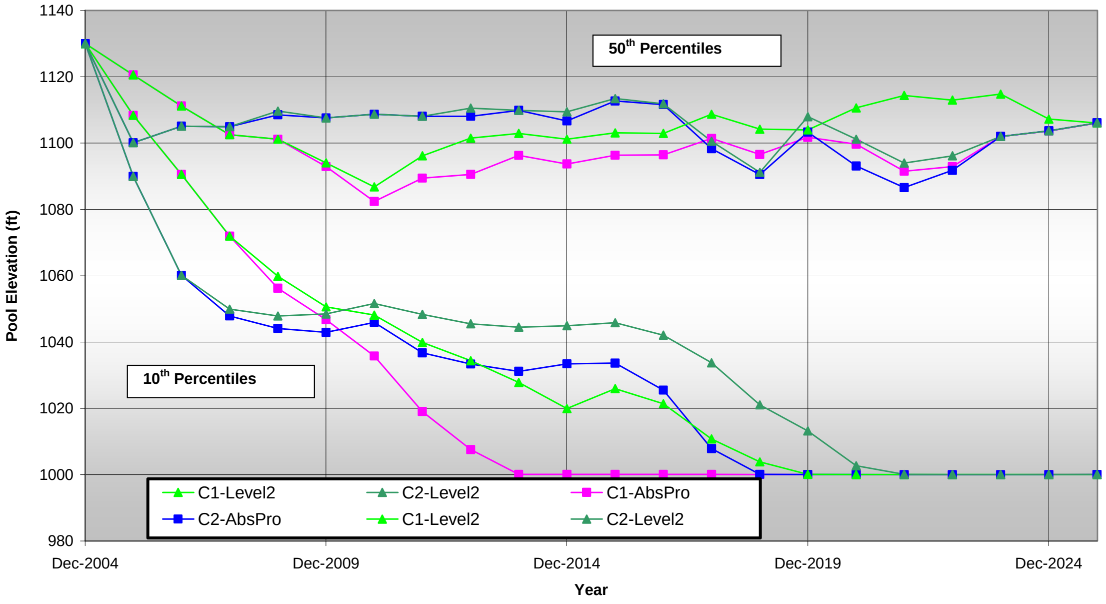


Figure 4-23 Mead EOCY Elevation Percentiles – C1 & C2

1.19.1.1 Powell EOCY Elevation

Powell clearly fares better with C1 than C2 at the median elevation. Only during 2005 and 2006 is Powell lower at the median under C1. The reason for this is that Powell is allowed a minimum annual release of 5.5 MAF under C2 whereas the minimum release under C1 is the ROM of 7.48 MAF. Powell must be below the LPT while Mead is above the WST for a ROM release to be made. Powell begins the simulation at 3564 ft, 4 ft above the LPT elevation. Powell’s median release under C1 in 2005 is 8.23 MAF compared to 6.09 MAF under C2 (Figure 4-29, 133). The immediate reduction of releases under C2 is the same reason the 10th percentile of C2 remains above that of C1 through 2009.

Through the interim period when the coordinated operation strategies are in effect the median for C1 is an average of 12 ft higher than C2. Other than the 5 ft difference between C2-AbsPro and C2-Level2 from 2020 to 2024, at the median, the effect of the shortage criteria is insignificant. As discussed in the section comparing C2 and the Baselines, this difference in the C2 scenarios is a result of significantly higher probability of Lower Basin and Mexico shortages that are incurred as early as 2007 under C2-Level thereby requiring a smaller equalization release from Powell during 2010 to 2017.

All scenarios, for each percentile, end at the same elevation. The ending elevation at the median is almost 90 ft above the initial elevation. After normal operations are restored in 2017, the probability of releasing the minimum objective release increases to about 62% for the rest of the simulation (Figure 4-28, 132). With the smaller chance of equalization releases, under average hydrology Powell's elevation steadily increases.

It is less clear examining the 10th percentile which strategy benefits Powell. The reason being that Powell's lower elevations are more influenced by the Lower Basin shortage criteria. The frequency and magnitudes of Lower Basin and Mexico shortages incurred affects the how often Powell can reduce releases below 8.23 MAF, either releasing a ROM release or reducing to equalize with Mead in the event that Mead is higher. Although the C2 scenarios never go above the C1 scenarios at the 10th percentile, there are more instances where they closer than at the median.

The ability of the C2-Level2 10th percentile to remain almost as high as C1-Level2 is due to the comparable probability of shortage and amount of shortage through 2016 (Figure 4-24, 128). In addition, a shortage under both scenarios is incurred early in the simulation. After 2016 Powell's elevation is no longer directly affected by shortages in the Lower Basin and Mexico. The large difference between the C2 and C1 strategies between 2016 and 2021 is the effect of much larger releases made under C2 in the years prior to 2016. From 2006 through 2016 the median release under C2 was 9.60 MAF versus 8.23 MAF under C1 (Figure 4-27, 132). Even with comparable shortage probability, C2-Level2 goes as far 40 ft below C1-Level2 during this time.

1.19.1.2 Mead EOCY Elevation

Opposite of Powell, Mead clearly fares better under C2 at the median elevation during the time the coordinated operation strategies are in effect. Mead benefits from the high median release from Powell during this time (Figure 4-27, 132). However, the C2 medians plunge in 2018 as a result of Powell returning to normal equalization conditions and the increased probability of minimum objective releases after 2016 (Figure 4-28, 132). Also through 2016, the C1-AbsPro median is the lowest of all scenarios resulting from a low probability of Lower Basin and Mexico shortages and a reduction in Powell’s release compared to C2.

The effect of imposing shortages early can be seen from the behavior of the C1-Level2 median. Although the median remains below those of C2 during coordinated operation it crosses them in 2016 and remains higher until all scenario medians meet at the end of the simulation. Only during 2005 through 2009 is the probability of shortage under C1-Level2 not the largest of all scenarios (Figure 4-24, 128). This is due to two reasons. One, the Level2 shortage criteria includes elevation triggers that trigger shortages at higher Mead elevations. Two, under the C1 scenarios, the probability of equalization releases from Powell is significantly less, 49% vs. 73% (Figure 4-29, 133).

The fact that the median elevations end at about the same elevation as they begin can be attributed to increasing Upper Basin consumptive uses over the length of the simulation. With the 2005 level of Upper Basin depletions, about 4.35 MAF, and under normal operations, Lower Basin depletions and the delivery to Mexico exceed the inflow to Mead. With a 0.5 MAF increase in Upper Basin depletion over the 21-year simulation period, this behavior is intensified. This is reflected in the shortage figures that illustrate the climbing shortage probabilities over the simulation length (Figure 4-24, 128 and Figure 4-25, 129).

C2-Level2 is able to maintain the highest 10th percentile due to frequent shortages (Figure 4-24, 128) and Powell's large and frequent equalization releases (Figure 4-29, 133). C1-AbsPro exhibits the steepest slope from 2005 to 2013 where it hits 1000. By 2021 the 10th percentile under all scenarios has reached 1000 ft and stays there for the remainder of the simulation. This behavior is regardless of the shortage probabilities that continue to increase. This behavior can be attributed to increased Upper Basin depletions and the fact that under normal operating conditions, the release required from Mead to meet downstream demands exceeds its long-term inflow.

1.19.2 Shortages to Lower Basin & Mexico

The figures below compare the probability of shortage, probability of shortage greater than 0.5 MAF and the maximum shortage for C1 and C2. The shortage criteria tend to dominate the trends of the shortage probabilities. Figure 4-24 on the following page illustrates that strategies with Level2 criteria exhibit both an earlier and a more frequent chance of shortage throughout the length of the simulation. Comparing C2 to C1 under the same shortage criteria, with C2, probability of shortage exists a year earlier. This can be attributed to both the higher probability of releases below 8.23 MAF in the early years of the simulation (Figure 4-28, 132) and a lower 10th percentile for Powell's release also during this time (Figure 4-27, 132).

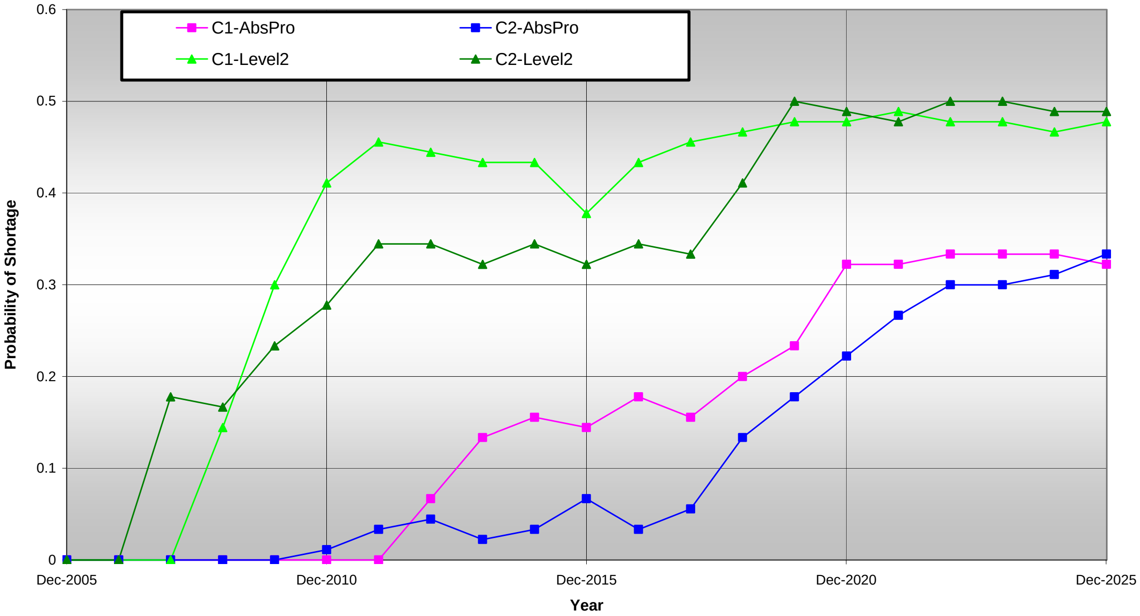


Figure 4-24 Probability of Lower Basin & Mexico Shortage – C1 & C2

C2-AbsPro maintains the lowest probability of any amount of shortage, for most of the simulation; however, it has the second highest probability of a more severe shortage, as illustrated in Figure 4-25. Both scenarios under the AbsPro criteria have a higher probability of a more severe shortage beginning in 2019. Also interesting to note is the difference in probabilities for each scenario between Figure 4-24 and Figure 4-25. C2-Level2 during the period coordinated operation is in place, through 2016, averages a shortage probability of about 25%. During this time, the probability of shortage greater than 0.5 MAF averages less than 1%, resulting in a 22% difference between the probability of any shortage and the probability of severe shortage. On the other extreme, the probability for shortage under C2-Level2 averages about 6% through 2016 and 4% for the probability of more severe shortage, a 2% difference. Although the AbsPro shortage criteria reduce the probability of shortage, there is a larger chance that the shortages incurred will be greater than 0.5 MAF.

The high frequency of equalization releases under C2 (Figure 4-29, 133) has the effect of reducing both the probability of shortage and the probability of severe shortage compared to the C1 strategy under the same shortage criteria.

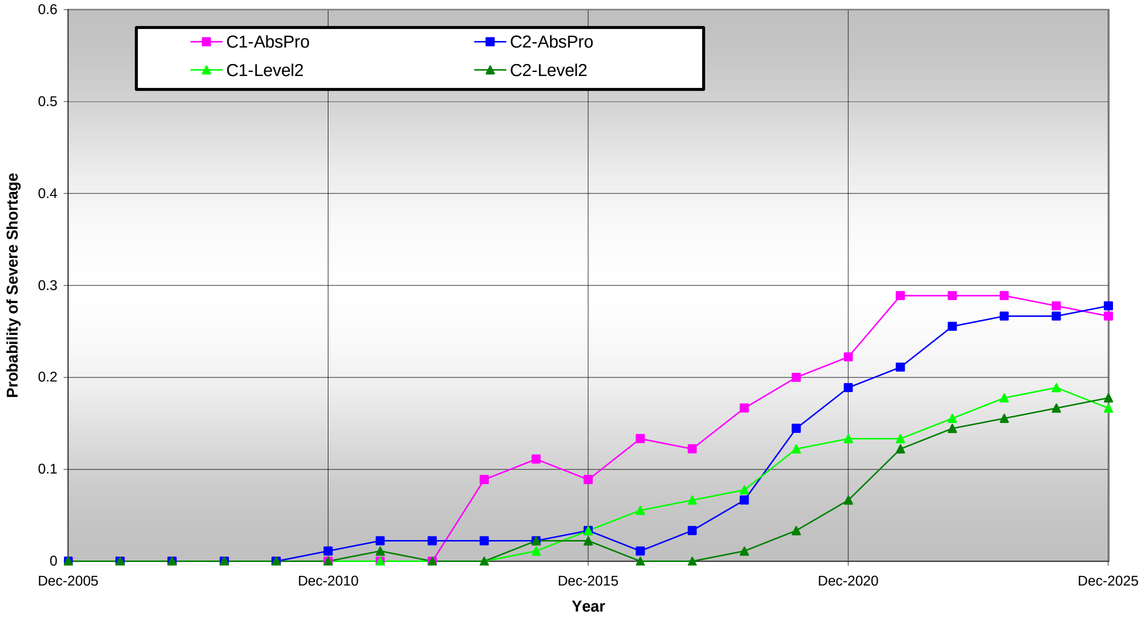


Figure 4-25 Probability of Shortage Above 0.5 MAF – C1 & C2

One exception to the trend is the decreased probability of shortage greater than 0.5 MAF of C2-AbsPro below C1-Level2 during 2016 and 2017. This is due to the fact that there are lower elevations at Powell during this time (see 10th percentile in Figure 4-22, 123). As Powell drops below the minimum power pool, the minimum release is increased from 5.5 MAF to 8.23 MAF, i.e. there is more water coming into Mead reducing the need for a severe shortage. However, the probability of any shortage at still increases at this time.

Figure 4-26 compares the maximum shortage amounts under C1 and C2. A hydrologic sequence characteristic of Trace 48 with a twelve-year period averaging 12.2 MAF at the beginning of the simulation yields shortages on the order of 2.5 MAF under C2-AbsPro. Just below that is a 2.0 MAF maximum shortage under C2-Level. Clearly, there is a likelihood of incurring shortages of greater magnitudes under the C2 strategies. Again, this results from the low minimum release from Powell of 5.5 MAF while Powell's elevation is above 3490 ft, approximately 4.0 MAF of storage. Because equalization is the driving operation, at this point, Mead will contain approximately 4.0 MAF of storage, which corresponds to an elevation of about 1000 ft. C1, on the other hand, requires that Powell revert back to releasing a minimum of 8.23 MAF once Mead drops below 1050 ft. Thus, Mead is protected at a higher elevation under the C1 strategy, which results in lower maximum shortages in drought conditions.

During the dry traces that result in these large shortage amounts, specifically Trace 48, Powell is drawn down to dead storage during one year in C2 under both shortage criteria. Although Powell goes below minimum power pool in C1, it is never reaches the top of dead storage.

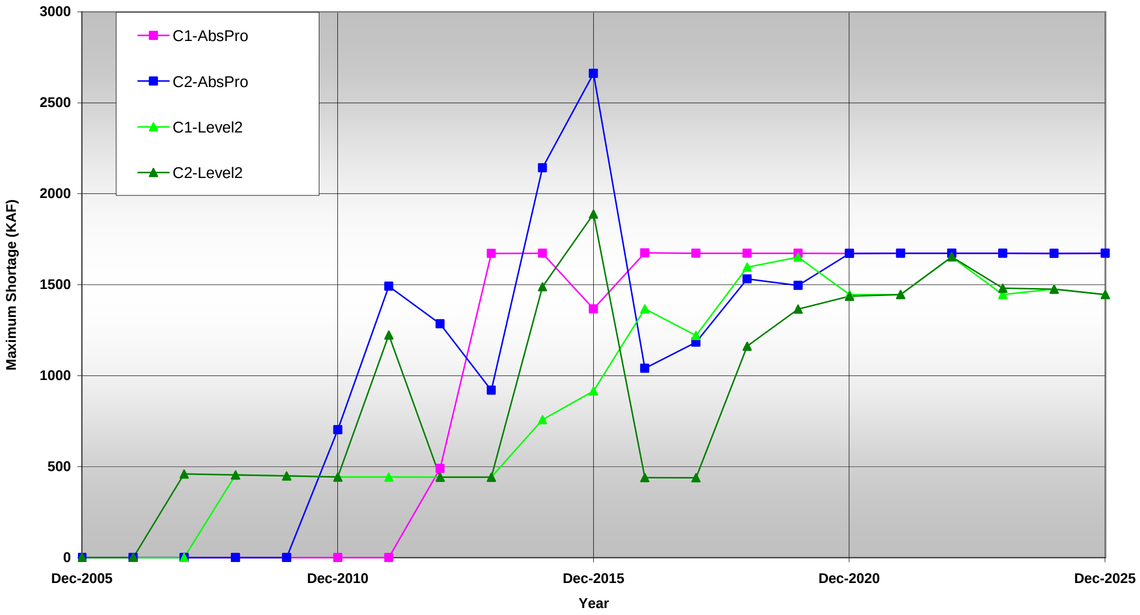


Figure 4-26 Maximum Lower Basin & Mexico Shortage – C1 & C2

1.19.3 Powell Release

As illustrated in Figure 4-27, C1 has both a higher 90th percentile and 10th percentile release while C2 exceeds the median release of C1 by almost 1.4 MAF. Because the median is greater under C2 from 2006 through 2016, less water available for larger releases, thus the 90th percentile of C2 is lower than that of C1. Mead benefits with C2 over C1 while Powell's capacity is greater and more frequent equalization releases are made. However, as Powell's capacity exceeds that of Mead, much lower releases are made than permitted under C1.

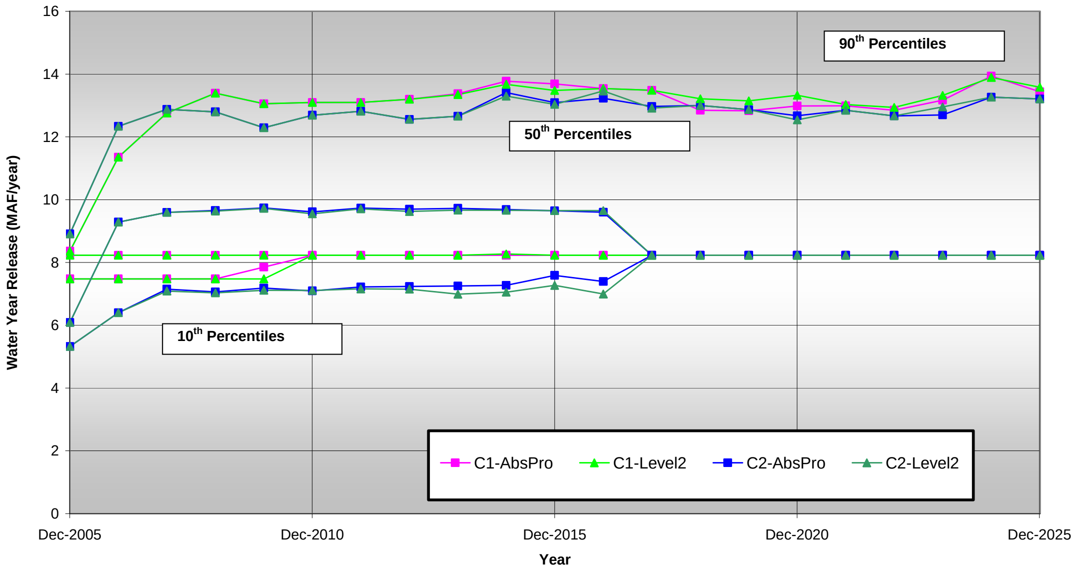


Figure 4-27 Powell Water Year Release – C1 & C2

Another effect of increased median releases under C2 is that as Powell returns to normal operating conditions in 2017, a larger decline in Mead's median elevation is experienced from Mead having grown accustomed to the high frequency of equalization thus imposing less Lower Basin and Mexico shortages. This is drop in elevation is depicted in Figure 4-23, 123.

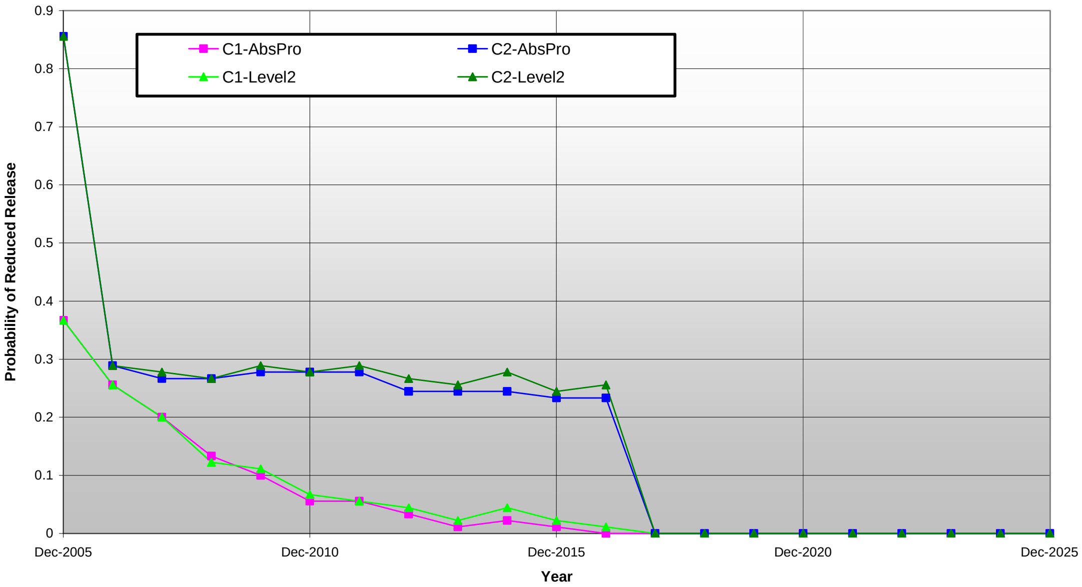


Figure 4-28 Probability of Reduced Release – C1 & C2

The probability of releases below the minimum objective release is highest under C2 from 2005 to 2016. This is because Powell can continue to release below 8.23 MAF until the elevation falls below 3490 ft whereas under C1, Powell must release a minimum of 8.23 MAF if Mead is below 1050. The extended duration of reduced releases under C2 has the effect of increased maximum shortages during drought conditions (Figure 4-26, 131).

As expected, depicted in Figure 4-29, the probability of equalization releases over 8.25 MAF is substantially higher with C2. This has the effect of reducing shortage probabilities under both shortage criteria, discussed in the previous section. Comparing the median release, from 2005 through 2016, approximately 17.3 MAF more water is released from Powell with C2. It can be assumed that the majority of this water is being released via equalization. Both strategies have a very low chance of equalization in 2005 as Powell begins the simulation with 40% less capacity than Mead.

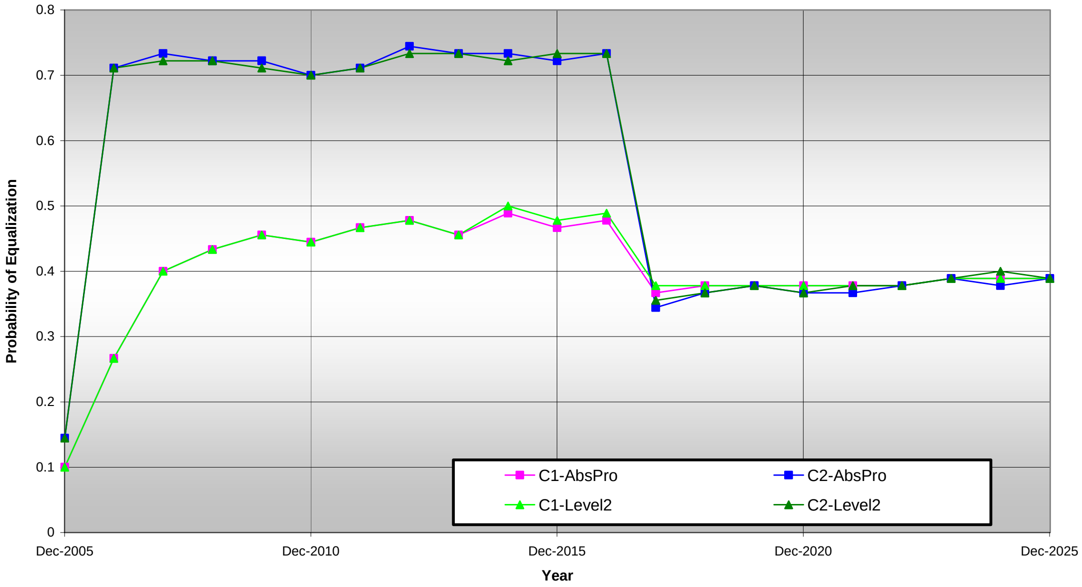


Figure 4-29 Probability of Equalization Releases – C1 & C2

1.20 Summary of Results

Because coordinated operation is not in effect through the duration of the run the results should be viewed in terms of behavior through 2016 when either coordinated operation strategy is in place and after 2016, when baseline i.e. normal operation procedures are restored. These two periods are not to be viewed independently, however. The resulting reservoir levels, release volumes and occurrence of shortage and shortage amounts from coordinated operation greatly influence the outcome once operations return to normal.

The effect of increasing Upper Basin consumptive use should be reiterated. By 2020, under all scenarios, Mead's 10th percentile elevation reaches 1000 ft and does not increase for the remainder of the simulation. In addition, median elevations ended at 1106 ft, approximately 24 ft below the starting elevation. As the Upper Basin use increases 0.5 MAF over the duration of the simulation, the 602(a) storage requirement correspondingly increases and the frequency of equalization releases is reduced. Thus, the minimum objective release is the governing operation. As Powell releases 8.23 MAF per year, under average long-term hydrology, the release required from Mead to meet Lower Basin demands and the Mexican treaty obligation, will exceed the inflow. In the Upper Basin, reduced frequency of equalization releases and average hydrology raise Powell from its low initial condition that reflects several years of record low hydrology. Powell ends the simulation, for all scenarios, about 85 ft higher than the initial elevation.

With little exception, both coordinated operation strategies, C1 and C2, improve 1) Powell's 10th percentile elevations during the onset of a drought and with low initial conditions; 2) Mead's median elevations as Powell recovers from drought and 3) lowers the probability of Lower Basin and Mexico shortage. These improvements are seen through 2016 and in comparison to the baseline using the same shortage policy.

Under C1 and C2, Powell's 10th percentile elevations increase from the ability to release below the minimum objective release at the onset of a drought and at low initial conditions. Because C2 allows a greater minimum annual release of 5.5 MAF, 10th percentile elevations are slightly higher, 12 ft (32 ft higher than Baseline), with the C2 strategy.

Increased median elevations at Mead result from Powell releasing large (greater than 8.25 MAF) equalization releases at a level below the 602(a) storage level, as Powell recovers from drought conditions. This mechanism allows Powell to relieve the deferred recovery of Mead and therefore improve the imbalance seen at this situation under baseline operations. Median elevations begin to increase at 2008 under C2 and 2011 under C1. Median elevations stay twice as high, about 18 ft per year, under C2 because Powell releases about 15% more water from 2006 through 2017.

Under C1 and C2 Powell's median elevations are lower than the baseline, as are Mead's 10th percentile elevations under C1. This is in exception to C2-Level2, which results in the highest 10th percentile elevations for Mead through 2016 and C2-AbsPro, which is higher than the Baseline under the AbsPro criteria. Again, this is due to the significant increase of water released from Powell under the C2 strategy. It should be noted that all Mead 10th percentile elevations are lower (average 28 ft with

AbsPro and 15 ft with Level2) with C1 and C2 until 2010. This is due to the high probability of reduced Powell releases with C1 and C2 during from 2005 through 2010 as Powell begins the run with about 5.7 MAF less storage than Mead. C1 and C2 try to adjust this balance by reducing releases from Powell.

Equalization at a level below the 602(a) storage requirement has the effect of decreasing Powell's median elevations from about 2008 through 2016. The median under the C2 scenarios stay an average of 24 ft for each year, 16 ft greater than the median reduction under C1.

After baseline operations are restored beginning in 2017, the Lower Basin shortage criteria in effect prior to 2017 and the minimum objective release, due to increasing Upper Basin use, drive the trends. The disparity in Powell's median elevation under C1 and C2 is corrected by the minimum objective release being the governing operation and all median elevations end together about 85 ft higher than the initial elevation. Also resulting from the increased frequency of minimum objective releases is Mead's 10th percentile elevations, which all reach 1000 by 2021 and remain there.

During 2016 through 2025, Mead's median elevation under C1-Level2 and Baseline-Level2 remain higher than the median elevations of all other scenarios. This can be attributed to the Level2 shortage measures under these two scenarios, beginning as early as 2008, that reduce demands at higher elevations, All median elevations end together, 14 ft below the initial elevation. Mead's initial elevation reflects a record drought condition which average hydrology cannot raise because of increased Upper Basin demands.

Another noteworthy result is the effect of the C2 strategy on Powell's 10th percentile elevations after 2016. After 2016, these elevations decline, reaching as low as 50 ft under the Baseline with C2-AbsPro and 20 ft under with C2-Level2. This can be attributed to 1) the increased volume released from Powell from 2005-2016 under C2 and 2) the effect that this increased release has by decreasing the probability of shortages. C2-AbsPro goes lower than C2-Level2 because the probability of shortage is less under the AbsPro strategy. All coordinated operation strategies end below (maximum of 15 ft) the Baseline 10th percentile elevation.

A clear outcome of coordinated operation is the reduction of Lower Basin and Mexico shortage probability. With this said, it should also be noted that with each coordinated operation scenario, a significant (up to 40% under C1-Level2) shortage probability occurs one to two years earlier compared to the Baseline of the same criteria. The shortage probabilities for all strategies stabilize after 2020 with strategies under the Level2 criteria at about 48% and those under AbsPro criteria at about 33%.

The Level2 scenarios represent a more precautionary approach in that two levels of shortages can be imposed. The first level involves shortages of smaller magnitudes (only CAP and SNWA are shorted) and is triggered earlier as a result of the 80P1050 Mead elevation triggers. Additional shortages are imposed under a Level2 shortage if the first level is not sufficient. The AbsPro scenarios are the opposite approach. Full schedules are satisfied until doing so will result in Mead dropping below 1000 ft. The general outcome of these distinctly different criteria is that shortages of a less magnitude occur more frequently under Level2 and shortages occur less frequently but are of a greater magnitude under AbsPro.

Reductions in shortage probabilities are greater under the C2 strategy compared to C1. C2-Level2 and C2-AbsPro reduce the shortage probability through 2016 by 10% and 11%, respectively. The reduction under the C1 strategy is on the order of 1-2% under both criteria.

The reverse behavior is seen regarding the probability of shortage greater than 0.5 MAF. Strategies under the AbsPro criteria have higher probabilities with C1-AbsPro the highest under the Baseline-AbsPro. Under C1-AbsPro there is a 10% chance of a shortage greater than 0.5 MAF in 2014, one year earlier than the Baseline and six years behind Baseline-Level2, the next scenario to reach a 10% probability.

Another significant outcome is the maximum shortages incurred under the scenarios. C1-AbsPro, which also has the highest probability of shortage greater than 0.5 MAF, under the hydrology of the critical period on record, imposes a maximum shortage of about 2.7 MAF. The second highest maximum is under C2-Level2 of 1.97 MAF. The high maximums under C2 can be attributed to the fact that Powell can release as low at 5.5 MAF per year until reaching minimum power pool. All coordinated operation strategies obtain higher maximum shortages than under Baseline-Level2.

1.21 Coordinated Operation Extended Through Run Duration

A dominating trend of the results presented thus far is the increasing Lower Basin and Mexico shortage and declining 10th percentile elevations at Mead as a result of increasing Upper Basin demands. Under baseline operating conditions increased demand in the Upper Basin results in a decreased frequency of equalization releases from Powell. Thus, it is interesting to examine the effects of maintaining coordinated operation for the duration of the simulation as to understand how reservoir elevations and Lower Basin shortages will respond to coordinated operation on a more long-term basis.

Four new scenarios (C1-AbsPro.2025, C1-Level2.2025, C2-AbsPro.2025, C2-Level2.2025) were generated by extending coordinated operation through 2025 for both strategies and shortage policies. Presented in this section are the 10th and 50th percentile elevation for Powell and Mead and the probability of Lower Basin and Mexico for these scenarios compared to the results of maintaining coordinated operation only through an interim period.

1.21.1 Powell & Mead Percentile Elevations

Continuing coordinated operation ultimately has the effect of reducing both the 10th and 50th percentile elevations at Powell as shown in Figures 4-30 and 4-31. The most significant reduction, averaging 43 ft, is that of the C2 strategies. Recall the higher volumes of water released from Powell under this strategy. Under baseline operations at low elevations, Powell releases 8.23 MAF regardless of Mead's elevation. Under C2 "*Balance Contents*" Powell must sometimes release greater than 8.23 MAF at low elevations if necessary to balance contents with Mead. This causes Powell's 10th percentile elevations to plummet in the long-term.

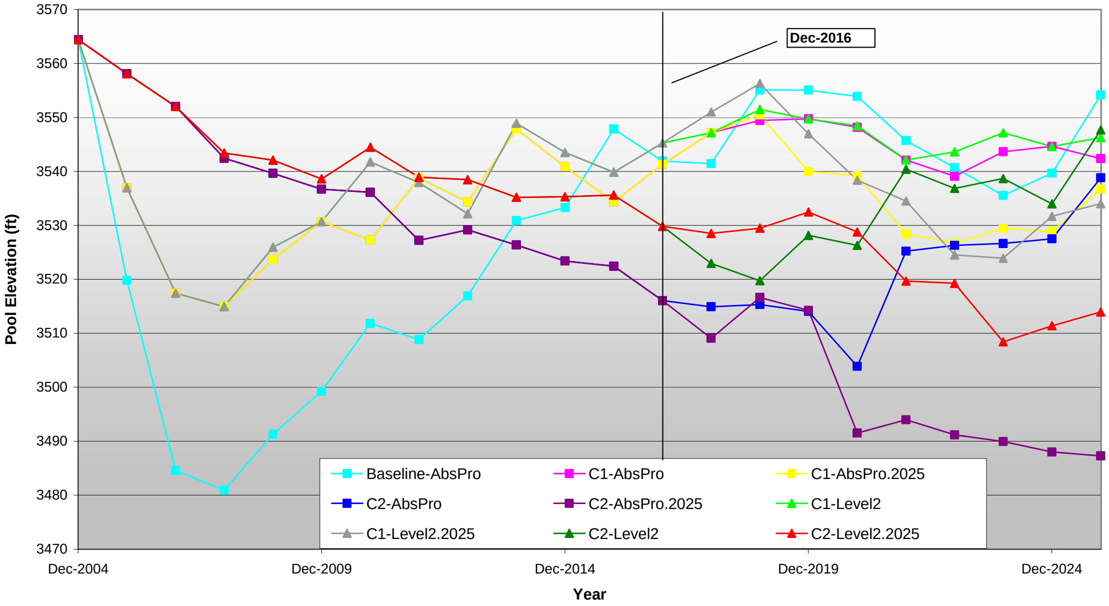


Figure 4-30 Powell 10th Percentile Elevation – C1 & C2 (2025)

The continuation of coordinated operation also results in decreased median elevation (Figure 4-31), averaging 30 ft less than the ending elevation under baseline conditions. This result is again attributed to the high volume of water released under coordinated operation. Although C1 and C2 through 2025 end at lower elevations, both exhibit a mostly positive slope although less steep after 2016. This behavior indicates that in the long-term, Powell will recover under average hydrology.

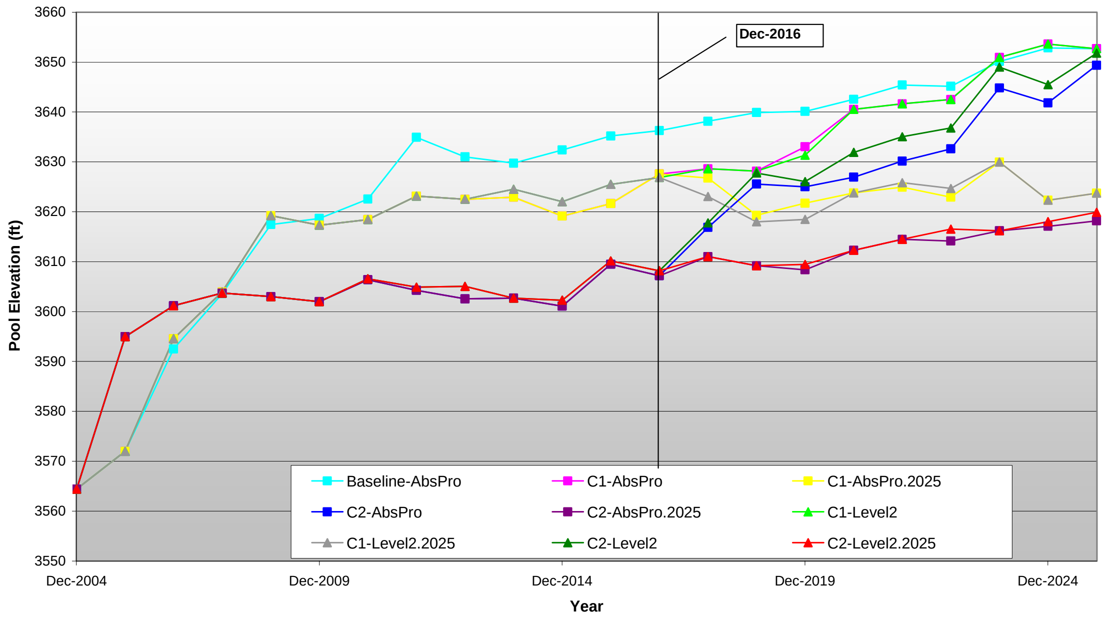


Figure 4-31 Powell 50th Percentile Elevation – C1 & C2 (2025)

If Powell's elevations decline by extending the period of coordinated operation, it can be expected that Mead's elevations will increase and end higher than under baseline conditions. In Figure 4-32, it can be seen that Mead's 10th percentile elevation ends highest under the C2-Level2 strategy in place through 2025. Even under coordinated operation through 2025, Mead's 10th percentile elevations decline through 2025. Although Powell will make equalization releases more frequently than under baseline conditions, Mead must still make releases for downstream demands which are about 9.0 MAF in a normal year. If Powell does not release at least this much, Mead will be in a deficit for that year.

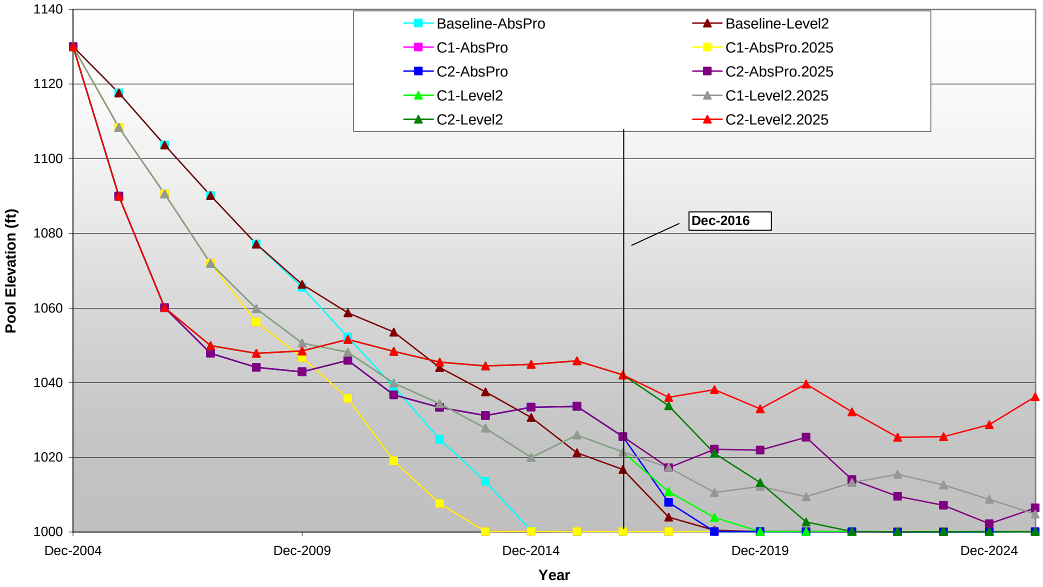


Figure 4-32 Mead 10th Percentile Elevation – C1 & C2 (2025)

Mead's median elevations (Figure 4-33) also improve by continuing coordinated operation and end higher than all other scenarios. Again, C2-Level2 through 2025 ends the highest. The effect of increased equalization releases from Powell drives the increased median elevations from continuing coordinated operation.

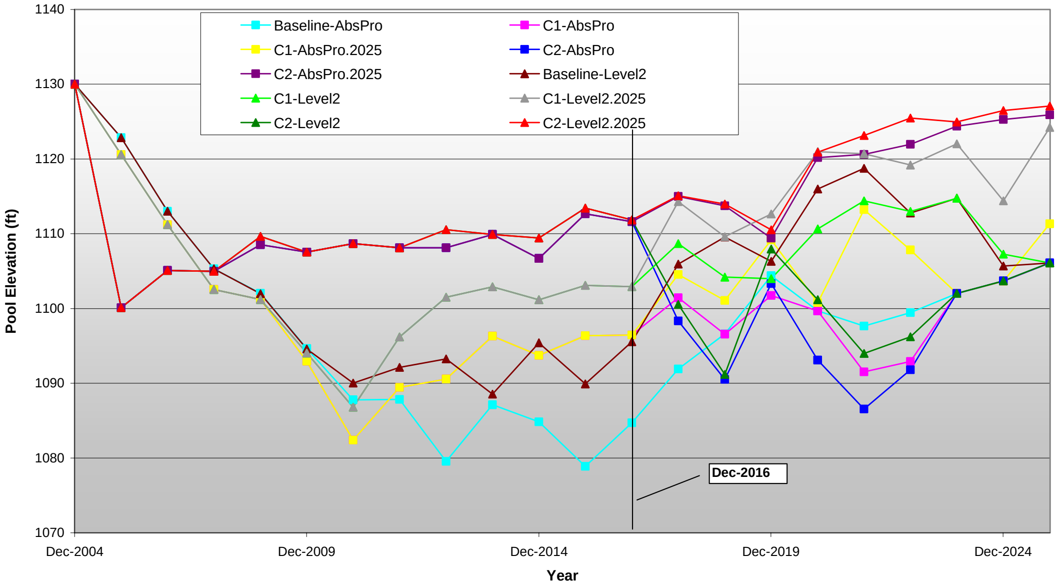


Figure 4-33 Mead 50th Percentile Elevations – C1 & C2 (2025)

1.21.2 Lower Basin & Mexico Shortage

Continuing coordinated operation reduces the shortage probability to the Lower Basin and Mexico as illustrated in Figure 4-34. This reduction is greatest under the AbsPro scenarios as C2-AbsPro through 2025 reduces the probability by greater than 20% for the last six years of the run. Similarly, C1-AbsPro reduces the probability by greater than 10% for the last six years. Not a dramatic of a reduction, but a reduction nevertheless, is seen under the Level2 scenarios. This is due to a high shortage trigger elevation in these later years resulting from increased Upper Basin demand.

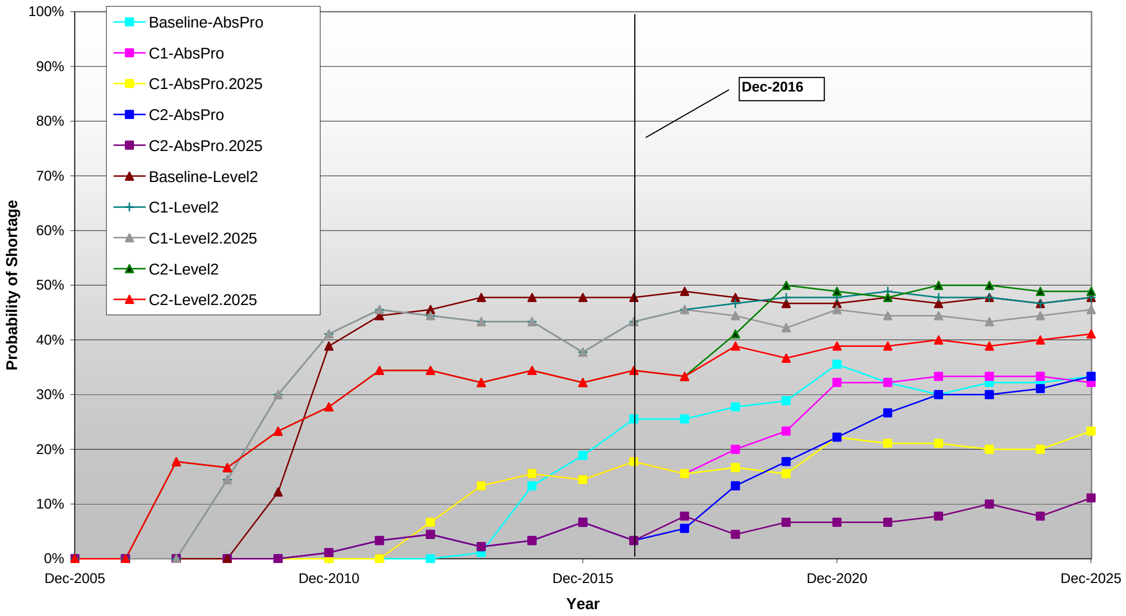


Figure 4-34 Probability of Lower Basin & Mexico Shortage – C1 & C2 (2025)

Results Discussion & Conclusion

This chapter concludes this research. It takes a closer look at the results of the coordinated operation strategies, C1 *"Relaxed MOR & EQ"* and C2 *"Balance Contents"*, in terms of the effects on hydropower production, recreation and evaporation and furthers the discussion from Chapter 4 on the impacts to Lower Basin and Mexico shortage. Included in the set of scenarios are the four additional scenarios where coordinated operation is continued through 2025. Viewing the results in terms of hydropower production, recreation, shortage and evaporation makes the potential benefits from an Upper and Lower Basin perspective and risk associated with the outcomes more visible. This chapter also addresses the strengths and limits of CRSS-Lite, the implications of its constraints and what results are politically relevant. Also discussed are any shortcomings of the analysis, to what extent those limits are liabilities, and how, in future work, those liabilities could be addressed.

1.22 Shortage

This section discusses the model results in terms of Upper and Lower Basin shortage and if coordinated operation is an appealing approach to that basin based on the outcome.

1.22.1 Upper Basin

The Severe Sustained Drought study modeled a strategy known as "reverse equalization", similar to C2, with and without a constraint in place which ensured that the Compact delivery requirement was met. With this constraint in place, the Upper Basin was shorted more severely than under baseline conditions and considerably less without the constraint in place. The hydrology for the SSD Study was derived from tree-rings, and represented a severe drought with a 2,000 to 10,000 year return period, considerably more severe than the period of record drought. For C1 and C2, under the hydrologic sequences contained in the period of record, the Compact delivery requirement is always met resulting in no Upper Basin shortage or implications of a Compact call.

The risk of coordinated operation to the Upper Basin, then, becomes the risk of an extremely dry hydrologic sequence that would result in the Upper Basin having to forego some amount of allocation in the event of a Compact call. It is difficult to know whether this risk is increased or decreased with coordinated operation in place. Because Powell could have potentially released less throughout the 10-year period (because not constrained minimally by the minimum objective release), a sequence of severely dry years could result in a Compact call whereas under baseline operations a Compact call could have been avoided. On the other hand, Powell also makes equalization releases at a level less than 602(a) storage; it is possible that a Compact call would be avoided compared to baseline operations.

1.22.2 Lower Basin

The reduction in shortage probability in the Lower Basin, attributed to more frequent larger releases from Powell, is a strong case for coordinated operation from a Lower Basin perspective. Under all scenarios the shortage probability is reduced compared to the baseline of the same shortage policy. The greatest reduction occurs under C2-AbsPro through 2025 where the shortage probability only once reaches 10%, a 20% reduction compared to the baseline. Of the Level2 scenarios, again C2 through 2025 exhibits the greatest reduction, averaging about 10% less than the baseline.

Although the probability of shortage is reduced under both C1 and C2 compared to the baseline with the same criteria, an interesting tradeoff with regards to the shortage policy is presented. Although the 80P1050 trigger in the Level2 policy results in earlier and more frequent shortages, these shortages are of smaller magnitudes. Shortage under the AbsPro policy, however less frequent and delayed, is greater in magnitude. It was common in many traces of the simulation to have AbsPro shortages imposed 4 to 5 years later on the order of 2 to 3 times the amount of annual Level2 shortage. The AbsPro policy introduces greater risk of severe shortage.

It is interesting to note how the Level2 policy, characteristic of frequent smaller shortages, might influence the thinking of Lower Basin users, specifically the CAP with the lowest priority of the Lower Colorado allocations. Since the signing of the Groundwater Management Act in 1980, substantial progress has been made in Arizona to move towards a more sustainable water future by decreasing dependence on nonrenewable groundwater supplies to increasing dependence on the Colorado River (Jacobs, 2004). With an increasing dependence on the Colorado and required to first curtail its usage in the event of a Lower Basin shortage, Arizona has high stakes in the Lower Basin shortage policy.

Whereas under the Level2 policy the CAP would receive frequent smaller shortage, under the AbsPro policy, a situation could exist where no shortage could be issued in the previous year and the next year could result in the CAP receiving no water. Frequent small shortages therefore may be more acceptable from the point of the view of the CAP because it would reduce the risk of more infrequent but larger shortages. In addition, more predictability is afforded under the Level2 policy lending to better drought protection planning.

1.23 Protection of Minimum Power Pools

This section discusses the protecion of minimum power pools at Powell and Mead under coordinated operation compared to the baseline. Two figures are presented that compare the probabilities that the reservoir elevation will be below minimum power pool for each scenario. This statistic is an indication of how well each scenario protects the minimum power pools, i.e. the lower the probability, the better protection of minimum power pool.

1.23.1 Upper Basin

Figure 5-1 displays the protection of minimum power pool at Powell. Very rarely does the probability of dropping below minimum power pool exceed 10%. Even at an already low probability of 10% under the baseline, the coordinated operation strategies reduce this probability to about 5% with C1 and to less than 1% with C2 through 2016. At the onset of a drought, Powell release below the minimum objective release under coordinated operation thus protecting 10th percentile elevations and hydropower. The C2 strategies exhibit a slightly higher probability (highest with C2-AbsPro through 2025 ending at 11%) in the later years of the run due to more frequent larger releases increasing the vulnerability of Powell’s lower elevations.

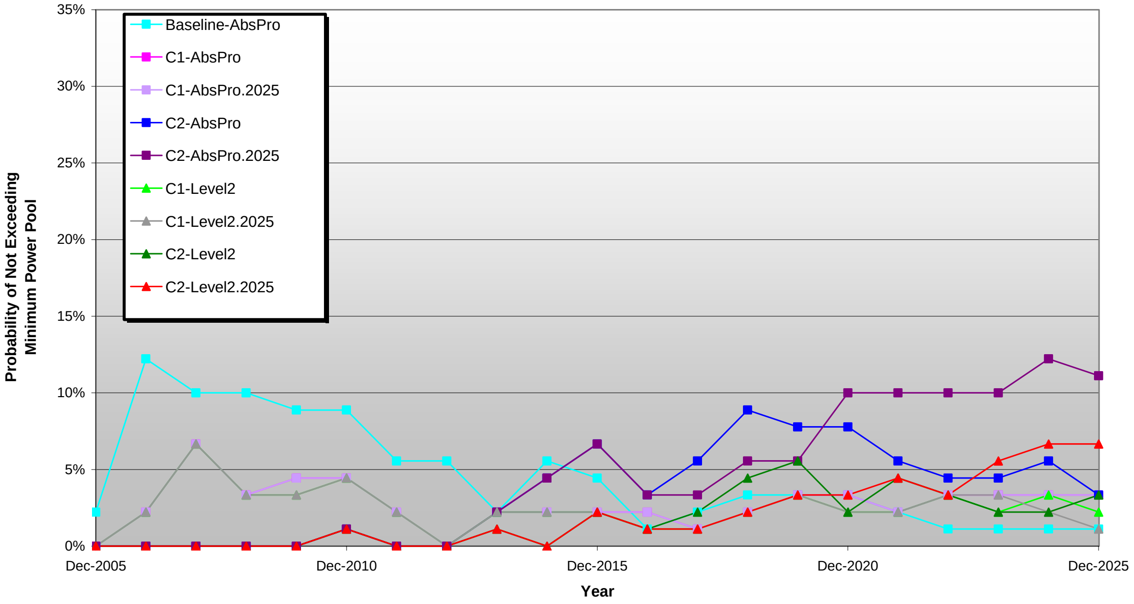


Figure 5-1 Minimum Power Pool Protection at Powell

The probability of Powell's elevation being below minimum power pool is reduced with coordinated operation. By allowing reduced releases from Powell at lower elevations, Powell's minimum power pool is better protected with coordinated operation and best protected with the C2 strategy "*Balance Contents*" through 2016. After 2016, the power pool is better protected under baseline operations. Coordinated operation is beneficial from an Upper Basin perspective in terms of prolonging the ability to generate power through the Glen Canyon Powerplant. The protection of minimum power pool also translates into the protection of reservoir based recreational benefits as well as providing a greater shortage buffer to the Upper Basin.

1.23.2 Lower Basin

Figure 5-2 displays the protection of minimum power pool at Mead. The probability of falling below minimum power pool at Mead reaches a significantly higher maximum than that of Powell due to the presiding deficit at Mead, as Upper

Basin demands increase. As Powell recovers after 2010 and makes larger releases under coordinated operation the protection of minimum power pool at Mead is greater

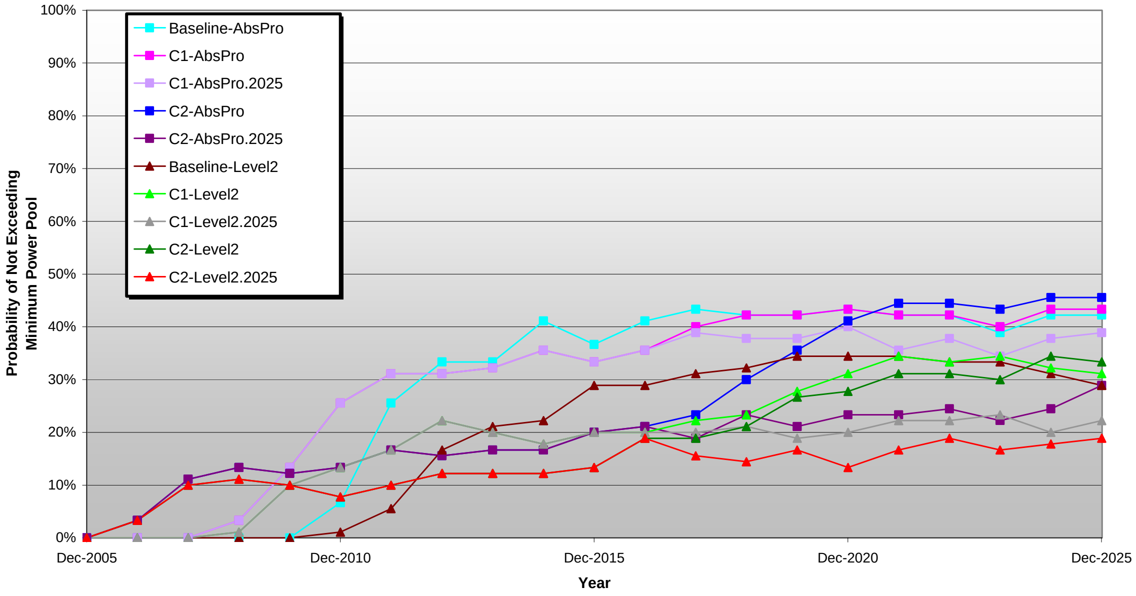


Figure 5-2 Minimum Power Pool Protection at Mead

Generally, scenarios with the Level2 policy have a slightly less probability throughout the run. This directly corresponds to the greater probability of shortage with Level2, which results in keeping Mead higher. Ending at a probability lower than the baseline are the coordinated operation strategies that remain in place through 2025.

Both C2 *"Balance Contents"* scenarios maintained through 2025 results in the protection of minimum power pool at Mead. This strategy is most beneficial from a Lower Basin perspective in terms of protecting efficient power generation as it reduces probabilities by nearly half compared to the baseline with the same shortage policy.

1.24 Recreation

The benefit of coordinated operation in terms of recreation is less quantifiable. Water-based recreation is a large part of many people's lives along the Colorado River Basin. Generally, the protection of both instream flows and reservoir levels will lead to a better recreational experience for users and economic benefits for recreation providers such as the National Park Service or rafting guide services. For the purpose of this research, reservoir recreation is addressed.

Because reservoir operation is primarily driven by meeting water demands for consumptive uses and power generation, few studies have attempted to correlate the impacts of reservoir level fluctuations to that of reservoir based recreation (Bookeret al., 1995). Little empirical work has been done, however, it is generally concluded that use of Colorado River reservoirs decreases as a function of reservoir content (Ward and Fiore 1987, Booker and Colby, 1995).

1.24.1 Upper Basin

In the long-term, Powell's 10th percentile elevations are kept highest under coordinated operation strategies that revert back to baseline operations after 2025. The C1 "*Relaxed MOR & EQ*" strategy keeps Powell higher than the Baseline for more years than the C2 strategy. Thus, through 2025, recreation at Powell is better protected with C1 in place. However, the short-term benefits to recreation are greater under the C2 strategy. Recall that this strategy greatly increases Powell's 10th percentile elevation in through 2016 by allowing releases below 8.23 MAF.

1.24.2 Lower Basin

Mead's lower elevations are protected better with coordinated operation compared to the baseline; the greatest protection is seen by continuing coordinated operation through 2025. Thus, reservoir based recreation interests would fare better under coordinated operation, best under the C2 *"Balance Contents"* strategy.

1.25 Powell & Mead Evaporation

The 1996-2000 Consumptive Uses and Losses Report reported that during 1996-2000 approximately 1.66 MAF of water was lost due to evaporation between Lakes Powell and Mead. About 64% of the evaporation loss was at Mead, which is situated in a more arid region at a lower elevation than Powell (USBR, 2000a). Table 2-1 in Chapter 2 contains the reservoir evaporation coefficients for Powell and Mead. The evaporation rate for each month at Mead is on the order of 40% higher than that of Powell.

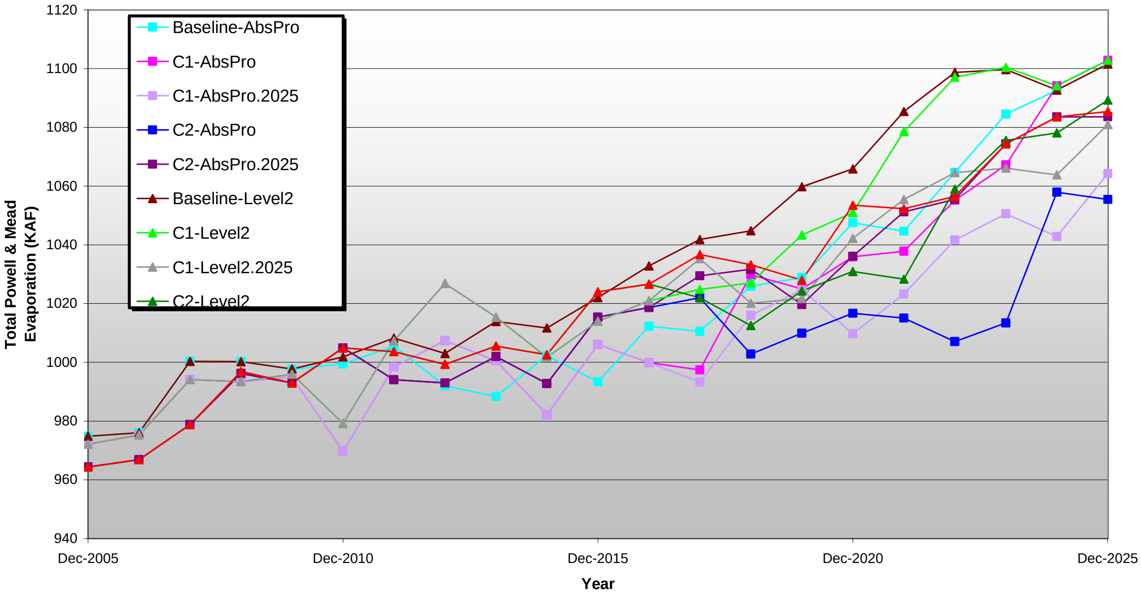


Figure 5-3 Combined Median Evaporation at Powell & Mead

Figure 5-3 shows the total median evaporation at Powell and Mead for all scenarios. For both shortage policies, coordinated operation reduces the amount of water lost, on the average per year, to evaporation for all scenarios. The greatest reduction occurs with C2 in which baseline operations are restored after 2016. These strategies reduce evaporation an average of 15 KAF annually.

Another interesting result is how increasing or decreasing evaporation correlates with the reservoir storage. Evaporation is a function of storage and the evaporation rate, i.e. the greater the reservoir capacity and evaporation rate, the higher the evaporation. Large drops in evaporation, such as in 2010 and 2014 under C1-AbsPro, correlate with drops in the median elevation at Mead and steady elevations at Powell.

The results of evaporation with coordinated operation convey the benefit of, under low reservoir conditions, reducing releases from Powell thereby allowing additional water to be stored, i.e., “storing high.” On the average through 2016, compared to the baseline scenario with the same shortage policy, less water is lost due to evaporation with coordinated operation. C2-Level2, on the average through 2016, results in the least amount of evaporation. The greatest savings under this scenario occur through 2008 when Powell’s median elevation is higher than the baseline and Mead’s is lower.

Less water loss to evaporation is a benefit to both basins because it means there is more water in the system lending to greater flexibility in reservoir operations. The results show that less overall evaporation occurs by storing more water in Powell.

This is beneficial to the Upper Basin in terms of power generation and reducing the potential for shortfalls.

1.26 Political Relevance of Results

Coordinated operation relaxes both the minimum objective release and the 602(a) storage guidelines set forth in the LROC. The interpretation of the *Law of the River*, for the purpose of this research is that, because the LROC is open to review and the Compact requirements are followed, coordinated operation is not in direct violation of the *Law of the River*. However, varying interpretations will affect to what extent these results are relevant from a standpoint of adhering to the *Law of the River*.

Other interpretations of the *Law of the River* made were regarding the Mexican Treaty Delivery. The event of a Level 2 Shortage was assumed to constitute an “extraordinary drought” pursuant to the Mexican Treaty. The “extraordinary drought” provisions were used to impose shortages to Mexico in proportion to consumptive use reductions in the U.S. This was implemented as a fifty-fifty split of MWD and Mexico of the remaining shortage needed to bring Mead above 1000 ft.

1.27 Strengths & Limitations of CRSS-Lite

CRSS-Lite is a policy screening model designed to provide a simplified and fast alternative to CRSS, Reclamation’s official monthly timestep planning model. Lite preserves the flexibility and accuracy of CRSS but reduces the simulation run-time by two-thirds. CRSSez, the Reclamation screening model of which Lite has replaced, is limited in that policies are hard-coded and can be neither viewed nor changed by a user. In Lite, operational policies are expressed via rule sets that are easily understood, easily modified and can be viewed explicitly by all.

Several Colorado River stakeholders were involved in the development and testing phases of Lite. Lite will be made available to stakeholders in the future to aid them in policy understanding and fortifying their positions with regard to shortage policy. The ability to view the policies representing the diverse objectives central to different bodies of stakeholders will promote and encourage an understanding of the difficulty of the managing the dams and reservoirs. Another strength is the use of the same model version by Reclamation and the stakeholders to evaluate alternatives. This consistency will further enhance and facilitate communication and collaboration among the involved parties

A limitation of Lite is the “hard-coding” of the Upper Basin above Powell. The disadvantage is that Upper Basin demands and hydrology cannot be directly modified to yield the same results as those modifications in the detailed model. However, this limitation can be overcome by either reverting back to the detailed model to simulate new Powell inflows based on desired changes or manipulating Powell’s inflow, albeit in a simplified manner, to reflect alternative Upper Basin demand or hydrology. If the Upper Basin reservoir operations are modified such that the capacity of Powell is a factor in their release decision both the detailed and Lite will be modified to reflect the modified operations.

1.28 Shortcomings of Analysis

The index sequential method has been recognized by a number of river operation officials, stakeholders and academics as a limitation in policy analyses such as this research. Because the ISM technique uses historical inflow values in the same sequence as they occurred in history, no new sequences are generated. Under the ISM method, a drought resembling that of the previous five years would have not been generated. However, the ISM has become institutionalized and continues to be the accepted method of accounting for hydrologic uncertainty in Reclamation’s planning studies.

The shortcoming of the analysis presented in this research as a result of using the ISM method is that ability to fully evaluate the risk of coordinated operation to the Upper Basin was limited. Quantifying the additional risk, if any, acquired by the Upper Basin under coordinated reservoir management would require investigating the coordinated operation strategies under more severe hydrologic sequences. This is an area of this research that warrants further research and analysis. Reclamation is working in collaboration with the University of Colorado to develop tree-ring derived sequences that could be used for this purpose.

1.29 Further Analysis

Some aspects of this research warrant further examination and analysis to shed more light on the value of the coordinated operation scenarios. As mentioned in the previous section, more severe hydrologic sequences are needed to more accurately assess the risk to the Upper Basin because current hydrology results in no Upper Basin shortage. More severe hydrologic sequences would also indicate to what extent shortages could be incurred in the Lower Basin.

In addition, it would be of value to take a more extended look at coordinated operation through increasing the length of the model runs, such that Upper Basin demand stabilizes. Constant Upper Basin demands result in the leveling out of both the 602(a) storage and the Level2 shortage triggers. A more explicit evaluation of the coordinated operation policies is gained by extending the length that they are in effect thereby exposing the long-term value and effects of the policy.

1.30 Conclusion

This research demonstrated the potential of coordinated reservoir operation as a management option under lower reservoir conditions on the Colorado River. Under baseline operating conditions, an imbalance in Powell and Mead storage capacities results at the onset of a drought or as the drought recovers. Coordinated operation maintains a balanced system during these times thereby reducing risk in the Basin that was previously on the low side of the imbalance with a disproportionately low storage capacity.

Modeling results show that coordinated operation can 1) reduce Lower Basin and Mexico shortage probabilities, 2) increase reservoir levels at Lakes Powell and Mead, 3) better protect minimum power pools and reservoir-based recreation interests and 4) reduce basin-wide evaporative losses. Of the scenarios investigated, there was not a single option that resulted in maximum benefits to both basins, however, the C1 "*Relaxed MOR & EQ*" strategy in place through 2016 provides benefits to both basins compared to baseline conditions.

The C2 *"Balance Contents"* strategy in place through 2025 was shown to be most beneficial from a Lower Basin perspective. With this strategy and the AbsPro shortage policy, the probability of a shortfall was reduced by more than 50%. Under the Level2 shortage policy Mead's minimum power pool is protected 15% more compared to baseline operations. The tradeoff of a low shortage probability with the

AbsPro policy is an increased probability of more severe (greater than 0.5 MAF) shortages.

The C2 *“Balance Contents”* strategy was also beneficial from an Upper Basin perspective, however only during the interim period. During this period, the probability of Powell declining below minimum power pool reaches a maximum of 2% and is zero for eight years. As lake levels begin to recover after 2016, the C2 strategy resulted in lower elevations at Powell compared to the baseline because of the considerable volume of water released that would be stored under baseline operations.

It is important to bear in mind that the results of this research are predicated on the hydrologic period of record dating from 1906 through 1995. Although it would be beneficial to analyze these strategies under more severe hydrology, as done in the SSD Study, applying the twelve-year critical period of 1953-1964 to the low initial conditions of these reservoirs constitutes a reasonably “severe” scenario.

CRSS-Lite, a policy screening model, was developed as part of this research as a means to conduct the coordinated operation policy analysis. This tool will be also be made available to Colorado River stakeholders to investigate and communicate the outcome of shortage policy as part of the process to establish official shortage guidelines on the river.

The research required the bringing together of policy expression, physical process modeling, hydrologic uncertainty and tradeoff analysis in a way that was used to effectively analyze alternatives, express and quantify preferences and communicate results.

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Appendix A Diversions Modeled in CRSS-Lite

State	Diversion
California	Coachella MWD IID FtMohaveReservation:Fort Mohave Ind Res CA FtMohaveReservation:Fort Mohave Land Devel CityOfNeedlesBenardinoCounty HavasuNWR:Havasu NWR CA LakeHavasuIDDChemehueviIndianRes:Chemehuevi Ind Res OthersAndMiscPresPerfRights ColoradoRiverIndianReservation:CRIR CA AllAmericanCanalYumaProj:Bard Unit AllAmericanCanalYumaProj:Quechan Res Unit CaliforniaPumpers TownOfParkerAndOtherUsers:Imperial NWR CA PaloVerdeIrrigationDistrictWQIP PaloVerdeIrrigationDistrict OtherPumpersBelowNIB
Arizona	CAP HavasuNWR:Havasu NWR AZ FtMohaveReservation:Fort Mohave Ind Res AZ ColoradoRiverIndianReservation:CRIR AZ ColoradoRiverIndianReservation:CRIR Pumped GilaAndYumaUses:Cocopah Ind Res GilaAndYumaUses:Yuma City and County WUA TownOfParkerAndOtherUsers:AZ Uses ArizonaPumpers GilaGravityMainCanal KingmanAZ LakeMeadNRA MohaveValleyIrrAndDrainDist LakeHavasuIDDChemehueviIndianRes:Parker Ag
Nevada	SNWA FtMohaveReservation:Fort Mohave Ind Res NV LaughlinMI MohaveSteamPlant

Appendix B Lower Basin Consumptive Use Schedules

	CALIFORNIA					ARIZONA			NEVADA			LB
Year	CA Other	MWD	IID	Coachella	CA TOTAL	AZ Other	CAP	AZ TOTAL	NV Other	SNWA	NV TOTAL	TOTAL
2005	447	647	2915	338	4346	1348	1452	2800	28	272	300	7446
2006	449	690	2891	312	4341	1353	1447	2800	28	272	300	7441
2007	451	688	2885	312	4336	1359	1441	2800	28	272	300	7436
2008	454	753	2793	316	4316	1364	1436	2800	29	271	300	7416
2009	456	761	2754	320	4291	1369	1431	2800	29	271	300	7391
2010	459	769	2715	324	4266	1375	1425	2800	29	271	300	7366
2011	463	774	2676	328	4241	1375	1425	2800	29	271	300	7341
2012	468	790	2655	342	4255	1376	1424	2800	29	271	300	7355
2013	472	796	2615	347	4230	1376	1424	2800	29	271	300	7330
2014	477	791	2590	352	4210	1377	1423	2800	29	271	300	7310
2015	482	787	2565	357	4190	1378	1422	2800	29	271	300	7290
2016	482	787	2540	362	4170	1378	1422	2800	29	271	300	7270
2017	482	787	2525	366	4159	1379	1421	2800	29	271	300	7259
2018	482	817	2718	384	4400	1380	1420	2800	29	271	300	7500
2019	482	847	2683	389	4400	1380	1420	2800	29	271	300	7500
2020	482	879	2645	394	4400	1381	1419	2800	29	271	300	7500
2021	482	892	2628	399	4400	1382	1418	2800	29	271	300	7500
2022	482	889	2625	404	4400	1383	1417	2800	29	271	300	7500
2023	482	887	2623	409	4400	1385	1415	2800	29	271	300	7500
2024	482	887	2618	414	4400	1386	1414	2800	29	271	300	7500
2025	482	887	2613	419	4400	1388	1412	2800	29	271	300	7500

Lower Basin consumptive use schedules were prepared by the Basin States and published in the SIA-FEIS with the exception of the schedules for IID, Coachella and MWD. These schedules were specified by the Colorado River Water Delivery Agreement and include paybacks for 2001 and 2002.

Appendix C Powell Operations

This Appendix describes the logic of operations for Powell under baseline operating conditions. The detailed implementation of these operations in CRSS-Lite can be found in the CRSS-Lite Overview & Users Manual.

1. Operations

The lowest priority operational policy determines the monthly release by based on a spring (January through July) or fall (August through December) operation. The spring runoff operation uses a forecasted spring runoff and computes the release required from Powell such that Powell will meet a July target storage of 23.822 MAF or 0.5 MAF of space. Similarly, the fall operation computes the release required from Powell assuming the reservoir will be drawn down to a December target storage of 21.900 MAF or 2.422 MAF of space. The monthly spring and fall operational release rates are constrained within a minimum and maximum range of 0.390 MAF and 1.50 MAF. These monthly constraints reflect the release constraints from Powell of 6,500 cfs and 25,000 cfs set forth by the 1996 Operation of Glen Canyon Record of Decision.

2. Minimum Objective Release

The release from Powell must meet the minimum objective release so long as it is physically possible. The minimum objective release is currently equal to 8.23 MAF over the water year. During periods when releasing 8.23 MAF will result in Powell reaching dead storage, the release is made such that Powell will remain above dead storage.

3. Limit Outflow & Smooth July Operation

The Limit Outflow and Smooth July Operation policies are two addition constraints placed on the monthly release computed in Operations. If the current month is July and Powell’s storage is greater than 23.0 MAF, the Limit Outflow policy constrains the release to be at least 1.0 MAF. From July through December the Smooth July Operation policy constrains the release to not exceed 1.5 MAF so long as the constrained release does not cause Powell’s storage to exceed 23.822 MAF.

4. Equalization

For equalization to occur the 1) current month must not be later than September, 2) the EOWY storage for Powell must be greater than the EOWY storage for Mead and 3) the storage in the Upper Basin must not violate the 602(a) Storage. Also, per the 2003 Final Environmental Assessment Adoption of an Interim 602(a) Storage Guideline, Powell’s EOWY storage must be equal to or greater than 14.85 MAF or the year be greater than 2016. If the conditions for equalization are met, an iterative procedure is used to compute the equalization release. If the conditions are not met, Powell's release is computed based on the other policies listed above. Described below are the calculations involved to compute the 602(a) storage, the forecasted EOWY storage for Powell and Mead and the iterative routine used to compute the equalization release.

602(a) Storage

The LROC set forth parameters to be used in the calculation of the 602(a) storage but does not provide a prescribed equation. An equation was developed for the original CRSS implemented in FORTRAN (USBR, 1985). This equation is still in use and is described below.

The equation computes the storage necessary to meet the Upper Basin depletions over the next "n" years while maintaining Powell's minimum objective release. It is assumed that the inflow during those years will be the most "critical period on record." In the Colorado River Basin, this critical period occurred in 1953 – 1964, a period of twelve years averaging 12.2 MAF of natural flow at the Lees Ferry gaging station. Therefore "n" is equivalent to twelve. The *602(a) storage* is computed as,

$$602aStorage = \left[\left(UBdep + UBevap \right) * \left(1 - \frac{short\%}{100} \right) + MOR - cpInflow \right] * cpLength + mppStorage$$

where,

UBdep	The average over the next "cpLength" years of the Upper Basin scheduled depletions
UBevap	The average annual evaporation loss in the Upper Basin.
short%	A specified shortage percentage applied to Upper Basin depletions during the critical period, currently set to zero.
MOR	Powell's minimum objective release to the Lower Basin.
cpInflow	The average natural inflow into the Upper Basin during the critical period, 1953-1964.
cpLength	The length of the critical period, 12 years.
mppStorage	The amount of minimum power pool to be preserved in the Upper Basin reservoirs.

One condition for equalization to occur is that the Upper Basin storage is greater than the 602(a) storage. Also, the equalization release may not cause the Upper Basin storage to fall below the 602(a) storage.

Forecasted EOWY Storage for Powell & Mead

One requirement to forecast the EOWY storage for Powell and Mead is the forecasted release from both reservoirs from the current month through September. The estimated release for Powell is based on the spring operation through July and the fall operation during August and September, constrained minimally by the minimum objective release. Mead's release is estimated based on the downstream depletions, reservoir regulation and evaporation losses in Mohave and Havasu and the gains below Mead. Using the forecasted releases for each reservoir, the EOWY storage for each by adjusting for downstream gains and losses and evaporation and bank storage losses.

Equalization Algorithm

Once it has been determined that the conditions for equalization are met, the equalization release required from Powell is computed in an iterative routine that computes the release for equalization by taking the dividing the difference in Powell and Mead's EOWY storage by two and dividing the result by the number of months remaining in the water year. With the computed release, the EOWY storages for Powell and Mead are again computed accounting for the difference in evaporation and bank storage losses. Each computed release is constrained to not cause the 602(a) storage to be violated, to not cause Mead to violate the exclusive flood control space requirement and to be less than or equal to Powell maximum allowable release. The EOWY storages must be within a user-specified tolerance, currently set to 0.10 MAF, for the iterative procedure to exit.

The resulting equalization release is adjusted by subtracting Powell's forecasted release. The result is again checked to ensure that it does not violate the 602(a) storage. The equalization release is then divided by the number of months remaining in the water year and added to Powell's current outflow determined by the operations described in 1 – 3 of this document.

5. Check Equalization 14.85 MAF

In addition to meeting the 602(a) storage requirement and the EOWY storage at Powell being greater than that at Mead, this check requires that the year be greater than 2016 or that Powell's EOWY storage be greater than or equal to 14.85 MAF for equalization to occur. In addition, if the equalization release requires that Powell's storage drop below 14.85 MAF during September of any year earlier than 2017 then the storage is constrained to be the minimum of 14.85 MAF and storage resulting from the minimum objective release for that month.

6. Spike Flow

The conditions for a Beach/Habitat Building Flow or spike flow were determined by the SIA-FEIS and ISG. These conditions are listed below:

- In January, the unregulated inflow forecast for January through July is greater than the January trigger volume. The January trigger volume is currently set to 13.0 MAF. The computation of the unregulated inflow forecast consists of the regulated inflow forecast without the adjustment for potential reservoir regulation.
- In January through July, the current month's release from Powell set by Operations, is greater than the release trigger or if the Operations release volume for the current month through July divided equally into the remaining months would result in a release greater than the release trigger. The release trigger is currently set to 1.5 MAF.
- A spike flow release has not yet been made in the current year.

In the event that the conditions have been met for a spike flow release, Powell's storage can be adjusted in one of two ways. If Powell would have to spill based on the Operations storage, the total release from Powell is not increased. If Powell is not scheduled to spill, the spike flow release is computed as the sum of the Operations release constrained to be at least the release trigger (1.5 MAF) , and the "Additional Bypass Volume", currently set to 0.20 MAF.

Appendix D Mead Operations

This Appendix describes the logic of operations for Mead. Mead's operations remain unchanged under all scenarios. The detailed implementation of these operations in CRSS-Lite can be found in the CRSS-Lite Overview & Users Manual. The release from Mead is the greater of the release required to satisfy downstream demands and the required release for flood control. Both of the computations are described below.

The Mead flood control algorithm is based on the Field Working Agreement between Reclamation and the Army Corps of Engineers. The algorithm consists of three procedures one of which is referred to as the Exclusive Flood Control Space Requirement. This requirement is in effect at all times and states that Mead must maintain a minimum of 1.5 MAF of space, the space above elevation 1219.61 ft. The second procedure is in effect during the spring runoff forecast season, January through July. In this procedure, an iterative algorithm is used in which five levels of discharge rates at Hoover Dam are used to route a maximum forecast inflow through Mead. It is assumed that Mead will reach an elevation of 1219.61 ft by the end of July. The third procedure is in effect during the drawdown season, August through December, with the objective of gradually increasing space in Mead in anticipation of the coming year's runoff.

1. Compute Release For Downstream Demands

The release required to meet downstream demands is computed as,

$$\boxed{\begin{aligned}&releaseForDemands = adjDiversion(CAP + MWD + IID + Mexico + Coachella) +\\&otherDepletionsBelowMead + deltaStorHavasu + deltaStorMohave + evapHavasu +\\&evapMohave - \inf\ lowsBelowMead\end{aligned}}$$

where,

adjDiversion(CAP+MWD+IID+Mexico+Coachella)	The sum of the monthly adjusted diversion for each entity.
otherDepletionsBelowMead	The sum of the monthly depletions below Mead not including CAP, MWD, IID, Mexico or Coachella.
deltaStorHavasu	The change in storage in Havasu over the current month.
deltaStorMohave	The change in storage in Mohave over the current month

evapHavasu	The monthly evaporation loss in Havasu.
evapMohave	The monthly evaporation loss in Mohave.
inflowsBelowMead	The sum of the monthly inflows below Mead.

2. Runoff Season Operation (January – July)

The first step in computing the release required for flood control during the spring runoff season is to compute a minimum average release (*minAvgRelease*) assuming a Level 1 discharge rate, from the current month through July. The five levels of discharge are listed below in Table D-1. This is computed as,

$$\boxed{\min Avg\,\mathrm{Re}\,lease = \max Inflow - (availSpaceMead + availSpacePowell) + \min Space - losses - SWNPdep - level1release}$$

where,

maxInflow	Maximum inflow forecast with 95% non-exceedance (described below).
availSpaceMead	Available space in Mead (live capacity storage – previous month storage)
availSpacePowell	Available space in Powell (live capacity storage – previous month storage)
minSpace	Exclusive Flood Control Space (1.5 MAF)
losses	Evaporation and bank storage losses in Mead and Powell
SNWPdep	SNWP depletion
level1release	Amount of water to be released from the current month through July at a Level 1 discharge rate.

The maximum inflow forecast is an estimated inflow that, on average, has a 95% non-exceedance. It is computed by adding to the regulated inflow forecast to Powell’s spring runoff forecast the gains between Powell and Mead and a maximum forecast error term taken from the original CRSS data.

The *minAvgRelease* is then compared to the Level 1 discharge. If the *minAvgRelease* is greater, it is recomputed with the Level 2 discharge. This procedure is continued until the *minAvgRelease* is less than or equal to the discharge level used in the computation. Once the iterations stop, a final check is made. If the *minAvgRelease* is less than the discharge at one level less than the level used in the computation, then the *minAvgRelease* is set equal to the discharge at one level less than the level used in the computation.

Discharge Level	Release (cfs)	Description
1	19000	Parker powerplant capacity
2	28000	Davis powerplant capacity
3	35000	Hoover powerplant capacity (1987)
4	40000	Max flow non-damaging to streambed
5	73000	Hoover control discharge capacity

Table D-1 Runoff Season Discharge Levels

4. Drawdown Season Operation (August – December)

During drawdown season, Mead's flood control operation is based on meeting specified space targets for each month. The space targets, listed below in Table D-2, may be reduced to a minimum of 1.5 MAF if Upper Basin reservoirs (Powell, Navajo, Blue Mesa, Flaming Gorge) have space available. The amount of space creditable to the required system space from each of these reservoirs is stored in listed in Table D-3.

Month	Required Space (MAF)
August	1.50
September	2.27
October	3.04
November	3.81
December	4.58
January	5.35

Table D-2 Required System Space

Reservoir	Maximum Creditable Storage Space (MAF)
Powell	3.8500
Navajo	1.0359
Blue Mesa	0.7485
Flaming Gorge and Fontenelle	1.5072

Table D-3 Maximum Creditable Space

The first step in this procedure is to determine the current space in Mead. This is done by solving for the storage using the release computed to meet downstream demands and then subtracting the resulting storage from Mead's live capacity storage. Next, the space available in the Upper Basin Creditable reservoirs is determined by subtracting the current storage for each by the live capacity storage for each. The total system space is computed by adding the available space in Mead to the space in the Upper Basin reservoirs. If the total system space is greater than the space requirement for the current month, Mead's storage is set to the live capacity minus the exclusive flood control space of 1.5 MAF. If the total system space is not sufficient, Mead's storage is set to the live capacity minus the system space requirement plus the Upper Basin Creditable space.

A mass balance computation is then performed using the resulting storage to solve for the necessary release. The release is constrained to not be greater than the maximum allowed flood control release during drawdown season of 28,000 cfs.

5. Constrained Flood Control Release

After it has been determined that Mead will make a flood control release for the current month a final check is made. The release is set to the greater of the release needed for downstream demands under surplus conditions and the flood control release. However, if the release to meet Mead's rule curve storage is large enough that the greater of the flood control and surplus release is satisfied, the release is set to the rule curve release.

Appendix E CRSS-Lite Implementation of C1 *"Relaxed MOR & EQ"*

This Appendix describes the model logic for the implementation of the C1 coordinated operation strategy.

January – September

1. The EOWY storage for both Powell and Mead is forecasted. The EOWY storage consists of a mass balance including the forecasted inflow, release, and evaporation and bank storage for each reservoir. Normally, the forecasted release for Powell is based on the spring operation through July and the fall operation during August and September, i.e. spill avoidance operations, constrained minimally by the maximum of Powell's minimum release and the minimum objective release. See Appendix C for a description of spring and fall operation. The forecasted release is also constrained to be less than Powell's maximum release. The minimum and maximum allowable releases from Powell are 6,500 cfs and 25,000 cfs, respectively. However, if the previous month's release from Powell was a ROM, the ROM replaces the 8.23 MAF for the minimum constraint on the forecasted release. The calculation for Mead's EOWY storage remains unchanged from baseline conditions.
2. A check is made to see if 1) the sum of the Upper Basin reservoir storages at the EOWY of the previous year is less than the 602(a) storage 2) the total release from Powell over the water year is less than 8.23 MAF 3) the forecasted EOWY storage for Powell is greater than the storage corresponding to the TEL and 4) the forecasted EOWY storage for Powell is greater than the forecasted EOWY storage for Mead. If *all* these statements are true, the release is computed from Powell such that the contents of Powell and Mead will be equal at the end of the water year. This is done using the "normal" equalization algorithm described in Appendix C The only difference is that the check to ensure that the equalization release does not drop the Upper Basin storage below the 602(a) storage level is removed and replaced with a check that ensures that the equalization release does not cause Powell to drop below the TEL.
3. If any conditions from 2. are false, the release from Powell is computed based on the regular policies that are still in effect and have not been modified for the strategy. These include Operations (Spill Avoidance), Smooth July Operation, Spike Flow Release and Limit Outflow. For a complete description of these policies see Appendix C.
4. The release computed in 3. is then constrained to be at least the minimum objective release. Whether the minimum objective release will be 8.23 MAF or the ROM release (7.48 MAF per year) is determined by comparing the EOWY elevation forecasts for Powell and Mead against the LPT and WST elevations, respectively. The EOWY forecast elevation for Powell must be less than the LPT elevation and the EOWY forecast elevation for Mead must

be greater than the WST elevation for the monthly release based on the ROM to be used. Otherwise, the monthly release is computed using 8.23 MAF. The monthly release of the minimum objective release and ROM is computed based on a monthly release pattern and the release made from Powell since the beginning of the water year.

October – December

1. Equalization is not activated during October through December. During these months, steps 1. and 2. from January through September are not performed.
2. Powell’s release is first computed based on the Operations (Spill Avoidance), Smooth July Operation, Spike Flow and Limit Outflow policies. The release is then constrained minimally by the minimum objective release.
3. The minimum objective release used, 8.23 MAF, or the ROM release, is determined by comparing the storages for Powell and Mead at September of the current year against the LPT and WST elevations, respectively. Powell’s September elevation must be less than the LPT elevation and Mead’s September elevation must be greater than the WST elevation for the ROM release to be used as the minimum constraint. The monthly ROM release is computed based on a monthly release pattern and the release made from Powell since the start of the water year. Otherwise, the 8.23 MAF minimum objective release is used.

Appendix F CRSS-Lite Implementation of C2 *"Balance Contents"*

This Appendix describes the model logic for the implementation of the C2 coordinated operation strategy.

January – September

1. The forecasted EOWY storage for Powell is computed using the same algorithm used under baseline conditions, which constrains the forecasted release by the minimum objective release of 8.23 MAF. This procedure is described in Appendix C. The forecasted storage must be greater than inactive capacity, 3.995 MAF, for equalization to occur.
2. If equalization was determined to occur, the release is computed using the same equalization algorithm used under baseline operations, described in Appendix C. The only difference is that the check to ensure that the equalization release does not drop the Upper Basin storage below the 602(a) storage level is removed.
3. A final check is made after the equalization release has been computed. If the release required for spill avoidance is greater than the equalization release, the release is made for spill avoidance.
4. If equalization was determined not to occur, the only reason being if the forecasted EOWY storage for Powell is less than inactive capacity, then the release is computed according to the monthly release pattern for the 8.23 MAF minimum objective release and the release made since the start of the water year.

October – December

1. Equalization is not active during these months. Powell's release is determined according to the normal operations: Spike Flow, Limit Outflow, Smooth July Operation and Operations. The minimum objective release of 8.23 MAF is also in effect.