**What drought intensities and durations can Lake Mead sustain?**

A bottom-up vulnerability analysis

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February 5, 2020

# Introduction

From 2000 to 2015, Colorado River flows averaged 13.4 million acre-feet (MAF) per year. Lake Mead’s water level also fell from 1,214 feet (25.2 MAF active storage, nearly full) to 1,089 feet (10 MAF of active storage, 40% of capacity). This decline has prompted widespread interest in questions such as what drought intensities and durations can Lake Mead sustain? And the related question: how much does reservoir storage buffer and delay the impact droughts?

In their seminal paper “When will Lake Mead go dry?”, [Barnett and Pierce (2008)](#_ENREF_1) framed these questions probabilistically as what is the likelihood a combined Lake Powell and Mead system will go dry by a certain year? They generated 10,000 realizations of river flow that were statistically consistent with historic variability from 1906-2005 and tree ring flow estimates over the last 1250 years, imposed a deterministic linear runoff trend over time, and found that there was a 50% chance to reach dead pool by 2053 even as managers reduced full deliveries by 10% after Mead fell below an active storage of 7.5 MAF (~1,048 feet). Since 2007, Lake Mead’s level has continued to fall and California, Nevada, and Arizona have agreed to a larger and earlier schedule of cutbacks called the Drought Contingency Plan.

Due to non-stationarity, past statistical descriptions of inflow, climate, demand, and reservoir operations (Level 2 uncertainty) may provide insufficient descriptions of future conditions. However, these uncertain future conditions can be described by scenarios of possible future conditions that do not have probability or rank (Level 3 uncertainty; Walker et al., …). Recent multi-objective robust decision making, dynamic adaptive policy pathways, and decision scaling efforts are coming online to work with Level 3 uncertainties that can only be described by scenarios. This brief report applies the multi-dimensional sensitivity analysis method of decision scaling to identify the combinations of drought intensities, durations, and starting reservoir storage that Lake Mead can sustain.

# Main Benefits from this Work

* Provide context for and show impacts of Homa’s and Dave T.’s hydrologic scenarios work
* Identify the combinations of flow intensity, flow duration, and starting reservoir storage conditions that drive Lake Mead to dead pool, to fill, or to a long-term steady storage value.
* Show interaction of flow interaction and duration factors and answer questions posed in many recent Colorado River Futures meetings.
* Provide a way to show impacts of transitions from dry to wet hydrology and vice-versa.
* Use decision scaling to extend [Barnett and Pierce (2008)](#_ENREF_1) stochastic treatment of inflow uncertainty (Level 2) to scenarios (Level 3).

# Methods Used

1. Defined scenarios of steady Lake Mead inflow from 5 to 12 million acre-feet per year (MAF/year) in increments of 0.5 MAF/year. Each steady inflow scenario repeats the same inflow value each year (e.g., 5, 5, 5, …, 5 MAF/year). These steady flow values represent the average flow of a multi-year event and can be converted to comparable average Colorado River flows reported from the historical and paleo records (see Step #7).
2. Defined scenarios of starting reservoir storage from 3 to 25 MAF in increments of 2 MAF. These starting reservoir storage values represent the volume of water managers have available to carry through a steady flow scenario. Current Mead active storage is 11.3 MAF (1094.9 feet). Higher start storages were ignored as 25.9 to 27.8 MAF is reserved empty to capture flood water.
3. Simulated each combination of a starting reservoir storage value and steady Lake Mead inflow. The simulation ran on an annual time step and used well-trodden, deterministic reservoir simulation method and data:
   1. Storage in the next year equals storage in the current year plus Mead Inflow minus Mead Release minus Mead Evaporation.
   2. Mead Release is specified by the 2019 Drought Contingency Plan schedule. Above 1,090 feet, release is the full 9.6 MAF/year (Lower Basin + Mexico + downstream evaporation losses). Below 1,090 feet, release is cutback according to the schedule (Figure X in uncertainty paper).
   3. The Mead evaporation rate used is 6.2 feet/year (Moreo et al, 2015; average value from 2010 to 2015). To obtain the evaporation volume, multiply the rate by the Mead pool area. The reservoir area-volume relationship for Lake Mead specified in the Colorado River Simulation System model (CRSS; Wheeler et al, 2019) was used to interpolate a pool area each year from the storage volume.
4. Ran each simulation year by year until one of three stop conditions was reached:
   1. Reservoir storage draws down to the Dead Pool (895 feet, 0 MAF of active storage; Years to Dead Pool)
   2. The reservoir fills to 25 MAF of active storage (Years to Fill)
   3. An iteration limit of 100 years is reached. These simulations achieve a steady reservoir storage (somewhere between dead pool and 25 MAF; Steady Storage).
5. Recorded the number of years to reach stop condition (a) or (b). This number of years represents the duration that the reservoir can sustain the specified hydrologic scenario when starting with the specified storage volume. For stop condition (c), the steady storage volume was recorded.
6. Visualized results by plotting the two main uncertain parameters of Steady Mead Inflow and Mead Active storage (and their scenario values) on the x- and y- axes. Within the plots, drew contours of years to dead pool, years to fill, and steady storage volume. Annotated the visualization with key reservoir storage elevations that include 1090 feet when Drought Contingency Plan starts cutbacks in release and 1025 feet when cutbacks reach their maximum value.
7. Linearly transformed the x-axis of Lake Mead steady inflow scenario values to other useful scales:
   1. A Powell Release equals the Steady Mead inflow minus 0.3 MAF/year. 0.3 MAF/year approximates average Grand Canyon tributary inflows between Lake Powell and Lake Mead (Paria, Little Colorado, Virgin, etc.) over the historical record. A Powell Release can also be interpreted as historical flow at Lee Ferry.
   2. A Lee Ferry Natural Flow equals the Steady Mead Inflow minus 0.3 MAF/year (Grand Canyon tributary inflows) plus 4.5 MAF/year (average Upper Basin consumptive use) plus 0.46 MAF/year (Lake Powell evaporation). The evaporation volume assumes an evaporation rate of 5.7 feet/year and lake area corresponding to 9 MAF of active storage. The effects of both assumptions are discussed under Caveats.

# Key Findings

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# Caveats

* This analysis ignores the intentionally created surplus program. Users who intentionally create surplus voluntarily cut back their delivery from Lake Mead, keep that water in the reservoir, and can later withdraw it (under certain conditions). These voluntarily cutbacks will delay time to reach dead pool or speed the time to fill. However, the maximum voluntary cutbacks allowed are 0.6 MAF/year and much smaller than the 1.3 MAF/year required by the DCP at 1,025 feet.
* Sidesteps Lake Powell-Lake Mead equalization and modeling of Powell.
  + Steady Mead inflow scenarios are also interpreted as Lake Powell release scenarios.
  + There are only effects of equalization at low Mead levels.
* The conversion of Steady Mead Inflow to Lee Ferry Natural Flow assumes a volume From the range of evaporation rates measured at Powell, evaporation volumes at 9 MAF of storage may vary ± 0.06 MAF/year. The evaporation volume and range both decrease as the storage volume decreases. Upper Basin consumption use may vary from year

# Challenges

*1) Measure water volume evaporated from reservoirs*. A program using eddy covariance to measure reservoir evaporation at Lake Mead has been underway since 2010 ([Moreo 2015](#_ENREF_2)). At Lake Powell, the most recent evaporation data are from 1977 ([Schmidt et al. 2016](#_ENREF_3)); the U.S. Bureau of Reclamation just started a measurement program. Analysis of eddy-covariance data can take months or years to provide evaporation rates that managers can use.

*2) Measure and verify user cutbacks in diversions and consumptive use*. Within the Lower Colorado River Basin (Nevada, California, Arizona, and Mexico), reductions in diversions are readily measured at individual canal and diversion points from the Colorado River. Little diverted water returns to the river, thus reductions in diversions reduce consumptive use. Between 2008 and 2017, the Lower Basin states have reduced diversions by 1,260,000 acre-feet as Intentionally Created Surplus (ICS) for Lake Mead. In the Upper Colorado Basin (Wyoming, Colorado, Utah, and New Mexico), article V of the Upper Colorado River Compact already charges reservoir evaporation to the state in which the reservoir is located.

*3) Rising reservoir storage means increasing evaporated volume and larger required cutbacks* (Figure 1, black dashed-dotted line). This relationship runs counter to standard reservoir operations that instead reduce deliveries and increase shortages as reservoir storage falls (e.g., Interim Shortage Guidelines [ISG] and recently signed Drought Contingency Plan [DCP]).

*4) Lower Basin states, Mexico, and the U.S. federal government have already pledged large cutbacks under ISG and DCP* (Figure 1, red and blue lines). DCP cutbacks start at a Mead Level of 1,090 feet (about 21.6 million acre-feet of combined Mead and Powell storage) and increase to 1,325,000 acre-feet per year. Below a combined storage of 15.4 million acre-feet (Mead level of 1,050 feet), cutbacks equal or exceed reservoir evaporation volume. At the same time, DCP and ISG cutbacks are only defined down to a Mead level of 1,025 ft (about 12 million acre-feet of combined storage). Below, this level, further cutbacks require re-negotiation by the states.

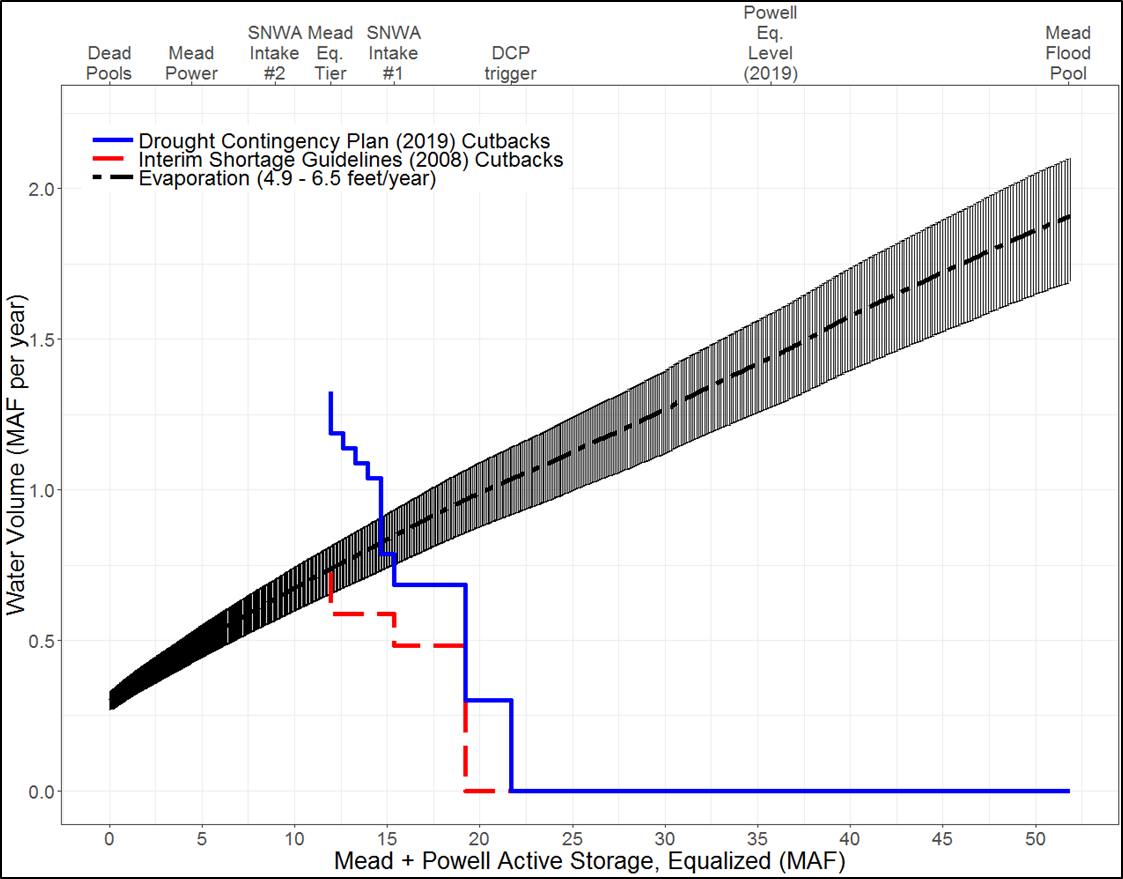


Figure 1. Annual reservoir evaporation volume (Powell + Mead) and cutbacks required by the Drought Contingency Plan and Interim Shortage Guidelines versus combined active storage. Uncertainty in reservoir evaporation volume is due to year-to-year variations of evaporation rates measured for Lake Mead ([Moreo 2015](#_ENREF_2)) and Lake Powell ([USBR 1986](#_ENREF_4)).

# Program to Address Challenges while Providing Flexibility to Users

*A) Evaporation Accounting*. Each state and user will have an evaporation account. Each year, each user 1) adds to their account a positive amount which is their prorata share of the total reservoir evaporation volume estimated from the most recent evaporation data and 2) subtracts reductions in withdraws and consumptive use the user made from their regular delivery amount. A positive account balance allows the user to borrow water from the reservoir and delay reductions in withdraws and consumptive use to a future year. The management paradigm does not need to specify the prorata shares; the states may negotiate these shares or tie then to states consumptive use in the prior year. Until better data for Lake Powell becomes available, use the historical evaporation rate of 5.7 feet/year.

*B) Account Limits*. There is an upper limit on the debt users can add each year to their evaporation account (annual limit) and maximum balance (overall limit). Additionally, when the total storage volume in Mead and Powell falls below a target (e.g., combined Mead and Powell active storage of 20,000,000 acre-feet), all outstanding evaporation account debts come due and users must cutback their diversions and consumptive use by the outstanding balance in their evaporation account. These requirements work similar to annual and overall limits and the trigger level for the ICS program.

*C) ICS Transfer*. States and users can transfer ICS credit to their evaporation account. This transfer decreases the user's ICS balance but allows the user to increase withdraw from the reservoir (or cutback less). This transfer allows users to apply prior-enacted and verified water conservation efforts towards reductions required by the reservoir evaporation accounting.

D) *DCP Cutbacks Reduce the Evaporation Account Balance*. The reduction to an evaporation account will be smaller of the user’s i) DCP cutback for the year or ii) their prorata share of the annual reservoir evaporation volume. This allowance recognizes the large cutbacks users will already implement under extreme drought conditions.

*E) Trade among Users*. By mutual agreement, states and users can trade or exchange balances in their reservoir evaporation accounts. This allowance follows trades allowed by the DCP and gives states and users further flexibility to manage their evaporation accounts.

Box 1 (next page) shows example evaporation accounting and trade program activities.

# Discussion

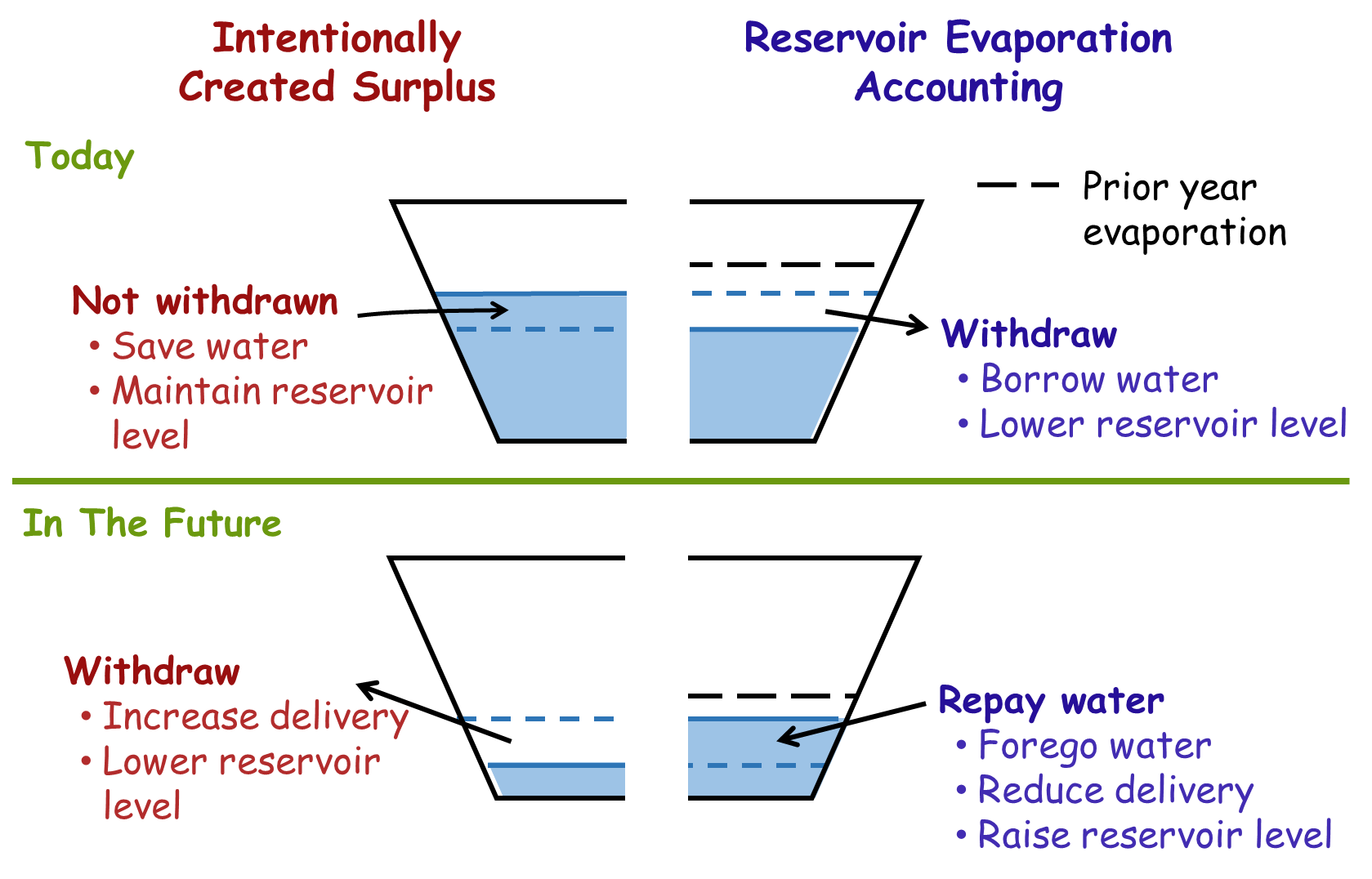


Figure 2. Comparison of Intentionally Created Surplus and Reservoir Evaporation Accounting Programs.

The proposed reservoir evaporation accounting and trade program builds on the existing ICS and DCP programs. ICS is a savings program where Lower Basin users voluntarily cutback deliveries and deposit conserved water into Lake Mead (the bank) to prop up the lake level now. Later, users withdraw conserved water from and lower the lake level. At low reservoir levels, users may not access their ICS water or ICS withdrawals will further strain an already strained reservoir system. In contrast, evaporation accounting is a flexible lending and debt program. Users are assessed a prorata share of reservoir evaporation volume each year but can borrow and withdraw that water from a reservoir (the bank) for immediate use. Later, users repay the borrowed water to a reservoir by reducing their diversions and consumptive use (Figure 2). When reservoir levels are low, repayment is required and will further serve to raise reservoir levels during these critical times.

Because the DCP already requires large cutbacks at low reservoir levels, the reservoir evaporation accounting and trade program recognizes these efforts. The program offers users additional tools to help users flexibly decide when, where, and how much they will cut back or trade with other users. The program allows users to access and move their ICS water into their evaporation account even when reservoir levels are low. Finally, by including reservoir evaporation as an active component of Lake Powell and Lake Mead management, the program 1) improves the balance of system supplies and demands, and 2) reduces the likelihood that the reservoirs will fall to very low levels and require the largest cutbacks under the DCP. Together, the program can 3) reduce the Colorado River structural deficit.

# Modeling in Colorado River Simulation System (CRSS)

Box 1. Examples of Reservoir Evaporation Accounting and Trade

**Example 1.** User A’s prorata share of reservoir evaporation is 85,000 acre-feet. User A elects to cut back their normal use by 40,000 acre-feet. User A is now obliged to cut back normal use by 45,000 acre-feet next year or a later year.

**Example 2.** User A from Ex. 1 also has 110,000 acre-feet of intentionally created surplus (ICS) credit. User A elects to transfer 85,000 acre-feet of ICS this year. User A takes their full delivery and retains 25,000 acre-feet of ICS credit.

**Example 3.** It’s an extreme drought year. Mead Level has fallen so that User B must, by the DCP, cutback 250,000 acre-feet. User B’s current evaporation account balance is zero and prorata share of last year’s reservoir evaporation is 175,000 acre-feet. User B cuts back 250,000 acre-feet and has an ending evaporation account balance of zero.

**Example 4.** User C’s and D’s prorata shares of this year’s reservoir evaporation volume are 90,000 and 220,000 acre-feet. User D offers to pay some User C farmers to fallow their lettuce and melon fields that ordinarily evapotransire 40,000 acre-feet per year. Thus, User C reduces its diversion and consumptive use by 40,000 acre-feet plus 90,000 acre-feet for its prorata share for a total of 130,000 acre-feet. User D reduces its normal use by 180,000 acre-feet.

Several aspects of this alternative management paradigm can be modeled in the Colorado River Simulation System (CRSS):

1. Duplicate the existing ICS policy group and rules and give the new policy group higher priority.
2. Add rules to assess reservoir evaporation, transfer ICS credit, and trade among states that do not exist in the ICS rules
3. Update annual and total limits on evaporation accounts and the reservoir trigger level that requires users to repay borrowed water.
4. Credit DCP cutbacks in evaporation accounts.
5. Define simulation scenarios. It is not possible to anticipate how states and users will behave with the new flexibility offered by the evaporation accounting and trade program. Instead, simulate two scenarios that represent likely upper and lower bounds on behavior
   1. Defer reductions - all states and users defer reductions in diversions and consumptive use to the maximum extent allowed by the evaporation accounting rules. Users keep large, positive balances in their evaporation accounts until total reservoir storage falls below the target volume.
   2. Reduce immediately - all states and users reduce diversions and consumptive use by their prorata share of reservoir evaporation volume each year. Users keep the balance of their reservoir evaporation accounts at zero.
6. Results analysis will focus on Lake Mead and Lake Powell storage volumes, evaporation volumes, and deliveries to users.

# Conclusion

A reservoir evaporation accounting and trade (EAT) program is proposed to give basin states and users flexibility in when, where, and how they cutback diversions to account for reservoir evaporation. Tools such as evaporation accounting, transfer of Intentional Created Surplus credits, recognition of cutbacks under the Drought Contingency Plan, and trade allow states and users to determine the volume, timing, and locations of cutbacks in their diversions.

# Outstanding Questions

1. To what extent are Mead and Powell evaporation rates in a particular year correlated? If correlated, the error bars in Figure 1 grow. Probably don’t have the data to answer this question right now.
2. Why have Nevada’s ICS balances of 511,023, 531,562, and 582,313 acre-feet in 2015, 2016, and 2017 exceeded its maximum allowed balance (deposit) of 300,000 acre-feet specified in the ISG (this is a good thing, saving more water). Was the max balance changed?
3. What authority, if any, does Reclamation have to implement some or all of this program on their own?
4. How is the minute process initiated with Mexico to include Mexico as one of the users? Would Mexico be willing to participate?

# References

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