Synchronous Model Support

Flex Accounting for a Combined Lake Powell-Lake Mead System

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Introduction

This document supports participants to use the synchronous model for a combined Lake Powell-Lake Mead system (Rosenberg, 2021d). Synchronous means multiple participants connect to the same cloud model and enter individual water conservation and consumption choices and group decisions as model time progresses year-by-year. The document provides context information for each individual and group choice and explains how choices build on existing Colorado River management (Appendix A). The document also suggest potential values to enter.

Find quick links to support information (the sections of this document) in the Model file, *Master* worksheet, Column N.

Quick Start

1. Review the main canons of existing Colorado River management (Appendix A).
2. One participant downloaded the Excel model file (Rosenberg, 2021d)
   a. Moved the file to Google Drive
   b. Opened in Google Sheets
   c. Shared with other participants
   d. Participants opened the *Master* worksheet to the top left cell (A1).

1.   Define Parties, Persons, and Strategies

- Five parties and one shared, reserve account derive standing from the 1922 Colorado River Compact, U.S.-Mexico Treaty, subsequent Minutes, Upper and Lower Basin drought contingency plan, and desire to include more parties (Table 1)(1922; IBWC, 2021; USBR, 2019; USBR, 2020).

Table 1.   Parties, Reason(s) to include in model, and Potential Strategies

Party	Reason(s) to Include	Potential Strategy(s)
Upper Basin	Article II(c to g) of the Colorado River Compact (1922).	• Continue to consume ~ 4.0 maf/year. This is historical consumptive use minus Lake Powell Evaporation. • Sell some water, get paid to conserve, and prepare for shortage and curtailment (Rosenberg, 2021e).
Lower Basin	Article II(c to g) of the 1922 Colorado River Compact (1922).	• Continue mandatory conservation and cutback from 7.5 maf per year as Lake Mead level declines (USBR, 2019). See cutback schedule in *MandatoryConservation* sheet. • Buy water from other parties to reduce mandatory conservation or save some water for future years.
Mexico	1944 U.S.-Mexico Treaty and subsequent Minutes	• Continue mandatory conservation and cutback from 1.5 maf per year as Lake Mead levels decline (IBWC, 2021). See *MandatoryConservation* sheet. • Conserve additional water beyond mandatory targets. • Sell some water to other parties to gain money to build non-water projects.
Colorado River Delta	Section VIII of Minute 323 (IBWC, 2021)	• Save until have enough water for a 0.06 maf pulse flood every few years. • Save until have enough water for a longer duration 0.08 maf pulse flood. Scientists are still figuring our the ecological and other benefits of 0.08 or 0.06 maf pulse flood. • Buy water and make more frequent pulse floods.
First Nations	• Include more parties (USBR, 2020) • Tribal water study (Ten Tribes Partnership, 2018)	• Develop and use 2.0 maf per year of rights. • Lease undeveloped water until use. • Save water for future use.
Shared, Reserve	Protect Lake Powell and Lake Mead elevations of 3,525 and 1,020 feet (USBR, 2019)	• Maintain combined protection volume (11.6 maf). • Account managed by consensus of all parties. • Assume parties do not agree on releases, so no releases, steady storage. • Transfer some water without payment to party in need.

Each participant can play one or more roles.

Representatives of individual states — e.g., Utah, Wyoming, Colorado, and New Mexico in the Upper Basin — can team up to role play a party like the Upper Basin. When teaming, draw on prior water sharing agreements such as an Upper Basin Compact where parties share water in specified percentages (Carson et al., 1948).

1A. Explain cell types

Four model cell types are defined by fill color (Table 2).

Table 2. Model Cell Types

Cell Type	Explanation
Physical watershed data	Flow and evaporation assumptions required by the model. Parties agree on this data and information.
Individual party decision	A party's strategy including decisions such as conservation, consumption, sales, purchases from a party's flex account.
Joint party decision	Decisions parties make together such as the reservoir protection elevations, how to split existing storage and inflow among parties, or how to split combined storage between Lake Powell and Lake Mead.
Calculated cell	Formula used to calculate cell such as reservoir evaporation or a party's available water.

1B. Make Assumptions

(i) The evaporation rates for Lake Powell and Lake Mead are taken as the midpoint within reported ranges of measurements (Table 3)(Schmidt et al., 2016). Evaporation rates for Lake Mead are presently measured and more reliable than Lake Powell. Lake Powell evaporation rates have not been measured in decades. A sensitivity analysis found that the lower and upper bounds on Lake Mead evaporation rates for a five year study for Lake Mead draw down saw variations of 0.25 maf or less in Lake Mead storage volume (Rosenberg, 2021a).

Table 3. Reservoir evaporation rates (feet per year)

Reservoir	Midpoint	Range
Powell	5.7	4.9 – 6.5
Mead	6.0	5.5 – 6.4

(ii) The **starting storage** is taken from data portals (USBR, 2021b; USBR, 2021c). Text in Column D lists the date.

(iii) The **protection elevations** of 3,525 feet for Lake Powell and 1,020 feet for Lake Mead are defined in the Upper and Lower Basin Drought Contingency Plans (USBR, 2019). As the reservoirs approach the protection levels, the plans state the parties will consult with the Federal Government to stabilize and prevent the reservoirs from falling below these levels. To stabilize, the parties will need to make reservoir releases plus evaporation less than inflow (Rosenberg, 2021a).

(iv) The **protection volumes** associated with the Lake Powell and Lake Mead protection elevations become the starting balance for the shared, reserve account.

Participants can enter lower protection levels and volumes than the default values. Lowering will reduce hydropower generation at Glen Canyon Dam and Hoover Dam. Lowering will also raise the temperature of water in Lake Powell, raise Glen Canyon Dam release water temperature, and pressure the native, endangered fish populations of the Grand Canyon. With warmer release water temperatures, non-native fish outcompete the native fish. Colorado River managers recommend to keep the default protection levels for now. Participants can also jointly lower the protection volume later during each year of model time.

(v) **Prior 9 year Lake Powell release** is 78.1 maf and is the release measured through Glen Canyon Dam from 2012 to 2021 (Figure 1).

(vi) **Prior 9-year Paria River flow** is 0.17 maf and measured just before the confluence with the Colorado River at Lee Ferry. We care about the 9-year Lake Powel release and Paria River flow because these volumes tell us how much the Upper Basin must deliver in the next 10th year (1st year of the model) to meet its 10-year delivery requirement of 82.5 maf each decade to the Lower Basin and Mexico via article III(d) of the 1922 Colorado River Compact and 1944 US-Mexico Treaty. Here,

$$82.5 \text{ maf} = (7.5)(10) + (1.5/2)(10)$$

Where 7.5 maf is the Upper Basin's annual delivery responsibility to the Lower Basin, (1.5/2) is the Upper Basin's half share of the U.S. responsibility to Mexico, and 10 is a consecutive 10 year period.

(vii) **Delivery to meet 10-year requirement** is the 82.5 maf requirement minus the Lake Powell Release minus the Paria flow. The Upper Basin must deliver 4.2 maf to the Lower Basin next year at Lee Ferry. The Upper Basin can keep all Lake Powell natural flow above 4.2 maf.
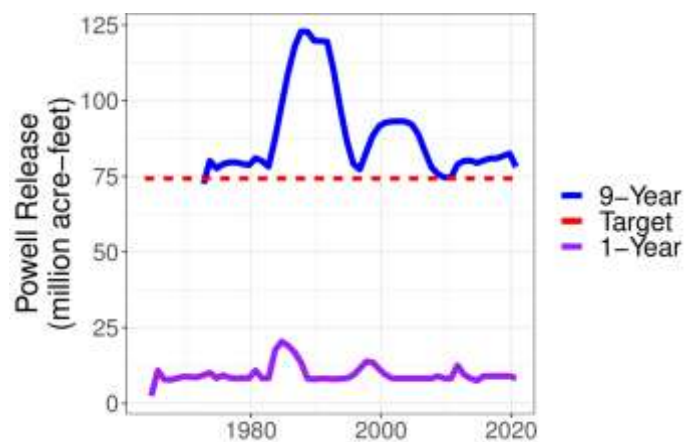
Figure 1. **Lake Powell Releases**

2.   Specify natural inflow to Lake Powell

Specify natural inflow to Lake Powell as the water in the Green, San Juan, mainstem Colorado, and other tributaries that would flow into Lake Powell if there were no upstream human consumptive use or reservoirs. Once a Lake Powell natural flow is specified, the rows below populate with data.

Because future flows are uncertain, we can only specify natural inflow to Lake Powell as a scenario of possible future flows. Specify a scenario from flows reconstructed from the historical (1905 to 2015) or paleo (1416 to 2015) periods (Meko et al., 2017; Prairie, 2020). See workbook tab *HydrologicScenarios* for some flow scenarios from these periods.

Alternatively, look at the mean natural flow of low-flow sequences in the paleo reconstructed or recent observed periods (Figure 2). For example, a 5-year drought that started in 1580 AD had a reconstructed average flow of 9 maf per year.
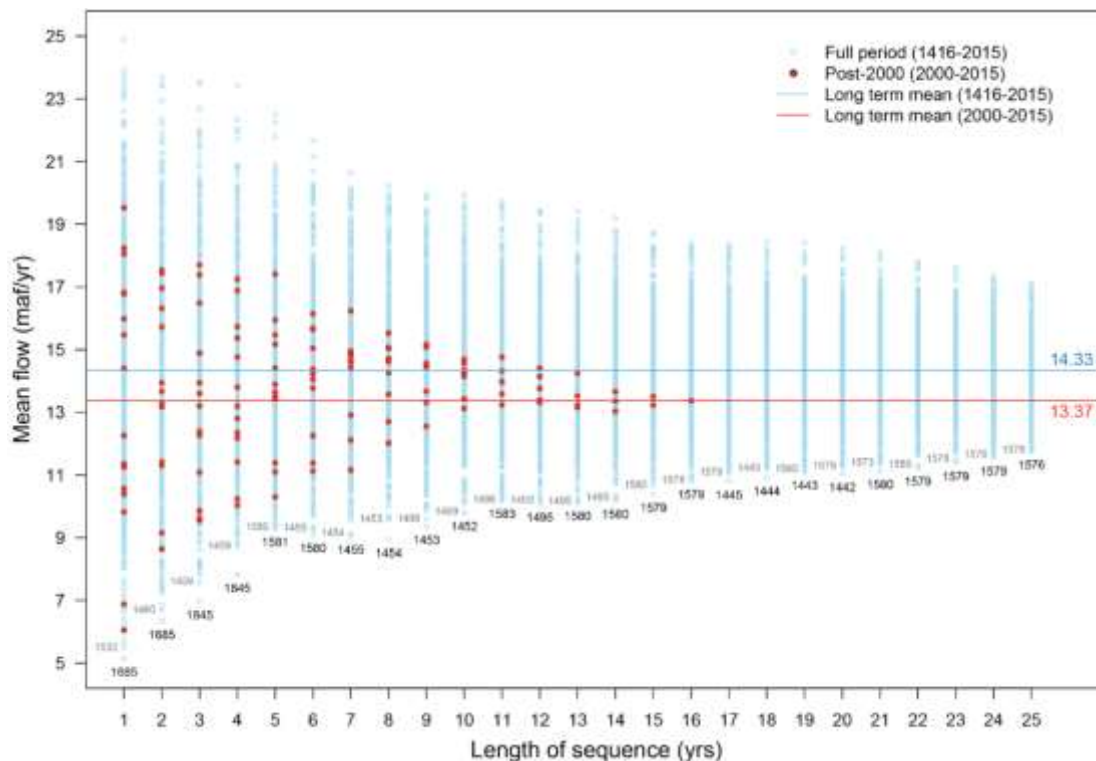

Figure 2.   Sequence-average plot of the tree-ring reconstructed flow of the Colorado River at Lees Ferry (Salehabadi et al., 2020).

Or include flows representative of the more recent observations. Use the unregulated inflow tracked and projected by (USBR, 2021d)(Figure 3) and add ~3 maf. The addition represents the non-reservoir consumptive use in the Upper Basin. Figure 4 shows how to conserve from unregulated to natural flow.
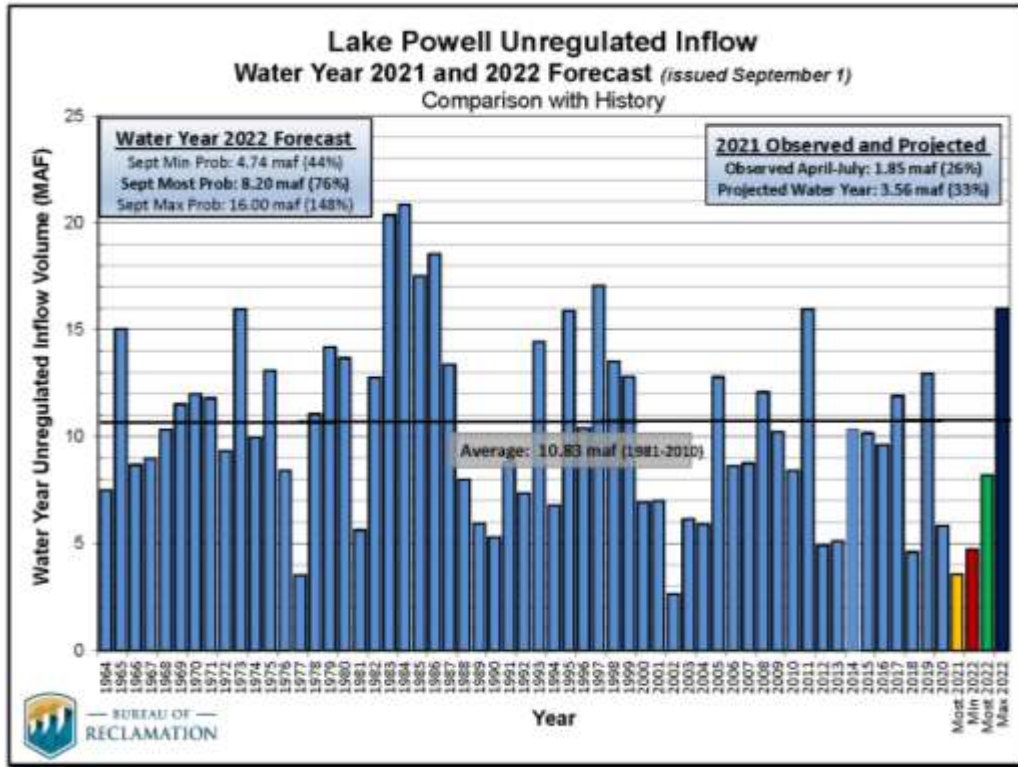
Figure 3.   Unregulated flow to Lake Powell (USBR, 2021d). Add ~ 3 maf for natural flow.
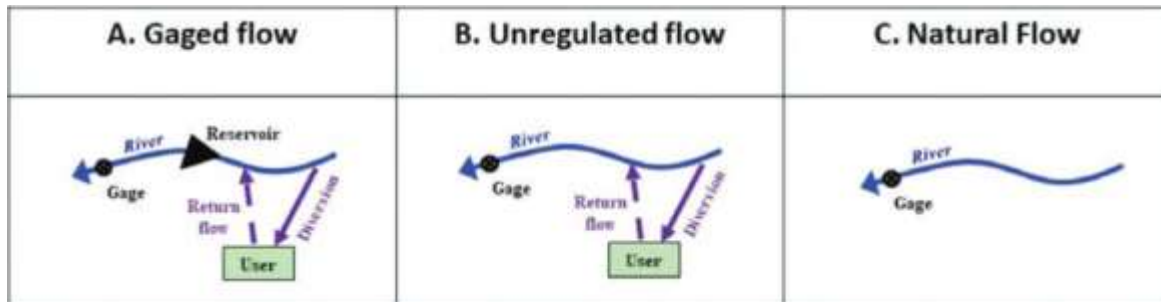
**Figure 4.   Process to go from gaged (measured) flow to natural flow (Wheeler et al., 2019).**

Alternatively, devise a time series of flows on your own or adapt values year-to-year as model time progresses.

The model uses natural flow as in input because the model first credits a share of the year's natural flow to each party's flex account. Then parties consume and conserve water. Consumed water is subtracted from the account balance to obtain the end-of-year reservoir storage.

2A.   Intervening Grand Canyon Flow

Enter the intervening flow from the Paria, Little Colorado, and Virgin rivers plus seeps on the Grand Canyon from Glen Canyon Dam and Lake Mead. This intervening flow excludes Lake

Powell release or other upstream consumptive use on the rivers. A compilation of USGS gaged data from 1990 to 2020 show a mean intervening Grand Canyon flow of 0.9 maf per year with 5-year sequences below 0.75 maf (Figure 4)(Rosenberg, 2021b). By default, the model uses an intervening Grad Canyon flow of 0.8 maf per year.
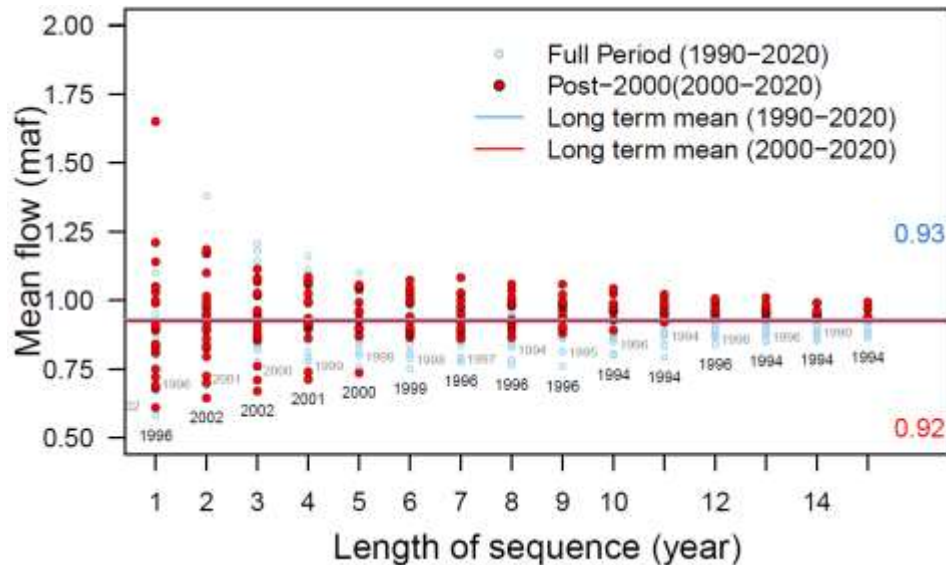
Figure 4. Mean Grand Canyon tributary flow (Glen Canyon Dam to Lake Mead) for different sequence lengths.

2B.   Mead to Imperial Dam intervening flow

Enter the intervening flow from Hoover Dam to Imperial dam. By default, this intervening flow is 0.2 maf per year and was estimated from the natural flow data set below Hoover Dam (Prairie, 2020).

## 2C.   Havasu/Parker evaporation and evapotranspiration

This value results evaporation from Lakes Havasu and Parker and the evapotranspiration of riverbank vegetation from Hoover Dam down to Lake Havasu. A default value of 0.6 maf per year is used and represents the value used in Lake Mead accounting. Find annual estimates of the Havasu/Parker evaporations and evapotranspiration from 1995 to 2014 at USBR (2021a).

3. Split existing reservoir storage among parties (year 1 only)

Split the starting combined reservoir storage (Figure 5) entered in Section 1B among the parties. These assignments are joint party decisions. There are many possibilities. Below, the default splits apply Interim Guidelines Intentionally Created Surplus (ICS) accounts, the Lower and Upper Basin drought contingency plans and the Minute 323 to the U.S.-Mexico Treaty (IBWC, 2021; USBR, 2019).

- Assign the 11.6 maf protection volume to the shared, reserve account (5.9 maf from Lake Powell plus 5.7 maf from Lake Mead).
- Assign the 0.17 maf in Mexico's Lake Mead conservation account to Mexico (USBR, 2021a).
- Assign the 2.8 maf balance in Lower Basin Lake Mead conservation (ICS) accounts to the Lower Basin.
- Assign the remaining Lake Mead storage to the Lower Basin.
- Assign the remaining storage in Lake Powell to the Upper Basin.
- In these assignments, the Colorado River Delta and First Nations do not get any storage. In actuality, the parties will
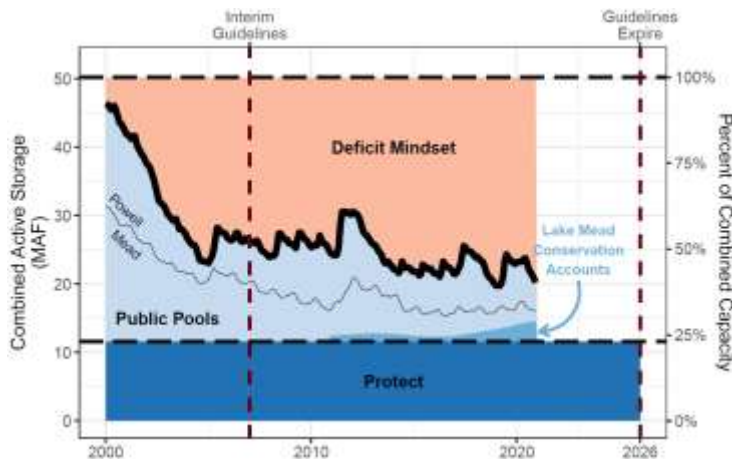
Figure 5. Assign combined Lake Powell and Lake Mead storage (left) to flex accounts (right).

3A. Beginning of year reservoir storage

In year, beginning of year reservoir storage is the Lake Powell and Lake Mead volumes specified in Section 1B.

In subsequent years, the Lake Powell and Lake Mead storage volumes are the volumes decided by parties at the end of the prior year.

3B.   Calculate Powell + Mead Evaporation

Reservoir evaporation volume is the product of (i) annual evaporation rate (see Section 1B), and the lake surface areas associated with the current reservoir volumes. Find the Elevation-Storage-Area relationships on the *Powell-Elevation-Area* and *Mead-Elevation-Area* worksheets (far right). Data were download from the Colorado River Simulation System (CRSS) model (Wheeler et al., 2019; Zagona et al., 2001).

The combined reservoir evaporation is divided among flex accounts in proportion to the flex account balance (Equation 1, evaporation terms in maf per year, balance and storage terms in maf).

$$Upper\ Basin\ Evaporation = \begin{pmatrix} Combined\ Reservoir \\ Evaporation \end{pmatrix} \frac{\begin{pmatrix} Upper\ Basin \\ Flex\ account\ balance \end{pmatrix}}{(Combined\ Reservoir\ Storage)}$$

For example, if the combined evaporation is 1.0 maf and Upper Basin has 10% of the combined storage, then the Upper Basin is assigned 10% of the combined evaporation or 0.1 maf that year.

3C.   Calculate Mexico Water Allocation

Mexico's water allocation is its 1.5 maf per year treaty amount minus mandatory conservation volumes specified in Minutes 319 and 323 for declining Lake Mead levels (IBWC, 2021). The *MandatoryConservation* sheet shows the conservation schedule.

4. Split combined natural inflow among parties

Split the combined natural inflow – natural inflow to Lake Powell, plus intervening Grand Canyon inflow, plus Mead to Imperial Dam intervening inflow, minus Havasu / Parker evaporation and ET – among accounts. This split is a political decision and Table 4 shows one way to split that draws on existing operations.

Table 4. Assign inflow to parties

Party	Volume (MCM)	Comment	Existing Operations
Shared, Reserve	Varies by Evap.	Assign the share of evaporation volume so inflow equals outflow (evaporation) and the account balance stays steady.	Drought Contingency Plans (USBR, 2019)
Colorado River Delta	0.016	Is 67% of the 9-year, 0.21 maf volume pledged by the U.S. and Mexico.	Minute 323 (IBWC, 2021)
Mexico	1.5 – mandatory conservation	Mandatory conservation volumes increase as Lake Mead level's decreases	Minutes 319 and 323 (IBWC, 2021)
Lower Basin	7.5	All remaining Grand Canyon tributary and Mead to Imperial natural flow plus smaller of remaining Lake Powell natural flow or 7.5 maf.	1922 Compact Article III(d)
Upper Basin	Remain	Remaining Lake Powell natural flow.	1922 Compact Article III(d)

Additional notes:

- In year 1, the Delivery to meet 10-year requirement (see Section 1B) is assigned to the Lower Basin. Then, remaining natural flow to Lake Powell is assigned to the Upper Basin. This assignment makes the 10-year delivery to the Lower Basin and Mexico become 82.5 maf.
- In Years 2 and higher, the first 8.23 maf of Lake Powell natural flow is assigned to Mexico and the Lower Basin. Any remaining natural flow goes to the Upper Basin.

5.   Player Dashboards – Conserve, Consume, and Trade

Each player has a dashboard where they can trade, conserve, and consume their available water (Figure 6). Within their dashboard, A participant can:
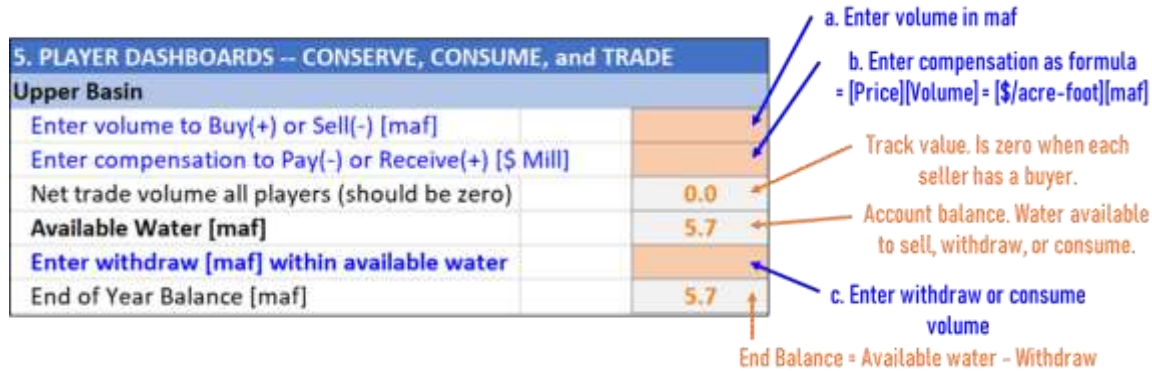
Figure 6.   Upper Basin Dashboard annotated. A Lake Powell natural flow of 9 maf gives the Upper Basin 5.7 maf of available water to sell or consume.

- Purchase or sell water from other player(s) with compensation.
- Purchases and sales must include at least one other participant so the net trade volume for all players is zero.
- Monitor their available water.

$$\text{Available Water} = \text{Flex Account Balance} + \text{Share of natural flow} - \text{Share of Evaporation} + \underbrace{\text{Purchases} - \text{Sales}}_{\text{Optional}} \quad \text{(Eq. 1)}$$

- Purchases add to the available water balance and sales lower the available water balance.

To calculate compensation for trades, multiply the purchase or sell volume in maf by the price in $ per acre-foot. Table 5 shows rough Colorado River water prices.

- For example, a purchase of 0.5 maf at $500 per acre-foot is (0.5)(500) = $250 million.
- If a party buys 0.5 maf at $500 per acre-foot from one party and 0.2 maf at $1,200 per acre-foot from a second party, enter the compensation formula as:

    Purchase Cost = (0.5)(500) + (0.2)(1,200) = $850 million.

Table 5.   Rough Colorado River water prices

Description	Price ($/acre-foot)
Low value agriculture – Upper Basin	$300 - $500

Agriculture - Lower Basin	$700 - $1,000
Desalination in the Sea of Cortez {James, 2021 #2767}	$2,000

Withdraws and consumptive use must stay within the available water. The withdraw cell fill will turn red when the withdraw exceeds the available water. No withdrawing more money than is in your bank account!

The dashboards repeat for the other parties.

5A. Shared, Reserve Dashboard

The dashboard for the shared, reserve account is orange fill – all parties must agree to a purchase or sale.

The current recommendation is keep the shared, reserve account balance steady – no sales or gifts to parties in distress.

Selling or gifting water from the shared, reserve account will lower Lake Powell and/or Lake Mead levels:

- Reduce the head available for hydropower generation, and speed the time that reservoirs reach their minimum power pools (where they can no longer generate energy). At present, the impacts of reduced hydropower generation are difficult to quantify. When, energy generation declines, the energy producers must go on the spot energy market to purchase the energy shortfall.
- Reduce storage in Lake Powell, heat the water temperature of Lake Powell storage (less stratification), increase the release water temperature, and make the native, endangered fish of the Grand Canyon more susceptible to prey by non-native fish. The worksheet *PowellReleaseTemperature* provides a table and figure of the impacts on fish of less water storage in Lake Powell.

Both impacts will depend on how combined storage is split between Lake Powell and Lake Mead (see next section).

6.   Summary of Player Actions

Shows player actions grouped by Purchases and Sales, Account Withdraws, and Account end-of-year balances. These groupings can help see whether sales balanced purchases and also overall water consumption for the year.

6A.   Combined Storage – End of Year

The combined storage – end of the year is the combined storage in Lake Powell and Lake Mead at the end of the year after all account withdraws and consumptive use. This volume is the sum of the end-of-year- balances in all accounts.

7. Assign Combined Storage to Powell and Mead

Assign the end-of-year combined storage to Lake Powell and Lake Mead. Enter as percent where 50% splits the combined storage equally between the two reservoirs and 75% places more storage in Lake Powell. After entering a percent split, the Powell and Mead storage volumes and levels populate. So does the Lake Powell release to achieve the Powell and Mead storage, the turbine release water temperature, and suitability of native, endangered fish of the Grand Canyon. Box 1 shows an example for 13.8 maf of combined storage.

Box 1. Impacts to assign 65% of 13.8 maf combined storage to Lake Powell

There is 13.8 maf of combined storage. The parties assigned 65% of the storage to Lake Powell. This leaves 9.0 maf in Lake Powell and 4.8 in Lake Mead. Both Powell and Mead are above their minimum power pool elevations of 3,490 and 955 feet.

Lake Powell releases 2.8 maf to Lake Mead this year to achieve the specified storage volumes. The release water temperature is < 18°C which may benefit the native, endangered fish of the Grand Canyon or they may face invasion from non natives.

Combined Storage - End of Year [maf]	13.8
6. Assign combined storage to Powell and Mead (Equalize = 50%; 75% = more in Powell)	65%
Powell storage (maf)	9.0
Mead storage (maf)	4.8
Powell elevation (feet)	3,569
Mead elevation (feet)	1,006
Impacts of Powell Release on Grand Canyon Endangered Fish	
Release to achieve storage in rows 131:132 (maf)	2.8
Turbine release water temperature (oC)	< 18
Suitability for native, endangered fish	May benefit or face invasion
Suitability for tailwater trout	Help grow + incubate

A release water temperature will help tailwater trout (introduced) grow and incubate.Lake Powell will need to receive 85% of combined storage to raise the storage to 11.8 maf, cool release temperatures, and increase the relative abundance of native, endangered fish.


There are three considerations to assign the combined storage to the two reservoirs:

- **Protect endangered, native fish of the Grand Canyon.** As storage in Lake Powell falls, the Lake Powell water temperature warms because there is less stratification (Figure 7). The release water temperature warms. Native, endangered fish of the Grand Canyon become more susceptible to prey by non-native fish. The worksheet *PowellReleaseTemperature* shows the break point Lake Elevations where suitability for native fish worsens (Figure 7). If water is released through the
- **Current operations**. Since 2007, the current operations sought to equalize storage in Lake Powell and Lake Mead (enter 50%){USBR, 2007 #2736}. Whereas prior to 2007, managers kept more storage in Lake Mead (Figure 7).
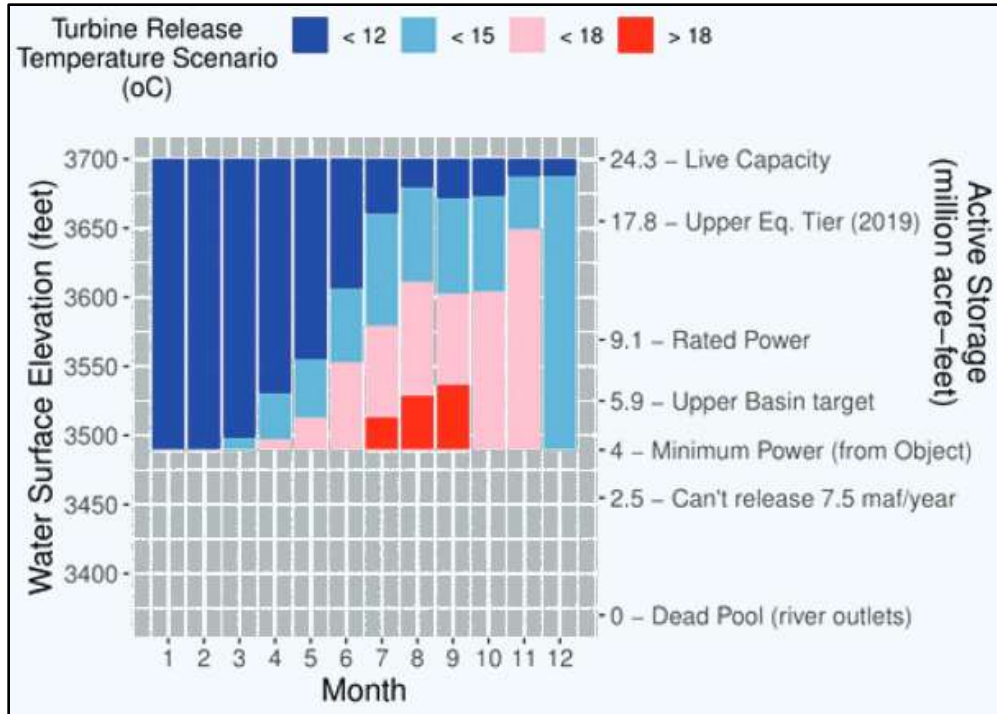
Figure 7. **Lake Powll turbine water release temperatures for different water surface elevations {Wheeler, 2021 #2802}.**
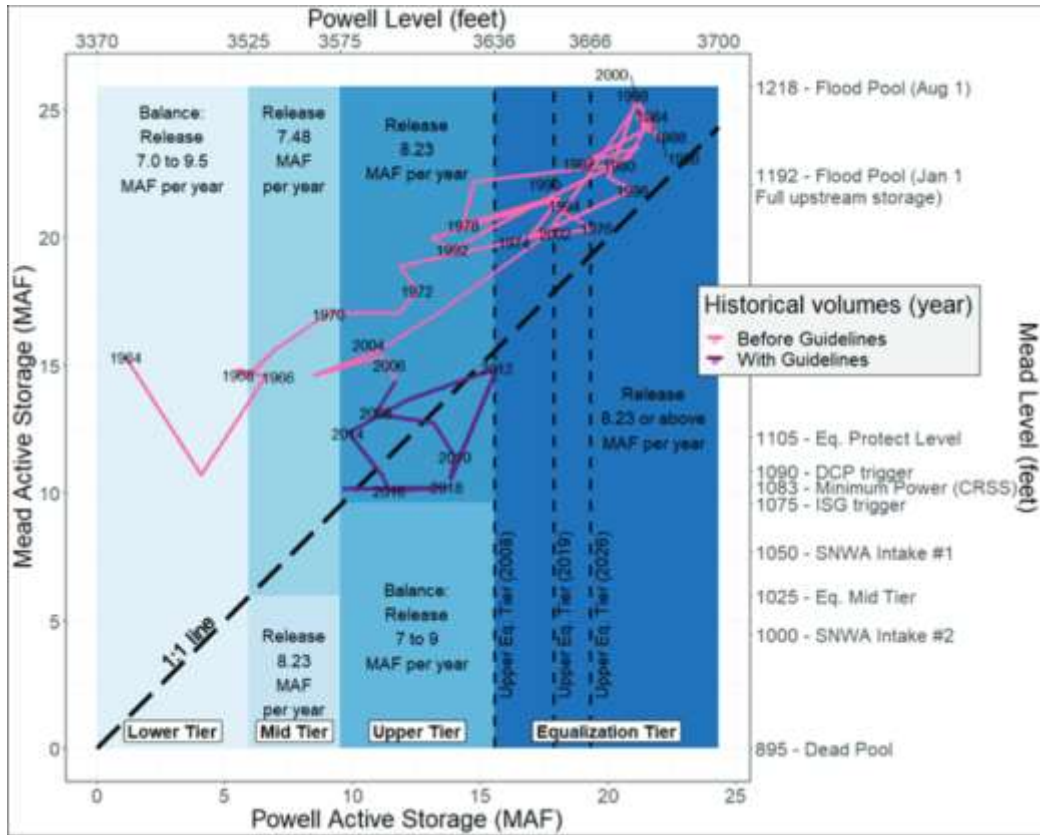
Figure 8. Diagram depicting the Lake Powell-Lake Mead coordination rules (blue fill) and historical lake levels before and after the 2007 interim guidelines (pink and purple lines){Wheeler, 2019 #2493}

8. Data, Model, and Code Availability

The data, code, and directions to generate figures in this post are available on Github.com at Rosenberg (2021c).

9. Acknowledgements

Requested Citation

David E. Rosenberg (2021). "Give Lake Mead managers more flexibility to conserve and stop draw down to the dead pool." Utah State University, Logan, Utah. https://github.com/dzeke/ColoradoRiverCoding/blob/master/BlogDrafts/3-GiveLakeMeadManagersMoreFlexibilityToConserveToStopDrawdownToDeadPool.docx.

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