Lessons from real-time, online collaborative modeling to discuss more adaptive reservoir operations

David E. Rosenberg

September 30, 2022

Key Points

• Created real-time, online collaborative modeling environments by using an interactive, web spreadsheet (Google Sheet) during video conference sessions.

• 26 Colorado River managers and experts participated.

• Within a session, up to 6 participants simultaneously consumed, saved, and traded water in six basin water accounts, protected reservoirs, and sustained endangered, native fish.

• Participants constructively improved basin water accounts rather than separately developed and tested competing alternatives.

• Synthesized 10 lessons to improve model process, build trust, increase operational flexibility, and generate more actionable suggestions for reservoir management.

Abstract

This work had the purpose to model and discuss in real-time more adaptive Colorado River reservoir operations with manager and experts. I created real-time, online collaborative modeling environments by using an interactive web spreadsheet (Google Sheet) during video

---

1 Professor, Department of Civil and Environmental Engineering and Utah Water Research Laboratory, 8200 Old Main Hill, Utah State University, Logan, Utah, 84322-8200, A.M. ASCE, david.rosenberg@usu.edu ORCID 0000-0003-2163-2907.
conference sessions. 26 Colorado River managers and experts participated. Within each session, up to 6 people from the same stakeholder group simultaneously consumed, saved, and traded water in six basin water accounts, protected reservoirs, and sustained endangered, native fish of the Grand Canyon. The collaboration differed from prior studies that excluded stakeholders, extracted data from participants, had a lead modeler or facilitation team mediate participant interactions with a model, or built a model then presented findings at the project end. Real-time, online engagement allowed groups to improve basin water accounts rather than separately develop and test competing alternatives. From participant feedback, I synthesized 10 lessons such as model to provoke discussion about new operations rather than propose a solution, solicit feedback early, allow trades to increase manager flexibility, and recognize limits of model acceptability and adoption. A next step is engage multiple groups simultaneously to generate more actionable suggestions for management.

Practical Applications

Researchers, consultants, facilitators, and project leaders can build their own real-time, online collaboration environments and models for their study system(s). Leaders can engage basin managers, stakeholders, colleagues, students, and the public to use the interactive online model(s) during video conference or in-person meetings. Leaders can use real-time, online model environment(s) to prompt discussion of future basin operations, solicit feedback to improve operations, and/or make the real-time collaborative environment more user friendly.

Keywords: Participatory modeling, water market, facilitation, alternative improvement, Colorado River
1. Introduction

This work had the purpose to model and discuss in real-time more adaptive Colorado River reservoir operations with manager and experts. Prior participatory processes either built an expert model then presented findings to participants at the project end (Horne et al., 2016), extracted data from participants (Voinov et al., 2016), had a lead modeler or facilitation team mediate participant interactions with the model across multiple sessions spaced in time (Bourget, 2011; Langsdale et al., 2013; Michaud, 2013; Van den Belt, 2004; Wheeler et al., 2018), or created a serious or in-person game for a hypothetical basin (Babbitt, 2019; Ewen and Seibert, 2016; Madani et al., 2017; Schulze et al., 2015; Seibert and Vis, 2012). There remains a need to give participants a more immersive and collaborative experience with more direct control and real-time feedback for an actual river basin. More direct control can also help participants more immediately discuss, adapt, and improve a reservoir management alternative rather than simply view results or test competing alternatives.

To give participants more control, this work created real-time, collaborative online modeling environments by using an interactive, web spreadsheet (Google Sheet) during video conference sessions. 26 Colorado River managers and experts participated. Within each session, up to 6 participants from the same stakeholder group choose Lake Powell natural inflow each year. Participants then consumed, saved, and traded water in 6 basin water accounts, protected target Lake Powell and Lake Mead elevations, and sustained endangered, native fish of the Grand Canyon. At the end of each session, participants were asked what they liked and what to improve.

The Colorado River basin accounts contrasted with existing operations that specify annual allocations to users, require increasing mandatory conservation for some users tied to
decling reservoir levels, equalize reservoir storage, manage water for sovereign First Nations under state water laws, expire in 2026, and evolved through treaties, compacts, court cases, and agreements negotiated over 100 years (Carson et al., 1948; Castle and Fleck, 2019; 1922; IBWC, 2021; Kuhn and Fleck, 2019; MacDonnell et al., 1995; Ten Tribes Partnership, 2018; U.S. Bureau of Reclamation and National Park Service, 2016; USBR, 2007; USBR, 2008; USBR, 2019). Hereafter, the term “First Nations” will collectively indicate the 29 Federally recognized sovereign Tribes within the Colorado River basin (Ten Tribes Partnership, 2018) that were represented with one basin water account. Real-time, online engagement allowed individual stakeholder groups to constructively improve basin water accounts rather than separately develop and test competing alternatives (Runge et al., 2015; USBR, 2007) in distributed instances of the same, licensed, offline desktop RiverWare software and Colorado River Simulation System (CRSS) model (Zagona et al., 2001).

This article synthesizes 10 lessons from the real-time, online modeling and discussions to help improve model process, increase operational flexibility, build trust, and generate more actionable suggestions for reservoir management. Sections 2 and 3 describe in more detail the composition of the real-time, online modeling sessions, participants use of the online spreadsheet to manage basin water accounts, plus similarities and differences to existing Colorado River operations. Sections 4 and 5 share lessons from the discussions and next steps to generate more actionable suggestions for reservoir management. Section 6 concludes.

2. Composition of Real-Time, Online Sessions

Between April and November 2021, I invited 32 Colorado River managers and experts to 13 video conference and 1 in-person sessions. Participating managers and experts were employed by the U.S. Federal Government, Upper Colorado River Commission, agencies of
Colorado River basin states, water districts, consulting firms, universities, a non-governmental organization, a foundation, and a First Nation. Three people participated in two sessions, three people started but did not complete a session, two people declined a request to participate, and one person never responded. During the same period, I also supervised real-time, online modeling sessions with 4 graduate students, 22 university colleagues, and 63 undergraduate students none of whom had Colorado River basin expertise. This article focuses on feedback from the 26 Colorado River managers and experts who completed a real-time, online session.

Sessions followed the general structure:

- Participants were solicited through email or by invite from a participant.
- Sessions were held with 1 to 6 participants from the same organization.
- Sessions lasted 1 to 3 hours.
- Each participant managed one or more basin water account.
- In sessions with a small number of participants, I managed one or more water accounts.
- Participants sometimes managed the water account for their stakeholder group, sometimes not.
- After play of 1 to 5 years, I asked participants what they liked and what to improve.

The next section further explains the set up and use of six basin water accounts in an interactive online spreadsheet.
3. Online Water Account Setup and Use

Six basin water accounts are available online as an interactive spreadsheet (Google Sheet) and help guide (Rosenberg, 2022b). Conceptually, the water accounts existed within a region of combined management that stretched from the natural inflows to Lake Powell down to Lake Mead releases (Figure 1). While the Upper Basin diverts and consumes water upstream of Lake Powell, an Upper Basin water account existed within the region of combined management by exchange of natural flow and stored water that is further explained in Step 3 of this section. The total of all account balances equaled the combined active storage in Lake Powell and Lake Mead.

Figure 1. Colorado River water account balances are the water stored in a region of combined Lake Powell-Lake Mead management (account balances not to scale).
In the initial rows of the online spreadsheet, participants chose a water account to manage, entered a strategy, and registered initial assumptions such as reservoir starting levels and protection elevations. This early engagement affirmed each participant’s ability to interact with the online spreadsheet. Subsequent rows comprised the remaining components of the water balance for a combined Lake Powell-Lake Mead system. The components included whole basin inflow, reservoir evaporation, available water, consumptive use, conservation, trade, and Lake Powell release that split the combined end-of-year storage between Lake Powell and Lake Mead. Columns represented years. Participants entered individual choices (strategy, consumption, and conservation) into peach-filled spreadsheet cells and after discussion, joint choices (trades, split combined storage) into orange-filled spreadsheet cells.

The purpose of basin water accounts were to offer participants more flexibility to adapt water conservation and consumption decisions to inflow independent of other parties. Participants completed 7 steps to step up and use the water accounts (Table 1).

Table 1. Steps that setup and used basin water accounts within the real-time, online collaborative model environment.

<table>
<thead>
<tr>
<th>Step</th>
<th>Decision Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Assigned water accounts and defined strategies.</td>
<td>Individual</td>
</tr>
<tr>
<td>2. Assigned existing reservoir storage to accounts.</td>
<td>Joint</td>
</tr>
<tr>
<td>3. Selected year’s natural inflow to Lake Powell.</td>
<td>Joint</td>
</tr>
<tr>
<td>A. Assigned inflow to water accounts.</td>
<td>Joint</td>
</tr>
<tr>
<td>4. Calculated available water for each account.</td>
<td>Calculated</td>
</tr>
<tr>
<td>5. Participants conserved, consumed, and traded within their available water.</td>
<td>Individual</td>
</tr>
<tr>
<td>6. Assigned combined storage to Lake Powell and Lake Mead.</td>
<td>Joint</td>
</tr>
</tbody>
</table>
1. **Assigned accounts and defined strategies** for the next few years. Participants selected an account and entered their strategy. For example, an Upper Basin strategy might be to increase water use or deliver the volume specified in Article III(d) of the 1922 Compact volume to Lower Basin (Colorado River Compact, 1922). Participants who wanted advice to formulate a strategy or see current operations consulted the online model guide (Rosenberg, 2022b).

The Upper Basin, Lower Basin, Mexico, Colorado River Delta, and First Nations water accounts represented entities defined in the 1922 Colorado River Compact, 1948 Upper Colorado River Basin Compact, 1944 U.S-Mexico Treaty, Minutes 319 and 323, and pledges to include First Nations (Carson et al., 1948; IBWC, 2021; Ten Tribes Partnership, 2018; USBR, 2020). The First Nations account allowed a participant to manage water independently from the Basin States in which the First Nations were located. This set up differed from current operations where Basin States administer water rights for the First Nations within state boundaries.

The shared reserve was endowed with 14.3 billion cubic meters (BCM) [11.6 million acre-feet (maf)] of water that represented the protect volumes of 7.3 BCM (5.9 maf) and 7.0 BCM (5.7 maf) in Lake Powell and Lake Mead that correspond to elevations 1057 m (3,525 feet) and 306 m (1,020 feet) defined in the Upper and Lower Basin Drought Contingency Plans (USBR, 2019). Hereafter, to follow practice with the Colorado River basin, this article will report elevations, depths, and volumes in customary units of feet and million acre-feet. The following conversion rates apply: 1 ft = 0.30 m and 1 MAF = 1.23 BCM.
The shared reserve prevented participants who drew down their water account balance to zero from further drawing down reservoir storage. At the same time, the 11.6 maf in the reserve comprised ~70% of the active storage in Lake Powell and Lake Mead at the time sessions were held. If all participants agreed, the reserve could transfer water to another account. When contemplating such transfers, consideration was given to the potential for reduced hydropower generation at one or both reservoirs and warmer Glen Canyon Dam release temperatures that threatened the status quo for native, endangered fish of the Grand Canyon (Wheeler et al., 2021).

2. **Assigned all existing reservoir storage to water accounts.** The participants jointly agreed on how to assign all active reservoir storage at the model start to the water accounts. The start volume varied from 21 to 16.2 maf as the actual Lake Powell and Lake Mead volumes drew down over the time period of the modeling sessions. Default assignments drew on existing agreements and operations. For example, participants assigned to Mexico the 0.17 maf that was the October 2020 balance in its Lake Mead conservation account (USBR, 2007; USBR, 2021). Participants assigned the Lower Basin the 2.8 maf balance in the Lake Mead conservation accounts for California, Arizona, and Nevada (USBR, 2007; USBR, 2021). Similarly, participants assigned the Upper Basin most of the Lake Powell storage that was not the protection volume. Participants assigned the shared reserve 11.6 maf as described in Step 1 (USBR, 2019). The assignments gave starting water account balances to the Upper Basin, Colorado River Delta, and First Nations plus allowed the Lower Basin and Mexico to move their Lake Mead conservation account balances into a more flexible
basin water account. There were many other ways to assign reservoir storage to the accounts.

3. **Selected year’s whole basin inflow and assigned to water accounts.** Participants chose each year’s natural inflow to Lake Powell to explore a broader range of hydrologic scenarios than historical flows. Participants used historical data in the model guide to inform choices. For example, participants often chose Lake Powell natural inflows below the 2000 to 2020 average (Salehabadi et al., 2020) of 12.4 maf per year and below the Lake Powell release target of 8.23 maf per year developed in the 1970s (Figure 2). Participants also changed the Lake Powell natural inflow from one year to the next. For example follow a year with historical average inflow (12 maf) by a dry year (7 maf). The Lake Powell natural inflow represented the flow if users above Lake Powell did not store, divert, or consume water (Prairie, 2020; Wheeler et al., 2019). Crediting this natural inflow to the basin water accounts allowed the Upper Basin and First Nations to divert and consume Colorado River water upstream of Lake Powell, deduct consumptive use from their account, then carry over the balance to the next year. This setup allowed the Upper Basin and First Nations located upstream of Lake Powell to store and administratively recover water in Lake Powell even though they did not physically withdraw water from Lake Powell. Below Lake Powell, the model added default inflows of 0.8 maf per year for intervening Grand Canyon inflow (Rosenberg, 2021; Wang and Schmidt, 2020) and 0.2 maf per year for Hoover to Imperial Dam intervening inflow (Prairie, 2020). The intervening Grand Canyon inflow included the Paria, Little Colorado, and Virgin rivers plus Grand Canyon seeps from Glen Canyon Dam to Lake Mead after
diversions from tributary users. 0.6 maf per year of intervening Grand Canyon inflow represented a 5-year sequence average for a dry period while 1.0 maf per year was the 30-year average.

![Histogram of Lake Powell Natural Inflow](image)

**Figure 2.** Participant choices for future Lake Powell natural inflow.

Participants also assigned the whole basin inflow -- Lake Powell natural inflow plus downstream inflows -- to the water accounts. Default assignments followed the existing priority of operations with changes for the shared reserve, Lake Havasu / Lake Parker evaporation and evapotranspiration, and First Nations that are not in current operations (Figure 3).
The assignments were:

a. Assigned the **shared reserve** inflow that equaled the water account’s share of reservoir evaporation because reservoir evaporation depletes inflow before other activities. This assignment kept the shared reserve balance steady and helped protect a combined storage volume of 11.6 maf that is the sum of Lake Powell and Lake Mead protect volumes in the Upper and Lower Basin DCPs (USBR, 2019).

b. Assigned inflow to equal Lake Havasu / Parker evaporation and evapotranspiration.

c. Assigned **First Nations** 1.9 maf per year of decreed water rights because this account managed water independently of the Basin States. The volume
included 1.06 and 0.95 maf per year above and below Glen Canyon Dam (Ten Tribes Partnership, 2018) and deducted First Nations in the Lower Basin’s portion of Havasu / Parker losses. The volume excluded claimed amounts.

d. Assigned **Colorado River Delta** 0.016 maf per year as 67% of the 9-year, 0.21 maf volume the U.S. and Mexico pledged in Minute 323 (IBWC, 2021).

e. Assigned **Mexico** 1.5 maf per year (1944 U.S.-Mexico Treaty), minus the mandatory conservation volume specified in Minutes 319 and 323, minus Mexico contributions to the Colorado River Delta, and minus Mexico’s portion of Havasu / Parker losses because the U.S. must deliver Mexico water first (IBWC, 2021). The mandatory conservation volume increased as Lake Mead level declined.

f. Split the next 2.4 maf per year of whole basin inflow between the **Upper** and **Lower Basins** because the Upper and Lower Basins have 1.2 and 2.45 maf per year of pre-1922 water rights (Leeflang, 2021) after deducting First Nations use.

g. Assigned the **Lower Basin** the next 5.3 maf per year. 5.3 maf plus 1.2 maf pre-1922 use plus 0.95 maf of water for First Nations below Hoover dam (Ten Tribes Partnership, 2018) plus half the Mexico assignment resulted in 8.2 maf per year that is the Lake Powell objective release.

h. Assigned the **Upper Basin** all remaining Lake Powell natural inflow.
Like assigning storage, the above inflow assignments are one of many ways to assign whole basin inflow to the water accounts.

4. **Calculated each water account’s available water** as the account balance (Step 2), plus share of inflow (Step 3), and minus share of reservoir evaporation (Eq. 1; all units maf). An account’s share of reservoir evaporation was the combined annual Lake Powell and Lake Mead evaporation prorated by the water account’s share of combined storage. Optional purchases from other accounts increased available water while sales decreased an account’s available water. The optional trades built on a feature of the Lower Basin drought contingency plan that let Lower Basin parties transfer their Lake Mead conservation account balance to another party (USBR, 2019).

\[
\text{Available Water} = \left( \text{Account Balance} \right) + \left( \text{Share of natural flow} \right) - \left( \text{Share of Evaporation} \right) + \left( \text{Purchases} \right) - \left( \text{Sales} \right)
\]  

(Eq. 1)

5. **Parties conserved and consumed within their available water independent of other parties.** Consumptive use withdrew from a basin water account. Conservation made water in the account available next year. Each party’s end-of-year account balance was their available water (Step 4) minus consumption. Account withdrawals from Lower Basin, Mexico, Delta, and First Nations accounts implied a withdraw from Hoover dam or Lake Mead.

6. **Assigned remaining combined storage to Lake Powell and Lake Mead.** This assignment was another joint (political) decision and gave parties flexibility to preferentially store water in one reservoir. The existing operations seek to equalize or
split storage 50%/50% (USBR, 2007). Parties withdrew from their water accounts whether water was physically stored in Lake Powell or Lake Mead. Two considerations to assign combined storage between Lake Powell and Lake Mead were:

(a) Maintain the status quo for endangered, native fish of the Grand Canyon by either (i) keeping Lake Powell elevation above 5.9 maf (3,525 feet) to maintain summertime turbine release temperatures below 18°C (Wheeler et al., 2021), or (ii) forego hydropower generation, and/or release more water through the river outlets.

(b) Keep Lake Powell and Lake Mead levels above the minimum power pool storages of 4.0 maf (3,490 feet) and 2.2 maf (955 feet) or require hydropower customers to purchase additional energy from more expensive sources.

7. **Continued to next year.** All end of year water account balances carried over to the beginning of the next year (Steps 3 to 6).

The table in Appendix A summarizes similarities and differences across 16 features between existing Colorado River operations and basin water accounts.

4. **Lessons**

Discussions of basin water accounts during the real-time, online collaborative modeling sessions led to 5 lessons to improve model process (Lessons #1-4 and 10) and 5 lessons to improve the substance of future operations (Lessons #5-9).

1. **Model to provoke discussion** about new operations rather than propose a solution. For example, at the end of the first online session, the first participant said to “continue to provoke
thought and discussion”. During subsequent sessions, I saw my role was to provoke thought and discussion about new operations rather than propose a solution. Further sessions elicited more discussion about features to like about basin water accounts and their implementation in a real-time, online collaborative model environment (Table 2).

Table 2. Features to like about basin water accounts and their implementation in a real-time, online participatory modeling environment

<table>
<thead>
<tr>
<th>Features to like</th>
<th>More features to like</th>
</tr>
</thead>
<tbody>
<tr>
<td>• I like it / It's neat / It's fun.</td>
<td>• More holistic approach to basin management.</td>
</tr>
<tr>
<td>• Interactive. I see the effect of choices.</td>
<td>• Make me think about the equity issue. How to factor in equity.</td>
</tr>
<tr>
<td>• See yourself in the model.</td>
<td>• What it means to have and use my own water account.</td>
</tr>
<tr>
<td>• See effects on native fish.</td>
<td>• I like the gaming.</td>
</tr>
<tr>
<td>• Drive a conversation around conservation with bad hydrology.</td>
<td></td>
</tr>
<tr>
<td>• Facilitates thought and conservation.</td>
<td></td>
</tr>
</tbody>
</table>

One participant suggested:

Start asking people from different parties to participate in the same session.

And another participant later wrote:

“I think others will find the same value in the exercise that I have seen…. its thought provoking.”

Many participants also encouraged to share with others and suggested specific people.

2. Solicit feedback early to allow participants to improve a single management alternative and the real-time, online environment in which the alternative was modeled. In the early weeks, I shared a first version for Lake Powell with students and a colleague. They suggested to reduce the number of years to 5. The next week, a Colorado River manager liked
the exercise and asked for a more complete picture for Lake Mead and down to the Mexico border. This comment kicked off a serial process where I met with new participant(s), solicited feedback, and used time before meeting with the next stakeholder group to improve the basin accounting alternative and/or its implementation in the real-time, online model environment.

The serial process resulted in 36 changes recorded in the Versions worksheet (Rosenberg, 2022b). The serial process allowed stakeholders from different parties to share ideas to improve basin water accounts as a single alternative for future operations rather than separately develop and test competing alternatives.

3. Identify points of conflict to focus limited time in real-time sessions to provoke discussion on future operations (Lesson #1) and solicit suggestions to improve (Lesson #2) rather than mediate or resolve conflicts. Multiple participants raised the conflict to split Lake Powell natural inflow among the Upper and Lower Basins. Was the 75 maf each 10 years in Article III(d) of the 1922 Compact a delivery or non-deplete requirement (Beckstead and Hoerner, 2012)? Can the Upper Basin deliver less water in the 1st model year and store more to recoup an over-delivery by 4 maf in the prior 9 years? How to deliver the 2.3 and 3.5 maf per year of pre-1922 water uses in the Upper and Lower Basins that have not yet been tested in 100 years since the Compact signing (Leeflang, 2021)? Can the Upper Basin store water in a basin water account for future use if Article III(e) of the Compact does not allow the Upper Basin to withhold water? One participant described 4 or 5 or 6 maf per year of Lake Powell natural inflow as unprecedented, never been done, and unclear what will happen.

Because different stakeholder groups kept identifying the split of Lake Powell natural inflow below 8.23 maf per year as a central conflict—a win-lose or zero-sum game—I came to see that basin water accounts could not resolve. Somehow in the modeling, the Lake Powell
natural flow had to be split among the accounts. The split would be better resolved through separate stakeholder negotiations rather than sequential modeling sessions. During the model sessions, time was better spent discussing future operations (Lesson #1) and identifying features to improve in basin water accounts and/or the real-time, online model environment (Lesson #2).

4. **Provide model options** to show different ways to approach points of conflict. This lesson builds on Lesson #3. After identifying points of conflict, I added model options to show different ways to address several win-lose conflicts inherent in Colorado River management. For example:

   a. Include a water account to allow First Nations to manage their water as sovereign nations rather than under existing state water rights laws. This setup reduced allocations to the Upper and Lower Basin accounts.

   b. Participants split existing reservoir storage among their water accounts. Assigning more storage to one account meant less to other accounts.

   c. Participants split whole basin inflow among the water accounts. Similarly, assigning more inflow to one account meant less to other accounts.

   d. Participants split combined storage between Lake Powell and Lake Mead.

   e. Participants subtracted reservoir evaporation from account balances.

   f. Participants could draw down the shared reserve and assign that water to one or more accounts.

These model options allowed participants to explore some of the many possibilities to resolve win-lose tradeoffs that are inherent to current Colorado River management. The options
turned conflicts into participant choices. Participants could then think about and discuss the choices rather than try to resolve points of conflicts.

5. **Prorate reservoir evaporation by water account balance.** This option was one way to address a win-lose conflict (Lesson #4) because some or all of Lake Mead and Lake Powell evaporation is not counted in current operations (Fleck and Castle, 2022; Schmidt et al., 2016). Participants offered accolades and support for 7 spreadsheet rows that prorated the split by water account balance. Prorating evaporation by account balance may be favorable because:

- Each party was treated equitably. Parties with larger account balances shared more responsibility for reservoir evaporation.
- The Upper and Lower Basins could shift some of their responsibility for evaporation onto other parties and the shared reserve.
- In model year 1, the shared reserve had the largest account balance and was charged ~70% of the combined reservoir evaporation.

Treating water accounts equitably may help parties overcome a win-lose conflict.

6. **Many options exist to govern draw down below the combined protection volume of 11.6 maf.** One participant recommended to keep the shared reserve at 11.6 maf. Another participant noted that 11.6 maf is a lot of water and there may be reasons to draw down the shared reserve below the combined protection volume. A third participant suggested to trust a third party such as Reclamation to manage the shared reserve. There was also a suggestion to allow water account managers to sell water to the shared reserve if no other party wanted to buy. These comments suggest that multiple options exist to drawdown Lake Powell and Lake Mead below 11.6 maf.
7. **Allow trades** to increase management flexibility. Within the real-time modeling environment, most participants voluntarily sold and purchased water even though few trades occurred under existing operations. During real-time sessions, many trades were for larger water volumes, more money, and involved more entities than the Lower Basin and Federal government’s recent $200 million plan to conserve 500,000 acre-feet in Lake Mead each year for 2 years (Allhands, 2021). For example, some participants who role played Mexico sold water to build non-water infrastructure projects. Some participants who played the Upper Basin sold some water to get paid to conserve to prepare for mandatory cutbacks to meet the 10-year delivery requirement. Trades were possible because the basin water account balances defined the water each participant had available to trade each year. Also, trades administratively transferred water from one account to another within the combined Lake Powell-Lake Mead system without physical movement. There was broad support among participants for trades because trades gave participants more flexibility to acquire, consume, store, sell, or buy water.

8. **Manage the combined storage in Lake Powell and Lake Mead** to offer more flexibility. Managing the combined storage offered participants more flexibility to store and access water in either Lake Powell or Lake Mead while sustain the status quo of cold water releases from Lake Powell to benefit native, endangered fish of the Grand Canyon. Managing the combined storage also let participants conserve and consume independent of other participants and independent of where water was stored. Managing the combined storage helped shift discussion about Lake Powell and Lake Mead as Upper and Lower Basin reservoirs towards joint system operations.

9. **Find common benefits such as more adaptability.** Lessons #5-8 combined to find common benefits for all participants as a way to escape win-lose conflicts. Each basin water
account enjoyed common benefits each year of more flexibility to consume and conserve water
independent of other accounts (lesson #8) and trade water with other participants. These common
benefits treated participants more equitably (lesson #5).

10. Recognize the limits of a model’s acceptability and potential adoption.

Participants identified many useful features of basin water accounts and its implementation in a
real-time, online collaborative modeling environment (Lessons #1-9). Participants also said basin
water accounts were:

- Very different than current operations.
- “A huge leap from management today and, when we roll up our sleeves, fraught
  with implementation issues.”
- A heavy lift from existing management to whole basin management.
- “Easy to suggest. Harder to get adopted.”

Participants also said:

- “Initially I freaked out to break the existing operations.”
- “I don’t know how you would ever do it. Hard to get traction on things that are
  less difficult than this.”
- I support use so long as not a substitute for negotiations.

These comments discounted the model’s legitimacy and actionability (Van den Belt,
2004; Wheeler et al., 2018). These repeated comments suggested to stop sessions and write up
lessons from the model sessions.
5. Discussion

This work used a real-time, online collaborative modeling environment to engage 26 Colorado River managers and experts to manage and discuss Colorado River basin water accounts as an alternative to current reservoir equalization operations that expire in 2026. Using an online spreadsheet during a video conference let participants immerse in basin accounts, view, and react to other participant’s entries in the same workbook in real time. The real-time, online modeling and discussion identified many positive features for future Colorado River management such as prorate reservoir evaporation by account balance, allow trades, and manage storage in Lake Powell and Lake Mead as a combined system. These features gave participants a common set of benefits and more flexibility to manage. The sequential engagement with different stakeholder groups allowed participants to constructively improve basin water accounts rather than separately develop and test competing alternatives. The real-time engagement turned conflicts over reservoir management into more collaborative efforts.

This collaboration is not possible with CRSS (Zagona et al., 2001), Water Evaluation and Planning (Yates et al., 2005), R, R Shiny, Python, or cloud notebooks (Abdallah et al., 2022). The real-time, online engagement with participants in a single session contrasted with no/little stakeholder interaction for 42 studies of environmental water decisions (Horne et al., 2016), efforts that extracted data from participants (Voinov et al., 2016), efforts that required a lead modeler or facilitation team to mediate participant interactions with the model across many sessions (Bourget et al., 2013; Langsdale et al., 2013; Michaud, 2013; Van den Belt, 2004; Wheeler et al., 2018), and the build-translate approach most researchers use to build a model on their own then present findings at the project end. The real-time, online collaboration also contrasted with current Colorado River basin practices where states undertake separate modeling efforts and Reclamation pushes out its model improvements in one-way communications.
Like other spreadsheet programs, the Google Sheet made difficult version control, organize an intuitive interface, validate user input, and automate tasks to support collaborative efforts. The serial process to engage stakeholder groups highlighted conflicts over how to divide Lake Powell natural inflow below 8 maf per year and may not lead to agreement or consensus. The annual model assumed participants knew whole basin inflow before making annual conservation decisions when in actuality managers start the water year with a flow forecast that may over- or under-estimate actual flow. While participants said the real-time modeling was fun and engaging, they also said basin water accounts “strayed too far from current operations.” The later comment raised issues of legitimacy and actionability.

To increase model legitimacy and actionability, researchers and facilitators can additionally ask participants to:

- Construct their own alternatives rather than chose options within a predefined alternative (Voinov et al., 2016).
- Within a session, engage with people from multiple stakeholder groups rather than a single group.
- Screen and improve multiple alternatives rather than experiment with one alternative.

To implement these added features, an important next step is to organize collaborative efforts where creative, productive, and connected participants from different stakeholder groups together design, build, and interact in the same real-time, online model environment. In such sessions, participants can learn together, build trust, generate and validate more innovative and actionable insights, and share findings with their communities (Van den Belt, 2004; Voinov et al., 2016). People intending to lead or join such efforts are challenged to assemble a team with
basin, modeling, discipline, integration, facilitation, guiding, communication, interpersonal, and political skills. Leaders are challenged to find money and time to support the team. The team has to convince potential participants to invest their time on the belief that collaboration will generate more innovative and actionable products than if groups work solo.

6. Conclusions

This work had the purpose to model and discuss in real-time more adaptive Colorado River reservoir operations with basin manager and experts. A real-time, online collaborative modeling environment was constructed by using an interactive web spreadsheet (Google Sheet) during video conference sessions. Within the online environment, 26 Colorado River managers and experts consumed, saved, and traded water in 6 basin water accounts, protected reservoirs, and sustained endangered, native fish of the Grand Canyon. Participants gave feedback to improve (i) basin water accounts as an alternative to existing operations, and (ii) the real-time environment in which the water accounts were modeled.

I synthesized ten lessons from the real-time, online collaborative sessions to improve model process and substance. Lessons included model to provoke discussion about new operations rather than propose a solution, solicit feedback early to allow participants to improve a management alternative and the model environment, identify points of conflict to focus limited time in sessions to provoke discussion and solicit feedback, and provide options to show different ways to approach conflicts. Further lessons were allow trades to increase manager flexibility, manage the combined storage in Lake Powell and Lake Mead, find common benefits such as more flexibility for all participants, and recognize the limits of a model’s acceptability and potential adoption.
The real-time, online collaborative model environment differed from prior studies that excluded stakeholders, extracted data from participants, required a lead modeler or facilitation team to mediate participant interactions with the model, or built a model then presented findings at the project end. Real-time, online engagement also contrasted with current Colorado River basin practices where states undertake separate modeling efforts and Reclamation pushes out its model improvements in one-way communications. Real-time, online collaboration also allowed different stakeholder groups to constructively improve an alternative rather than separately develop and test competing alternatives. Next steps are to engage multiple organizations simultaneously in sessions to more collaboratively generate, improve, and validate actionable insights for future reservoir management.

Data, Model, and Code Availability

The data, model, code, and directions for the Colorado River basin water accounts are available at Rosenberg (2022b), "Colorado River Basin Water Accounts: Provoke discussion about more adaptive operations." HydroShare.org.

https://doi.org/10.4211/hs.eb2ae94405324fe7818e8404ad855afa. The data, code, and directions to generate Figures 2 and 3 are also available at Rosenberg (2022b).

Acknowledgments

I thank the 26 Colorado River managers and experts for their time, engagement, and discussion. This work benefited from a $50 donation from a private individual. The donation was used to purchase software to generate the online model guide. Five individuals—four of whom were also participants—and two anonymous reviewers gave feedback that improved this article. This work represents the views of the author not Utah State University.
References


Rosenberg, D. E. (2022a). "Adapt Lake Mead Releases to Inflow to Give Managers More Flexibility to Slow Reservoir Drawdown." *Journal of Water Resources Planning and Management*, 148(10), 02522006. [https://doi.org/10.1061/(ASCE)WR.1943-5452.0001592](https://doi.org/10.1061/(ASCE)WR.1943-5452.0001592).


http://dx.doi.org/10.1016/j.envsoft.2014.11.029.


http://dx.doi.org/10.1016/j.envsoft.2015.11.016.


https://doi.org/10.1007/s10113-018-1304-z.


### Appendix A. Comparison of existing Colorado River operations to basin water accounts

<table>
<thead>
<tr>
<th>Feature</th>
<th>Existing operations</th>
<th>Basin water accounts</th>
</tr>
</thead>
</table>
| **Purposes** | • Encourage conservation  
• Plan for shortages  
• Closer coordinate Lake Powell and Lake Mead operations  
• Address future controversies through consultation and negotiation not litigation (USBR, 2020) | • Same as existing operations.  
• Additionally give each party more flexibility to manage their water account independent of other parties. |
| **Accounts** | Lake Mead conservation accounts only for 3 Lower Basin states and Mexico. | 6 water accounts in the combined Lake Powell-Lake Mead system. |
| **Colorado River Delta** | Non-governmental organizations secure water from the U.S. and Mexico for each pulse flow (IBWC, 2021). | Separate water account in combined Lake Powell-Lake Mead system. |
| **First Nations** | Managed in trust under state water rights systems. | Separate water account in combined Lake Powell-Lake Mead system. |
| **Account sales and trades** | Only between Lake Mead conservation accounts for Lower Basin states. | Between all water accounts in combined Lake Powell-Lake Mead system. |
| **Reservoir protection volumes** | 5.9 and 5.7 maf that correspond to elevations 3,525 and 1,020 feet in Lake Powell and Lake Mead (USBR, 2019). | Shared reserve account with initial 11.6 maf volume in combined system. Participants can vary storage over time. |
| **Adaptation triggers** | Reservoir storage. | Inflow and storage (Rosenberg, 2022a). |
| **Voluntary water conservation** | Lake Mead conservation account for each Lower Basin state and Mexico (IBWC, 2021; USBR, 2007). | Six Basin water accounts (all parties). |
| **Mandatory water conservation** | Increases for Lower Basin states and Mexico as Lake Mead draws down (IBWC, 2021; USBR, 2007; USBR, 2019) | Each party consumes water within their account balance. |
| **Reservoir evaporation** | Ignore ~0.5 maf of Lake Mead evaporation and 0.16 to 0.23 maf of Colorado River evapotranspiration prior to build Glen Canyon Dam (Fleck and Castle, 2022; Schmidt et al., 2016). | Subtracted all Lake Mead and Lake Powell evaporation in proportion to water account balances. |
| **Lake Powell releases** | Target 8.23 maf per year with allowances to equalize Lake Powell and Lake Mead storage (USBR, 2007). | Calculated each year after participants choose how to split combined storage between Lake Powell and Lake Mead. |
| **Manage for endangered fish of Grand Canyon** | Endangered Species Act. | Participants choose split of reservoir storage to main cold water releases from Lake Powell beneficial to native fish. |
| **Expiration date** | 2026 | None; Manage year-to-year. |
| **Model environment** | Offline, licensed, distributed RiverWare/CRSS model instances on desktop machines. | Single shared online, open-source interactive spreadsheet (Google Sheet). |
| **Model components** | • 12 reservoirs.  
• 29 flow gages.  
• 520 water user objects.  
• 145 rules (Wheeler et al., 2019). | • 142 rows on 1 master worksheet.  
• 4 data support worksheets.  
• ReadMe worksheet.  
• Versions worksheet. |
| **Model support** | Reclamation staff | Linked online user’s guide to each spreadsheet row (Rosenberg, 2022b). |