Implementation Effects of New Evaporation Coefficients for Lake Mead and Lake Mohave

Lake Mead and Lake Mohave, Nevada and Arizona
Lower Colorado Basin Region

U.S. Department of the Interior February 2, 2022

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Technical Memorandum

Prepared by:

Boulder Canyon Operations Office
River Operations Group
Genevieve Allan, Hydrologist
Noe Santos, P.E., Civil Engineer

Boulder Canyon Operations Office
Research and Modeling Group
Sarah Baker, Ph.D., Civil Engineer
Robert Alan Butler, P.E., Civil Engineer

Review and Contributions:
Michael Bernardo, P.E., Deputy Chief, Boulder Canyon Operations Office
Daniel Bunk, Chief, Boulder Canyon Operations Office
Alexander Pivarnik, Hydrologist, Boulder Canyon Operations Office
Balaji Ramakrishnan, PhD, P.E., Civil Engineer, Boulder Canyon Operations Office
Meghan Thiemann, P.E., Civil Engineer, Boulder Canyon Operations Office
Shana Tighi, Hydrologist, Boulder Canyon Operations Office

Peer Reviewers:
Jennifer Johnson, P.E., PhD, Supervisory Civil Engineer, Columbia Pacific Northwest Region
Dagmar Llewellyn, Supervisory Civil Engineer, Albuquerque Area Office – Upper Colorado Basin Region
Jonathan Rocha, Civil Engineer, Columbia Pacific Northwest Region

Cover Photo: Eddy Covariance Station at Lake Mead (Moreo & Swancar, 2013)

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Executive Summary

The Bureau of Reclamation's (Reclamation) Boulder Canyon Operations Office (BCOO) funded a multi-year evaporation study to be performed by the United States Geological Survey's (USGS) Nevada Water Science Center in Henderson, Nevada. The initial study's objective was to measure real-time evaporation at Lake Mead using the latest technology available. The goal of the study was to determine new static monthly coefficients for calculating evaporation losses from Lake Mead based on the average monthly surface area. An Eddy Covariance (EC) station and a floating meteorological platform were set up at Lake Mead in March 2010 to collect sub-daily datasets of multiple physical parameters to accurately determine new static evaporation coefficients (average number of feet of evaporation per month) for Lake Mead. The USGS published an initial Scientific Investigations Report (SIR) with the study's methodology and findings from March 2010 – February 2012 (Moreo & Swancar, 2013) covering the Lake Mead Study. In 2013, the study was expanded to further collect data at Lake Mohave, the immediate downstream reservoir from Lake Mead, using identical methods. The USGS published an Open File Report (OFR) detailing the data collection and results for both Lake Mead and Lake Mohave from March 2010 – April 2019 (Earp & Moreo, 2021) which was also used to support this technical memorandum.

The Moreo and Swancar study (2013) initially found that peak evaporation lagged peak net radiation by two months since a larger proportion of the net radiation is converted to stored heat during the spring and summer. The USGS found that evaporation rates are sustained through the fall, despite the declining net radiation, as the stored energy is released. The overall uncertainty in measuring evaporation was estimated to be within 5 to 7 percent. The USGS also employed the Bowen Ratio Energy Budget (BREB) method to validate the EC evaporation measurements at the annual timescale. The use of the BREB method resulted in a good agreement between annual corrected EC and BREB evaporation estimates. The Annual BREB method was 6% higher than the EC process in the first year of the study and 8% higher in the second year of the study.

Reclamation modelers in BCOO's River Operations Group (River Operations) performed sensitivity analyses and evaluated the impacts of the new evaporation coefficients on the daily/mid-term operations and long-term planning models. The new evaporation coefficients replaced values that were originally published in 1958, at Lake Mead, using evaporation pans (Harbeck et al., 1958). The updated evaporation coefficients resulted in minimal impacts to projected elevations and operations tiers for the April and August runs of the Colorado River Mid-Term Modeling System (CRMMS) deterministic 24-Month Study Mode (24MS), the probabilistic runs using the CRMMS ensemble streamflow prediction (ESP) mode (known as CRMMS-ESP), and the Colorado River Simulation System (CRSS).

This evaporation study at Lake Mead and Lake Mohave resulted in a better understanding of the seasonality and magnitude of evaporation at two of the Lower Colorado Basin Region's largest reservoirs. With this information, River Operations plans to implement new evaporation coefficients in the operations models to provide the Colorado River Basin's management and stakeholders with model projections that incorporate the best available information.

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Acronyms

24MS	24-Month Study
Basin	Lower Colorado River Basin
BCOO	Boulder Canyon Operations Office
BREB	Bowen Ratio Energy Budget
CBRFC	Colorado Basin River Forecast Center
CRMMS	Colorado River Mid-Term Modeling System
CRSS	Colorado River Simulation System
CY	Calendar Year
EC	Eddy Covariance
EOCY	End of Calendar Year
EOWY	End of Water Year
ESP	Ensemble Streamflow Prediction
ft	Feet
Guidelines	Colorado River Interim Guidelines for Lower Basin Shortages and the Coordinated Operations for Lake Powell and Lake Mead
ICS	Intentionally Created Surplus
kaf	Thousand Acre-Feet
LCBR	Lower Colorado Basin Region
m	meters
maf	Million Acre-Feet
mm	millimeters
NFM	Natural Flow Model
OFR	Open File Report
Reclamation	Bureau of Reclamation
SIR	Scientific Investigations Report
USGS	United States Geological Survey
UTM	Universal Transverse Mercator
WY	Water Year

1. Introduction

The study and understanding of evaporation processes at large/deep reservoirs requires in-depth understanding of the physical processes involved. An improved understanding of the physical processes, through modern instrumentation, is also key in providing reliable results for system modeling. This technical memorandum provides the summary of the evaporation study performed at Lake Mead and Lake Mohave in the Lower Colorado River Basin (Basin) and how implementing new coefficients affects the Lower Colorado Basin Region's (LCBR) operations and planning models. See Figure 1 below for the study area overview.

The study's objective was to provide a modern estimate of monthly evaporation and to derive new coefficients which could then be used to improve operations modeling. Reservoir evaporation is a widely researched subject with multiple available methodologies. For this study, Reclamation's LCBR partnered with the USGS to employ the EC method to measure evaporation at the sub-daily and monthly intervals to estimate the true rate of seasonal evaporation (Moreo & Swancar, 2013).

Current Reclamation estimates for Lake Mead evaporation are based on a USGS study dating back to 1952-1953 which depended on the use of evaporation pans to develop monthly evaporation rates (Harbeck et al., 1958). While the Harbeck et al. (1958) study attempted to be rigorous in its execution of the energy balance method (considering the best/state of the art technology at the time), the heat storage of a large/deep reservoir likely plays a more significant role than what could be measured from shallow pans near the shoreline (Zhao & Gao, 2019; Zhao et al., 2020).

This technical memorandum will summarize the data collection results from the USGS study and the projected impacts and sensitivity analysis using LCBR reservoir operations models – two Basin-wide mid-term models and a Basin-wide long-term planning model. The outcome of the sensitivity analysis will provide insight into the potential impact to operational decisions and will be used to support the implementation of new evaporation coefficients.

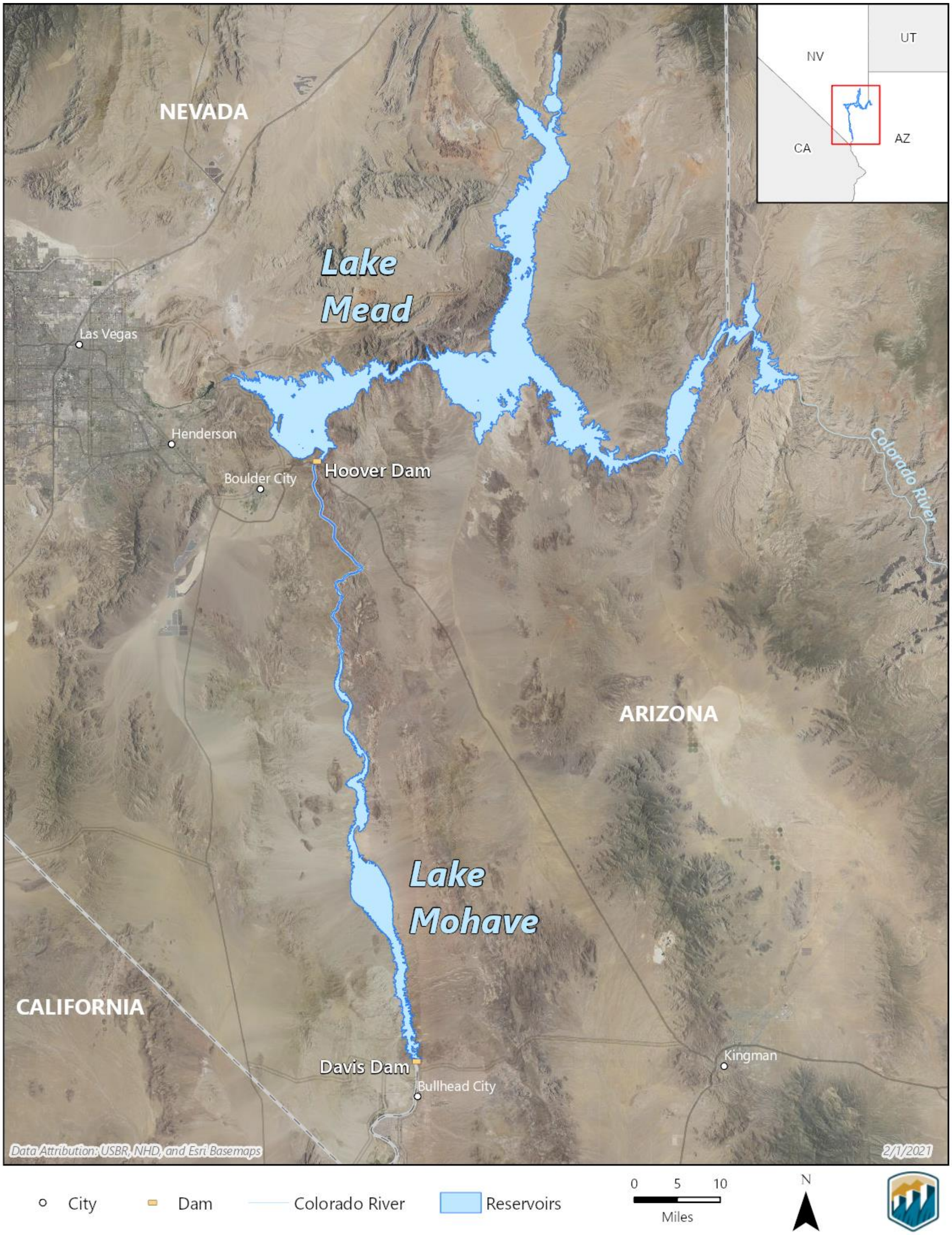

Figure 1 – Aerial image of study region with Lake Mead and Lake Mohave (Map credit to M. Potter, LCBR – Resource Management Office).

2. Lake Mead and Lake Mohave

The history of water rights in the Basin was contentious during the early history of western settlement. The multitude of issues in the early 1900s resulted in compacts, federal laws, court decisions and decrees, contracts, and guidelines which dictate river operations and are collectively known as “The Law of the River” (Reclamation, 2008). Following the division of the entire Colorado River Basin into an Upper and Lower Basin by the 1922 Colorado River Compact, the Boulder Canyon Project Act of 1928 authorized the construction of Hoover Dam which formed Lake Mead. Davis Dam, which formed Lake Mohave, was authorized by the 1944 U.S. and Mexico Water Treaty for the re-regulation of water releases from Hoover Dam for the purpose of making water deliveries to Mexico. Davis Dam is located 67 miles downstream from Hoover Dam and 88 miles upstream from Parker Dam (the last major Reclamation dam in the Basin).

Lake Mead and Lake Mohave are the two largest Reclamation reservoirs in the Basin. Lake Mead has a maximum live storage of 26.12 million acre-feet (maf) excluding exclusive flood control space and a corresponding surface area of 157,500 acres at an elevation of 1,219.61 feet (ft) (Tighi & Callejo, 2011). Under flood control conditions, Lake Mead has a maximum water surface elevation of 1,229.00 ft which corresponds to a storage of 27.62 maf and a surface area of 162,900 acres (Tighi & Callejo, 2011). Lake Mohave has a maximum live storage of 1.81 maf and a corresponding surface area of 28,170 acres at an elevation of 647.00 ft. The elevation-capacity/area tables for Lake Mohave are referenced from an internal Reclamation document and are not currently available online.

Water entering Lake Mead originates in the headwaters of the Upper Colorado River Basin in the states of Wyoming, Utah, Colorado, and New Mexico. Additional water enters the mainstem of the Colorado River through the various tributaries. The Colorado River and its mainstem tributaries are funneled through a system of reservoirs and dams until it reaches Lake Powell at Glen Canyon Dam near Page, Arizona. Glen Canyon Dam releases are the primary source of inflow for Lake Mead. Additional water enters the Colorado River downstream of Glen Canyon Dam through surface runoff and groundwater interaction. The Little Colorado River, Paria River, Muddy River, and Virgin River are the primary sources of tributary inflow into Lake Mead. The calculation of additional inflow to Lake Mead, downstream of Glen Canyon Dam, is performed using a mass balance method and is referred to as the “intervening flow” or “gain/loss.”

Releases from Lake Powell and Lake Mead are governed by the 2007 Colorado River Interim Guidelines for Lower Basin Shortages and the Coordinated Operations for Lake Powell and Lake Mead (Guidelines) (Reclamation, 2007). Between Water Years (WY) 2010 and 2020, total inflow into Lake Mead (sum of Glen Canyon releases and intervening flow) ranged between 8.16 maf to 13.68 maf. The Glen Canyon Dam release varied between 7.48 maf and 12.52 maf while the intervening flow ranged between 677 thousand acre-feet (kaf) and 1.16 maf. Between WY 2010 and 2020, the inflow component from Glen Canyon Dam made up between 89% and 93% of the total inflow to Lake Mead.

Powerplant releases, diversions, and consumptive use are measured on a Calendar Year (CY) basis in the LCBR. Between CY 2010 and 2020, Lake Mead was operated under the Normal Condition and releases from Hoover Dam were governed by downstream water demands. BCOO’s River Operations Group determines the monthly energy generation targets for Hoover Dam (associated with the volume of water to meet downstream demands and reservoir regulation); however, the Western Area Power Administration uses Hoover Dam as a peaking power plant and controls the minute-to-minute releases at Hoover Dam. Hoover Dam’s CY releases, between 2010 and 2020, ranged between 8.51 maf to 9.61 maf.

Lake Mohave’s primary source of inflow is the release from Hoover Dam. Unlike the reach from Glen Canyon Dam to Lake Mead, the reach between Hoover Dam and Davis Dam tends to be a losing reach. This means that the Colorado River loses water in the reach due to groundwater interactions, evaporation, and phreatophyte consumptive use. It is important to note that evaporation in the Hoover

Dam to Lake Mohave reach is not explicitly modeled; rather, evaporation between Hoover Dam and Lake Mohave is lumped into the mass balance for Lake Mohave's intervening flow calculation. Equation 2, in Section 3.2.1, describes the Lake Mohave mass balance which incorporates any losses in the reach as part of the intervening flow for the reservoir. The CY intervening flow in the Hoover Dam to Lake Mohave reach during the study period of 2013 to 2020 ranged between -214 kaf to -74 kaf. Due to the peaking-power plant behavior of Hoover Dam, Lake Mohave acts as a buffer for the high variability in hour-to-hour releases from Hoover Dam. Lake Mohave releases are dictated at a daily and hourly resolution by River Operations and take into account downstream water demands, the Lake Mohave seasonal guide-curve, special construction projects or requests downstream, and the Lake Havasu guide-curve. Davis Dam's CY releases, between 2013 and 2020, ranged between 8.20 maf and 9.35 maf.

3. Methodology

The methods deployed by the USGS, for the purpose of measuring evaporation at Lake Mohave and Lake Mead, were chosen based on the ability to deliver highly accurate monthly evaporation rates for each reservoir. For the purpose of this Memorandum, details into the study methodology and energy budget calculations will be briefly mentioned. For a more in-depth analysis regarding the energy budget methodology, instrumentation, and data collection results, please refer to the peer reviewed Moreo & Swancar (2013) and Earp & Moreo (2021) USGS study reports.

3.1 USGS Data Collection

The USGS set up an EC station as well as a floating platform in order to measure and record all energy budget terms. Table 1 below summarizes the instruments used for the data collection process, Figure 2 shows an example floating instrumentation platform at Sentinel Island, and Figure 3 and Figure 4 indicate the location of the EC/floating platform station throughout the duration of the study at Lake Mead and Lake Mohave, respectively.

Table 1 – Instrumentation for energy budget measurements at the Sentinel Island Platform (Moreo & Swancar, 2013).

Measurement	Manufacturer	Instrument and Model Number	Placement
Air Temperature & Humidity	Vaisala	Hmp45c Trh Probe	2.2 meters (m) Above Water Surface
Wind Speed & Direction	R.M. Young	5106 Wind Monitor, Marine	2.9 m Above Water Surface
Solar Radiation	Li-Cor	Li-200	2.8 m Above Water Surface
Net Radiation	Kipp & Zonen	Cnr-1, Cnr-2	1 m Above Water Surface
Surface-Water Temperature	Campbell Scientific	107 Temperature Sensor	Water Surface
Water Temperature	Ysi	6600 Multiparameter Sonde	1 m to 81 m Below Water Surface
Voltage	Campbell Scientific	Cr10x, Cr3000 Datalogger	1.5 m Above Water Surface

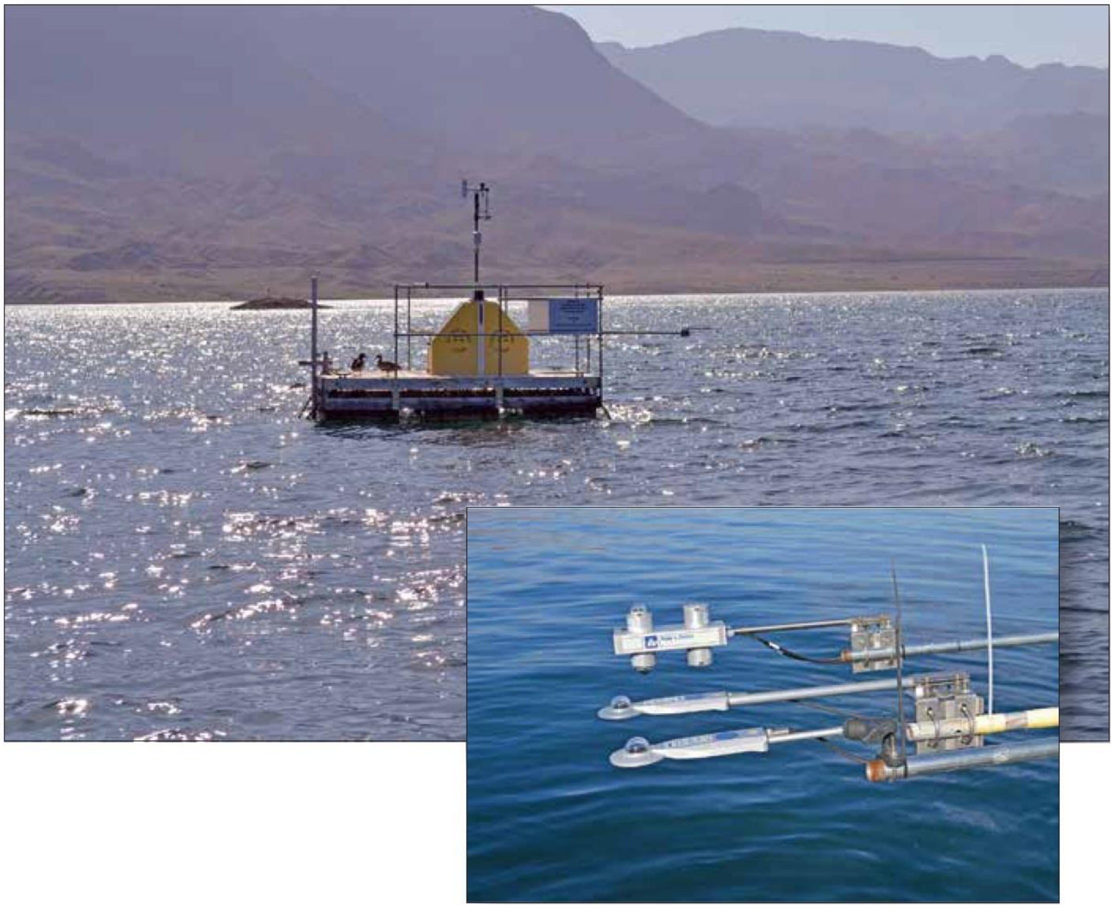

Figure 2 – Sentinel Island platform at Lake Mead with radiometer extending from the platform and inset showing radiometer intercomparison (CNR1 in the background and CNR2 in foreground) (Moreo & Swancar, 2013).

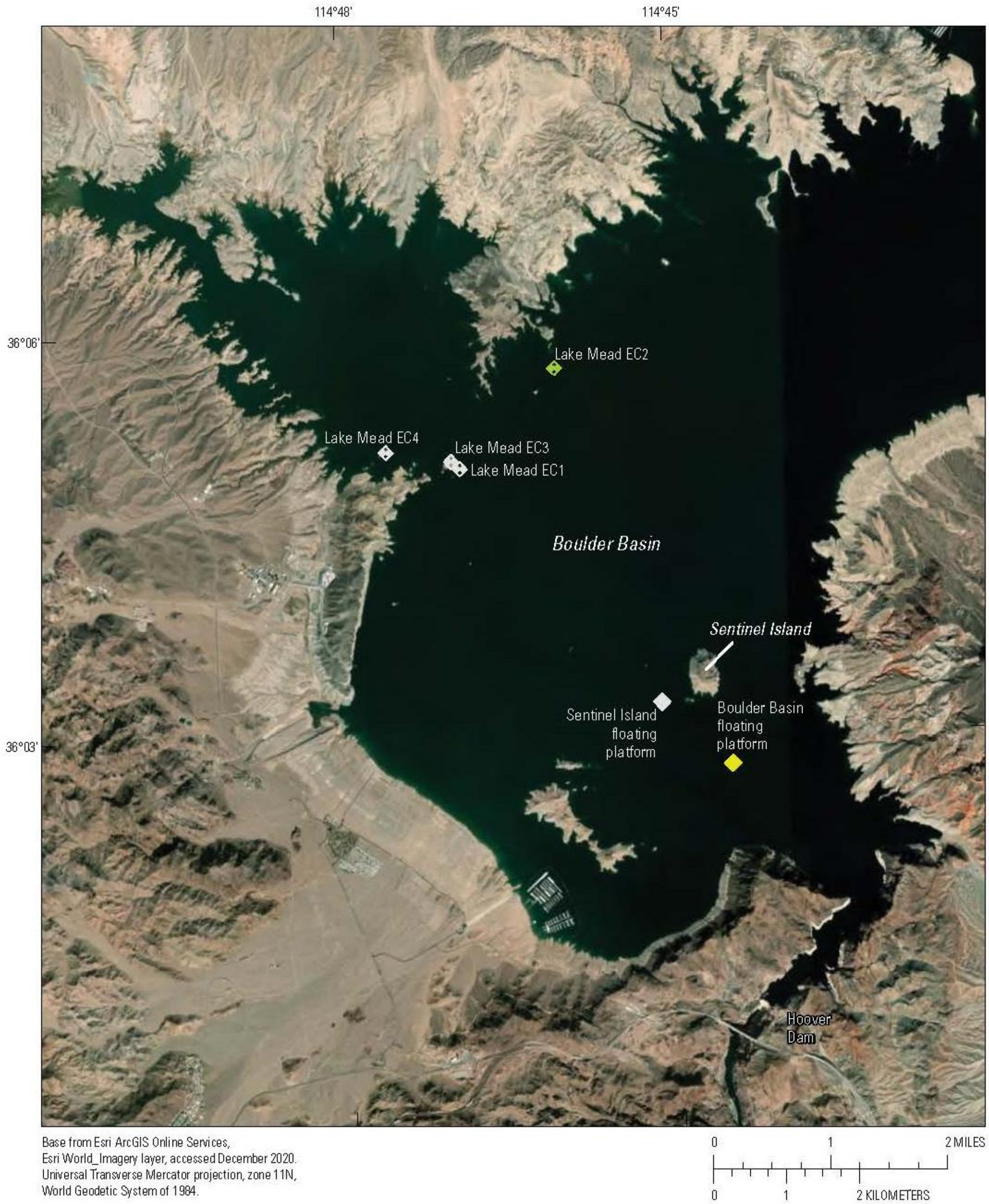

Figure 3 – EC and floating platform sites in Boulder Basin, Lake Mead (Earp & Moreo, 2021).

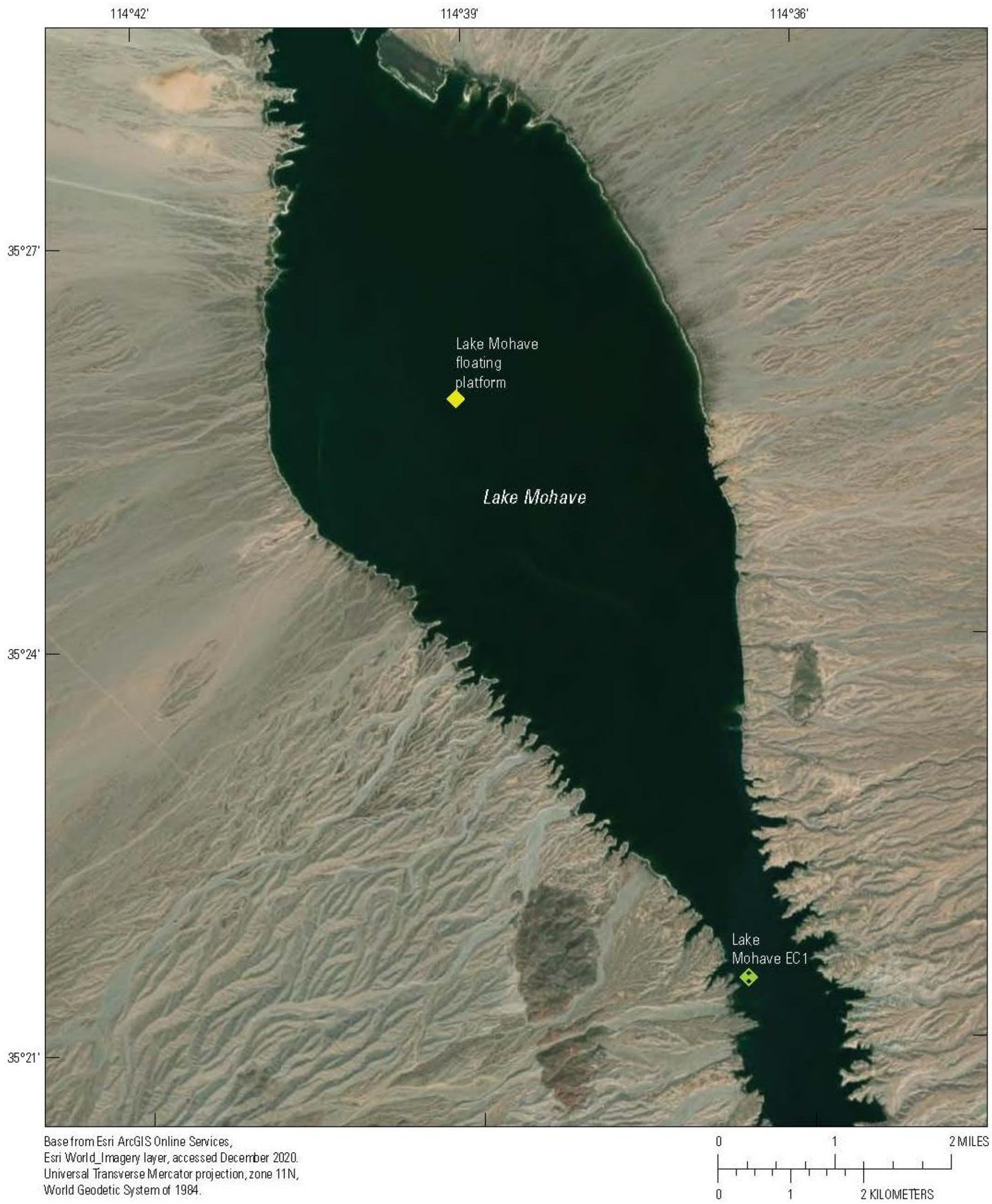

Figure 4 – EC and floating platform site at Lake Mohave (Earp & Moreo, 2021).

According to Moreo & Swancar (2013), the ideal location for the EC station required the surrounding terrain to be flat and homogenous and for the "fetch" of the surface-of-interest to be longer than the turbulent-flux (transport by quasi-random eddies or swirls) source area. "Fetch" refers to the upwind distance from the measurement point to the shore and surface-of-interest refers to the open water surface of Lake Mead and Lake Mohave. After considering options such as deploying an EC station from a raft or having multiple EC stations along the shoreline, the USGS decided to take advantage of historically low Lake Mead elevations by setting up a single EC station on exposed rock outcrops. Lake Mohave's monthly elevation guide-curve allowed for the selection of a single site that met the previously mentioned requirements. This choice was also cost effective since it allowed for the installation/maintenance of only one EC station at each reservoir.

The Lake Mead EC station was relocated four times as the elevation of Lake Mead rose and fell through the duration of the study. The EC-1 through EC-4 points in Figure 3 – EC and floating platform sites in Boulder Basin, Lake Mead (Earp & Moreo, 2021) indicate the locations where the single EC station was situated between March 2010 and May 2019. Because the EC station was located far from the shoreline, the fetch for the instrumentation varied between 2,000 m and 16,000 m (6,562 ft to 52,493 ft) at Lake Mead. Table 2 below summarizes the location and period-of-record for each EC site and meteorological platform where data was collected during the course of the study. Coordinates are in the Universal Transverse Mercator (UTM) Zone 11 projection. The data from all sites and time periods were included in the analysis and generation of final results.

Table 2 – Location and period of record for reservoir instrumentation at Lake Mead and Lake Mohave (Earp & Moreo, 2021).

Site Number	U.S. Geological Survey Site ID	North UTM	East UTM	Period of Record
EC-1	360500114465601	3995454	699677	03/01/10 to 05/24/11
EC-2		3996845	700974	05/24/11 to 08/25/11
				05/08/13 to 05/01/19
EC-3		3995555	699560	08/25/11 to 11/23/11
				06/19/12 to 05/08/13
EC-4		3995677	698662	11/23/11 to 02/29/12
Lake Mead Sentinel Island Platform	360314114450500	3992265	702540	03/01/10 to 4/22/13
Lake Mead Boulder Basin Platform	360246114443000	3991423	703436	4/22/13 to 04/25/17
Lake Mohave EC1	352129114363501	3914696	717197	05/01/13 to 04/30/19
Lake Mohave Floating Platform	352550114390700	3923324	713155	04/11/13 to 09/30/16

With regards to the site on Lake Mohave, the USGS followed the same procedures and used the same equipment as in the first phase of the Lake Mead study as shown in the Moreo & Swancar (2013) report. The Lake Mohave aspect of the study, as well as an update to the Lake Mead study, is fully documented in the 2021 OFR published by Earp & Moreo (2021).

Besides the study reports, the USGS also provided two separate data releases which cover the period of the study. Evaporation data is available online through April 2015 (Moreo, 2015) and additional meteorological data is available online from April 2013 – April 2017 (Moreo, 2018).

3.2 Reclamation Modeling

River Operations runs and maintains several Basin-wide reservoir operations models. The operations models are developed using the river basin modeling software RiverWare. The RiverWare platform was developed by the Center for Advanced Decision Support for Water and Environmental Systems (CADSWES) at the University of Colorado, Boulder (Zagona et al., 2001). The operations models discussed in this report include the following:

1. Daily Operations Model
2. Gain/Loss Model
3. CRMMS: 24MS Mode
4. CRMMS: ESP Mode
5. Natural Flow Model
6. CRSS

All models simulate the operation of the major reservoirs on the Colorado River system and provide projected operations data for Reclamation's main facilities. Output variables include reservoir storage and elevation, dam releases/spills, energy generation, the streamflow at various points throughout the system, and diversions/return flows from water users throughout the system. Each model uses static monthly evaporation coefficients for Lake Mead and Lake Mohave to calculate reservoir evaporation. These monthly coefficients are multiplied by the average reservoir surface area, between the current and previous time step, to calculate the evaporation volume. CRSS is a multidecadal probabilistic model with the ability to support long term planning and risk analysis. CRMMS is a mid-term model with the ability to simulate a single hydrologic trace when run in 24MS Mode or an ensemble of hydrologic traces. Figure 5 and Figure 6 below illustrate how each model is used for different operational activities and decisions as well as the structural differences between the mid-term and long-term planning models.

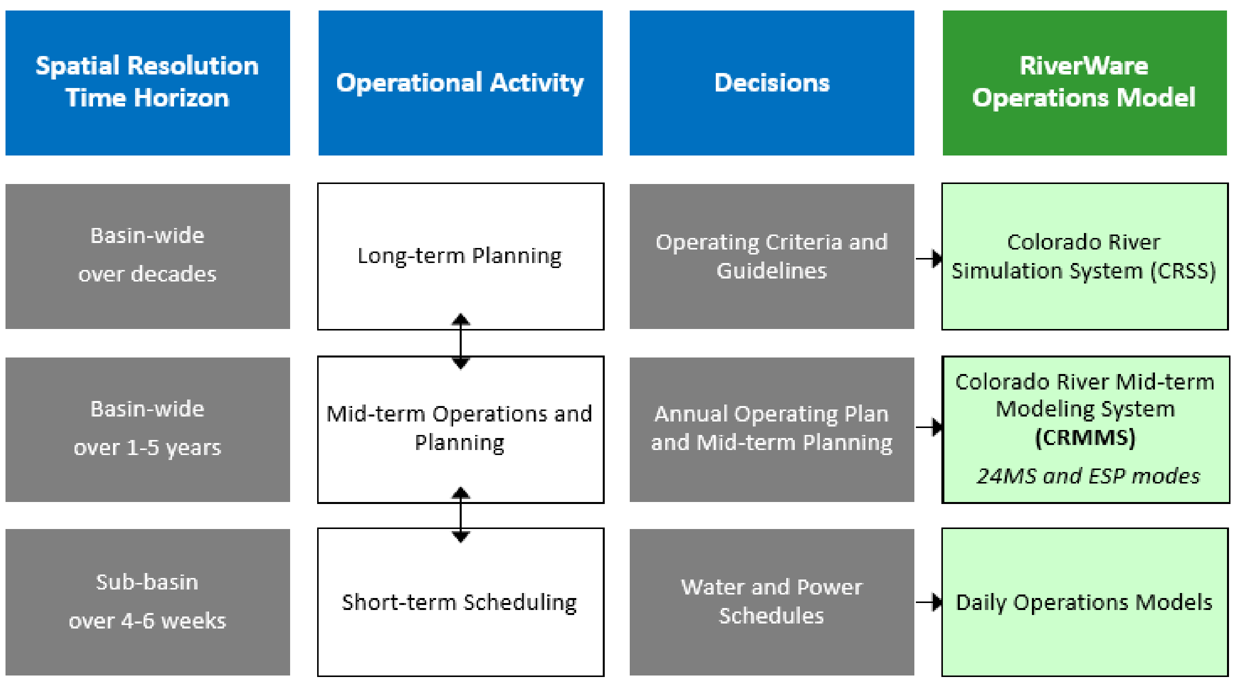

Figure 5 – Comparison of Reclamation's Colorado River Basin Models and Their Mission Utility.

	Colorado River Mid-term Modeling System (CRMMS)		CRSS
	24-Month Study Mode (Manual Mode)	Ensemble Mode (Rule-based Mode)	
Primary Use	AOP tier determinations and projections of current conditions	Risk-based operational planning and analysis	Long-term planning, comparison of alternatives
Simulated Reservoir Operations	Operations input manually	Rule-driven operations	
Probabilistic or Deterministic	Deterministic – single hydrologic trace	Deterministic OR Probabilistic 35 (or more) hydrologic traces	Probabilistic – 100+ traces
Time Horizon (years)	1 - 2	1 - 5	1 - 50
Upper Basin Inflow	Unregulated forecast, 1 trace	Unregulated ESP forecast, 35 traces	Natural flow; historical, paleo, or climate change hydrology
Upper Basin Demands	Implicit, in unregulated inflow forecast		Explicit, 2016 UCRC assumptions
Lower Basin Demands	Official approved or operational		Developed with LB users

Figure 6 - Mid-Term and Long-Term Model Architecture Comparison.

In this report, results/plots labeled “USBR Coefficients” refer to the current evaporation coefficients in Reclamation’s models while the label “USGS Coefficients” refers to the newly developed coefficients using the energy balance method with the EC station.

3.2.1 Reservoir Mass Balance

River Operations’ Colorado River models use a mass balance (water budget) approach, which accounts for all water entering, stored in, and leaving the system. Reservoir outflow (release), reservoir storage, evaporation, diversions, return flows, and bank storage are explicitly modeled. The residual of this equation is referred to as the intervening flow (also referred to as side inflow or gain/loss). This variable represents the sum of tributary inflows, precipitation/runoff, river reach evaporation, and any groundwater losses or gains. This term also incorporates any potential error from other components of the mass balance models.

The mass balance equations can be solved to determine the intervening flow for Lake Mead and Lake Mohave. Equation 1 solves for the intervening flow for the reach between Glen Canyon Dam and Lake Mead while Equation 2 solves for the intervening flow for the reach between Hoover Dam and Lake Mohave. Evaporation in the river between two sites is not explicitly modeled and is instead lumped in as part of the total intervening flow.

Equation 1: $\text{Intervening Flow}_{\text{Glen to Mead}} = O_H + \Delta S + D + E_{Mead} + \Delta BS - O_{GC} - R$

where

- O_H is the outflow from Hoover Dam in acre-feet
- ΔS is the change in Lake Mead Storage in acre-feet
- D is the sum of all diversions from Lake Mead in acre-feet
- E_{Mead} is the total evaporation from Lake Mead in acre-feet
- ΔBS is the change in Lake Mead bank storage in acre-feet
- O_{GC} is the outflow from Glen Canyon Dam (Lake Powell upstream) in acre-feet
- R is the total return flow to Lake Mead in acre-feet

Lake Mead has a fixed 0.065 coefficient used to determine the bank storage of the reservoir which was determined from a past water balance study (Rechard, 1965). The coefficient is multiplied by the change in reservoir storage to determine the change in the bank storage.

Equation 2: $\text{Intervening Flow}_{\text{Hoover to Mohave}} = O_D + \Delta S + D + E_{Mohave} - O_H - R$

where

O_D	is the outflow from Davis Dam in acre-feet
ΔS	is the change in Lake Mohave Storage in acre-feet
D	is the sum of all diversions from Lake Mohave in acre-feet
E_{Mohave}	is the total evaporation from Lake Mohave in acre-feet
O_H	is the outflow from Hoover Dam in acre-feet
R	is the total return flow to Lake Mohave in acre-feet

Unlike Lake Mead, Lake Mohave does not have a bank storage term associated with its mass balance.

3.2.2 Daily Operations Model

The Daily Operations model spans one to three months and is run on a daily timestep. It is used to plan and project daily reservoir conditions, releases, and power generation for Lake Mead, Lake Mohave, and Lake Havasu – the next reservoir downstream of Lake Mohave and the last major Reclamation facility in the Basin. The Daily Operations model is critical to the short-term operation and regulation of the Basin. Daily operations are closely monitored and coordinated with the Yuma Area Office to ensure that enough water is released out of the Basin’s reservoirs to meet downstream demands on a daily basis.

3.2.3 Gain/Loss Model

The Gain/Loss model runs on a monthly time-step and is used to calculate the historical intervening flow for the Basin between Glen Canyon Dam and the Northerly International Boundary with Mexico. The Gain/Loss model uses historical water use, stream gage data, and reservoir operations data to solve for the monthly intervening flow. The calculated intervening flow is further used to calculate a five-year running average on a monthly time step. This five-year average is primarily used as the projected intervening flow in the 24-Month Study model for the future time-steps.

3.2.4 CRMMS Modeling System

CRMMS is a Mid-Term, Basin-wide model that can be run either with a single hydrologic trace or with an ensemble of hydrologic traces. When the model is run with a single two-year hydrologic trace with manually input operations, it is called 24-Month Study Mode. When CRMMS is run with an ensemble of traces going out five years, it is called CRMMS-ESP Mode.

3.2.4.1 CRMMS-24-Month Study Mode

CRMMS 24-Month Study Mode, more commonly known as the 24-Month Study (24MS), is a Basin-wide, mid-term, deterministic model that runs on a monthly timestep, with an official simulation period of up to two years. The model uses a “most probable” unregulated inflow forecast, provided by the Colorado Basin River Forecast Center (CBRFC), for the Upper Colorado Basin Region reservoirs. The CBRFC’s forecasts rely on the ESP method to generate multiple forecast streamflow time series. Each time series is developed using initial model conditions for soil moisture/snowpack and historical climatology (precipitation and temperature) over the model calibration period (1981 through 2015 for the analysis performed in this study). The end-product of the ESP modeling is a monthly unregulated inflow forecast for each of the Upper Basin reservoirs for the current WY. The “most probable” unregulated inflow forecast provided by the CBRFC statistically would be exceeded 50% of the time.

The 24MS is run and published monthly to provide regular updates on projected Basin-wide conditions and operations using the “most probable” unregulated inflow forecast, water use schedules, and reservoir operations. In addition to the “most probable” run, “probable minimum” and “probable maximum” 24MS runs are published four times a year under normal circumstances. The “probable maximum” unregulated inflow forecast reflects a wet scenario which statistically would be exceeded 10% of the time. The “probable minimum” unregulated inflow forecast reflects a dry scenario which statistically would be exceeded 90% of the time. There is approximately an 80% probability that a future elevation will fall inside the range of projected elevations from the minimum and maximum probable unregulated inflow scenarios in the first year of the simulation run. For the second year of the model run, the “probable maximum” and “probable minimum” runs represent the 25^{th} and 75^{th} exceedance probabilities, respectively.

The August “most probable” 24MS projections of the end of calendar year (EOCY) elevations of Lake Mead and Lake Powell are used to determine the Lower Basin operating condition for the following CY and the Powell release volume for the following WY. The April “most probable” 24MS projections of the end of water year (EOWY) elevations of Lake Mead and Lake Powell are used to determine whether an adjustment to the Lake Powell WY release will be made under certain operating conditions.

A summary of the coordinated operations policy for Lake Powell and Lake Mead is shown below in Figure 7. The Normal or Intentionally Created Surplus (ICS) Surplus Condition has been the primary operating tier for Lake Mead since the establishment of the Guidelines. The August 2021 24-Month Study projected Lake Mead to end December 2021 at 1,065.85 feet (below the 1,075 feet tier) which resulted in declaring a level one shortage condition for CY 2022 – the first of its kind in the history of the Basin. With this in mind, there is some sensitivity to the analysis performed in this report using historical model runs and whether an update to evaporation coefficients and intervening flow would have resulted in a different operating condition/tier at Lake Powell or Lake Mead. A similar change in operating tiers at Lake Powell could have resulted in a different WY release volume as shown in Figure 7. A detailed description of the coordinated operations and shortage policies can be found in Section 2 and Section 6 of the Guidelines (Reclamation, 2007).

Lake Powell

Elevation (feet)	Operation According to the Interim Guidelines	Live Storage (maf)[1]
3,700		24.3
	Equalization Tier Equalize, avoid spills, or release 8.23 maf	
3,636-3,666 (2008-2026)		15.5-19.3 (2008-2026)
	Upper Elevation Balancing Tier[3] Release 8.23 maf; if Lake Mead < 1,075 feet, balance contents with a min/max release of 7.0 and 9.0 maf	
3,575		9.5
	Mid-Elevation Release Tier Release 7.48 maf; if Lake Mead < 1,025 feet, release 8.23 maf	
3,525		5.9
3,490	**Lower Elevation Balancing Tier** Balance contents with a min/max release of 7.0 and 9.5 maf	4.0
3,370		0

Lake Mead

Elevation (feet)	Operation According to the Interim Guidelines	Live Storage (maf)[1]
1,220		25.9
	Flood Control Surplus or Quantified Surplus Condition Deliver > 7.5 maf	
1,200 (approx.)[2]		22.9 (approx.)[2]
	Domestic Surplus or ICS Surplus Condition Deliver > 7.5 maf	
1,145		15.9
	Normal or ICS Surplus Condition Deliver ≥ 7.5 maf	
1,075		9.4
	Shortage Condition Deliver 7.167[4] maf	
1,050		7.5
	Shortage Condition Deliver 7.083[5] maf	
1,025		5.8
1,000	**Shortage Condition** Deliver 7.0[6] maf Further measures may be undertaken[7]	4.3
895		0

Diagram not to scale

[1] Acronym for million acre-feet;
[2] This elevation is shown as approximate as it is determined each year by considering several factors including Lake Powell and Lake Mead storage, projected Upper Basin demands, and an assumed inflow; [3] Subject to April adjustments which may result in a release according to the Equalization Tier;
[4] Of which 2.48 maf is apportioned to Arizona, 4.4 maf to California, and 0.287 maf to Nevada;
[5] Of which 2.40 maf is apportioned to Arizona, 4.4 maf to California, and 0.283 maf to Nevada;
[6] Of which 2.32 maf is apportioned to Arizona, 4.4 maf to California, and 0.280 maf to Nevada;
[7] Whenever Lake Mead is below elevation 1,025 feet, the Secretary shall consider whether hydrologic conditions together with anticipated deliveries to the Lower Divison States and Mexico are likely to cause the elevation at Lake Mead to fall below 1,000 feet. Such consideration, in consultation with the Basin States, may result in the undertaking of further measures, consistent with applicable Federal law.

Figure 7 – Operational table for the 2007 Interim Guidelines for the Operations of Lake Powell and Lake Mead (Reclamation, 2021).

3.2.4.2 CRMMS-ESP Mode

CRMMS-ESP is the probabilistic mode in CRMMS and is used for probabilistic mid-term operations with a two to five-year planning window. CRMMS-ESP mode is used to provide information about risk and uncertainty to Basin stakeholders. The CRMMS-ESP mode uses an ensemble of Upper Basin hydrologic unregulated inflow forecasts (currently 30) provided by the CBRFC. The ensemble simulation provides a range of potential future reservoir conditions and operations. Unlike the 24MS, where the operations are manually input, operations in this probabilistic mode of the modeling system are simulated using ruleset logic. Additionally, the CRMMS-ESP mode results are used to initialize the CRSS model in January and April to provide a broader understanding of potential future system conditions.

3.2.5 Natural Flow Model

The Natural Flow Model (NFM) is used by Reclamation to produce/update the Natural Flow Record (Reclamation, 2020). Natural flow is the historical flow (measured flow at gages or dams) adjusted for the impact of consumptive use, system losses, and reservoir regulation. The result of this adjustment is the flow that would have been observed absent all of the anthropogenic impact. The natural flow dataset is used in the CRSS model as the main hydrologic input and resampled using the indexed sequential method to produce probabilistic results.

3.2.6 CRSS

CRSS is a probabilistic long-term planning model that is used to project Basin-wide conditions through 2060 on a monthly timestep. CRSS is used in risk analyses and policy development to analyze the impacts to Basin conditions under new or alternative Basin operating agreements. CRSS uses natural flow, which is the observed flow corrected for the effects of upstream reservoirs and depletions, as the input hydrology. Similar to CRMMS-ESP, reservoir operations in CRSS are set by a ruleset which guides the decision making for each hydrologic trace. Hydrologic traces are resampled using the Index Sequential Method (Ourda et al., 1997).

4. Results and Analysis

4.1 Evaporation Coefficients

Monthly evaporation coefficients were calculated for use in Reclamation models by taking the average of the observed monthly evaporation totals computed by the USGS. The Lake Mead evaporation coefficients are based on the average of ten years of data (March 2010-September 2020) and the Mohave coefficients are the average of six years of data (April 2013-April 2019). Results using these coefficients are referred to as “USGS Coefficients” throughout this section. These are compared to the existing coefficients, referred to as “USBR Coefficients” throughout this section.

Figure 8, Figure 9, and Table 3, below, compare the evaporation coefficients for Lake Mead and Lake Mohave between the current (USBR Coefficients) and new (USGS Coefficients) evaporation coefficients. With the new USGS coefficients Lake Mead’s total annual evaporation is 6.26 ft., which is 0.24 ft lower than the current USBR coefficients. The evaporation is higher in May, June, and October through December and lower January through April and July through September. With the new coefficients, Lake Mohave’s total annual evaporation is 5.62 ft, which is 1.69 ft lower than the current coefficients. The monthly Lake Mohave coefficients were lower for every month except for October through December. A conversion factor of 0.003281 ft/mm was used to convert between millimeters and feet in Table 3 – Comparison of USBR and USGS evaporation coefficients for Lake Mead and Lake Mohave.

Table 3 – Comparison of USBR and USGS evaporation coefficients for Lake Mead and Lake Mohave.

	Lake Mead			Lake Mohave		
Month	USGS Coefficient (mm/month)	USGS Coefficient (ft/month)	USBR Coefficient (ft/month)	USGS Coefficient (mm/month)	USGS Coefficient (ft/month)	USBR Coefficient (ft/month)
Jan	96	0.31	0.36	101	0.33	0.36
Feb	89	0.29	0.33	86	0.28	0.36
Mar	97	0.32	0.37	112	0.37	0.48
Apr	132	0.43	0.46	140	0.46	0.61
May	166	0.54	0.53	158	0.52	0.81
Jun	204	0.67	0.64	155	0.51	0.93
Jul	196	0.64	0.80	138	0.45	0.93
Aug	212	0.70	0.85	174	0.57	0.84
Sep	207	0.68	0.70	185	0.61	0.68
Oct	196	0.64	0.51	167	0.55	0.56
Nov	172	0.56	0.51	149	0.49	0.40
Dec	140	0.46	0.44	147	0.48	0.35
Total/Year	**1,907**	**6.26**	**6.50**	**1,712**	**5.62**	**7.31**

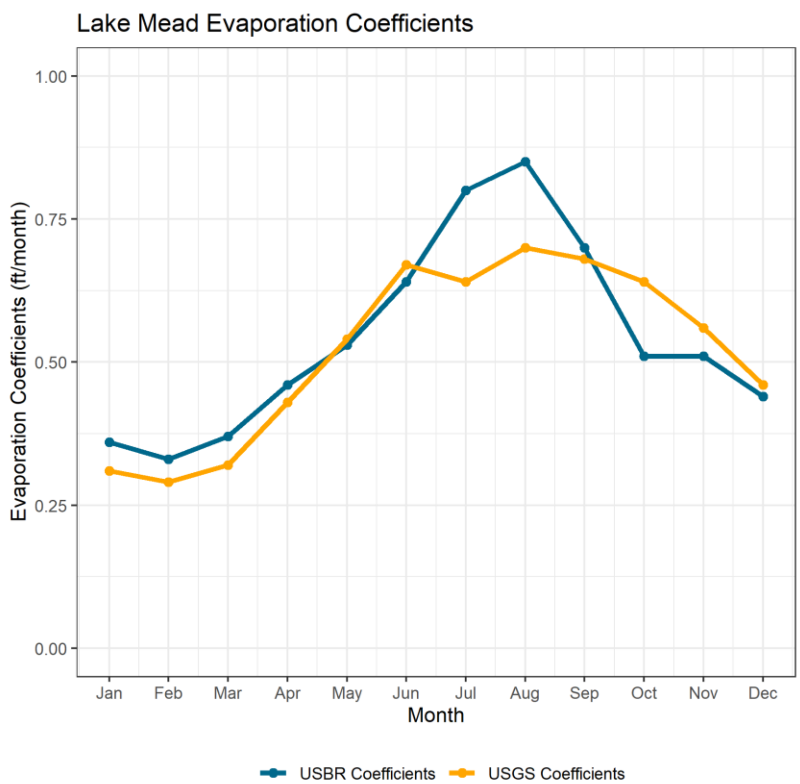

Figure 8 – Comparison of USBR and USGS evaporation coefficients at Lake Mead.

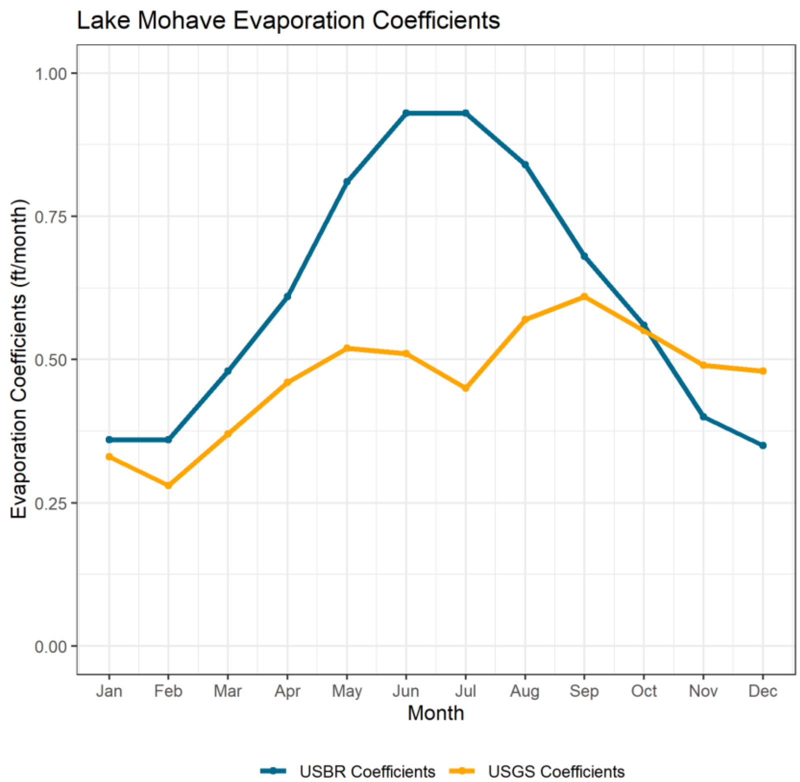

Figure 9 – Comparison of USBR and USGS evaporation coefficients at Lake Mohave.

Lake Mohave's evaporation decrease in the summer was found to be associated with the slightly shallower reservoir and the higher temperature of Davis Dam releases. The net advected heat was persistently negative since Lake Mohave's inflow consisted of the cold water originating deep in Lake Mead while Lake Mohave's outflow consisted of warmer water. This negative net advected heat resulted in less energy being available for evaporation (Earp & Moreo, 2021).

Given the length of study period, there was interest in understanding the relationship between Lake Mead evaporation and air temperature. To this end, evaporation was plotted against the measured environmental variables and regressions were developed. To evaluate the relationship between evaporation and the atmospheric variables, the coefficient of determination (R^2) is used as a measure of the goodness of fit between two independent variables. An R^2 value of 1 denotes a perfect fit and a value of zero denotes no relationship. Although there is a slight relationship between evaporation and air temperature, the R^2 value of 0.16 indicates a weak relationship. Regressions were also developed relating evaporation to windspeed and evaporation to relative humidity. These regressions had R^2 values of 0.39 and 0.21, respectively. Not surprisingly, evaporation had a stronger relationship to wind speed and relative humidity. The plots with these relationships are shown in Figure 10.

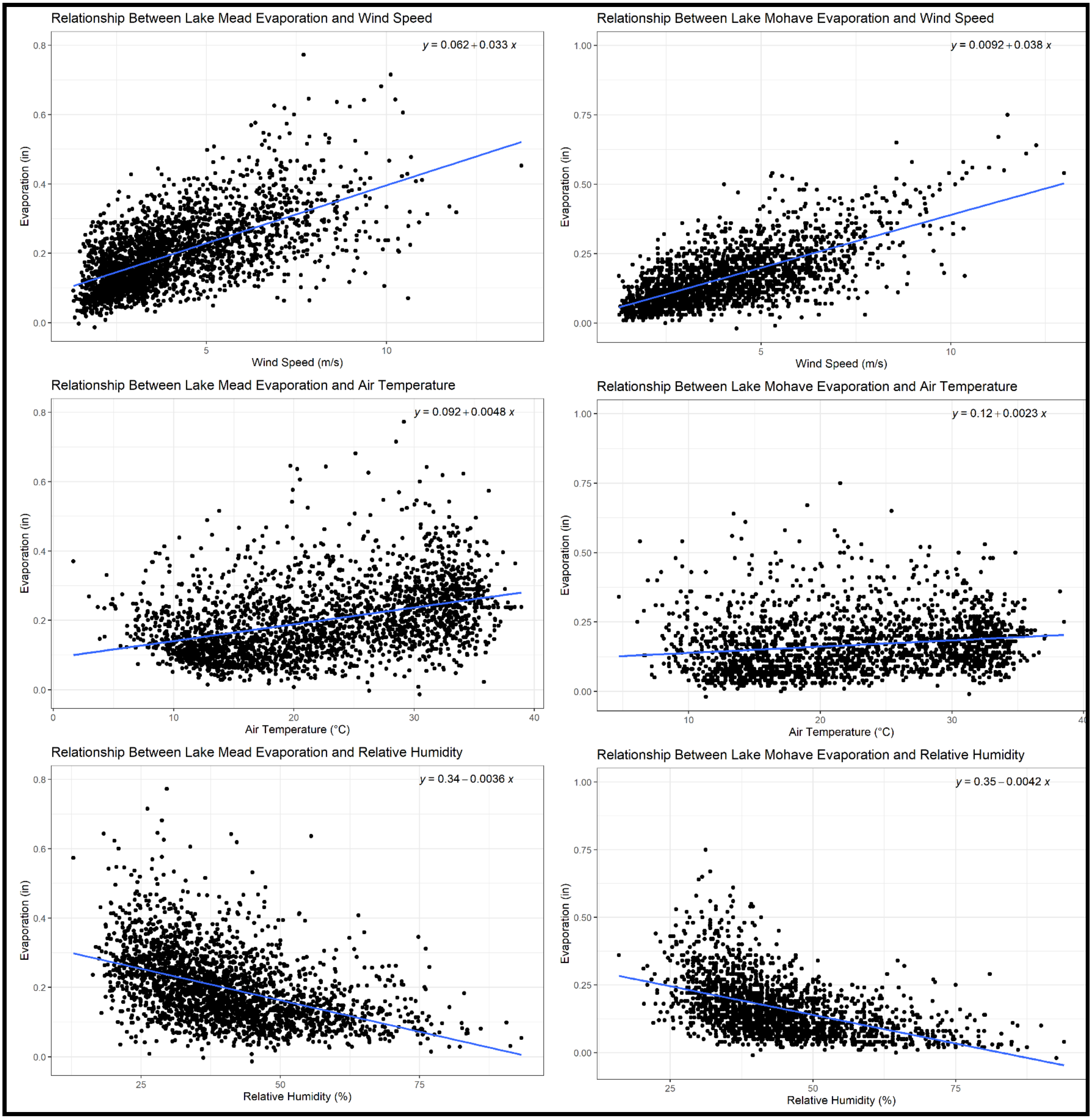

Figure 10 – Environmental Factors for Lake Mead and Lake Mohave Evaporation.

4.2 Gain/Loss Model

The Gain/Loss model was rerun with the USGS evaporation coefficients for the period of 1976 to 2019 to ensure that the mass balance was properly recomputed for use in projecting intervening flows in the sensitivity runs in CRMMS, 24MS and ESP modes. The model run resulted in projected CY and WY intervening flow totals that are lower in the Glen Canyon to Lake Mead reach and higher losses in the Lake Mead to Lake Mohave reach. Intervening flows are lower every month apart from May, June, and October in the reach from Glen Canyon Dam to Lake Mead, due to lower evaporative losses in all but the three months. Intervening flows are lower at Lake Mohave every month except for November and December. These changes in the gain/loss totals illustrate how the mass balance computations compensate for lower net annual evaporation volumes at both reservoirs. Figure 11 and Figure 12, below, compare the intervening flow and evaporation at Lake Mead and Lake Mohave between the USBR and USGS evaporation coefficients.

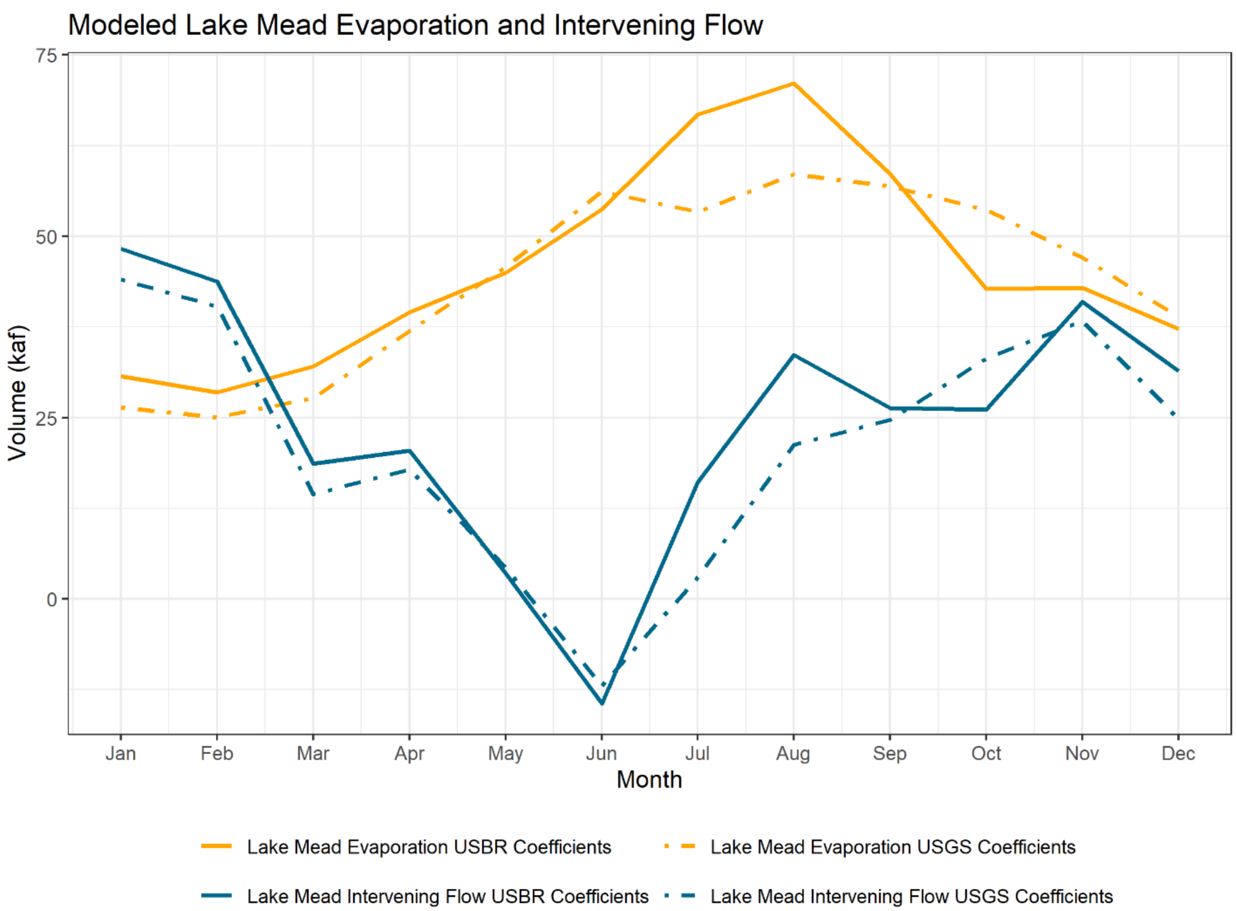

Figure 11 – Comparison of Lake Mead evaporation and intervening flow between the USBR and USGS evaporation coefficients.

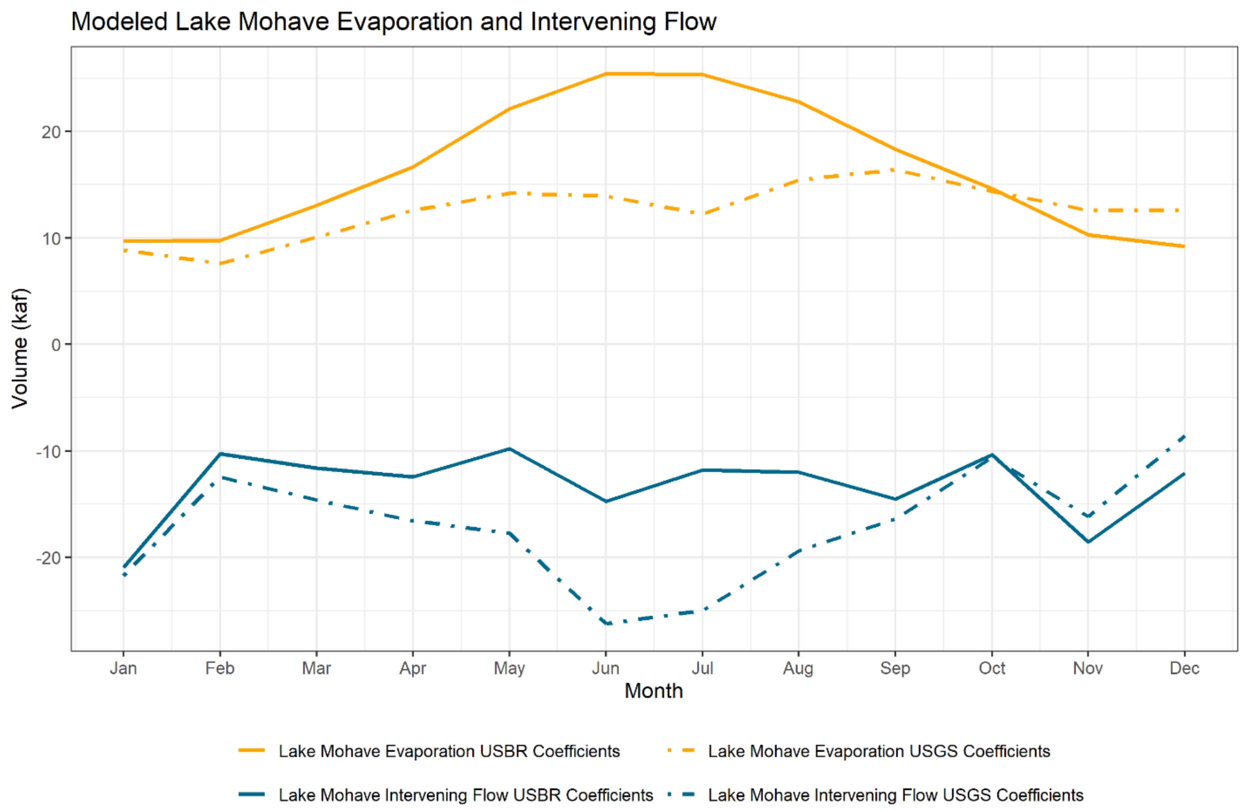

Figure 12 – Comparison of Lake Mohave evaporation and intervening flow between the USBR and USGS evaporation coefficients.

The improvement of the evaporation seasonality also benefits in capturing a more accurate representation of seasonal intervening flows. Since a five-year average is currently being used to project future intervening flow in CRMMS: 24MS mode, improvements in the intervening flow seasonality is expected to benefit the 24MS during the decision-making months of April and August.

4.3 24-Month Study

The 24MS uses an average of the previous five years of observed monthly intervening flow, simulated by the Gain/Loss model, to project future intervening flow. The five-year average between the USGS Grand Canyon Gage to Lake Mead and from Lake Mead to Lake Mohave were recreated for the 24MS sensitivity runs. The previous five April and August 24MS runs were re-simulated with the new coefficients.

In the August 24MS runs, the modeled August through December evaporation volume is slightly higher at both reservoirs resulting in lower outflows being simulated for the CY. In the April 24MS runs, the net evaporation volume from April through September is lower and therefore the WY outflows are lower. These model runs were chosen because they are the Lake Powell and Lake Mead tier determination studies and provide insight on whether the changes in the volume and temporal distribution of evaporation would have had an impact on any tier determinations. The decision-making horizons are illustrated in Figure 13.

Net outflows from Lake Mead are lower when there is less evaporative loss from Lake Mohave and higher when there is more Mohave evaporative loss. Since Lake Mohave is operated on a guide curve, releases from Hoover Dam are adjusted by the model to make up for the increase/decrease in evaporation at Lake Mohave. In all runs the average CY outflow is 4 af lower in the sensitivity runs as shown in Table 4 and Table 5. The average CY difference in the outyear's (second year in the simulation run) Lake Mead outflow volume is 179 af. These are very minor changes when considering that the sensitivity run for CY Lake Mead outflows from the outyear of both April and August studies range from 8.61 to 9.25 maf.

Changes to modeled CY evaporation volumes in the 24MS were balanced out due to the inverse relationship between intervening flow and evaporation (as seen in Equations 1 and 2) and as calculated by the gain/loss model. Differences in monthly intervening flow in the reach from Glen Canyon to Hoover Dam range from -19 to 14 kaf with an average CY volume of -3 kaf and a WY volume of -2 kaf. In the outyear, the average difference in CY intervening flow total is -30 kaf and -27 kaf in the next WY.

Monthly differences in evaporation volumes vary from -14 to 13 kaf with an average first year CY difference of -3 kaf in August runs and WY difference of -1 kaf in April runs. In the outyear, CY changes in evaporation average -20 kaf and WY evaporation changes average -21 kaf.

Month	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
April 24MS	**Historical**						**Projected**					**Decision Point**	**Projected**		
August 24MS	**Historical**										**Projected**				**Decision Point**

Figure 13 – 24 Month Study decision making horizons.

April 24MS EOWY elevation differences at Lake Mead varied from -0.07 to 0.01 ft. EOCY Lake Mead elevation projections from the August 24MS varied from -0.04 to 0.10 ft. The difference in elevation projections is due to the temporal distribution of evaporation and intervening flow volumes and surface area. Lake Mohave elevations do not vary after the first out-month because they are governed by an elevation guide-curve. None of the 24MS sensitivity runs resulted in a change to operational tiers (as previously shown in Figure 7) since none of the trial studies were within a tenth of a foot from a different operating tier. Table 4 and Table 5, below, summarize the sensitivity runs for the April and August 24MS and how close each run was to critical elevation tiers.

Table 4 – April 24MS EOWY elevation projections from official and sensitivity analysis runs for Lake Mead.

Year	Official Run EOWY Elevation Projection (ft)	Sensitivity Run EOWY Elevation Projection (ft)	Difference	Official Run Elevation Relative to Critical Elevation Tiers (ft)	Sensitivity Run Elevation Relative to Critical Elevation Tiers (ft)
2016	1,073.69	1,073.62	-0.07	-1.31	-1.38
2017	1,080.87	1,080.85	-0.02	5.87	5.85
2018	1,078.94	1,078.93	-0.01	3.94	3.93
2019	1,081.60	1,081.60	0.00	6.60	6.60
2020	1,084.17	1,084.18	0.01	9.17	9.18

Table 5 – August 24MS EOCY elevation projections from the official and sensitivity analysis runs for Lake Mead.

Year	Official Run EOCY Elevation Projection (ft)	Sensitivity Run EOCY Elevation Projection (ft)	Difference	Official Run Elevation Relative to Critical Elevation Tiers (ft)	Sensitivity Run Elevation Relative to Critical Elevation Tiers (ft)
2016	1,078.93	1,079.03	0.10	3.93	4.03
2017	1,083.46	1,083.46	0.01	8.46	8.46
2018	1,079.50	1,079.50	0.00	4.50	4.50
2019	1,089.40	1,089.36	-0.04	14.40	14.36
2020	1,085.28	1,085.26	-0.02	10.28	10.26

4.4 CRMMS-ESP

The results discussed in this section discuss changes to operating tiers as shown in Figure 7. The August 2020 and January 2021 CRMMS-ESP runs used the 1976 to 2015 reconstructed Gain/Loss results for Glen Canyon Dam to Hoover Dam and Lake Mead to Lake Mohave reaches and the USGS evaporation coefficients for both reservoirs. In the August 2020 run, one trace switched from the Normal or ICS Surplus Lake Mead condition into a Level 1 Shortage in the final year of the run. In the second year of the run, one trace switched from a >8.23 maf Powell release to an 8.23 maf Powell release followed by a switch from an 8.23 maf Powell release to a >8.23 maf Powell release in the following year. In the final year of the run, one trace switched from a Lake Powell release of 7.48 maf to an 8.23 maf Powell release (Figure 14 through Figure 16 and Table 6).

In the January 2021 run, one trace switched from a Lake Powell 8.23 maf release to a >8.23 maf release in the first year and one trace switched from Normal or ICS Surplus condition to a Level 1 Shortage in the final year (Figure 17 through Figure 19, Table 7). These changes are due to slight differences in Lake Mead elevations that were very close to operational tiers to begin with. Many of the tier changes in the outyears are due to the effects of the changes in operating tiers in earlier years.

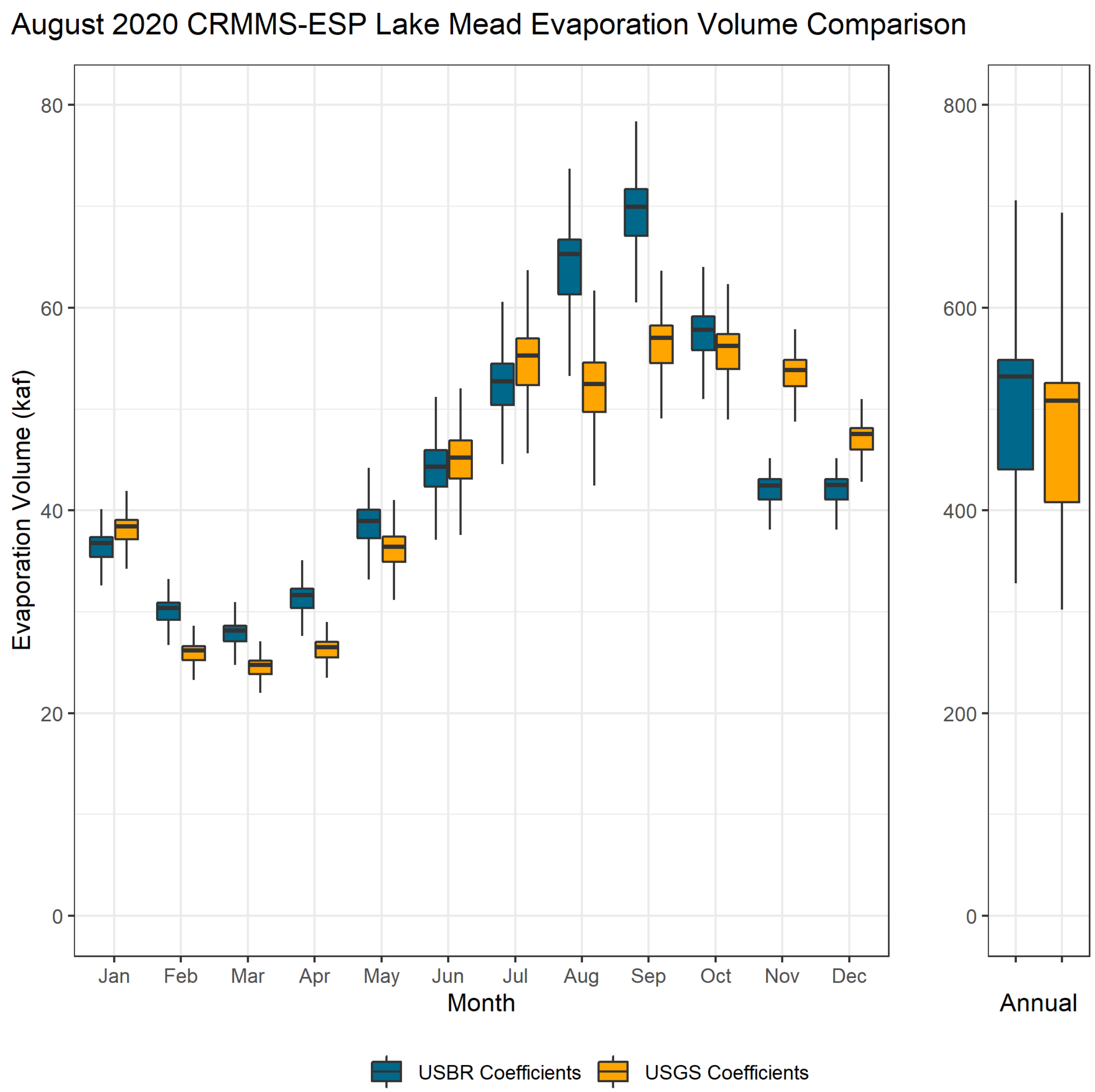

Figure 14 – Monthly and annual evaporation from Lake Mead in the August 2020 CRMMS-ESP run.

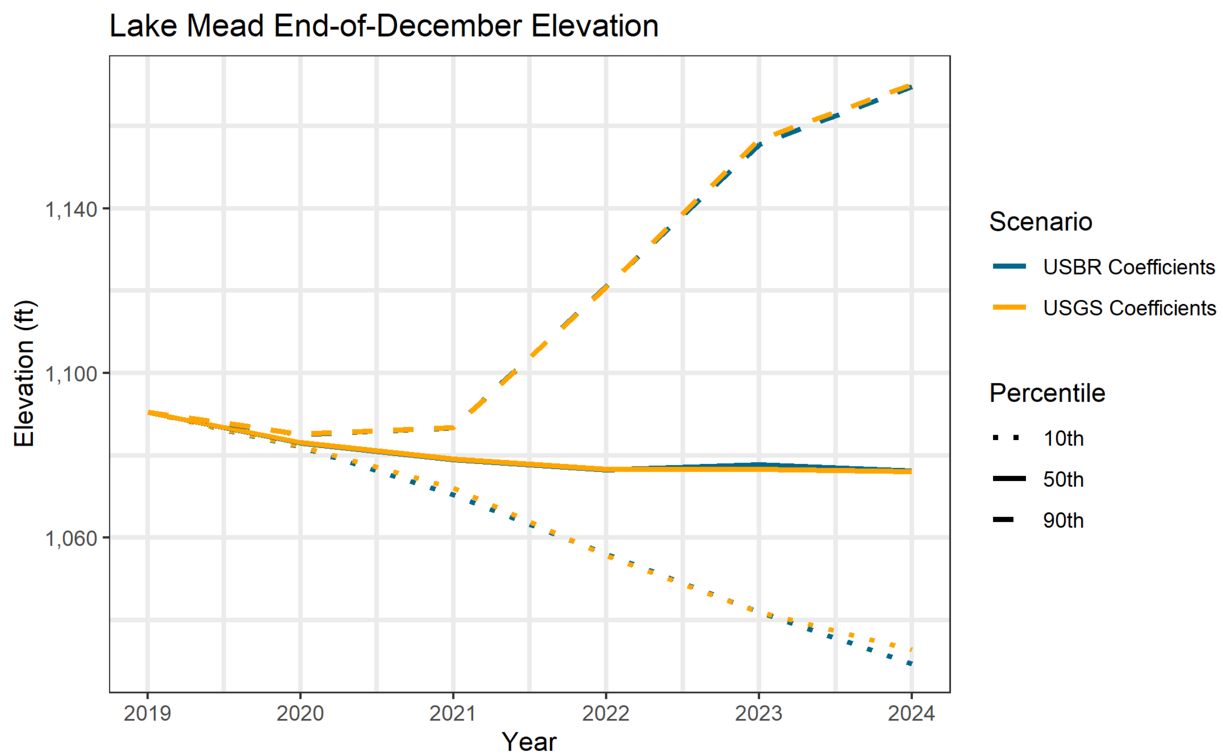

Figure 15 – Comparison of the projected 10th, 90th, and 50th percentile of EOCY Lake Mead elevations from the August 2020 CRMMS-ESP scenarios.

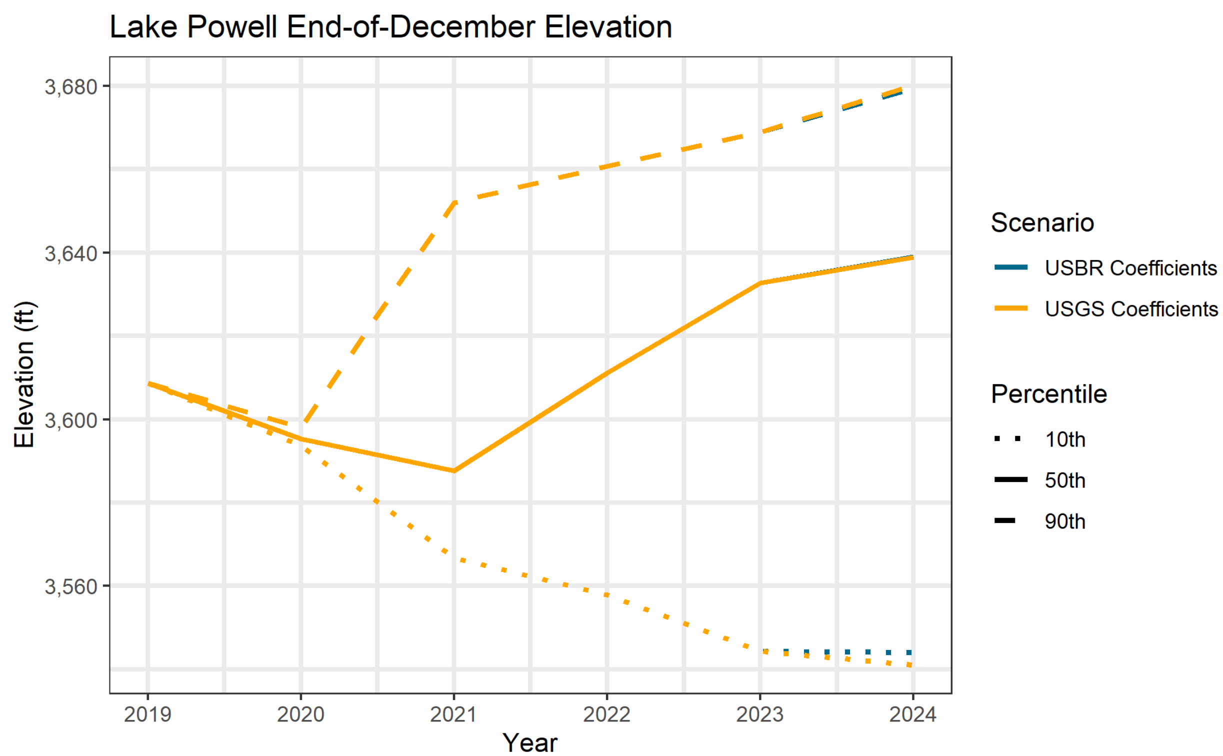

Figure 16 – Comparison of the projected 10th, 90th, and 50th percentile of EOCY Lake Powell elevations from the August 2020 CRMMS-ESP scenarios.

Table 6 – Comparison of percent traces in any operating condition from the August 2020 CRMMS-ESP scenarios.

Event or System Condition	2021	2022	2023	2024	2025
Lake Powell					
Equalization - annual release > 8.23 maf	0	0	0	0	0
Equalization - annual release = 8.23 maf	0	0	0	0	0
Upper Elevation Balancing - annual release > 8.23 maf	3	0	0	0	0
Upper Elevation Balancing - annual release = 8.23 maf	-3	0	0	0	0
Upper Elevation Balancing - annual release < 8.23 maf	0	0	0	0	0
Mid-Elevation Balancing - annual release = 8.23 maf	0	0	0	0	0
Mid-Elevation Balancing - annual release = 7.48 maf	0	0	0	0	0
Lake Mead					
Shortage - 1st level (Mead<= 1,075 and >= 1,050)	0	0	0	0	3
Shortage - 2nd level (Mead<1,050 and >= 1,025)	0	0	0	0	0
Shortage - 3rd level (Mead< 1,025)	0	0	0	0	0
Surplus Condition - any amount (Mead >= 1,145 ft)	0	0	0	0	0
Normal or ICS Surplus Condition	0	0	0	0	-3

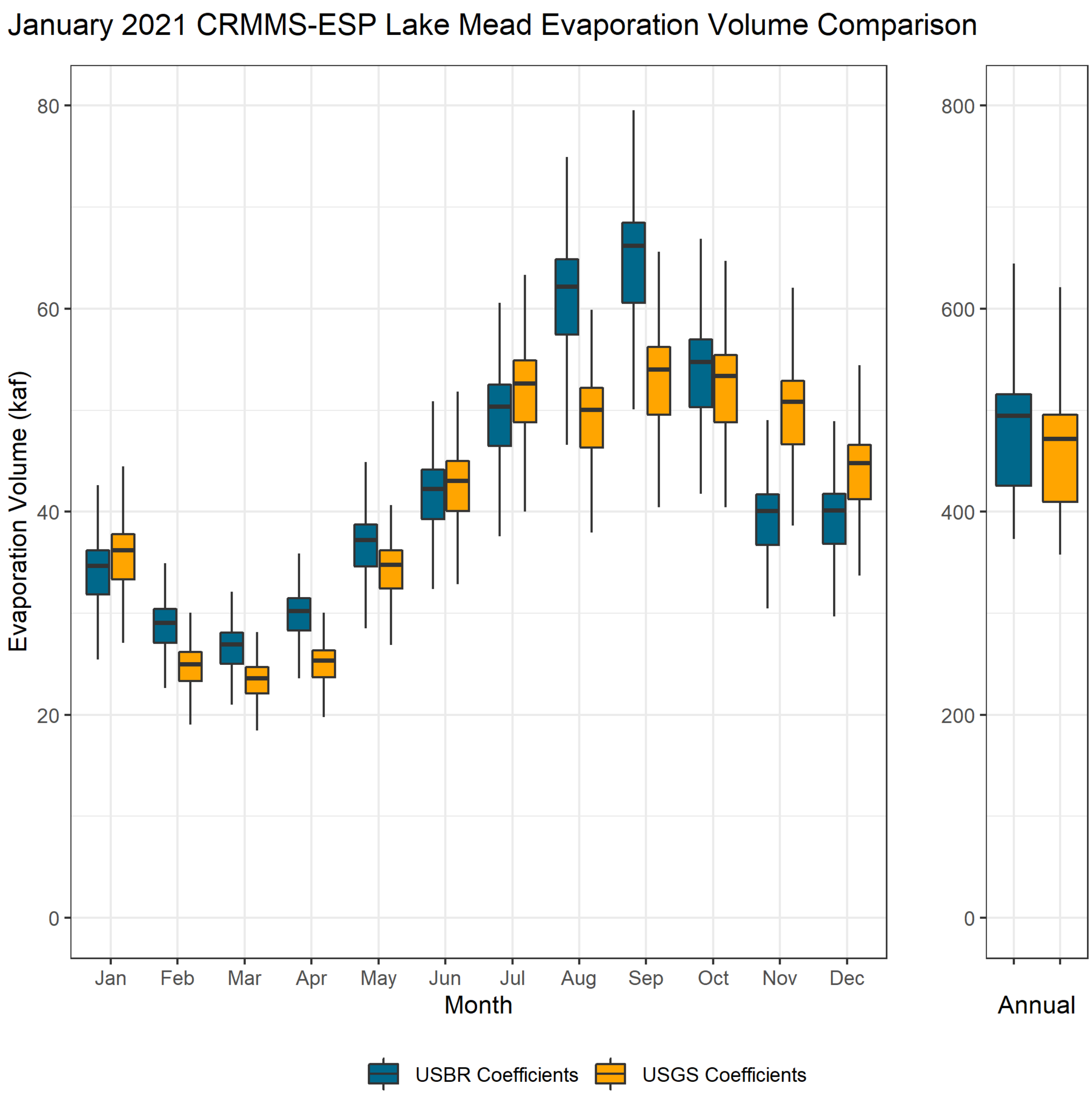

Figure 17 – Monthly and annual evaporation from Lake Mead in the January 2021 CRMMS-ESP run.

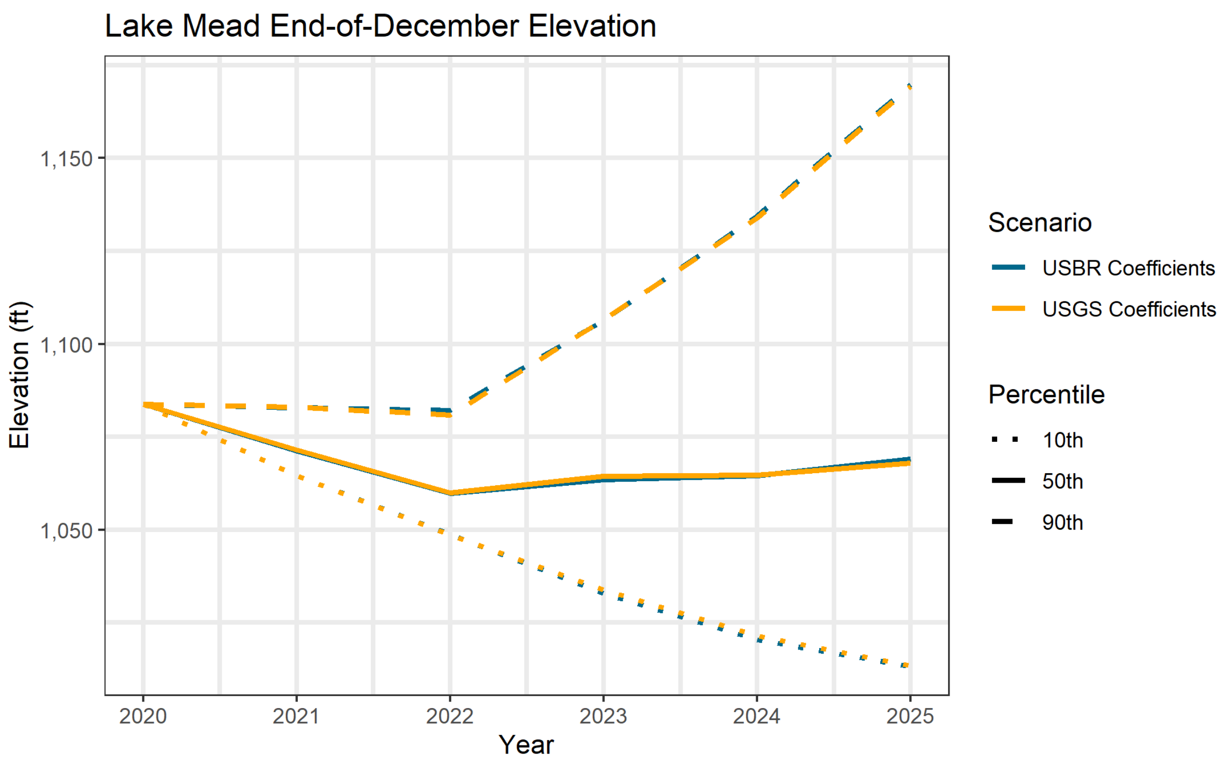

Figure 18 – Comparison of the projected 10th, 90th, and 50th percentile of EOCY Lake Mead elevations from the January 2021 CRMSS-ESP scenarios.

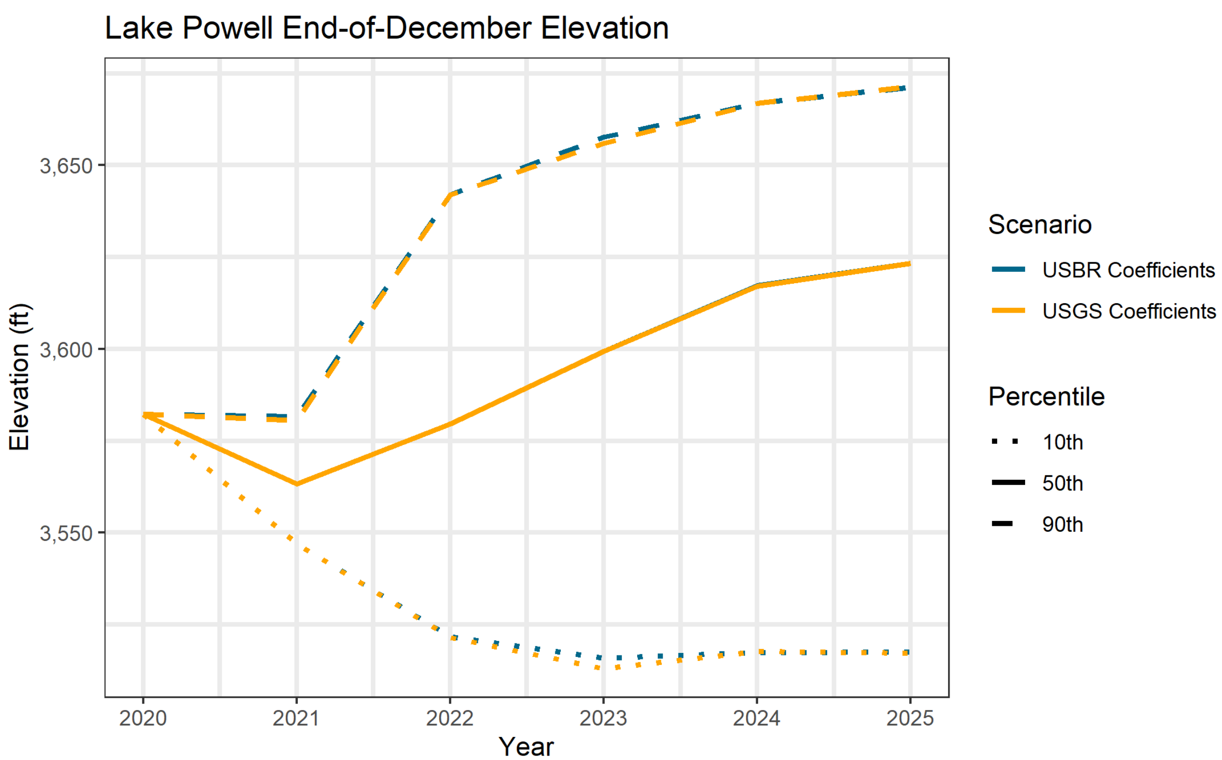

Figure 19 – Comparison of the projected 10th, 90th, and 50th percentile of EOCY Lake Powell elevations from the January 2021 CRMSS-ESP scenarios.

Table 7 – Comparison of percent traces in any operating condition from the January 2021 CRMMS-ESP scenarios.

Event or System Condition	2021	2022	2023	2024	2025
Lake Powell					
Equalization - annual release > 8.23 maf	0	0	0	0	0
Equalization - annual release = 8.23 maf	0	0	0	0	0
Upper Elevation Balancing - annual release > 8.23 maf	3	0	0	0	0
Upper Elevation Balancing - annual release = 8.23 maf	-3	0	0	0	0
Upper Elevation Balancing - annual release < 8.23 maf	0	0	0	0	0
Mid-Elevation Balancing - annual release = 8.23 maf	0	0	0	0	0
Mid-Elevation Balancing - annual release = 7.48 maf	0	0	0	0	0
Lake Mead					
Shortage - 1st level (Mead<= 1,075 and >= 1,050)	0	0	0	0	3
Shortage - 2nd level (Mead<1,050 and >= 1,025)	0	0	0	0	0
Shortage - 3rd level (Mead< 1,025)	0	0	0	0	0
Surplus Condition - any amount (Mead >= 1,145 ft)	0	0	0	0	0
Normal or ICS Surplus Condition	0	0	0	0	-3

4.5 Daily Operations Model

The monthly evaporation coefficients were incorporated for Lake Mead and Lake Mohave in the Daily Operations model. The model was run on July 20, 2021 and ran through August 31, 2021. On a daily basis, changes in Lake Mead's elevation varied from -0.02 to 0.00 ft. The cumulative evaporation for Lake Mead for the month of August is projected to be 54.92 kaf which is 11.77 kaf lower than the projected volume in the baseline Daily Operations model. This difference is accounted for in adjustments to the side inflows. Based on these small differences no daily operational changes would have been warranted.

4.6 Natural Flow Model

Reclamation's NFM was also updated with the new USGS evaporation coefficients. A summary of the change in the annual naturalized intervening flows for the USBR and USGS coefficients are shown in Figure 20.

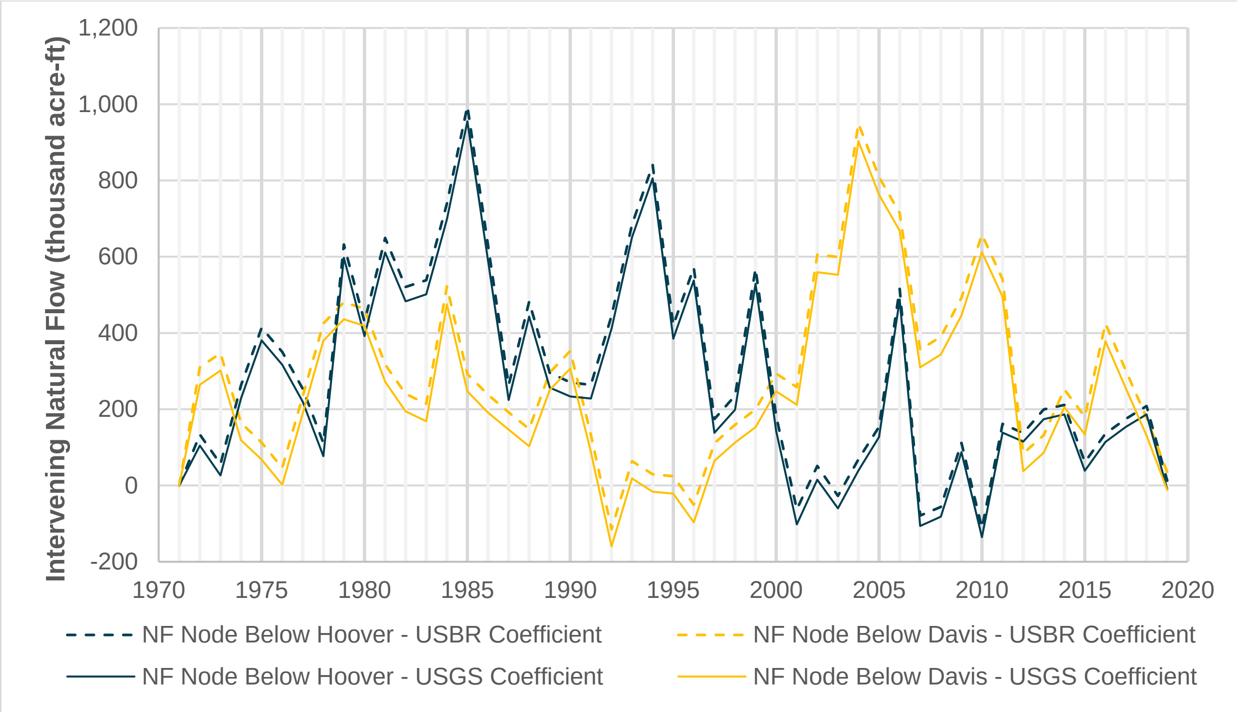

Figure 20 - Comparison of Annual Naturalized Intervening Flow for USGS and USBR Coefficients.

On average, between 1971 and 2019, there is a decrease of 32 kaf of naturalized intervening flow at the NFM's node below Hoover Dam (Lake Mead) and a decrease of 46 kaf of naturalized intervening flow at the NFM's node below Davis Dam (Lake Mohave). The same mass balance mechanism that applies to the Gain/Loss model applies to the NFM. Since less evaporation is occurring in the reservoirs, less naturalized intervening flow is modeled in the system mass balance.

4.7 CRSS

The sensitivity analysis in this technical memorandum uses one scenario developed from the observed natural flow record, computed with Reclamation's NFM (Reclamation, 2020), as the future hydrology. The "full hydrology" resamples the full hydrologic record (currently 1906-2018) using the Index Sequential Method (Ouarda et al. 1997) resulting in 113 hydrologic inflow traces[1]. Similar to CRMMS-ESP, operations in CRSS are simulated with ruleset logic. CRSS is used to make projections in January, April, and August and as necessary for other processes or analyses. For this technical memorandum, the January 2021 official model was used to project system conditions from 2022 – 2060 using both the full and stress test hydrology. CRSS was initialized with EOCY 2021 conditions from CRMMS-ESP using the "most probable" January 2021 inflow forecast. The analysis uses the 2016 Upper Colorado River Commission demand schedule for the Upper Division States' future water demands. Future water demands for the Lower Division States, during normal conditions, are according to the schedules provided for the 2007 final environmental impact statement for the Guidelines modeling with updates to Nevada's demands dated May 2019.

The CRMMS-ESP section shows that the changes in evaporation and reservoir elevation/operating tiers are minimal over a five-year period. However, small annual changes in the total reservoir evaporation can

[1] Other hydrology scenarios exist, including the "stress test" hydrology, which is more representative of the ongoing drought than the full historical record. However, this analysis is focused on the comparison of evaporation coefficients, rather than a comparison of projections using different hydrology scenarios. Additionally, while the overall magnitudes of evaporation are lower when using the stress test hydrology, due to lower reservoir elevations, the relative difference between the different evaporation coefficients is similar.

compound over the years and may affect reservoir elevation and operating condition beyond five years. To understand the effects beyond five years, CRSS was used to simulate system conditions from 2022 through 2060.

The simulated monthly and annual Lake Mead evaporation volumes are shown in Figure 21. The USGS evaporation coefficients have a different monthly pattern than the currently used USBR coefficients. The new coefficients show lower evaporation volumes in the winter and summer and higher volumes in the spring and fall. This difference is most apparent in July and August when the median monthly evaporation volume with the USGS evaporation coefficients is over 11 kaf lower than with the USBR coefficients. The variable changes to the monthly evaporation coefficients result in a minimal change to the annual evaporation volume. The annual evaporation volume with the new USGS evaporation coefficients is slightly lower than the USBR coefficients, with a median decrease of only 15.2 kaf annually, which is a median decrease of 3.0%.

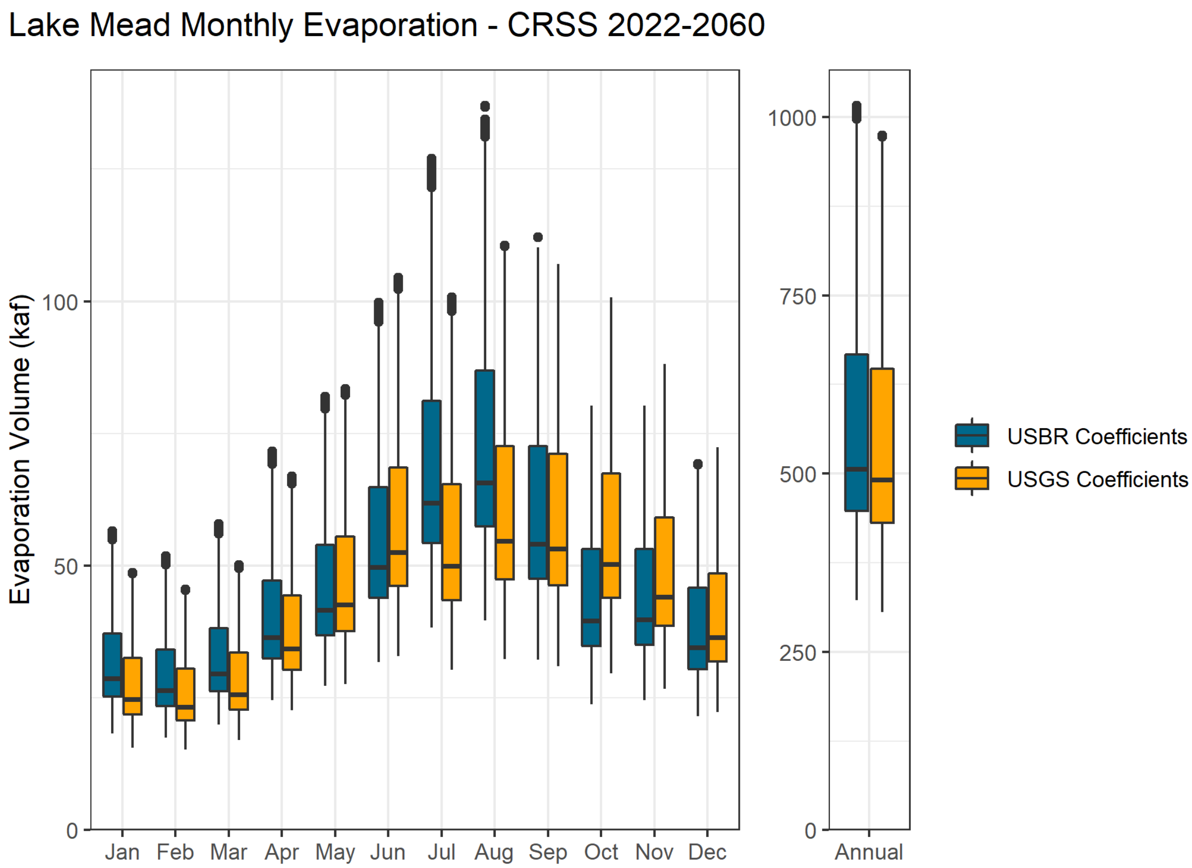

Figure 21 – Monthly and annual evaporation from Lake Mead from the January 2021 CRSS run from 2022 through 2060 with the full natural flow record hydrology (1906-2018).

For Lake Mohave, the annual evaporation volume also decreases, but by a larger volume than at Lake Mead. Since Lake Mohave is operated to meet guide-curve elevations, there is no variability in the monthly and annual evaporation. Table 8 summarizes the Lake Mohave evaporation volumes from the two sets of coefficients. The annual volume with the USGS coefficients results in a decrease of 46.3 kaf annual, a decrease of 23.5%.

Table 8 – Lake Mohave monthly and annual projected evaporation volumes from the January 2021 CRSS run from 2022 through 2060 with the full natural flow record hydrology (1906-2018).

Month	USGS Coefficient Evaporation Volume (kaf)	USBR Coefficient Evaporation Volume (kaf)	Difference in Evaporation Volume (kaf)
January	8.8	9.6	-0.8
February	7.6	9.7	-2.1
March	10.1	13.1	-3
April	12.6	16.7	-4.1
May	14.2	22.1	-7.9
June	13.9	25.4	-11.5
July	12.3	25.3	-13
August	15.5	22.8	-7.3
September	16.4	18.3	-1.9
October	14.4	14.6	-0.2
November	12.6	10.3	2.3
December	12.6	9.2	3.4
Total	**150.9**	**197.2**	**-46.3**

The effect of these reductions in evaporation on Lake Mead and Lake Powell's projected EOCY pool elevations from 2022 through 2060 are shown in Figure 22 – Comparison of the projected 10th, 50th, and 90th percentile of EOCY Lake Mead elevations from the January 2021 CRSS run from 2022 through 2060 with the full natural flow record hydrology (1906-2018). and Figure 23, respectively. Lake Mead's median pool elevation is slightly higher with the USGS coefficients (approximately 1.3 ft higher for 2045-2060) compared to the USBR coefficients as expected due to decreases in evaporation volumes at Lake Mead and Lake Mohave. The 10^{th} percentile pool elevation is slightly higher with the USGS coefficients; however, the 90^{th} percentiles does not show much change. Since the operations of Lakes Powell and Mead are coordinated, changes in the water balance at Lake Mead will affect the pool elevation at Lake Powell. Though changes to Lake Powell pool elevation are visible in Figure 23, they are very small. The Lake Powell projections do not have as distinct of a trend as Lake Mead with some year's pool elevations being slightly higher and lower with the USGS coefficients, though the elevations are on average higher with the USGS coefficients (approximately 0.7 ft higher for 2045-2060).

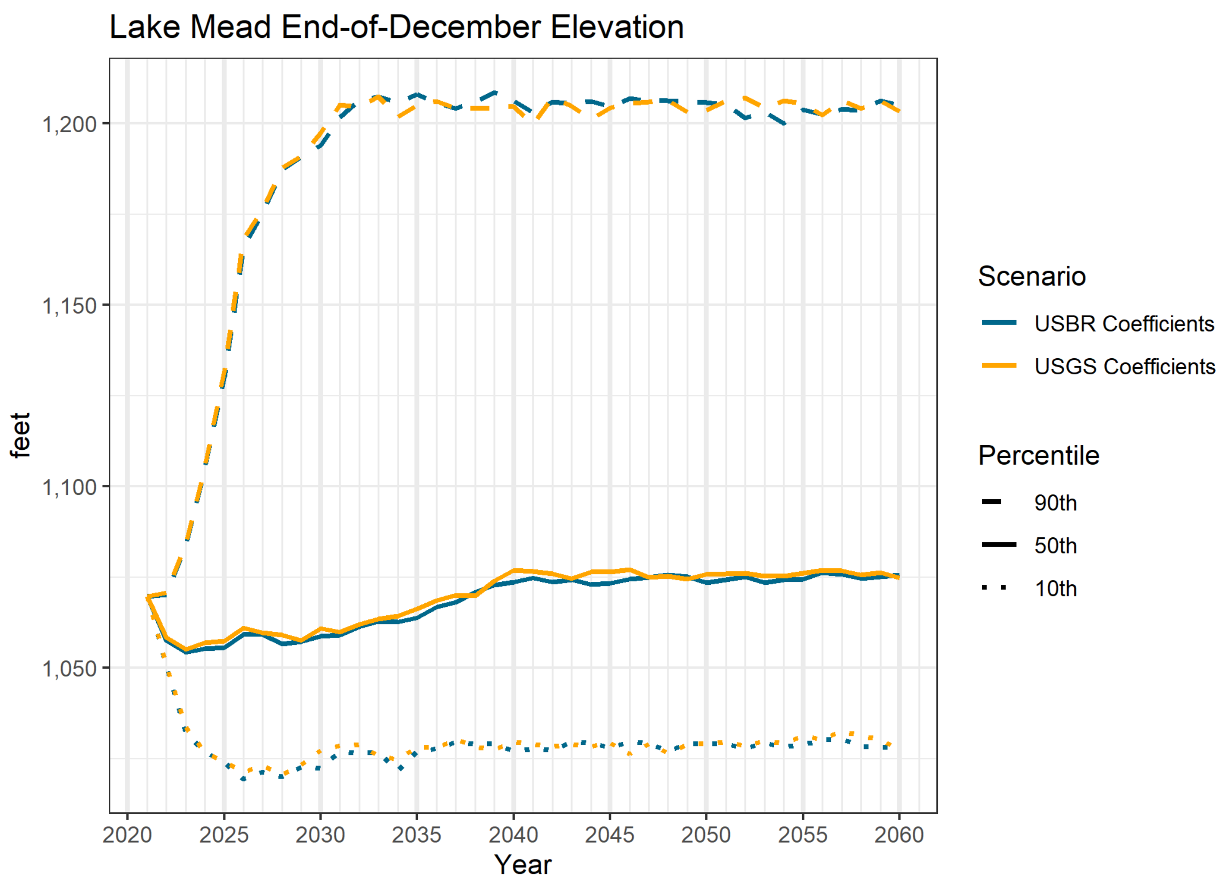

Figure 22 – Comparison of the projected 10th, 50th, and 90th percentile of EOCY Lake Mead elevations from the January 2021 CRSS run from 2022 through 2060 with the full natural flow record hydrology (1906-2018).

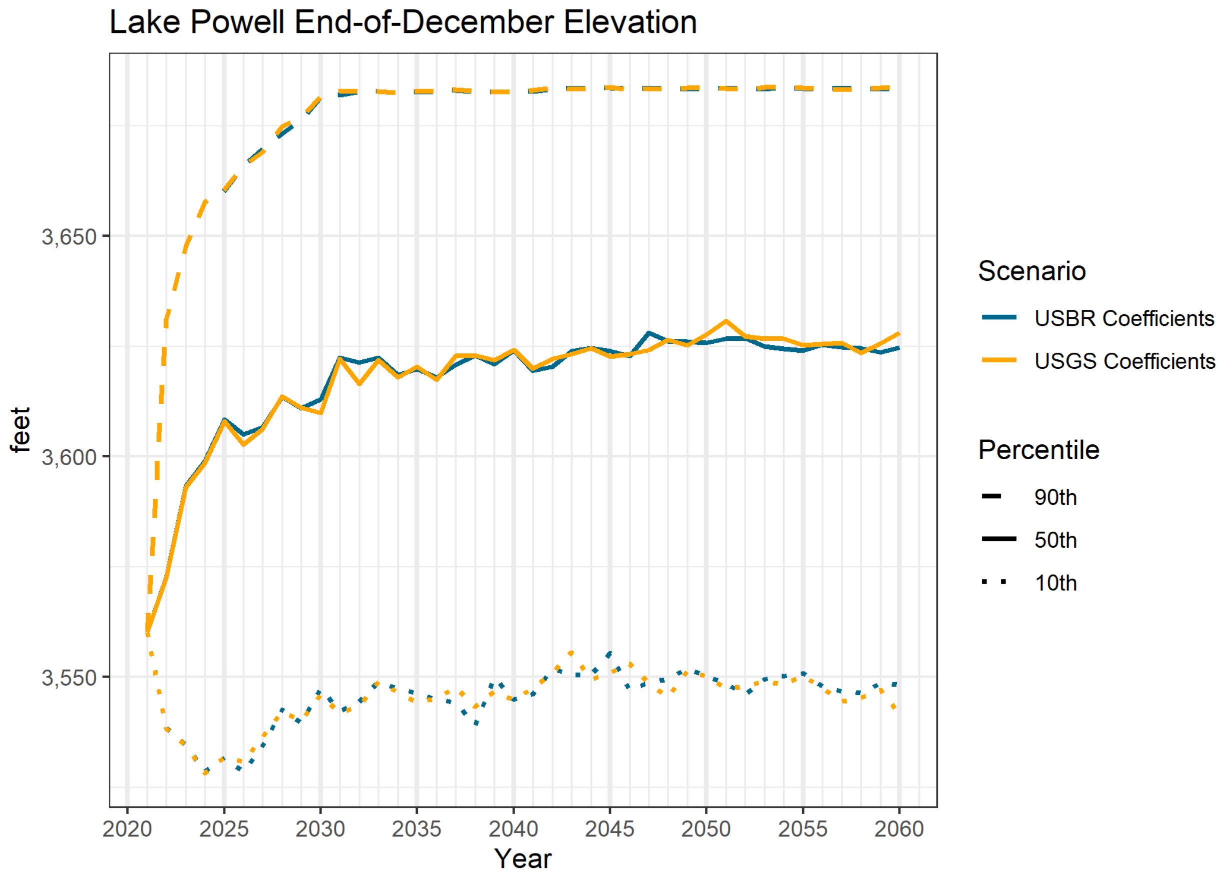

Figure 23 – Comparison of the projected 10th, 50th, and 90th percentile of EOCY Lake Powell elevations from the January 2021 CRSS run from 2022 through 2060 with the full natural flow record hydrology (1906-2018).

Even with small changes in elevation it is possible that the operating tier at either Lake Powell or Lake Mead can change due the compounding effects of operations over time. Figure 24 is an example of changes in operating conditions using the percent of traces that project the Lower Basin to be in shortage conditions. Consistent with the changes in Lake Mead elevations, projections beyond 2030 with the USGS coefficients show slightly lower percentages of Lower Basin shortage (an average of 4.9% lower for 2045-2060) compared to the USBR coefficients through the end of the simulation period.

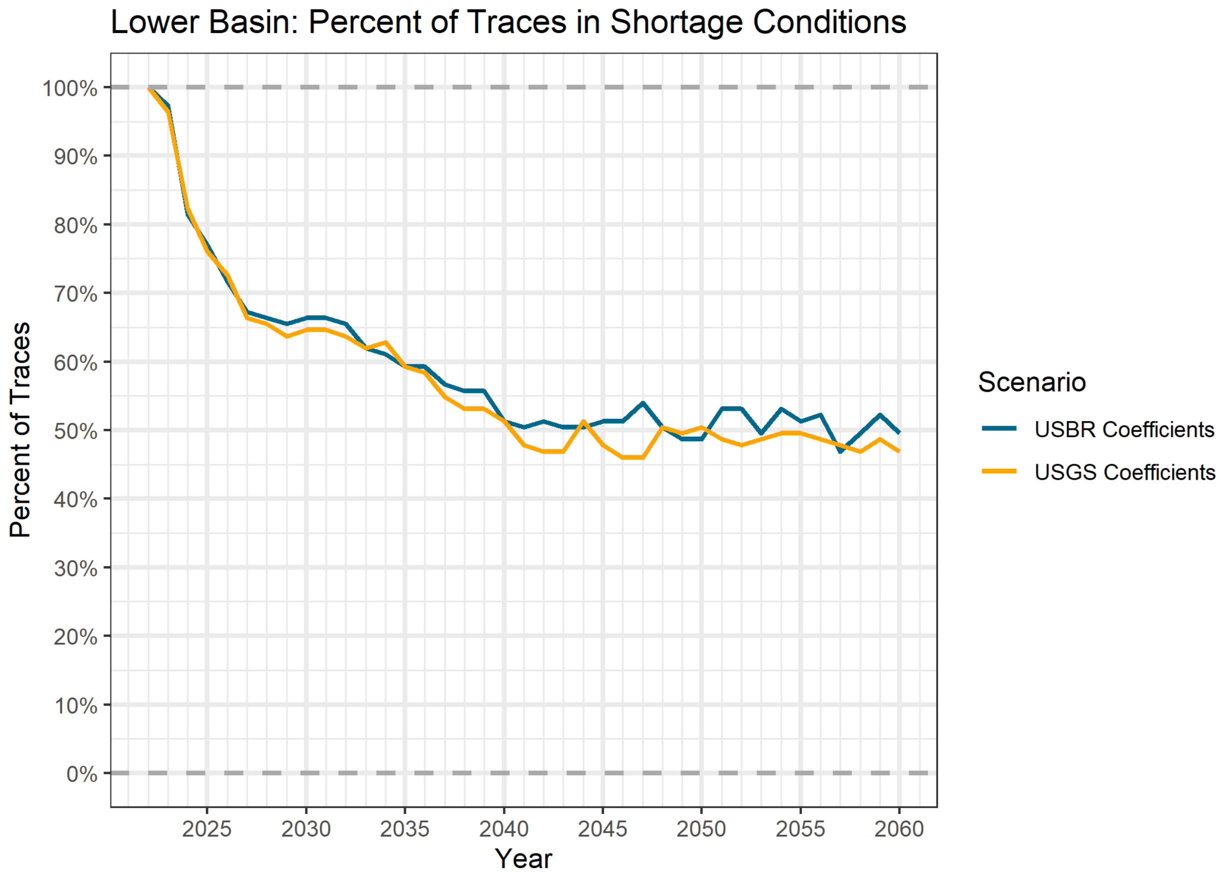

Figure 24 – Comparison of the precent of traces in Lower Basin shortage from the January 2021 CRSS run from 2022 through 2060 with the full natural flow record hydrology (1906-2018).

5. Conclusions

The Eddy-Covariance evaporation data collected over the period of 2013 to 2017 at Lake Mohave and 2010 to 2020 at Lake Mead determined that evaporation was being over-projected for both Lake Mohave and Lake Mead in Reclamation's Basin-wide models, especially in the summer months. Although peak radiation occurs in the summer and spring, lower evaporation was measured because the net radiation is converted to stored heat during the spring and summer. The fall and winter evaporation rates do not decline as much as originally presumed because despite the drop in net radiation, the stored energy from the spring and summer heat is released during these months.

Overall, the differences between the previous set of static monthly evaporation coefficients and those developed in this study minimally impact elevation projections for Lake Mead and Lake Mohave in all sensitivity model runs. Use of the coefficients developed in this study would have resulted in no operational or release tier changes in any of the April and August 24MS model runs from 2016 to 2020; additionally, there were very few differences in tier determinations in the CRMMS-ESP runs and CRSS showed only small differences in the chances of shortage simulated through 2060. In CRMMS-ESP, the differences in tier determination only occur in simulations for which Lake Mead's projected EOCY and EOWY elevations are within hundredths of a foot of an operational tier and when these changes in operating tier are perpetuated in the outyears for the specific hydrologic trace. The CRSS projections show that even small changes can compound over time and result in different operating tiers; however, this only happens in a relatively small (~5%) number of projections.

Capturing a more accurate temporal distribution and evaporation magnitude at Lake Mead and Lake Mohave is critical in projecting accurate intervening flow for the Lower Basin. Accurate intervening flow projections are especially important during operational decision-making months which may impact water releases from Lake Powell or shortage determinations for the Lower Basin states. The results of this technical memorandum support the implementation of new evaporation coefficients for Reclamation's LCBR models. The outcomes of this study provide stakeholders with the knowledge that the best available information is being used appropriately to project annual operating conditions at Lake Mead and Lake Powell. Reclamation will continue to monitor real-time evaporation at Lake Mead to better understand how evaporation is impacted by Lake Mead's declining elevation and by regional climate change impacts. The evaporation coefficients will be revisited and adjusted in the future to incorporate the most recent trends.

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