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Evaluating the Accuracy of Reclamation's 24-Month Study Lake Powell Projections

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An analysis of the accuracy and bias of the 24-Month Study projections for future Lake Powell inflows and elevations in the midst of ongoing aridification of the Colorado River basin

Point Summary:

1. The '24 Month Study,' the Bureau of Reclamation's monthly-issued forecasting report for elevations at Lake Powell and other reservoirs, relies on two very different estimation techniques that are applied to the first year of the forecast window and to the second year. **Projections for reservoir elevations during the next few months are based on predictions of reservoir inflow using a widely accepted watershed hydrologic model run by the Colorado Basin River Forecast Center.** The input data for that model are observed snowpack in the watershed, soil moisture, and anticipated precipitation and temperature. **Projections for reservoir elevations beyond the immediately proximate winter, a year or more in the future ('second year projections'), are based on statistical probabilities calculated using analyses of past inflows during a 30-year reference period.** Reclamation issues three different forecasts using three different inflows called Maximum Probable, Most Probable and Minimum Probable.

2. Analyses of past inflows use a 30-year reference period that is updated each decade. Until recently, that reference period was the estimated unregulated flows that occurred between 1981-2010. In fall 2021 the reference period was updated to the 1991-2020 period. The median annual inflow from the earlier 1981-2010 reference period was higher than more recent periods—3% higher than the updated reference period and 9% higher than the unregulated inflows that have occurred since onset of the Millennium Drought. **Our analysis of the accuracy and bias of second-year projections made in the 24 Month Studies issued from 2010-2021 demonstrates that the most probable projected inflows were higher than what actually occurred by as much as ~7 million acre feet (maf) in some years, and predicted reservoir elevations were also higher than what occurred in some years.**

3. During the years when the 1981-2010 reference period was used for forecasting (prior to fall 2021), the driest conditions of the Millennium Drought were not well anticipated or predicted until January of the year being forecast. In the very driest year, inflow predictions were consistently high until the entire snowmelt runoff season had ended. **Multi-year periods of very low inflow were also not well predicted by projections based on the 1981-2010 reference period. These multi-year periods of very low inflow are a significant risk to sustainable water-supply management during the on-going Millennium Drought.**

4. The accuracy of the first year of the forecast window improves as the winter progresses, and the uncertainty of the projections of reservoir inflow is reduced. However, there remains some uncertainty for inflow projections in the first year of the forecast window, because precipitation and temperature during the last months of winter and spring are also based on the statistical probabilities derived from the 30-year reference period.

5. During years 2010-2021, the Most Probable August 24-Month Study (used for determining the Lake Powell Operation tier for the upcoming year), tended to overestimate the end-of-calendar-year Lake Powell elevation

by as much as ~10 feet. The September 24-Month Study came closer to the mark, and was within ~5 feet of what actually occurred. Similarly, the April forecast, used for adjusting the Lake Powell Operation tier in the middle of the water year, either overestimated or underestimated the actual end-of-water-year elevation by as much as 20 feet. The uncertainty of the May forecast was reduced to +/- 10 feet. **From an accuracy perspective, the September and May forecasting reports are more accurate tools for determining and adjusting Lake Powell operation tiers than are the August or April estimates.**

6. The bias for inflow predictions will likely be reduced now that the reference period includes a more recent, and somewhat drier, span of time, but projections of future inflows are likely to remain biased, because the hydrology of the 1991-2020 reference period was still wetter than the current Millennium Drought. These findings are consistent with Kuhn's (2021) observation that **the hydrology used in the 24 MS does not fully capture the risks of ongoing aridification of the Colorado River basin and that water-supply planning ought to better anticipate the risks of decreasing inflows to Lake Powell.**

This is the seventh in a series of white papers from the Future of the Colorado River Project.
See the full list of white papers and summaries at this link, including:

6. Alternative Management Paradigms for the Future of the Colorado and Green Rivers (2021)
Describes how declining runoff and increased consumptive use will impact water supplies and ecosystems on the Colorado and Green Rivers, and considers how these risks can be addressed.

5. Stream flow and Losses of the Colorado River in the Southern Colorado Plateau (2020)
Exploring uncertainty in quantifying stream flow and losses of the Colorado River in the southern Colorado Plateau, including Lake Powell, the Grand Canyon, and Lake Mead.

4.The Future Hydrology of the Colorado River Basin (2020)
Summarizes the current understanding of future hydrology with perspective of how it can be incorporated into CRSS and other river planning models. Provides scenarios that characterize and estimate plausible future drought conditions based on the record of past droughts in historic and tree ring-estimated natural flow.

3. Managing the Colorado River for an Uncertain Future (2020)
Explores strategies that are both adaptable and flexible to address uncertainties in future Colorado River hydrology, water demands, and ecosystem conditions.

2. Water Resource Modeling of the Colorado River: Present and Future Strategies (2019)
Provides an overview of the CRSS and its utility in analyzing alternative management paradigms concerning the future of the Colorado River.

1. Fill Mead First – A Technical Assessment (2016)
Explores the establishment of Lake Mead reservoir as the primary water storage facility of the main-stem Colorado River and relegating Lake Powell reservoir to a secondary water storage facility to be used when Lake Mead is full.

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Supporting Data:

- Previous 24-Month Studies: https://www.usbr.gov/lc/region/g4000/24mo/index.html
- Code and data for figures 5 through 8 can be found at: https://www.hydroshare.org/resource/366ed14bfd154ee3b6a528d3488717fe/
- Figure 9 courtesy of Brad Udall.

Introduction

Among the many projections of future water supply made by the Bureau of Reclamation, the agency's estimate of elevation and water storage in Lake Powell reservoir during the coming two years attracts widespread attention. These projections are published each month in a report, the 24-Month Study (24 MS), which has been issued monthly since 2010. Predictions are based on likely future inflows using three different inflow sequences (maximum, most and minimum probable), rules concerning downstream releases from Lake Powell, and assumptions about evaporation, seepage into the regional ground-water system, and local precipitation.

Reclamation states that "the Probable Minimum inflow scenario reflects a dry hydrologic condition which statistically would be exceeded 90% of the time. The Most Probable inflow scenario reflects a median hydrologic condition which statistically would be exceeded 50% of the time. The Probable Maximum inflow scenario reflects a wet hydrologic condition which statistically would be exceeded 10% of the time. There is approximately an 80% probability that a future elevation will fall inside the range of the minimum and maximum inflow scenarios." (24 MS, https://www.usbr.gov/lc/region/g4000/24mo/index.html)

These projections have significant impact on management, policy, and public perception about the future. Projections made in September 2021 (Fig. 1A) created widespread alarm when Lake Powell was projected to fall to nearly 3525 ft above sea level (asl) between February and April 2022, based on the assumption that future inflows would be the 'most probable' inflow scenario considered at that time. Even greater concern about the September 2021 prediction was fueled by the possibility that Lake Powell might fall to an even lower elevation if future inflows were similar to the 'minimum probable,' rather than the 'most probable,' future condition. The forecast made in December 2021 projected even lower future reservoir storage conditions (Fig. 1B) and caused even greater alarm. The December projection indicated that Lake Powell would fall below 3525 ft asl between February and May 2022 and again between August 2022 and May 2023 under the 'most probable' hydrology. If the 'minimum probable' inflows were to occur, Lake Powell was predicted to fall below 3490 ft asl in September 2022 and would remain below that level for more than a year. Concern about a future water storage crisis subsided somewhat when the January 2022 projection (Fig. 1C) predicted that Lake Powell would not fall below 3490 ft asl during the next two years, even if future inflows were at the 'minimum probable'. However, the February 2022 projection (Fig. 1D) again triggered alarm, because Lake Powell elevations are now projected to drop below 3525 ft between December 2022 and May 2023 under the 'most probable' inflow scenario.

These forecasts, and the month-to-month changes in the forecasts, generate great interest among water supply and hydropower managers, because the minimum elevation at which power can be produced (minimum power pool), is 3490 ft asl. Below this low reservoir elevation, water cannot be released downstream through the penstocks and turbines, and water can only be released downstream through river outlets whose elevation is 3370 ft asl. In that situation, the maximum rate of release of water through the outlets will be 15,000 ft^3/s, but the release rate will decrease greatly as the reservoir falls towards 3370 ft asl due to physical hydraulic limitations. Because these projections suggest a potential crisis in water supply and hydroelectricity production, **it is useful to understand why the 24-Month Study projections change from month-to-month and to understand what affects the uncertainty of these projections. We also ask "How accurate were projections made in past 24-Month Studies?"**

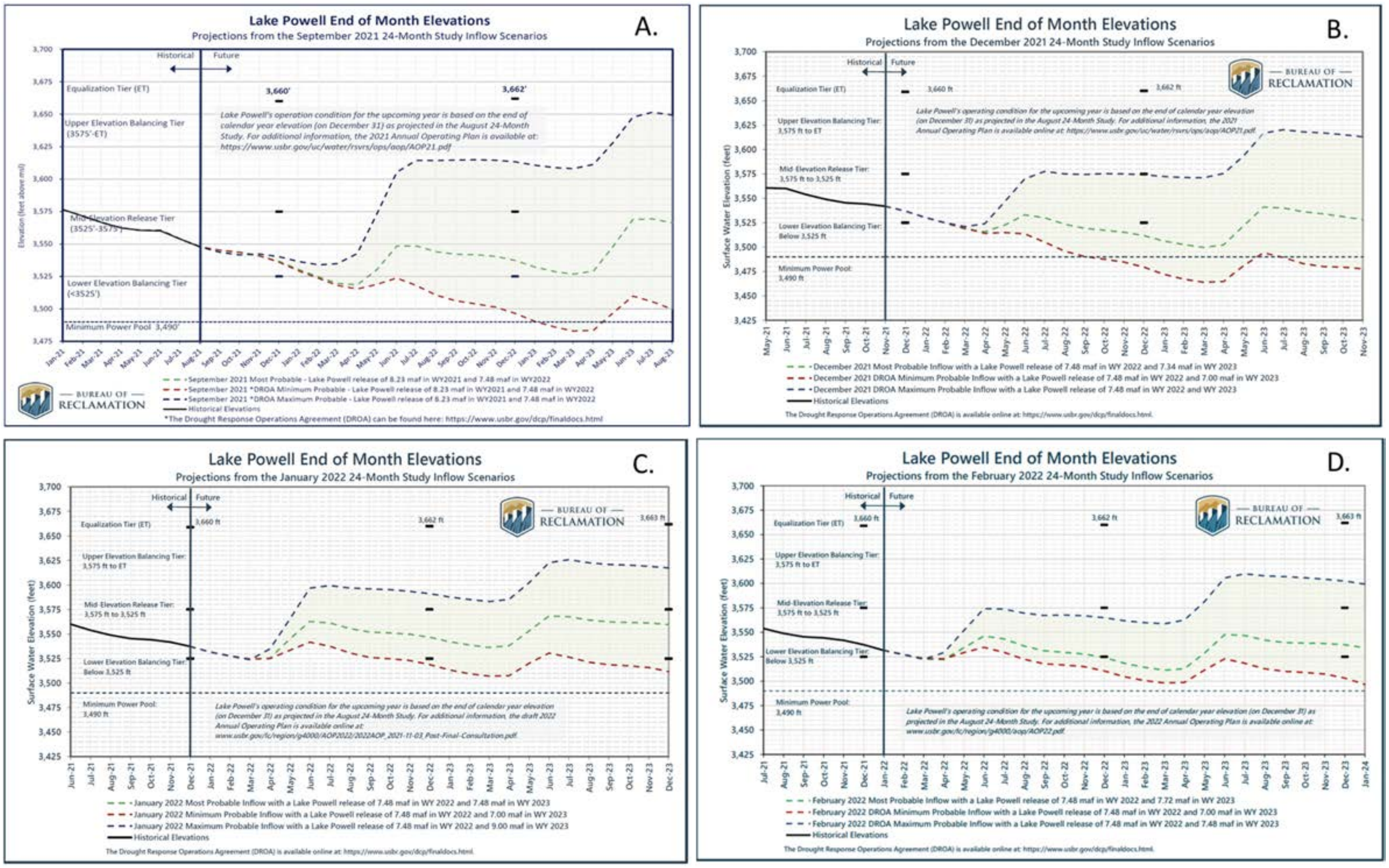

Figure 1. Graphs showing end-of-month projections of Lake Powell elevation based on scenarios of inflows during the next 24 months. A. Projection made in September 2021. B. Projection made in December 2021. C. Projection made in January 2022. D. Projection made in February 2022. Note that the 'most probable' prediction decreased from September to December, increased from December to January, and decreased from January to February. The uncertainty between the maximum probable and minimum probable predictions narrowed with time. Note that the September 2021 forecasts were made using the 1981-2010 climate normals while the other forecasts were made using the newer 1991-2020 climate normals. https://www.usbr.gov/uc/water/crsp/studies/images/PowellElevations.pdf.

How is the elevation of Lake Powell projected?

The elevation of Lake Powell is determined by the amount of water stored in the reservoir, and predictions of future elevations are based on predictions of future water storage. The relationship between water storage and reservoir elevation (Fig. 2) is based on measurements of the bathymetry of the reservoir, and resurveys are made approximately every decade. Reservoir elevation is more sensitive to water storage volume when the reservoir is low, because less water can be stored when Lake Powell is entirely confined within its canyon walls—as the reservoir elevation drops the amount of storage per foot of elevation decreases, indicated by the steepening line below 5 maf in the plot below.

The amount of water in Lake Powell depends on the inflow to the reservoir, releases downstream, evaporation from the reservoir, and seepage into and out of the surrounding bedrock. In turn, inflow to the reservoir depends on the natural runoff, upstream reservoir storage and releases, and the magnitude of upstream consumptive uses and losses. A water budget representing the amount of water that enters and leaves Lake Powell is:

$$\Delta S_{LP} = CR_C + GR_{GR} + SJR_B + \Sigma tribs + P - E +/- G_r - CR_{GCD} - G_{CR}$$

where ΔS_{LP} is the change in water storage in Lake Powell during a specified period of time, and CR_C, GR_{GR}, and SJR_B are the inflows measured at the three long-term USGS gages on the primary branches of the Colorado River: USGS gage 09180500 (Colorado River near Cisco, UT), USGS gage 09315000 (Green River at Greenriver, UT), and USGS gage

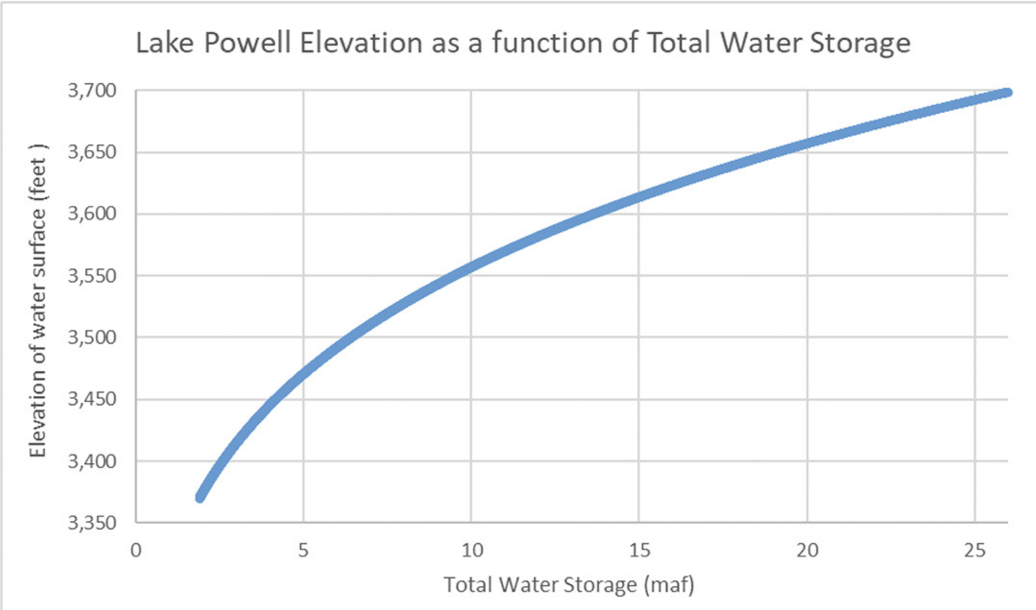

Figure 2. Graph showing elevation of the surface of Lake Powell as a function of the total amount of water stored. The elevation of the penstocks is 3490 ft asl, and the minimum elevation at which water can be released through the river outlets is 3370 ft asl. There is approximately 1.9 million acre feet of water in "dead pool" when the reservoir is at 3370 ft asl, and water can no longer be released downstream. Data from Reclamation (2007a).

09379500 (San Juan River near Bluff, UT), respectively. Other parameters of Lake Powell's water budget are $\Sigma tribs$ which is the total stream flow that enters the river system or reservoir downstream from the three gages, P is the precipitation that falls on the reservoir, E is the evaporation from the reservoir, and G_r is bank seepage that exits or enters the reservoir into the regional ground-water system. Outflow from Lake Powell is CR_{GCD} which is the release measured by Reclamation at Glen Canyon Dam. There is additional outflow (G_{CR}) that seeps from the reservoir into the surrounding bedrock and returns to the Colorado River in the 15 mi between Glen Canyon Dam and Lees Ferry. This seepage is measured as the difference between releases at the dam and stream flow at USGS gage 09380000 (Colorado River at Lees Ferry, AZ). Wang and Schmidt (2021) estimated that bank seepage that returns to the Colorado River downstream from Glen Canyon Dam is approximately 150,000 acre ft/yr.

Projections of future water storage of Lake Powell are primarily influenced by the projections of future inflows as the magnitude of these inflows are much greater than the other variables in the equation. These forecasts are focused on predicting the inflow of the upper Colorado, Green, and San Juan Rivers, and many other variables of the equation are estimated or parameterized. The uncertainty of predictions for the three primary inflows to Lake Powell differs depending on the time horizon of the forecast window. Estimates of inflow in the first year of the two-year forecast window are made by the Colorado Basin River Forecast Center (CBRFC) and are updated monthly. As the first-year's winter snowfall season progresses, the amount of spring runoff is more accurately predicted, and the uncertainty estimating reservoir inflow decreases. Nevertheless, uncertainty can never be entirely eliminated, even at the end of winter, because of the uncertainty in springtime weather.

The impact of accumulating snowpack on the forecast of inflow is demonstrated by comparing the accumulation pattern of the current year's snowpack (Fig. 3) with the changing reservoir elevation forecasts shown in Figure 1. Figure 3 shows the accumulating snowpack as a thin black line; the amount of water in the snowpack, averaged for the entire Colorado River basin that drains into Lake Powell, is calculated as snow water equivalent (SWE). In the background are color bands that span pink to purple and represent the lowest 10% up to the highest 10% of the past 30 years. This 30-year period is a reference defined, and updated each decade, in agreement with World Meteorological Organization (WMO) standards. Currently, the reference period[1] is the '1991-2020 climatic and hydrologic normal', and the methods used to calculate the attributes of this period are discussed here: (https://www.nrcs.usda.gov/wps/portal/wcc/home/snowClimateMonitoring/30YearNormals/).

At the beginning of the 2021/2022 winter, little was known about what lay ahead, and the prediction for inflow and reservoir elevation (Fig. 1A) were based on up-to-date basin soil moisture and the statistical attributes of snowfall of the past 30 years. On December 1, 2021, there had been unusually low snowfall, and the projection of future reservoir elevation (Fig. 1B) reflected the small SWE of the watershed. There was a large amount of snowfall in December, and the SWE of the watershed increased greatly. The January 1 prediction

1 Prior to fall 2021, the 'climatic and hydrologic normal' period was 1981 to 2010.

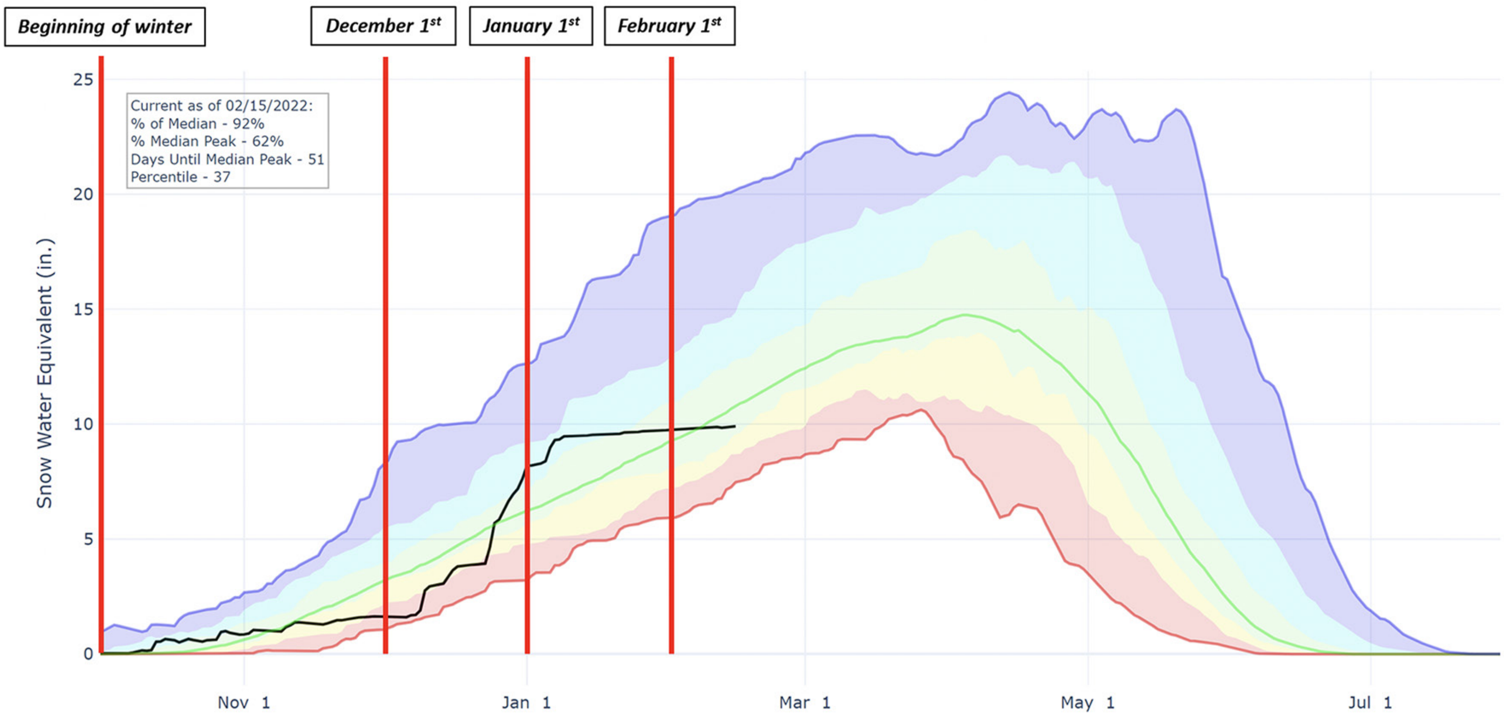

Figure 3. Graph showing snow water equivalent (SWE) of the snowpack of the entire Colorado River that drains to Lake Powell as of February 15, 2022, estimated by the Natural Resources Conservation Service (NRCS) and the National Water and Climate Center (NWCC). The color bands, from pink to purple, represent percentiles of the 30 previous years of SWE accumulation. Pink is the lowest 10% of all years, yellow and pink (together) are the lowest 30% of all years, green is the middle 40% of all years and spans the thin green line that is the median value, blue and purple (together) are the highest 30% of all years, and purple is the highest 10% of all years. Vertical red lines are indicated dates. Downloaded on February 15, 2022, at https://www.nrcs.usda.gov/Internet/WCIS/AWS_PLOTS/basinCharts/POR/WTEQ/assocHUC2/14_Upper_Colorado_Region.html.

of future reservoir elevation (Fig. 1C) was revised upward. In January 2022, unusually low snowfall occurred, which caused the February prediction of future reservoir elevation to again drop (Fig. 1D).

The different strategies for predicting inflow have been summarized by the CBRFC and Reclamation (Fig. 4). Estimates of reservoir inflow by the CBRFC during the first few months (blue, purple, and pink blocks in Fig. 4) of the forecast window are based on a widely used soil moisture–runoff model called the Sacramento Soil Moisture Accounting model. This hydrologic model uses up-to-date soil moisture and snowpack data, combined with a set of historical time series of precipitation and temperature that matches the reference period. Uncertainty in model results are predicted using the Ensemble Streamflow Predictions (ESP) technique that generates multiple forecasted streamflow traces, including a "most probable" inflow forecast. This approach is used in the time periods labeled in Figure 4 as RFC (blue blocks), Official A-J (purple blocks), and ESP Jan to Dec (pink blocks). The number of future months in which this modeling scheme is used varies between 5 and 16, depending on when the forecast is made. Reclamation forecasts for the later months (yellow blocks) of the 24-month forecast period are based on statistical characterization of the measured flows of the reference period. An interpolation scheme is used to estimate inflow for a two-month period (green blocks) that links the early-period estimates generated by hydrologic modeling and the later-period estimates developed from historical records. Each January, April, August, and October, Reclamation also predicts future reservoir elevation based on CBRF's predictions of the maximum probable and the minimum probable inflow.[2] In the first year of the forecast window (Fig. 4), the estimated maximum probable inflow is a value exceeded less than 10% of the time in the various ESP traces, and the minimum inflow is a value exceeded 90% of the time in the ESP traces. Estimates for inflows during the second year of

2 In 2021, the maximum and minimum probable predictions were run every month as required by the Drought Response Operations Agreement.

Most Probable

Month Issued	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
Jan	RFC	RFC	RFC	Official A-J	Official A-J	Official A-J	Official A-J	ESP Jan	ESP Jan	inter-polate	inter-polate	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med											
Feb		RFC	RFC	RFC	Official A-J	Official A-J	Official A-J	ESP Feb	ESP Feb	inter-polate	inter-polate	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med		
Mar			RFC	RFC	RFC	Official A-J	Official A-J	ESP Mar	ESP Mar	inter-polate	inter-polate	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med		
Apr				RFC	RFC	RFC	Official A-J	ESP Apr	ESP Apr	inter-polate	inter-polate	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med		
May					RFC	RFC	RFC	ESP May	ESP May	inter-polate	inter-polate	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med		
Jun						RFC	RFC	RFC	ESP Jun	ESP Jun	ESP Jun	ESP Jun	ESP Jun	ESP Jun	ESP Jun	ESP Jun	ESP Jun	ESP Jun	ESP Jun	ESP Jun	ESP Jun	inter-polate	inter-polate	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med		
Jul							RFC	RFC	RFC	ESP Jul	ESP Jul	ESP Jul	ESP Jul	ESP Jul	ESP Jul	ESP Jul	ESP Jul	ESP Jul	ESP Jul	ESP Jul	ESP Jul	inter-polate	inter-polate	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med		
Aug								RFC	RFC	RFC	ESP Aug	ESP Aug	ESP Aug	ESP Aug	ESP Aug	ESP Aug	ESP Aug	ESP Aug	ESP Aug	ESP Aug	ESP Aug	inter-polate	inter-polate	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med		
Sep									RFC	RFC	RFC	ESP Sep	ESP Sep	ESP Sep	ESP Sep	ESP Sep	ESP Sep	ESP Sep	ESP Sep	ESP Sep	ESP Sep	inter-polate	inter-polate	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med		
Oct										RFC	RFC	RFC	ESP Oct	ESP Oct	ESP Oct	ESP Oct	ESP Oct	ESP Oct	ESP Oct	ESP Oct	ESP Oct	inter-polate	inter-polate	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med		
Nov											RFC	RFC	RFC	ESP Nov	ESP Nov	ESP Nov	ESP Nov	ESP Nov	ESP Nov	ESP Nov	ESP Nov	inter-polate	inter-polate	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	
Dec												RFC	RFC	RFC	ESP Dec	ESP Dec	ESP Dec	ESP Dec	ESP Dec	ESP Dec	ESP Dec	inter-polate	inter-polate	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med

RFC values are issued by the Colorado Basin River Forecast Center (RFC) as the official forecast values for the next three-month period of time. The values are calculated using Ensemble Streamflow Predictions (ESP) modeling. This official forecast has the least amount of error associated with it.

Official A-J values are official forecast values issued by the RFC for the April-July runoff period using ESP. Apr-Jul water supply forecast volume is disaggregated by the RFC.

91-20 Med values are the monthly median inflow values generated from water years 1991-2020 calculated using the database maintained by the Bureau of Reclamation Upper Colorado Region (UCBOR). A water year begins October 1 and ends September 30.

Interpolated values are calculated by UCBOR and are based on percent of the 91-20 median. The method takes the precent of median of the previous month's forecast value and interpolates over two months to the percent of median for the month following the interpolation period. This is done to smoothly transition between the end of the current water year and the next water year.

ESP monthly values are generated using the RFC ESP forecasted volume for the water year using the current month's initial hydrological conditions. The RFC provides monthly volumes consistent with the 3-month forecast and the water year ESP volume.

* Light grey text indicates that the model is run in this month, however, only results for the first 24 months of the model run (black text) are published in the 24 Month Study report

Maximum Probable

Month Issued	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
Jan	RFC	RFC	RFC	A-J Coord 90th %ile	A-J Coord 90th %ile	A-J Coord 90th %ile	A-J Coord 90th %ile	inter-polate	inter-polate	75th %ile of 91-20	75th %ile of 91-20	75th %ile of 91-20	75th %ile of 91-20	75th %ile of 91-20	75th %ile of 91-20	75th %ile of 91-20	75th %ile of 91-20	75th %ile of 91-20	75th %ile of 91-20	75th %ile of 91-20	75th %ile of 91-20	inter-polate	inter-polate	91-20 Med											
Feb																																			
Mar																																			
Apr				A-J Coord 90th %ile	A-J Coord 90th %ile	A-J Coord 90th %ile	A-J Coord 90th %ile	inter-polate	inter-polate	75th %ile of 91-20	75th %ile of 91-20	75th %ile of 91-20	75th %ile of 91-20	75th %ile of 91-20	75th %ile of 91-20	75th %ile of 91-20	75th %ile of 91-20	75th %ile of 91-20	75th %ile of 91-20	75th %ile of 91-20	75th %ile of 91-20	inter-polate	inter-polate	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med		
May																																			
Jun																																			
Jul																																			
Aug								RFC	RFC	RFC	90th %ile Aug ESP	90th %ile Aug ESP	90th %ile Aug ESP	90th %ile Aug ESP	90th %ile Aug ESP	90th %ile Aug ESP	90th %ile Aug ESP	90th %ile Aug ESP	90th %ile Aug ESP	90th %ile Aug ESP	90th %ile Aug ESP	inter-polate	inter-polate	75th %ile of 91-20	75th %ile of 91-20	75th %ile of 91-20	75th %ile of 91-20	75th %ile of 91-20	75th %ile of 91-20	75th %ile of 91-20	75th %ile of 91-20	75th %ile of 91-20	75th %ile of 91-20		
Sep																																			
Oct										RFC	RFC	RFC	90th %ile Oct ESP	90th %ile Oct ESP	90th %ile Oct ESP	90th %ile Oct ESP	90th %ile Oct ESP	90th %ile Oct ESP	90th %ile Oct ESP	90th %ile Oct ESP	90th %ile Oct ESP	inter-polate	inter-polate	75th %ile of 91-20	75th %ile of 91-20	75th %ile of 91-20	75th %ile of 91-20	75th %ile of 91-20	75th %ile of 91-20	75th %ile of 91-20	75th %ile of 91-20	75th %ile of 91-20	75th %ile of 91-20		
Nov																																			
Dec																																			

RFC values are issued by the Colorado Basin River Forecast Center (RFC) as the official forecast values for the next three-month period of time. The values are calculated using Ensemble Streamflow Predictions (ESP) modeling. This official forecast has the least amount of error associated with it.

Coord A-J 90th %ile are the official forecast of the total April-July volume issued by the RFC for the April-July runoff period using ESP. Monthly values are disaggregated using the 1991-2020 median monthly distribution.

75th %ile of 91-20 values are the monthly 75th percentile (25% exceedance) inflow values generated from water years 1991-2020 calculated using the database maintained by the Bureau of Reclamation Upper Colorado Region (UCBOR). A water year begins October 1 and ends September 30.

Interpolated values are calculated by UCBOR and are based on percent of the 1991-2020 median. The method takes the precent of average of the previous month's forecast value and interpolates over two months to the percent of median for the month following the interpolation period. This is done to smoothly transition between the end of the current water year and the next water year.

90th %ile Jan/Apr/Aug/Oct ESP values are generated using the RFC ESP forecasted volume for the water year using the monthly initial hydrological conditions. Monthly values are disaggregated from the total water year ESP volume using the median 1991-2020 statistical monthly distribution, consistent with the 3-month forecast. ESP forecasts are issued for each month of the base flow period to the end of the current water year for the 24-Month Study.

* Light grey text indicates that the model is run in this month, however, only results for the first 24 months of the model run (black text) are published in the 24 Month Study report

Minimum Probable

Month Issued	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
Jan	RFC	RFC	RFC	A-J Coord 10th %ile	A-J Coord 10th %ile	A-J Coord 10th %ile	A-J Coord 10th %ile	inter-polate	inter-polate	25th %ile of 91-20	25th %ile of 91-20	25th %ile of 91-20	25th %ile of 91-20	25th %ile of 91-20	25th %ile of 91-20	25th %ile of 91-20	25th %ile of 91-20	25th %ile of 91-20	25th %ile of 91-20	25th %ile of 91-20	25th %ile of 91-20	inter-polate	inter-polate	91-20 Med											
Feb																																			
Mar																																			
Apr				A-J Coord 10th %ile	A-J Coord 10th %ile	A-J Coord 10th %ile	A-J Coord 10th %ile	inter-polate	inter-polate	25th %ile of 91-20	25th %ile of 91-20	25th %ile of 91-20	25th %ile of 91-20	25th %ile of 91-20	25th %ile of 91-20	25th %ile of 91-20	25th %ile of 91-20	25th %ile of 91-20	25th %ile of 91-20	25th %ile of 91-20	25th %ile of 91-20	inter-polate	inter-polate	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med	91-20 Med		
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Nov																																			
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RFC values are issued by the Colorado Basin River Forecast Center (RFC) as the official forecast values for the next three-month period of time. The values are calculated using Ensemble Streamflow Predictions (ESP) modeling. This official forecast has the least amount of error associated with it.

Coord A-J 10th %ile are the official forecast of the total April-July volume issued by the RFC for the April-July runoff period using ESP. Monthly values are disaggregated using the 1991-2020 median monthly distribution.

25th %ile of 91-20 values are the monthly 25th percentile (25% exceedance) inflow values generated from water years 1991-2020 calculated using the database maintained by the Bureau of Reclamation Upper Colorado Region (UCBOR). A water year begins October 1 and ends September 30.

Interpolated values are calculated by UCBOR and are based on percent of the 1991-2020 median. The method takes the precent of average of the previous month's forecast value and interpolates over two months to the percent of median for the month following the interpolation period. This is done to smoothly transition between the end of the current water year and the next water year.

10th %ile Jan/Apr/Aug/Oct ESP values are generated using the RFC ESP forecasted volume for the water year using the monthly initial hydrological conditions. Monthly values are disaggregated from the total water year ESP volume using the median 1991-2020 statistical monthly distribution, consistent with the 3-month forecast. ESP forecasts are issued for each month of the base flow period to the end of the current water year for the 24-Month Study.

* Light grey text indicates that the model is run in this month, however, only results for the first 24 months of the model run (black text) are published in the 24 Month Study report

Figure 4. Tables summarizing methods used by the Colorado Basin Forecast Center for estimating Upper Colorado unregulated inflows (https://www.usbr.gov/lc/region/g4000/riverops/model-info.html). Note that 1991-2020 reference period data were first utilized in fall 2021. Before that, 1981-2010 data were used for 24-Month Studies (Jeff et al., 2020, Fig. 3.4).

the forecast window are based on the statistical attributes of the 30-year reference period.

CBRFC accounts for all known upstream regulation and measured depletions when forecasting future Lake Powell inflows, also called the unregulated inflow[3]. It is the observed flow adjusted to include the upstream adjustments (depletion, export/import and change in storage at the reservoir). For example, Lake Powell unregulated inflow accounts for all measured Upper Basin depletion and upstream reservoir storage changes, including those reservoirs that are not shown in the 24 MS. CBRFC obtains reservoir data primarily from reservoir operators and managers, or inferred from USGS streamflow gages. The detailed description of the methods for calculating unregulated inflows for each part of the river and its reservoirs can be found at https://www.cbrfc.noaa.gov/wsup/guide/2022/guidepoints.html and https://www.cbrfc.noaa.gov/wsup/guide/sticks.php.

The Colorado River Mid-term Modeling System (CRMMS) is then used to simulate Lake Powell and other major reservoir storage in the basin. CRMMS is implemented through the commercial river modeling software RiverWare™ developed by the Center for Advanced Decision Support for Water and Environmental Systems (CADSWES). There are 12 reservoirs (9 in the Upper Basin and 3 in the Lower Basin) in CRMMS, and operations for these reservoirs are assumed to be consistent with the Law of the River. Lower Basin and Mexico water demand are modeled explicitly in CRMMS, while Upper Basin water demand is embedded in the unregulated flows. Within the model, flow elements of Lake Powell's water budget, including CR_C, GR_{GR}, and SJR_B, are included in the unregulated inflow to Lake Powell. Other elements of Lake Powell's water budget, such as $\Sigma tribs$, P, E, and G_r, are held constant or are parameterized in relation to reservoir storage. More detailed descriptions of model assumptions can be found at https://www.usbr.gov/lc/region/g4000/riverops/model-info.html. Results from CRMMS project future conditions of Lake Powell and other reservoirs under three inflow scenarios (shown in Fig. 4) and are reported through the 24 Month Study.

The 'range of uncertainty' in forecasts is an important attribute, as it informs policy and operational decisions.

Concerning Accuracy and Bias

Accuracy and Bias Defined

Obviously, the ability to predict future inflows improves as winter snowfall is better known, and the uncertainty in predicting the future decreases with time. We evaluated **accuracy** of forecasts made since 2010 and how the accuracy of forecasts improved with time by calculating the difference between the forecast values with what actually occurred. Until fall 2021, all forecasts were based on the 1981-2010 reference period. The smaller the difference between the forecasted inflow and the actual inflow, the greater the accuracy. Another statistical attribute is the **bias** of forecasts. From a statistical perspective, 50% of unbiased forecasts of the 'most probable' inflows should be greater than what occurred, and 50% should be less. Forecasts were considered biased if they were consistently greater or less than what occurred.

The 'most probable' inflow forecasts are used to predict reservoir water storage and reservoir elevation 'tiers,' as defined in the 2007 Interim Guidelines and other administrative agreements and are especially important in determining reservoir operations and the rules concerning releases from Lake Powell (Reclamation, 2007b). The **range of uncertainty** in forecasts, defined as the range between the 'maximum probable' and 'minimum probable' forecasts is another important attribute of forecasts, because this uncertainty range informs policy and operational decisions that consider risk of the reservoir drying or overflowing. We evaluated the uncertainty range by analyzing whether what occurred was within the range between the 'maximum probable' and the 'minimum probable' forecast. The probability that the maximum probable forecast was exceeded by actual inflows should be 10% of the time, and actual inflows should be less than the 'minimum probable' forecast 10% of the time. We evaluated if that was the case.

Accuracy and Bias of Inflow Predictions and How Predictions Change with Time

Not surprisingly, **years of average inflow were more accurately predicted further in advance than were unusually dry years**, because the second year of the forecast window is based on the statistical characteristics of the 30-year 'climatic and hydrologic normal' period. Average inflow years were well described by those statistical characteristics[4], such

3 CBRFC definition of unregulated inflow and Reclamation's definition of unregulated inflow are slightly different, see https://www.cbrfc.noaa.gov/wsup/doc/ConsumptiveUseDefinitions_forWeb_v1.pdf and https://www.usbr.gov/lc/region/g4000/riverops/model-info.html Hydrology Tab.

4 In the case of WY2014, WY2015, and WY2016, the 30-yr reference period was 1981-2010.

as in WY2014, WY2015, and WY2016, when future runoff was accurately predicted during the entire 24-month forecast period (Fig. 5). Not surprisingly, the five driest years were not well described by the 30-year normal period, and none were predicted at the beginning of the 24-month forecast window. It was not until the first months of winter that the likelihood of unusually low runoff in WY2012 and WY2018 were realized, and the severely dry conditions of WY2012 were not accurately predicted until the water year was almost over. The earliest prediction of total WY2012 inflow had been made in October 2010 and was 11.2 maf, more than twice what occurred. The forecast was not significantly reduced during the next 15 months, and the dryness of the year was not anticipated until January 2012, three months into WY2012, when the forecast was decreased to 9.0 maf. It was not until May 2012, after most of the spring snowmelt runoff had occurred, that severely dry conditions were accurately estimated at ~5.0 maf. Dry conditions in WY2018 were accurately predicted somewhat earlier, providing a slightly longer planning horizon. It wasn't until August 2012 when the early forecast range for WY2013 identified the dryness of the coming year, two months before the water year began. In WY 2020, forecast ranges remained greater than what actually occurred until the end of WY 2020. The dry conditions for WY 2021 were not identified by the early forecast range until January 2021. It is notable that the August and October forecast range with 12- and 14-months lead times were larger than the forecast range made in January and April with 18- and 21-months lead times. This conflicts with the understanding that uncertainty is systematically reduced as more information about watershed conditions is obtained. This happens because CBRFC forecasts made in the August and October with 12- and 14-months lead times capture 80% of all ESP possibilities (indicated by pink blocks in Fig. 4, middle and lower panels), while Reclamation assumptions used in that January and April with 18- and 21-months lead times only capture 50% of inflow statistical attributes of the 30-year reference period (indicated by bright yellow blocks in Fig. 4, middle and lower panels).

We summarized the changing accuracy and bias of forecasts for the two-year forecast window preceding the end of each water year, representing our results as box-and-whisker plots summarizing all years (Fig. 6). We calculated the difference between the forecasted and actual inflow in each year; 50% of the years were within the 'box' of each month in Figure 6. For example, in October, two years before the end of the water year being forecast, 50% of the 'most probable' forecasts were between ~0.5 and ~7 maf greater than what occurred. 50% of the 'maximum probable' forecasts were between ~3 and ~8 maf greater than what occurred, and 50% of the 'minimum forecasts' ranged from ~1.5 above to ~3 maf less than what actually occurred. With time, the difference between the forecasts and actual inflows decreased, indicated by the decreasing size of the boxes on the right side of Figure 6.

These data show that **the forecasted 'most probable' annual Lake Powell inflow made for the second year of the forecast period, i.e., made for conditions more than one year in advance, was typically biased towards wetter conditions. Approximately 60% to 75% of all forecasts made between October and May of the year preceding the water year being forecast overestimated actual future inflows, and the range of inaccuracy in forecasts was approximately 7 maf. Between June of the preceding year and December of the water year being forecast, the forecasts were unbiased—but the range of inaccuracy remained ~7 maf.** It was not until January of the water year in question that the uncertainty of forecasts was significantly reduced.

'Minimum probable' inflow forecasts for the second year of the forecast window poorly anticipated unusually dry future conditions.

The 'maximum probable' inflow forecast for the second year of the forecast window was approximately twice what occurred in dry years. To be consistent with the definition of 'maximum probable' used by the Reclamation, 10% of the actual inflow forecasts should have exceeded the 'maximum probable' prediction, and that never was the case. **'Minimum probable' inflow forecasts for the second year of the forecast window poorly anticipated unusually dry future conditions.** In more than 25% of the cases, actual inflow was less than the minimum probable forecasts in the second year, indicating that the minimum forecasts were a biased prediction for the risk of low runoff. Inflow forecasting is a worldwide challenge, especially for multi-year forecasts, because inaccuracy and bias are introduced due to deep uncertainty about future climates.

Accuracy of Reservoir Elevation Projections during Multi-Year Periods of Declining Storage

It is not surprising that overestimation of future inflows based on the 1981-2010 reference period led to overestimation of projected future reservoir elevations, especially in very dry years.

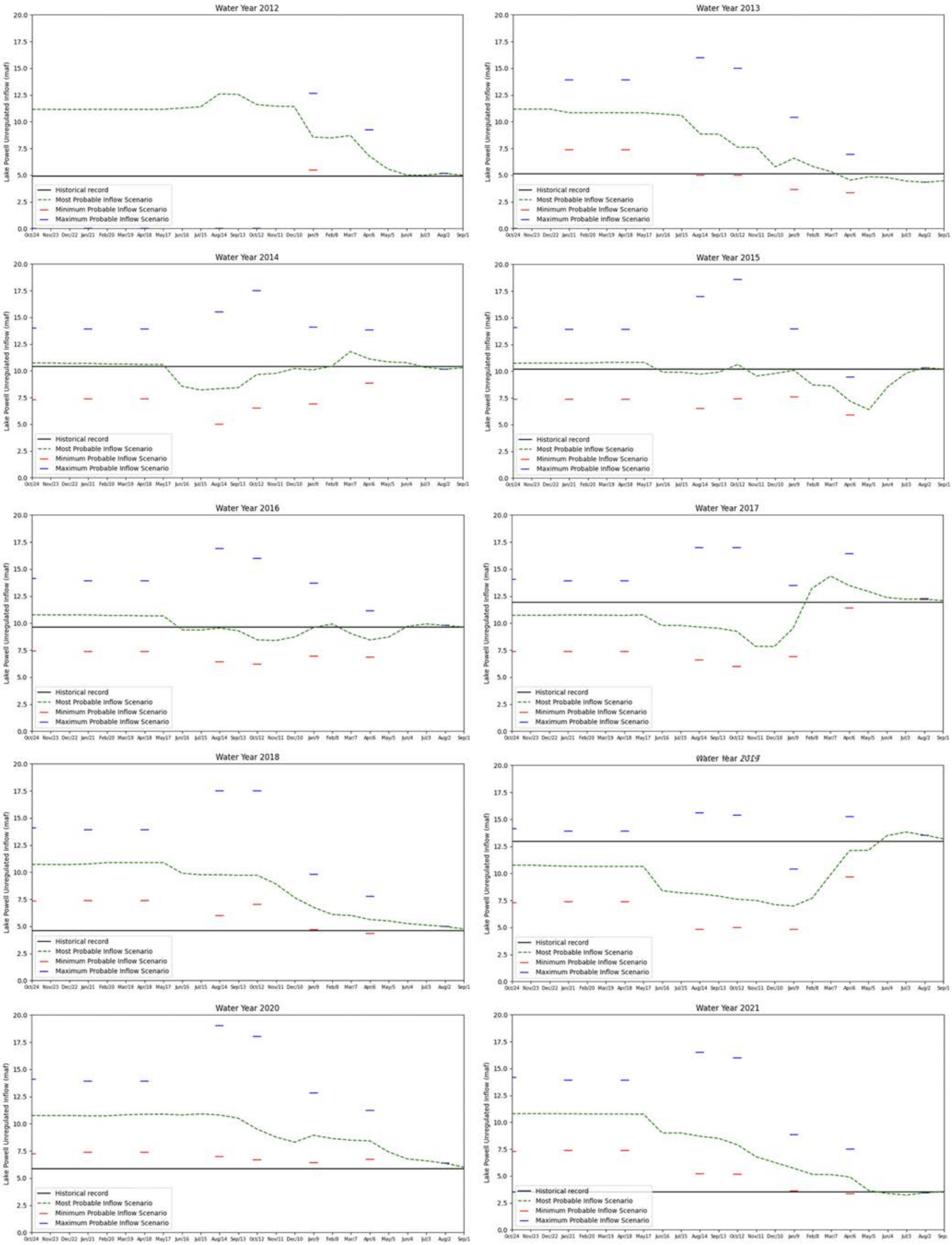

Figure 5. Graphs showing projected and actual Lake Powell annual inflows for each water year. The x-axis represents months when 24 MS projections were published/lead time in months, and y-axis represents Lake Powell unregulated inflow. Solid black horizontal lines represent actual values, dashed lines represent forecasts with the maximum probable (blue), the most probable (green), and the minimum probable (red) inflow scenarios. These graphs demonstrate that years with average inflow were more accurately predicted with more lead time than were unusually dry years.

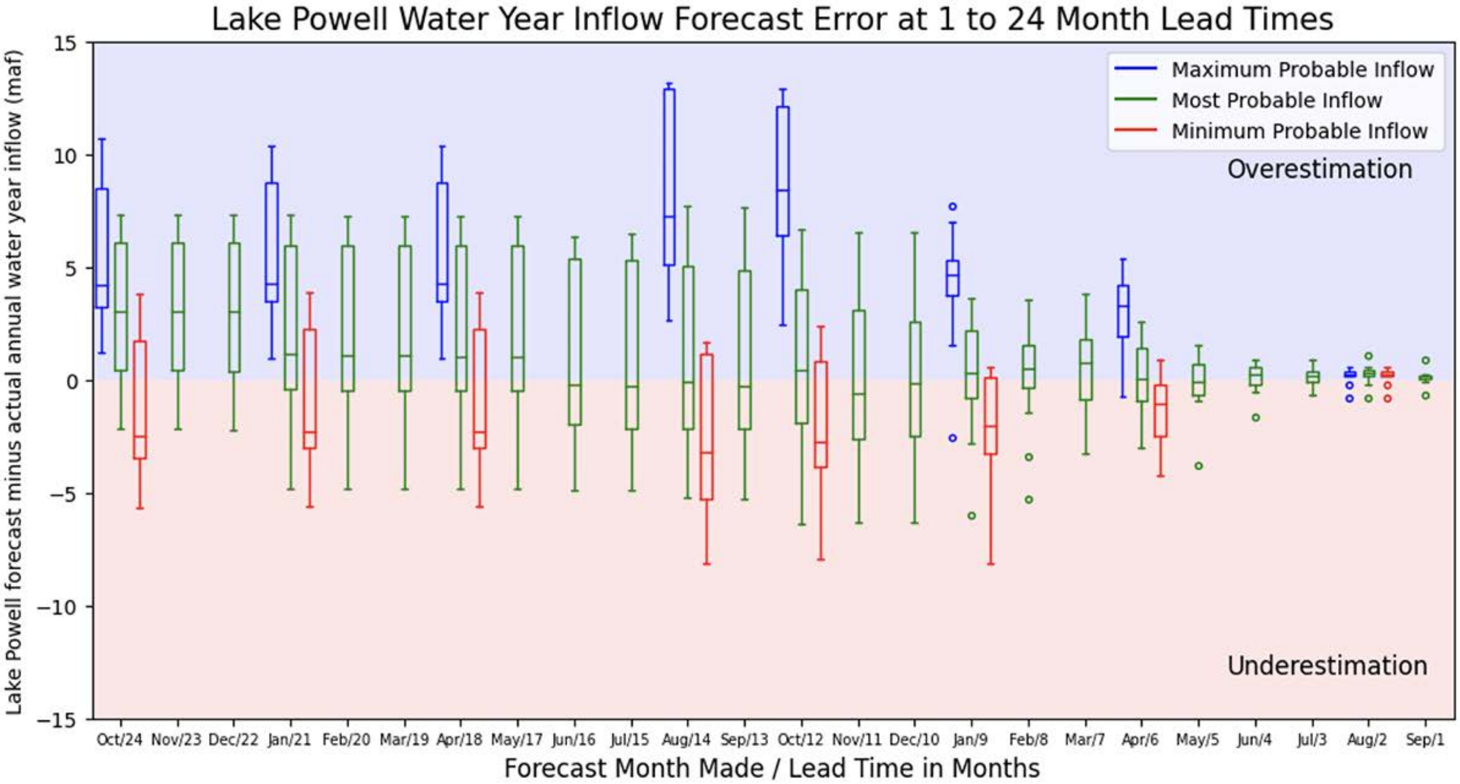

Figure 6. Graph showing Lake Powell annual unregulated inflow forecast accuracy of the max/most/min probable forecasts (blue, green, red boxes) for Forecast Lead Times from 1 to 24 months (x-axis) for the forecasted Water Year inflow. This graph demonstrates that forecasted annual Lake Powell inflow for all three inflow scenarios made more than one year in advance was typically biased towards wetter conditions. For unbiased forecasts, the 90th percentile (between upper whisker and upper box edge) on the red box, the 50th percentile (middle line) of the green box, and the 10th percentile (between lower whisker and lower box edge) on the blue box should be on the 0 line. The x-axis shows the month the forecast was made and the number of months until the end of the forecasted Water Year. The y-axis represents the deviation of the forecast Lake Powell inflow from the actual flows; positive values represent overestimation and negative values represent underestimation. The median of all deviations is the horizontal line within each box; 50% of the deviations are included within each rectangular box.

Of greater concern to water resource managers, however, is the fact that underestimate of a sequence of very dry or dry inflow years led to **the failure of the 24 MS in anticipating notable multi-year periods of declining reservoir storage. Inability of the forecasting methods to anticipate these multi-year periods of drought is a challenge toward managing water supply in a secure and reliable way.**

Inability of the forecasting methods to anticipate these multi-year periods of drought is a challenge toward managing water supply in a secure and reliable way.

There were three periods of prolonged, severe decline in reservoir elevation: July 2011 to March 2014; July 2017 to March 2019; and June 2020 to the present. In January of WY2012 and WY2020, future Lake Powell elevation was significantly overestimated, and actual reservoir elevation during the ensuing 24 months was less than the forecasted 'minimum probable' reservoir elevation. These overestimates are illustrated in Figure 7; black lines show the Lake Powell elevation that occurred, and dashed lines are the range of reservoir elevation projections made in January, April, August, and October of that year (vertical rows in Figure 7). Projections of reservoir elevation based on the maximum probable (blue), most probable (green), and minimum probable (red) inflow scenarios are shown, and the shaded green areas are the uncertainty range between the 'maximum' and 'minimum' projections. Overestimation of future Lake Powell elevation was indicated where the black line falls below the range of projections depicted by the shaded area. In some cases, the 24 MS projections overestimated future reservoir elevation by as much as ~20 ft.

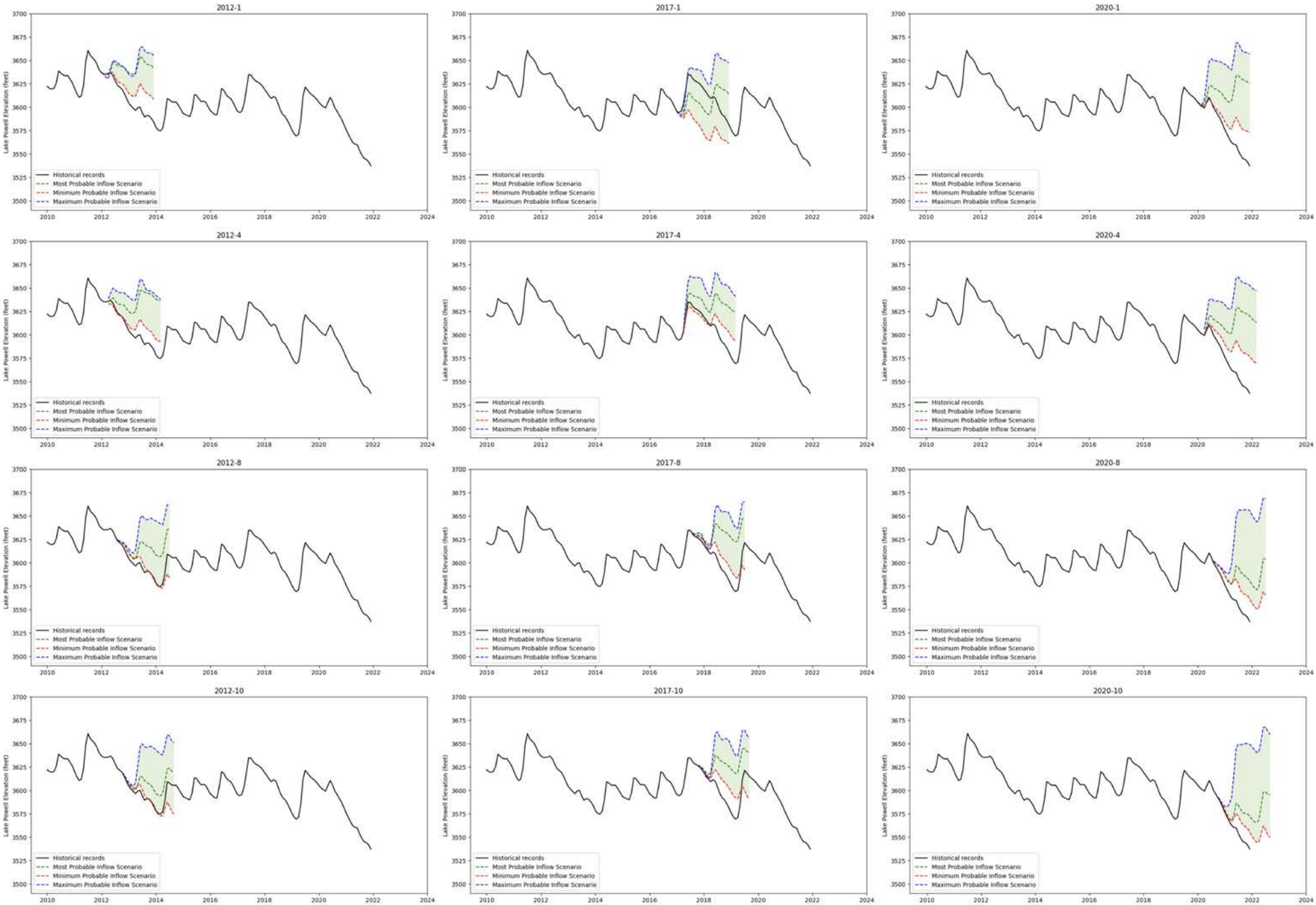

Figure 7. Graphs showing 24-Month Study projections at the beginning of three periods of severe elevation decline. These graphs show that at the onset of consecutive dry years, 24 MS forecasts may miss the possibility of future prolonged declines in reservoir storage.

Although the 24 MS projections made in January did not anticipate the onset of prolonged reservoir decline in WY2012 and WY2020, the accuracy of projections for these years improved, because inflow was more accurately projected in April and in August. For example, the uncertainty range of the April 2012 forecast overestimated future reservoir elevation, the projections made in August 2012 and October 2012 defined an uncertainty range that anticipated what occurred during the next two years. This pattern of improved prediction was less evident in WY2020, and the uncertainty range in April, August, and October 2020 did not anticipate future conditions. Similarly, predictions in WY2017 overestimated future reservoir elevation.

How the Accuracy and Bias of Predictions for Future Reservoir Elevation Changed with Time

The uncertainty of future projections decreased, and the accuracy of those projections improved, as the projection timeframe shortened. We evaluated how the accuracy of projections improved during the 24-month forecast period by calculating the difference between the forecast made in each month and the actual reservoir elevations (Fig. 8). We evaluated the rate that accuracy improved from forecasts initially made in July, to those made in October and January.

The green box-and-whisker plots summarized these analyses of the estimates of 'most probable' reservoir elevation. The blue box-and-whisker plots summarized the 'maximum probable' estimate of reservoir elevation, and the red box-and-whisker plots summarized 'minimum probable' estimates of reservoir elevation. Analysis of the accuracy of the 'most probable' estimate of reservoir elevation includes 24 boxes that coincide with the 24 months following the beginning of the forecast window. The interquartile range (i.e., the boxes) decreased in size as one moves through the 24-month forecast window showing that the accuracy improved as the target date of the forecast (e.g., the end of the water year) was approached. The y-axis of each figure is the distribution of the difference between the forecasted Lake Powell elevation and the actual elevation. The horizontal bar in each box is the median of all years estimated. The forecasts of reservoir elevation were biased too high if the median value was positive or if the boxes in Figure 8 (i.e., the interquartile range) was skewed to a positive value. **In most cases, future reservoir elevation (reflected in the median value of each green box) was overestimated.**

The bias associated with predictions within the first year and second year of the forecast window are illustrated in Figure 9. As described above, an unbiased forecast of the 'most probable' Lake Powell elevation/volume exists if 50% of the box plot is higher than the actual value and 50% lower. However, both the 12-month and 24-month lead forecasts (middle panel in Fig. 9) show a bias toward a high value (indicated by the black circles above the horizontal 0-line). The 12-month 'Most Probable' over-forecast bias was more reasonable, while the 24-month 'Most Probable' over-forecast bias continued to be exceptional with the 0-line cutting through nearly the bottom of the box plot, indicating that 70% of forecasts were too high, and only 30% too low. **The bias for the median forecast was ~1 maf higher than the actual value.**

The 'minimum probable' elevation forecasts (left panel in Fig. 9) yield larger biases compared to the 'most probable' elevation forecast biases. The 'minimum probable' inflow forecasts are said to be statistically exceeded 90% of time, meaning that 90% of the elevation forecasts should indicate lower elevations/volumes than what actually occurred. However, with a 12-month lead, the 0-line cut the box at ~70% of the distribution. To create a 12-month lead forecast that is entirely unbiased, the box would need to shift lower by ~1.2 maf (as indicated by the black triangle on the left). For the 24-month lead forecast, the 0-line cut at ~85% of the distribution, but is biased too wet by ~2 maf. This suggests the unbiased lower boundary of Lake Powell storage should be ~2 maf lower than is reported.

The 'maximum probable' elevation forecasts (right panel in Fig. 9) were biased wet, with the largest biases among the three inflow scenarios. The 'maximum probable' forecasts are the inverse of the 'minimum probable' forecasts — 90% of the time these forecasts should be high, and 10% should show lake elevations/volumes below what actually occurred. The 12-month lead forecast has the 0-line cutting halfway between the 90th percentile (square mark) and the bottom of the whisker. The 0-line is thus at about 95%, and 5% higher than expected. There are no occurrences of under-forecasting in the 24-month lead forecast, even though 10% under-forecasts should be expected. To make these two forecasts unbiased, the boxes would need to be shifted down by ~2 maf and ~3 maf, respectively. Although the 'maximum probable' forecast is currently of less concern, having a less biased forecast would put a more reasonable upper bound on forecasts for how much the reservoir might fill. **For all three inflow scenarios discussed here, Lake Powell elevation/ volume forecasts were biased high; 24-month lead forecasts were biased higher than 12-month lead forecasts.**

Modifying Assumptions for the 24 MS Inflow Forecast to Increase Accuracy and Reduce Bias

The forecast accuracy for the first year of the forecast window is partly dependent on the statistical characteristics of the 30-year reference period, because those statistics are used in the hydrologic model that predicts runoff in the remaining

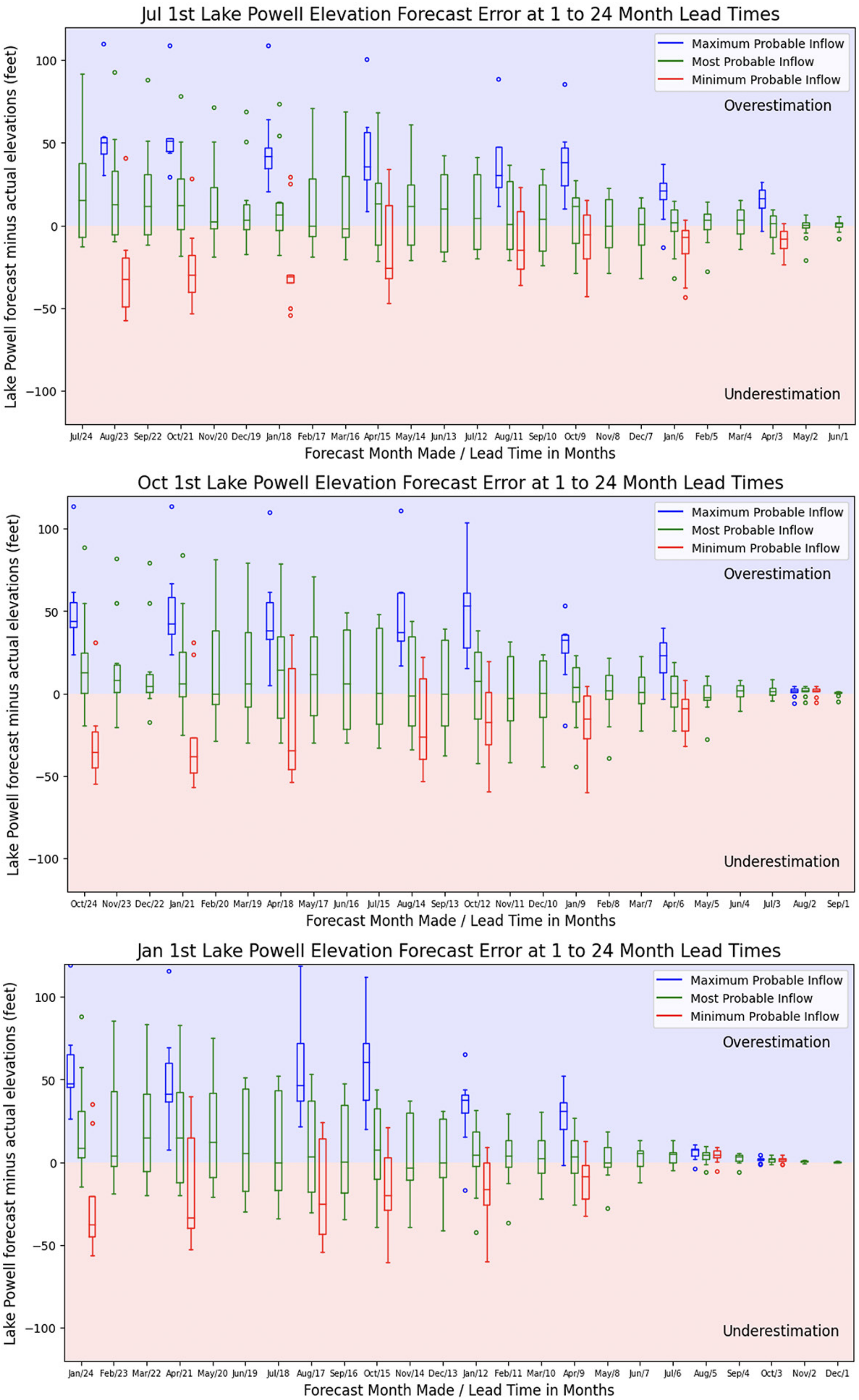

Figure 8. Graph showing the reservoir elevation at Lake Powell (A) July 1, (B) October 1, and (C) January 1 with forecast accuracy of the max/most/min probable forecasts (blue, green, red boxes) for Forecast Lead Times from 1 to 24 months (x-axis). For unbiased forecasts, the 90th percentile (between upper whisker and upper box edge) on the red box, the 50th percentile (middle line) of the green box, and the 10th percentile (between lower whisker and lower box edge) on the blue box should be on the 0 line. These graphs show that, in most cases, the future reservoir elevation was overestimated.

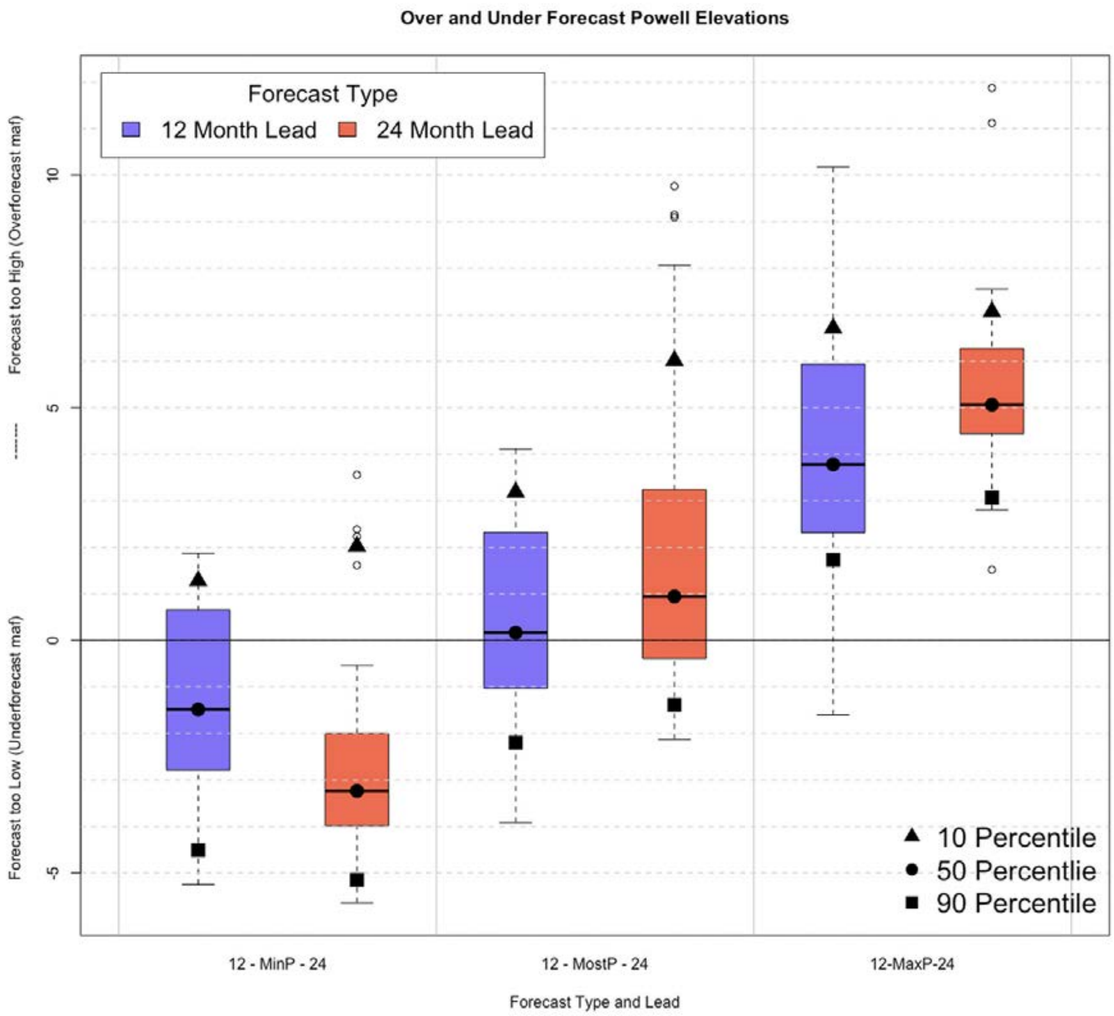

Figure 9. Forecast error of 12-Month and 24-Month forecasts under most probable, minimum probable, and maximum probable inflow scenarios, including the 10th, 50th and 90th percentiles marked with black triangles, circles and squares, respectively. These graphs illustrate that most of these forecasts are biased to be wetter than reality for all three inflow scenarios. For an unbiased forecast, the markings should line up on the 0 Forecast Error line for the 'minimum probable' (10th percentile inflow with the triangle mark), 'most probable' (50th percentile inflow with the black circle/ boxplot line), and 'maximum probable' (90th percentile inflow with the square mark) forecasts.

months of the water year. Projections for the second year of the forecast window are entirely dependent on the statistical characteristics of the 30-yr reference period. As demonstrated above, use of the 1981-2010 reference period biased projections of future conditions, because the reference period included the unusually wet years of the mid-1980s. Use of the 1991-2020 reference period eliminates the bias of including the mid-1980s, but nevertheless includes 10 years of flow conditions that precede onset of the Millennium Drought that began in 2000**.** Table 1 summarizes the statistical characteristics of the two reference periods. The median inflow of the 1981-2010 period was 9.5 maf/yr and the median inflow of the 1991-2010 period was 9.2 maf/yr. Nevertheless, the 1991-2020 reference period is 0.5 maf greater than the median inflow of the 2001-2020 period. **If inflows in the 21st century continue to be drier than those of the 20th century, then use of statistics for the past 20 years (2001-2020) might better anticipate future dry conditions than use of the 1991-2010 reference period.**

The 24-Month Study has used 1991 to 2020 climate conditions and inflows to calculate inflow forecasts since October 2021. Forecasts made in October 2021 represent the initial forecast for the inflows in WY2023, and this initial estimate will increase or decrease as the time period of the forecast window shortens, as shown in Figure 5. Since the forecast of inflow during the second year of the forecast window is only based on statistical characterization of the 30-yr reference period, we can evaluate the effect of the change in refer-

Table 1. Lake Powell inflows (maf) at 10th, 50th and 90th percentiles using different reference periods.

Percentile	1981-2010	1991-2020	2001-2020
10th	5.9	5.1	4.9
50th	9.5	9.2	8.7
90th	17.6	14.6	12.8

Note: Statistical characteristics are calculated based on annual (water year) Lake Powell inflows. Annual inflows from https://www.usbr.gov/rsvrWater/HistoricalApp.html

Table 2. Second Water Year annual inflow forecast in October 24-Month Studies

Date of the Study	Forecast Water Year	With most probable inflow scenario (maf)	With minimum probable inflow scenario (maf)
Oct 2021	2023	**9.4**	**6.8**
Oct 2020	2022	10.1	7.1
Oct 2019	2021	10.8	7.3
Oct 2018	2020	10.7	7.2
Oct 2017	2019	10.8	7.3
Oct 2016	2018	10.7	7.3
Oct 2015	2017	10.7	7.4
Oct 2014	2016	10.8	7.4
Oct 2013	2015	10.7	7.4
Oct 2012	2014	10.7	7.3

Note: The Oct 2020 24-Month Study used 1985-2015 as the reference period.

ence period on these forecasts. Table 2 shows the effect of this change from the 1981-2010 to the 1991-2020 reference period. In the 'most probable' inflow scenario, the October 2019 prediction of inflow for WY2021 based on the 1981-2010 reference period was ~10.8 maf. However, the October 2021 projection of inflow for WY2023 is 9.4 maf, because the characteristics of the 1991 to 2020 reference period are now being applied. Projections of the 'minimum probable' inflow scenario have similarly been reduced. These decreases in second water year inflow forecasting are likely to help decrease the inflow forecast bias but may not be sufficient if the Millennium Drought continues.

The ongoing usefulness of applying the 30 yr reference period of climatological and hydrological information to inflow forecasting may require reconsideration. Under a stable climate, the standard has been to use 30 years of data to represent the likelihood of unusually wet and dry conditions. However, the Colorado River basin's climate has not been stable, and the basin's climate is getting drier and hotter. If the Millennium Drought continues, 2001-2020 climatological and hydrological data might provide a better reference period, even though the duration of that period is shorter.

More frequent updates of the reference period may also be helpful to manage more accurate forecasting in the unstable climate. Unfortunately, there are no specific rules from World Meteorological Organization/ National Oceanic and Atmospheric Administration to handle the circumstance of an unstable climate, and the CBRFC and Reclamation are in unknown scientific territory when dealing with the situation. **Development of new guidelines concerning prediction of future runoff in an unstable and evolving climate should be considered for forecasting something as foundational as Lake Powell future conditions.**

Additionally, it is questionable to assume that consecutive severe droughts are not a possibility when forecasting for the next two years. The 'minimum probable' inflow scenario assumes the second water year's inflow is equal to the 25th percentile of the 1991-2020 inflow—and will be exceeded 75% of time in the forecasts. The cut off at the 25th percentile indicates drought, but the conditions this forecast considers does not seem to be sufficiently severe to capture current circumstances. The logic behind this assumption is that multiple years of extreme conditions in a row should not occur. However, in years 2000 to 2004, and the recent 2020 to 2021 inflow records, the reality of consecutive severe droughts has been clearly demonstrated. **We therefore suggest using 10th percentile data instead of 25th for forecasting in the second *water year.*** This change would allow for more capability in identifying severe water supply issues and would allow forecasts to capture the prolonged declines in reservoir storage that we have recently experienced (Fig. 7).

Implications for Water Resource Planning and Policy

Lake Powell operation conditions for the upcoming year are based on the end-of-calendar-year elevation as projected in August, **but the projections in the September and October 24 MS are significantly more accurate of future conditions than the August projections.** Figure 8 (lower panel) indicates that, for the 'most probable' inflow scenario, **there is more than a 75% chance for Lake Powell's actual January 1 elevation to be lower than projections made in August.** The highest overestimation is ~10 ft (approximately 1 maf of water when the elevation at Lake Powell is at 3600 ft asl). However, projection accuracy for January 1 improved significantly based on the September and October projections; overestimation was reduced to within ~5 ft. Results from either month would be a better indicator of potential future system conditions and using those more accurate results would allow a more accurate operational tier for Lake Powell for decision making purposes.

Similarly, May or June projections are more accurate than the April projections. April adjustments of Lake Powell operation conditions are based on the April projections of Lake Powell elevation on September 30. The middle panel in Figure 8 suggests that with the 'most probable' inflow scenario, the range between maximum and minimum Lake Powell elevation projections was ~40 ft—such a large range may lead to inaccurate adjustments for Lake Powell operation tiers. Except for the outliers, the forecast range was greatly reduced to ~20 ft based on the May projections and ~10 ft with the June projections; from an accuracy perspective, these two months would be more functional as mid-year adjustments.

Overestimations have not been uncommon occurrences during the past 10 years of forecasting, managers should be mindful that reality may be even drier than projections suggest. If past information is an accurate representation of future conditions, the 24 MS forecasts, with updated stress test hydrology, may become more accurate and chances of overestimation may be decreased. However, **if the current 1991-2020 reference period does not adequately predict future conditions, we continue to risk overpredicting future Lake Powell elevations.**

If the current 1991-2020 reference period does not adequately predict future conditions, we continue to risk overpredicting future Lake Powell elevations.

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