CBRFC Water Year in Review

An Overview of Operational Changes, Improvements, and Investigations over the course of Water Year 2023

October, 2024

National Oceanic and Atmospheric Administration (NOAA)

National Weather Service (NWS)

Colorado Basin River Forecast Center (CBRFC)

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1 INTRODUCTION

1.1 Purpose

This document, an annual product from the Colorado Basin River Forecast Center (CBRFC), describes the forecasting activities, research, and improvements undertaken by the CBRFC over the course of water year 2023. An overview of the climate and significant weather events and patterns is presented to provide context regarding the CBRFC's forecasts, with particular emphasis on volumetric water supply forecasts and efforts to improve those forecasts, especially in response to stakeholder needs.

The activities and results presented here are intended to be comprehensive, and some may be of interest to a narrow range of stakeholders. As such, any omissions are inadvertent, but may be incorporated into a future version of this document if the need arises.

1.2 Water Year 2023 Climate and Significant Weather Events

Following a drier than average 2022 water year, numerous concerns over the state of reservoirs within the Colorado River Basin and eastern portion of the Great Basin were paramount, and resulted in increased interest in early-season runoff forecasts and weather and climate conditions from both regional stakeholders and the national media. As late as May 2022, Lake Powell's surface water elevation fell to a historic low of just below 3,523 feet, which triggered mitigation efforts in the Upper Colorado River Basin to ensure that hydropower generation could continue at Glen Canyon Dam (minimum power pool at Glen Canyon Dam is 3,490 feet). Approximately 500 KAF of water was released from Flaming Gorge Reservoir, and approximately 480 KAF of scheduled releases were withheld from Glen Canyon in an effort to ensure continued hydropower generation through water year 2023. In the Great Basin, the Great Salt Lake fell to a record low level in November, 2022 (approximately 4,188 feet) prompting numerous calls to action to mitigate a developing ecological disaster.

water year 2023 provided a much needed reprieve, as record setting precipitation and snowpack accumulation resulted in well above normal runoff for both the Colorado River Basin and Great Basin. This was the result of a series of unusually active and strong atmospheric river events that brought precipitation to much of California, the Great Basin, and Colorado River Basin (Figure 1). The unregulated seasonal (April through July) inflow volume into Lake Powell was calculated to be 10.619 MAF (166% of average) and Lake Powell's surface water elevation rose

approximately 50 feet over the course of the runoff season. The Great Salt Lake saw a rise of approximately 5.5 feet and the filling of many reservoirs on its tributaries. While the record-setting year in no way reversed the impacts of persistent and severe drought experienced in the region over the past 20 years, it did alleviate some concerns regarding water supply and hydropower generation in the short-term.

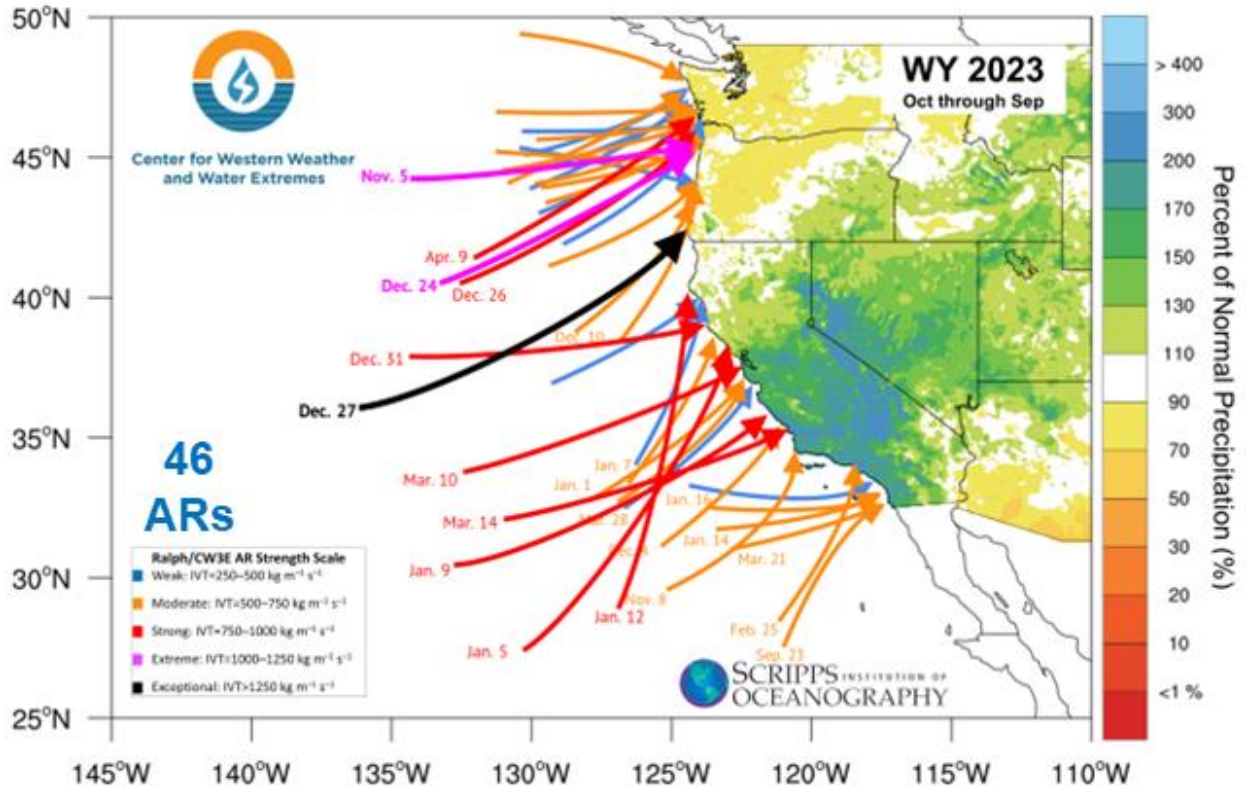

Figure 1: This graphic, from the Center for Western Weather and Water Extremes, shows the impact of 46 atmospheric weather events over water year 2023. These events brought much above normal precipitation to much of the American West.

The 2023 water year began with frequent storm events impacting the Lower Colorado River Basin during the first half of October. Later in the month, the storm track shifted, bringing much-needed snowfall to the Upper Colorado River Basin and Great Basin. November was calmer, as storms primarily impacted much of Utah, southwestern Wyoming, and northwestern Colorado. It was December that set the tone for the rest of the water year, as storm events brought precipitation nearly every day of the month, resulting in precipitation amounts generally in the top 10 of the historical record at Upper Colorado River Basin SNOwpack TELemetry (SNOTEL) locations maintained by the Natural Resources Conservation Service (NRCS), with record and near record amounts of precipitation being recorded in the Green River Basin and

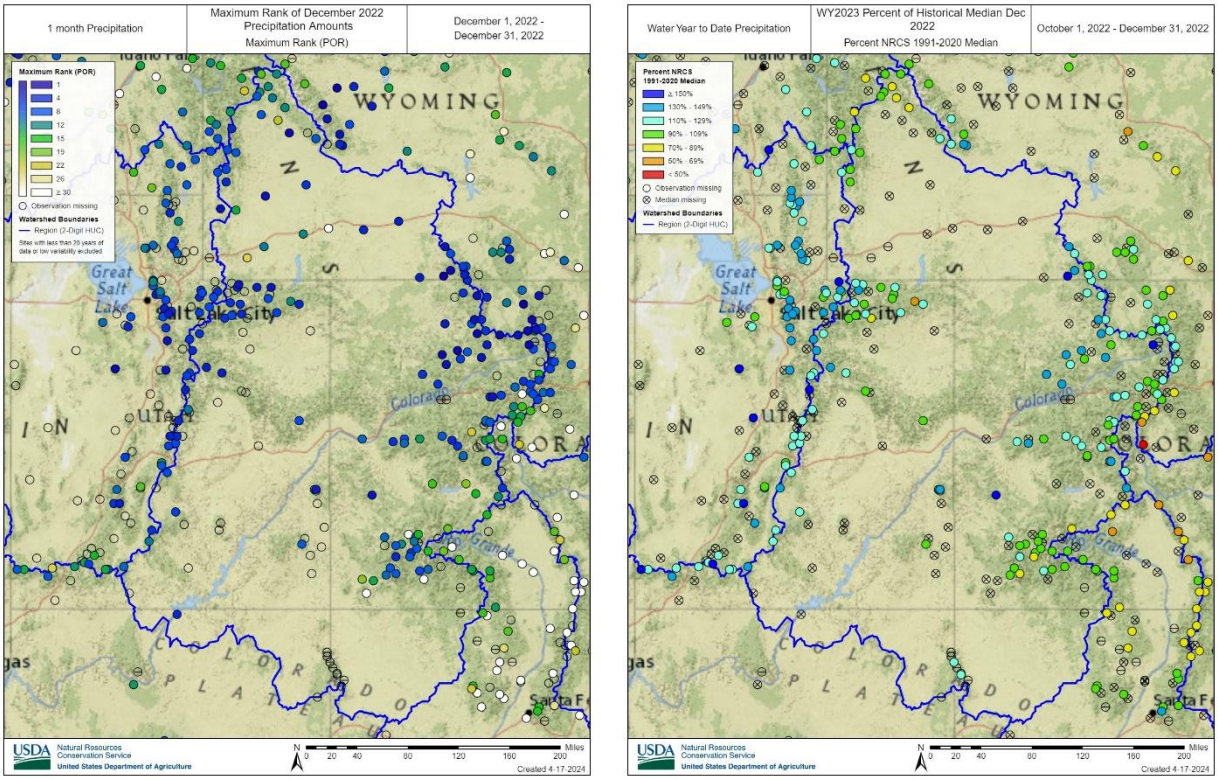

Figure 3: The figure on the left shows the maximum rank of December 2022 precipitation amounts over area SNOTEL locations in the Upper Colorado and Great Basin regions. The figure on the right shows water year 2023 to date (October through December) over the same region; water year to date values are generally near 120% of normal at this point.

near the Colorado River Headwaters (Figure 3). The first official water supply forecasts from the CBRFC issued in January were generally at or near average throughout the Upper Colorado River Basin and above average through the Great Basin. The CBRFC's area experienced heavy precipitation in January 2023, with most basins receiving over 300% of average precipitation (Figure 2). December 2022 and January 2023 combined ranked as one of the wettest 2-month periods on record for much of the area. This period of active precipitation continued into February and March, with above-average precipitation events accompanied by colder-than-normal temperatures that rarely reached normal daily highs (Figure 4). These cooler

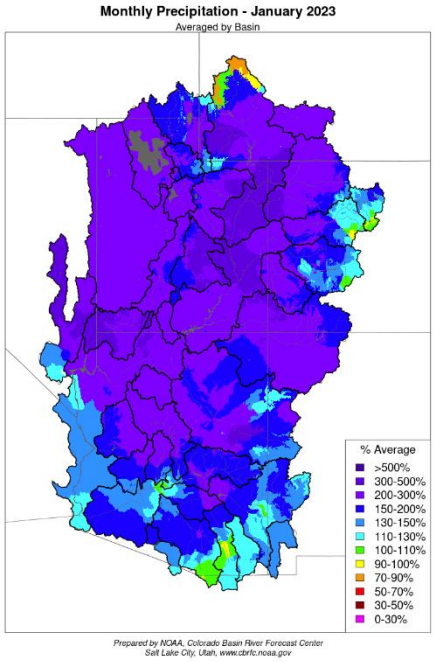

Figure 2: Most basins over the CBRFC's area of responsibility experienced over 300% of average precipitation in January, 2023.

temperatures aided in snowpack accumulation across the Colorado River Basin and Great Basin, even at higher elevations throughout Arizona.

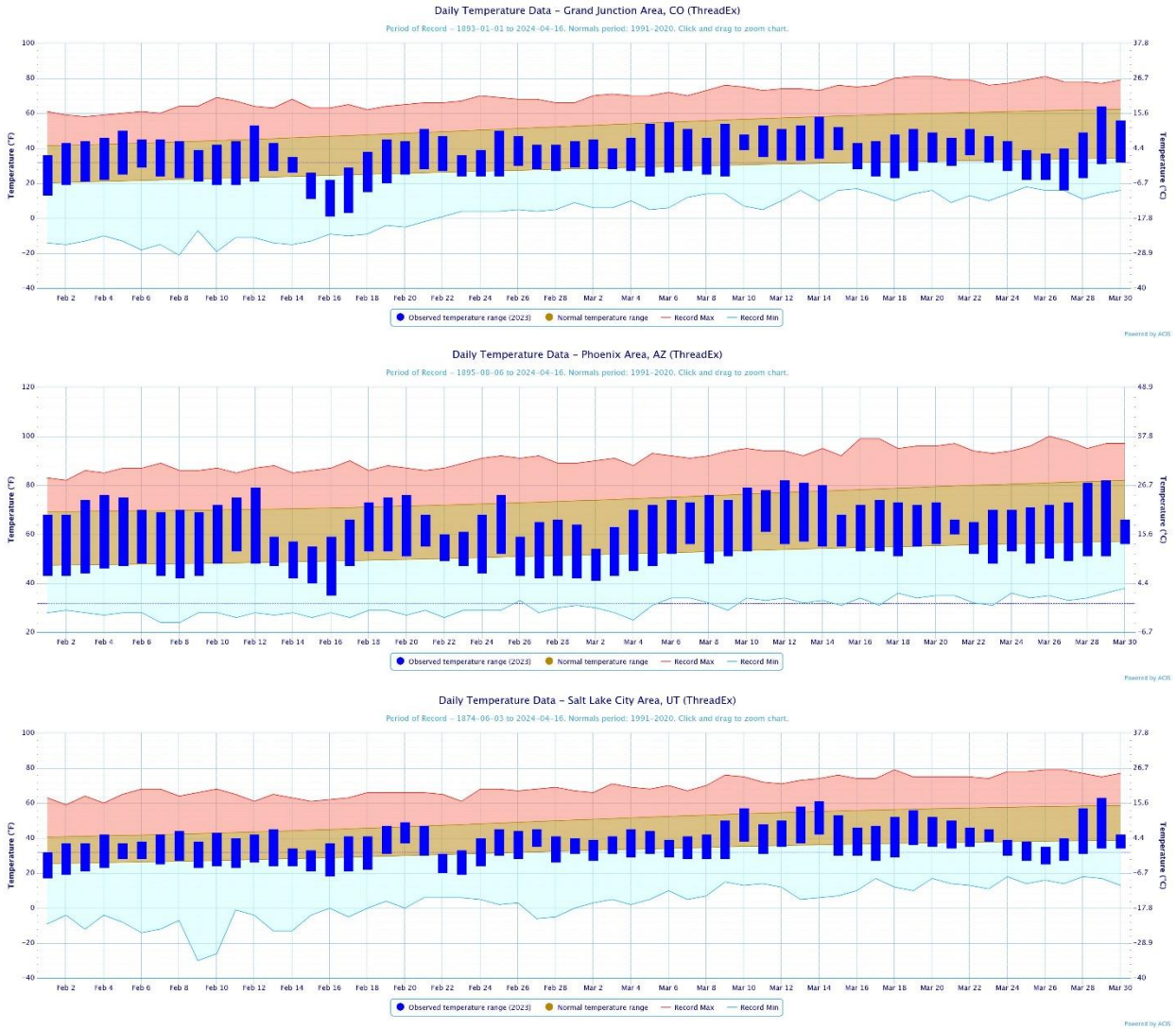

Figure 4: Daily temperature profiles spanning February 1 through March 30, 2023 for the Grand Junction, CO area (top), Phoenix, AZ area (middle), and Salt Lake City, UT area (bottom). Temperatures rarely exceeded normal highs, but were frequently cooler than normal.

April 1st snowpack amounts over the Colorado River Basin and Great Basin were among the highest on record, particularly over the eastern Great Basin and Lower Colorado River Basin. Record and near-record conditions were observed near the headwaters of the Yampa and Colorado Rivers, as well as parts of the Gunnison and San Juan River Basin (Figure 6). As a result, April 1 forecasts from the CBRFC were well above average over the CBRFC's area of responsibility, with some record-high forecasted values over the Great Basin (Figure 5).

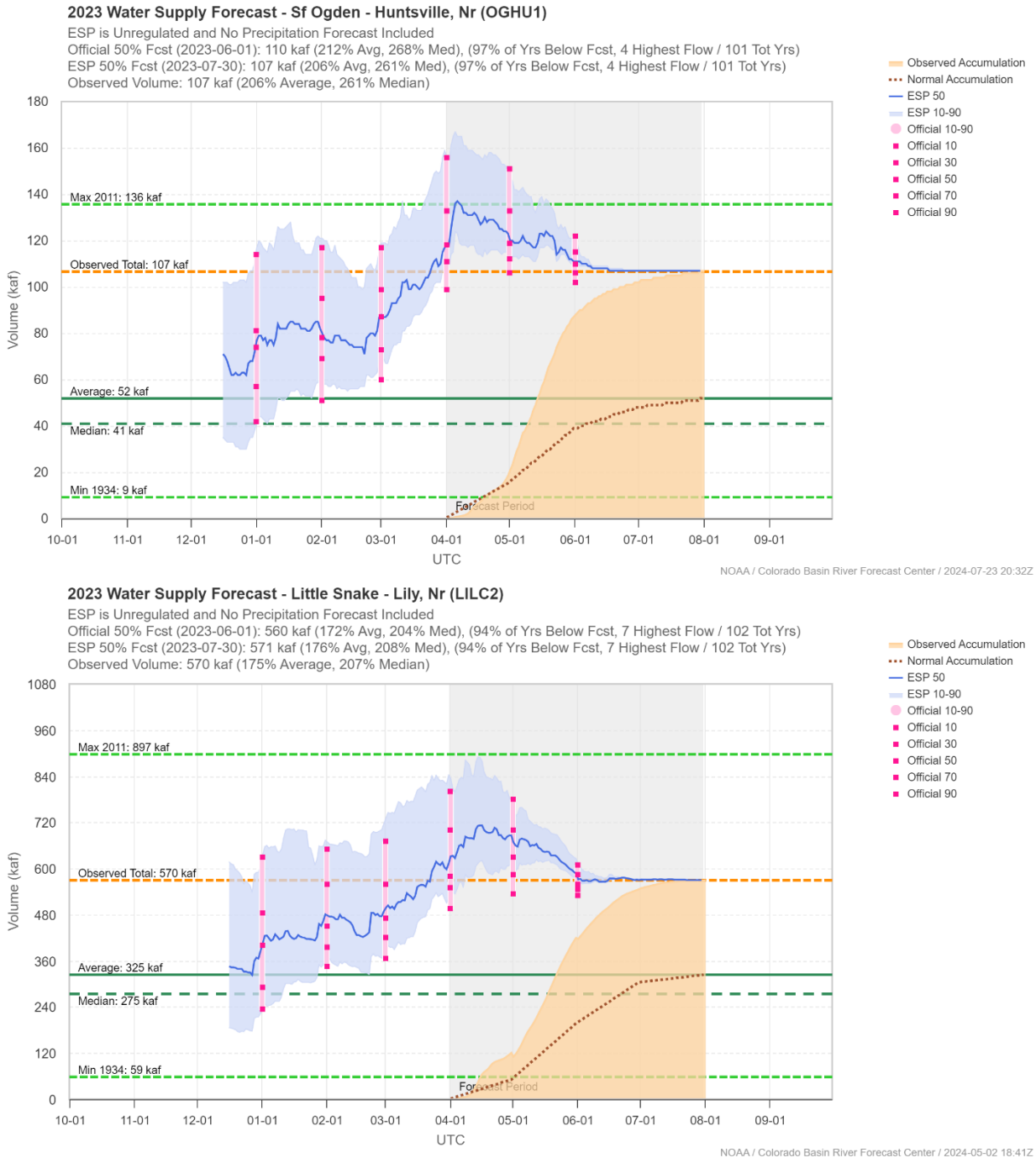

Figure 5: The top figure illustrates the evolution of water supply forecasts at the Big Cottonwood Creek near Salt Lake City, Utah (BCTU1); the median official April 1 forecast is above the maximum observed volume from 2011. The bottom figure illustrates the evolution of water supply forecasts at the Little Snake River near Lily, Colorado location; while not forecasted at record levels, the April 1st forecast was still significantly above average.

1.2.1 Threat of Flooding and Mitigating Conditions

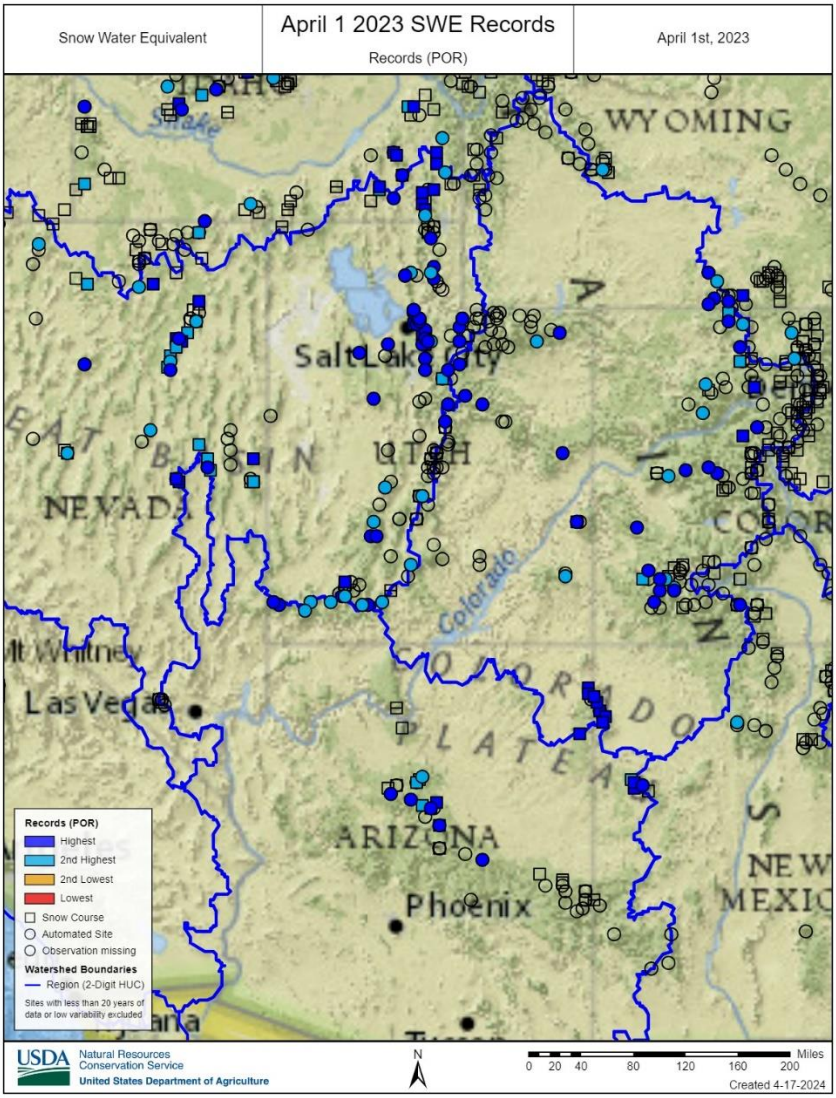

Figure 6: Record and near-record April 1 SWE values were observed over much of the Great Basin, and parts of the Colorado River Basin.

The CBRFC produces forecasts of seasonal peak flow values to aid in the assessment of flood threat potential throughout the basin. It is important to note that these peak flows are the result of snowmelt driven runoff, and precipitation and temperature play a significant role in the realization of these events. Due to the well above average snowpack conditions throughout the Upper Colorado River Basin and Great Basin regions, many areas were forecasted to reach flood stage in excess of 25% probability; and some locations showed the likelihood of exceeding flood stage to be greater than 50%. Anecdotally, the risk of exceeding flood stage in some areas was exacerbated by flood control conveyance systems that had not been maintained over the years and had been affected by fire-related debris flows and vegetation growth.

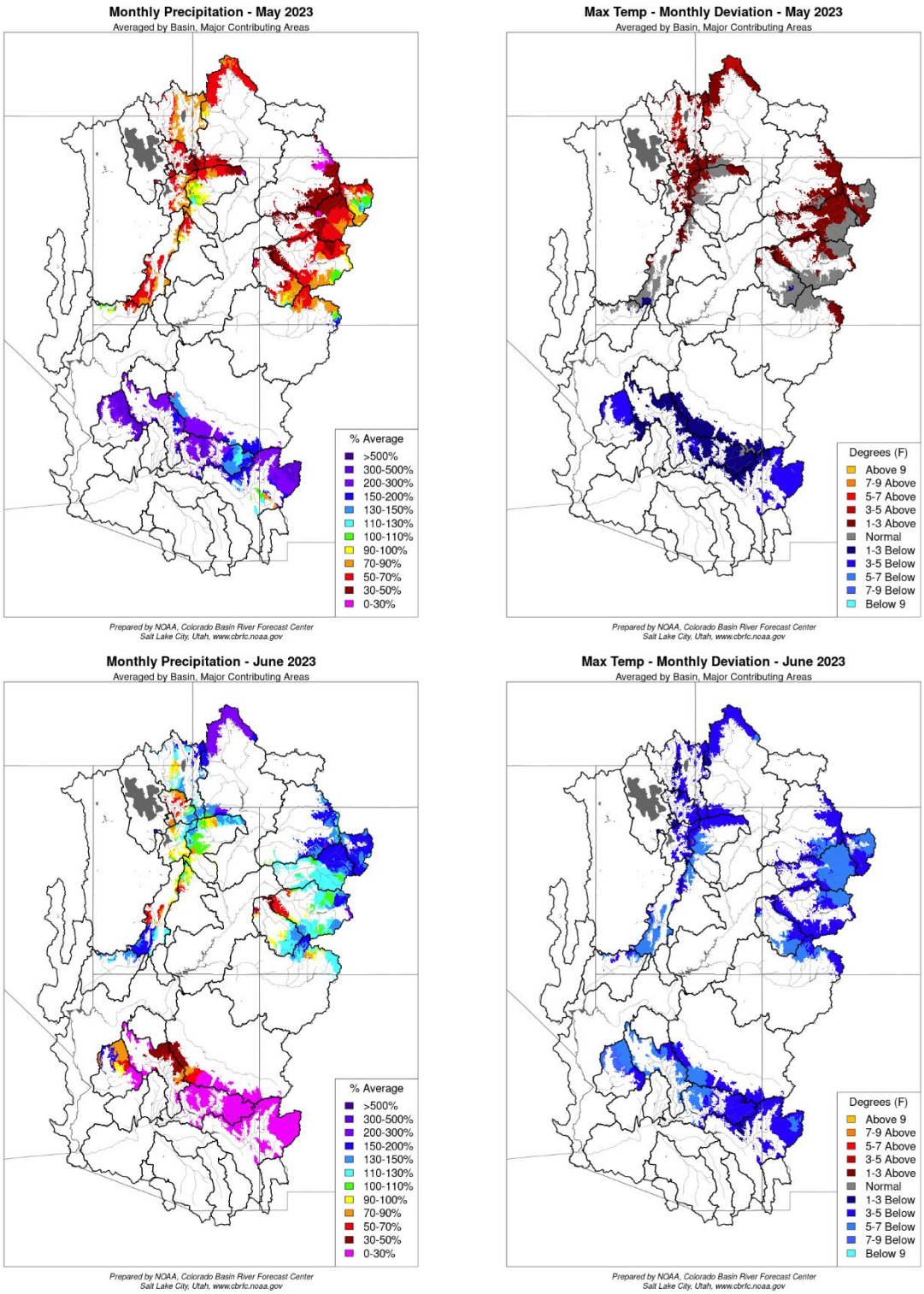

Figure 7: May (top row) brought drier conditions and near to slightly above average temperatures. While June (bottom row) was wetter, temperatures were below average, slowing snowmelt rates and mitigating flooding. These maps depict conditions in the areas that contribute the vast majority of snowmelt runoff

Fortunately, widespread flooding was largely avoided. While the Great Basin experienced some flooding, particularly in the Bear River Basin, drier conditions arrived in May with only slightly above average temperatures. This was followed by a much cooler than normal June, which slowed the snowmelt rate and mitigated the potential for widespread flooding (Figure 7).

1.2.2 Verification of Lake Powell Forecast and Impacts to Lake Powell and Lake Mead

The observed unregulated seasonal (April through July) inflow into Lake Powell for water year 2023 was 10.619 million acre-feet, or 166% of average. Water year 2023 was the 12th wettest on record (dating back to 1964), which coincides with just under the 10% exceedance value over the historical record (approximately 13% exceedance). In January, the 10% exceedance value forecasted was 11.53 million acre-feet. Through the March forecast, the 10% exceedance value was near 11 million acre-feet. After the historically wet March, the median April forecast rose to 11.3 million acre-feet before declining and meeting the observed volume. Considering the final observed value and the historically wet March, the water supply forecasts at Lake Powell verified very well (Figure 8).

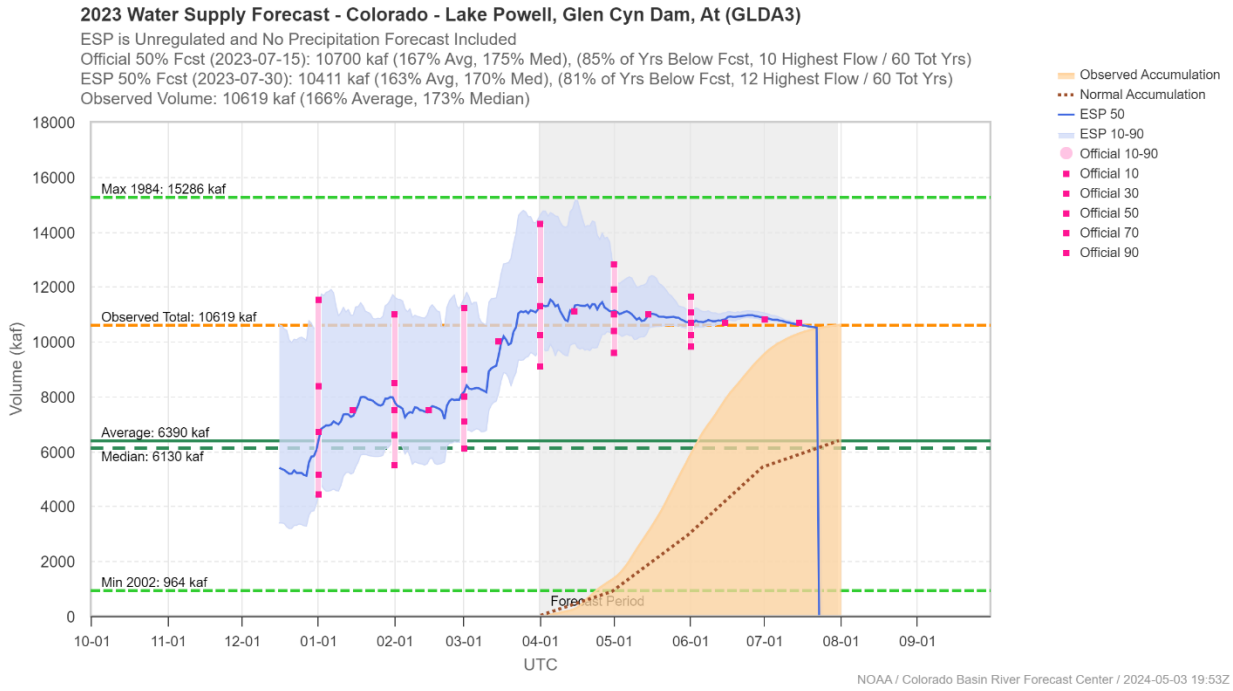

Figure 8: This figure illustrates the evolution of the water supply forecast at Lake Powell at Glen Canyon Dam. Initial forecasts in January through March appropriately captured the placement of the final observed volume, and after a historically wet March, forecasts were within approximately 5% of the observed volume.

Reclamation utilizes CBRFC forecasts to aid in the determination of reservoir operations throughout the Colorado River Basin. Due to the much above average runoff throughout the Colorado River Basin this year, Lake Powell's surface water elevation rose nearly 60 feet from April through July. Lake Mead, in response to increased releases from Glen Canyon Dam and decreased downstream use due to storm events, rose nearly 20 feet by the end of the water year[1].

2 Summary of Major Water Year 2023 Improvements

The CBRFC constantly evaluates and works to improve its hydrologic model and methodology, including updating calibrations of specific forecast points when necessary. Additionally, there were several operational improvements at the CBRFC impacting a broad range of stakeholders that will be summarized here, and discussed in more detail in the sections that follow. This year, improvements have been broken down into the following categories:

- New Impact Based Decision Support Services (Section 3)
- Research, Investigations, and Collaborations (Section 4)

[1] Much of this information has been taken from issuances of Reclamation's 24-Month Study Report. The current and archived reports are available at: https://www.usbr.gov/lc/region/g4000/24mo/index.html

Over the course of water year 2023, the CBRFC worked to provide forecasts to new and traditional stakeholders to meet their decision support goals. In particular, the CBRFC worked closely with the Salt Lake City Weather Forecast Office and partners at the National Park Service to provide increased guidance regarding flooding issues at Zion National Park and investigated trends in forecast accuracy in the Upper Colorado River Basin and Great Basin.

3 New and Enhanced Methods to Improve, Communicate and Distribute Forecasts

3.1 Development of an Improved Methodology to Support National Park Service Risk Management over the Subway Trail at Zion National Park

In early 2023, the National Park Service (NPS) contacted the Salt Lake City Weather Forecast Office (SLC) asking for additional support and guidance regarding closure of the Subway Trail in Zion National Park. The Subway Trail is impacted by flows at North Creek, and high flows driven by snowmelt runoff in the area have led to numerous search and rescue events (SARs) over the past decade. Traditional NPS guidance has closed the Subway Trail when SWE amounts at the nearby Kolob SNOTEL site have exceeded 35 inches on April 16th; the trail remained closed until SWE values fell below 10 inches. The NPS asked for guidance that could more reliably limit the number of SARs on the Subway Trail.

Since there is no gage data available over North Creek within the Subway Trail, the CBRFC and SLC worked with the NPS to correlate historical SAR events with snowpack information at both the Kolob and Webster Flat SNOTEL sites, as well as modeled snowpack information near the North Fork of the Virgin River. The CBRFC found that melt rates approaching the first percentile of the historical record, combined with SWE thresholds at Kolob (32 inches) and Webster Flat (26 inches) SNOTEL stations correlated to an increased risk of SAR events. SLC communicated this information and coordinated implementation efforts with the NPS.

The NPS implemented the guidance recommended by SLC and the CBRFC on a test basis due to the well above average snowpack conditions in the area. The CBRFC provided periodic updates to the NPS as melt rate thresholds and SWE values were met. On April 8th (8 days earlier than traditionally implemented guidance), the Subway Trail was closed based on information provided

to the NPS by the CBRFC. NPS personnel confirmed higher flows in North Creek corresponding to CBRFC forecasts at the North Fork of the Virgin River.

SLC followed up with the NPS regarding their experience using CBRFC guidance. The NPS responded that they found the information very beneficial and will likely work towards officially updating their closure guidance to use CBRFC information; most importantly, despite the record snowpack and high flows, there were 0 SAR events on the Subway Trail this year. Analysis and communication by the CBRFC and SLC with the NPS was integral in ensuring the success of this project.

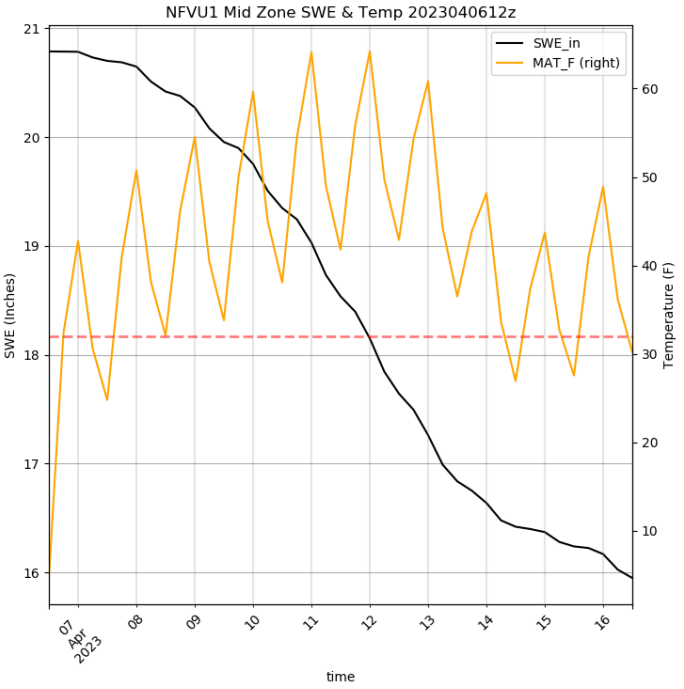

Figure 9: This figure illustrates forecasted temperatures and modeled snowmelt over the North Fork of the Virgin River Basin. This information was key to informing safe closure of the Subway Trail at Zion National Park

3.2 Development of an Improved Stakeholder Engagement Meeting

Prior to 2023, the last Stakeholder Engagement Meeting hosted by the CBRFC was held in October, 2020 and was strictly a virtual meeting due to the COVID-19 pandemic. Due to the nature of the virtual meeting format leading to a lack of engagement, the CBRFC's annual stakeholder engagement meeting was postponed until 2023.

Instead of a traditional meeting format with presentations held in a meeting room with little movement or opportunities for conversations in small groups, the 2023 stakeholder broke attendees into small groups to participate in four stations. Each station focused on various aspects that have been of recent interest to registrants and the broader stakeholder community. The revised format increased participation from registrants and was found to be more enjoyable

and informative than past stakeholder engagement meetings. Presentation materials and agenda can be found on the CBRFC website here[2].

3.3 Improvements to Peak Flow Webpage

Due to the historic amount of snowpack observed over the Upper Colorado River Basin and Great Basin, forecasted snowmelt driven runoff was projected to be unusually high; as such, the potential of exceeding flood stage at many locations was increased. In an effort to provide additional impact-based decision support to area WFOs and others impacted by high flows and increased flood potential, the CBRFC redesigned its peak flow webpage to simplify and clarify the products. This includes:

- Tables showing exceedance probabilities, a snapshot of the latest peak flow forecast information, and how the current year's peak flow forecast ranks among other years

- Simplified combined plot of the daily forecast probabilities, and current simulation of the flow at the location of interest (Figure 10)

Stakeholder feedback on the redesigned page was overwhelmingly positive.

[2] For those unable to access the hyperlink: https://www.cbrfc.noaa.gov/present/2023/forum/2023forum.htm

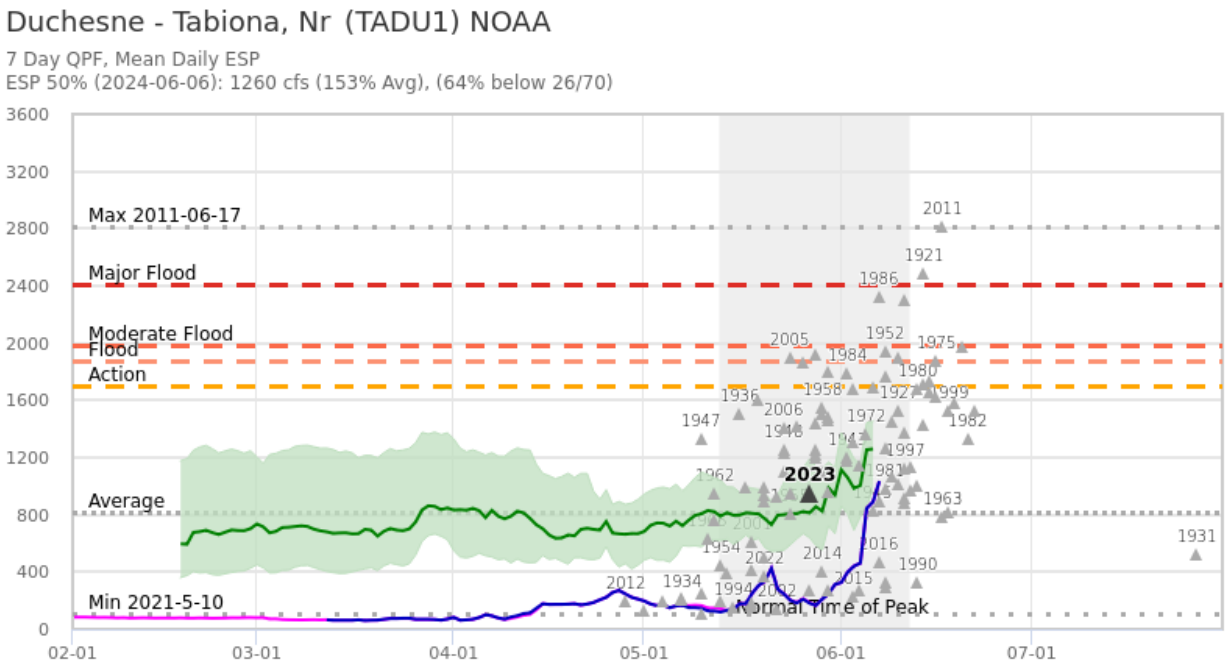

Figure 10: Example of redesigned peak flow graphic.

3.4 Implementation of HEFS and National HEFS Demonstration Page

The goal of the NWS Hydrologic Ensemble Forecasting Service (HEFS) is to improve the probabilistic forecast time horizon from traditionally issued weeks to seasons to new products and services that span hours to years depending on forecast input. Particularly with regards to short-term forecasts, HEFS forecasts would present probabilistic information that captures uncertainty in deterministic forecasts. HEFS forecasts are developed using precipitation and temperature forcing data from the Global Ensemble Forecast System (GEFSv12) and range in lead time from 15 days to potentially 35 days. The CBRFC was able to implement and make publicly available HEFS forecasts spanning the entire CBRFC area of responsibility (Figure 12).

The CBRFC also took the lead on developing, hosting, and maintaining a national HEFS landing page for the NWS. The page is available here[3] (Figure 11).

[3] For those unable to access the hyperlink: https://www.cbrfc.noaa.gov/dbdata/station/ensgraph/map/ensmap.html

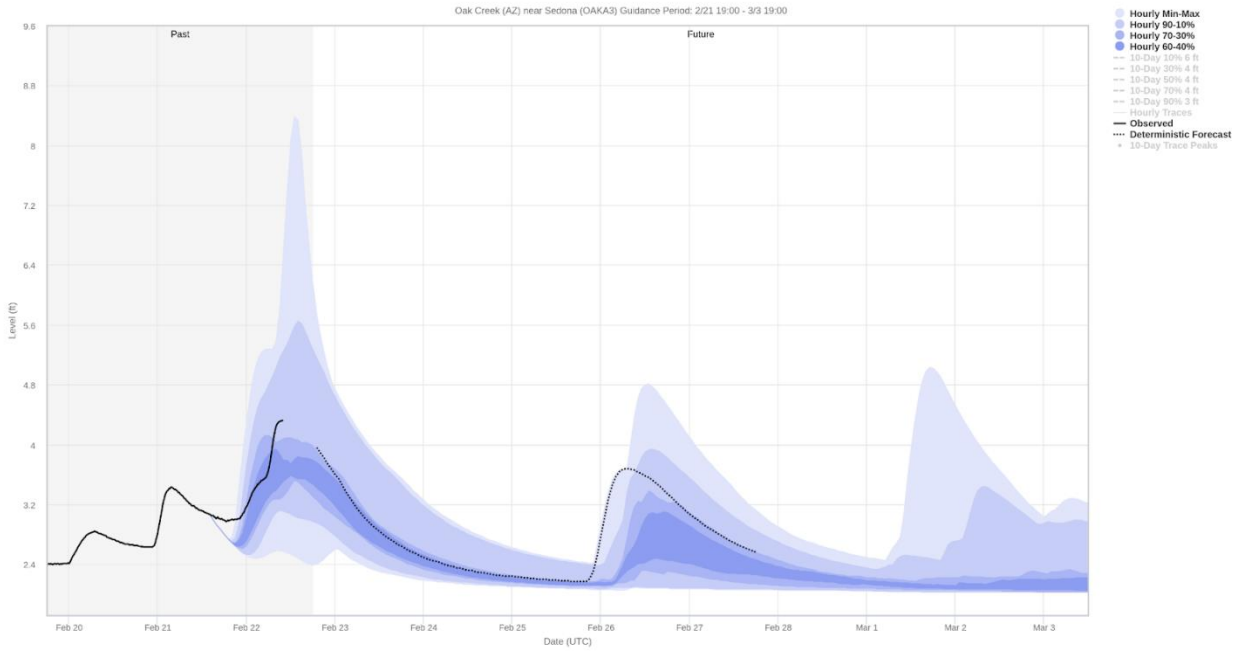

Figure 12: An example of a 15-day HEFS forecast issued for the Oak Creek near Sedona forecast point (OAKA3). The CBRFC deterministic forecast is in black.

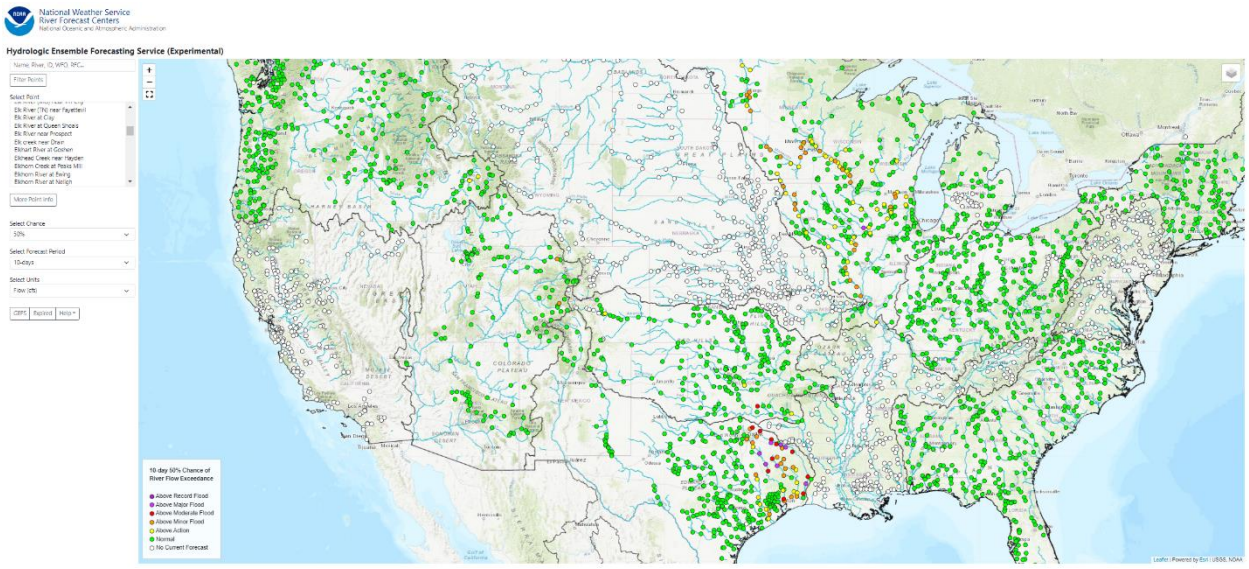

Figure 11: A screenshot of the National HEFS demonstration page developed, hosted, and maintained by the CBRFC.

4 Research, Investigations, and Collaborations

4.1 Investigation Into the Historical Trend of Forecast Performance – Are CBRFC Forecasts Getting Worse?

Recent perception from some water users and stakeholders over the Colorado River Basin has been that forecast accuracy from the CBRFC has been declining due to climate change. In an effort to address these concerns, the CBRFC examined mean absolute error, by month, from past issued forecasts over Upper Colorado and Great Basin forecast points. Using 139 historical forecasts, forecasts generally improve month to month, as SWE accumulation becomes better known and seasonal weather variability decreases with time (Figure 13). A similar trend was found when mean absolute error was assessed by forecast group (Figure 14).

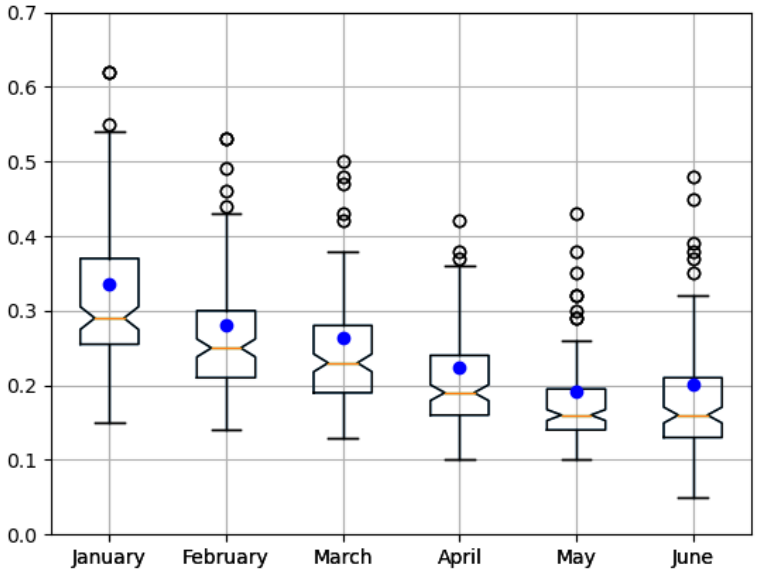

Figure 13: The above figure shows the percent mean absolute error (y-axis) against forecast month issuance. Average percent mean absolute error (blue dot) and median percent mean absolute error (orange line) decrease as the season progresses.

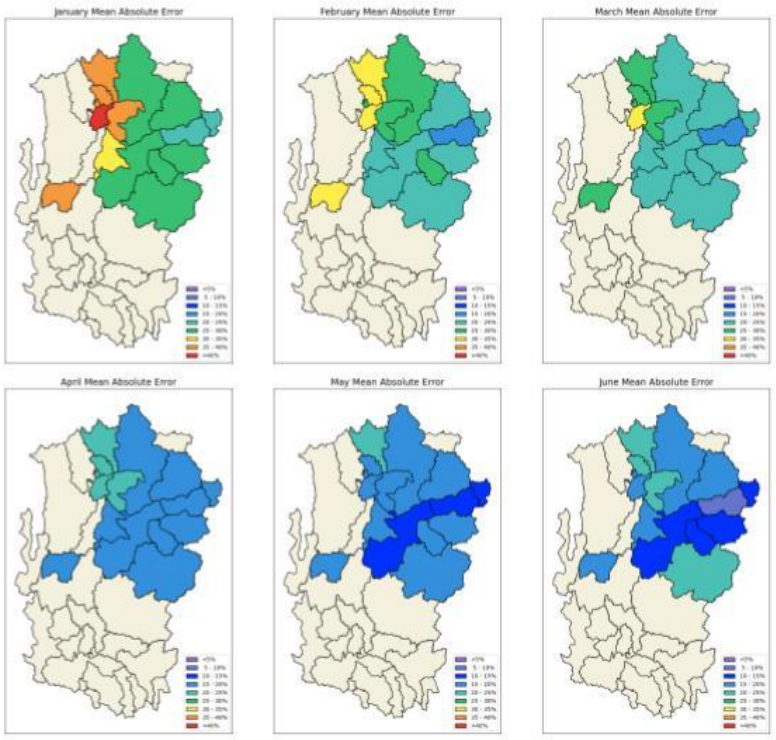

Figure 14: Percent mean absolute error by forecast group from January through June.

The trend in forecast accuracy was also investigated. Overall, no significant trend in error was observed at any forecast point throughout the Upper Colorado River Basin and Great Basin at the 95% confidence interval. An increasing trend in forecast error was calculated mostly over the San Juan River Basin in January; however, this trend is reduced in February, and not apparent by March. In June, there is some scattered decreasing trends in error throughout the basin (Figure 15).

4.2 Coordination with Reclamation to Advance Snow-Related Research and Activities

Reclamation received funding from Congress to work with NOAA and the NRCS on the advancement of snow-related projects which would aid in the progression and development of SWE data and models that would presumably lead to more skillful and accurate hydrologic modeling over the Western United States (including the CBRFC's area of responsibility). The

CBRFC worked with past research partners to develop scopes of work that were ultimately funded by Reclamation. These projects are funded typically through 2 years and will begin in early 2024.

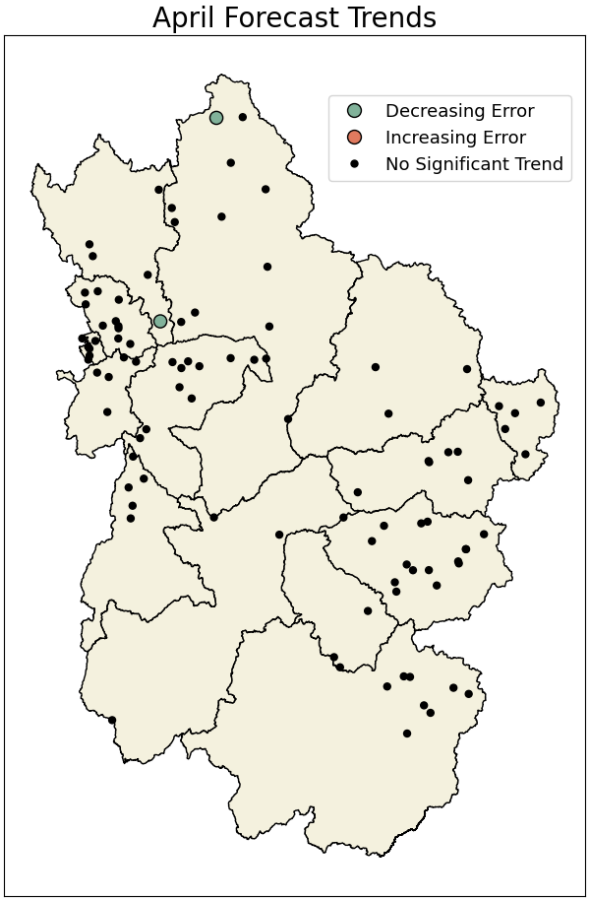

Figure 15: There has been no trend in forecast accuracy for those forecasts issued in April at the 95% confidence interval for the vast majority of stations over the Upper Colorado River Basin and Great Basin regions.

4.2.1 Development of a Snow Water Equivalent "Landing Strip" for Use Towards Improved CBRFC Water Supply Forecasts

This project, in cooperation with Boise State University, builds needed research capacity at the CBRFC by funding a research hydrologist to work closely with CBRFC hydrologists to further develop a physically based, energy-balance snow model (iSNOBAL). The research hydrologist and CBRFC are developing a framework and associated metrics to quickly and objectively evaluate multiple SWE datasets, including, but not limited to those currently developed and in development, and solutions obtained through Reclamation's recent prize competition ("Snowcast Showdown"). This evaluation of datasets is complementary to efforts described in Section 4.2.3 as it will serve as foundational information for which SWE datasets are skillful and applicable for CBRFC hydrologic models. Further, a physically based snow model will develop data and information that Project 3 can utilize to calibrate and develop a distributed hydrologic model. Additionally, the framework developed to evaluate SWE datasets will also allow for the implementation of recommendations found through the project described in section 4.1.2 to be easily and quickly implemented. Pathways to implementing datasets and models shown to be adding skill to CBRFC products will be developed and shared with other RFCs.

4.2.2 Improving the Use of An Energy-Balance Snow Model (iSNOBAL) through the Use of Remotely Sensed Cloud Cover and Radiation

The CBRFC has been working with the University of Utah to evaluate the use of iSNOBAL operationally. This project would continue that collaboration with the University of Utah and further the development of the operational framework that utilizes iSNOBAL through the incorporation of remotely sensed surface and atmospheric variables (i.e. cloud cover and net radiation) through the activities of two postdoctoral researchers. The goal of this project would be to continue advancing the use of physically based and distributed modeling capability to improve water supply forecasts at the CBRFC. Data would be daily, at a minimum, for CBRFC forecasters to compare current model results and fluxes. It is anticipated that this work would be transferable and scalable to other RFCs in the Western U.S. The work in this project would complement efforts in Project 1, as it would continue the development of the operational framework, which would be quickly implemented and evaluated through activities in the project described in section 4.1.1. The further development of the operational framework would be beneficial to evaluating datasets developed through efforts completed through the project described in section 4.1.3. It is anticipated that the model and implementation strategies developed through this project would be scalable to other RFCs.

4.2.3 Application of real-time and derived snow water equivalent data for water resources decision-making at the Colorado Basin River Forecast Center

There have been numerous efforts recently to improve gridded estimates of SWE, through various methods (e.g., satellite imagery, low-flying aircraft operations, modeled data which incorporates a variety of gage and other observations, etc.). The goal of this project, in collaboration with RTI, would be to utilize machine learning (ML) algorithms to develop a framework that would merge available SWE datasets for operational use by the CBRFC. An emphasis of this project would be to not only develop a SWE dataset that leverages the strengths of available SWE datasets to produce an accurate representation of SWE over the CBRFC's area of responsibility, but also a SWE dataset that improves the skill of the CBRFC's operational hydrologic model; that is, this project would produce a dataset that is representative of regional SWE conditions and also most appropriate for the CBRFC's modeling paradigm. The project would be able to use information developed from the project described in section 4.1.1 to identify skillful SWE datasets, and projects described in section 4.1.1 and 4.1.3 would be able to

utilize information developed from this project to assess its impact to CBRFC products and forecasts. It is anticipated that the methodology developed through this project would be scalable and transferable to other RFCs.

4.2.4 Expanding Distributed Modeling in the River Forecast Centers

The proposed projects revolve around improving methods that would aid in the progression and development of snow water equivalent data and modeling that would presumably lead to more skillful and accurate hydrologic modeling over areas in the Western United States. One common thread in all the projects is the use of distributed data — in particular, the iSNOBAL project employs a distributed snow model to take advantage of distributed inputs and snow observations. The western RFCs (i.e., CBRFC, CNRFC, and NWRFC) currently employ lumped snow and soil moisture hydrologic models for operational forecasting. The current form of the existing hydrologic models requires simplifications of the distributed snow estimates to allow application to the underlying soil moisture models. It is anticipated that advancing the soil moisture modeling towards more distributed forms will better utilize the enhanced SWE estimates and improve forecasts in the western USA. This scope of work, proposed by and in collaboration with RTI, focuses on evaluation and application of distributed soil moisture modeling coupled with the enhanced snow products generated by the accompanying projects. Implementing the distributed soil moisture model will include evaluating NextGen National Water Model components, particularly the national HydroFabric which is an enhanced version of the National Hydrology Dataset with fine resolution sub-basin delineations with associated basin characteristics. Additionally, this project will include setting up the distributed models in CHPS, model calibration, exploration of scale, sub-basin distribution, model structure, and evaluation.

4.3 Participation in NWS Dam Break Mutual Aid Group

NWS WFOs have the responsibility for issuing public watches and warnings related to dam failures or potential dam failure; additionally, RFCs play an important support role such as providing forecast information from dam break tools and hydrologic models. This may include routing forecasted or actual flows after a dam failure through the RFC hydrologic model to provide downstream guidance to area WFOs. An RFC may use a local dam break model or information from an Emergency Action Plan to aid in this effort. RFCs also provide advice,

training and expertise to WFOs as needed to support the issuing of flood products. The CBRFC partnered with WFO and RFC personnel nationwide to develop and participate in a Dam Break Mutual Aid Group to supplement the RFC response to a dam break, find or build the tools needed, and modernize the dam break response workflow.

4.4 Methodology for Improving ESP Uncertainty Bounds

Over the course of developing probabilistic water supply forecasts, the CBRFC's ESP methodology captures uncertainty in the forecast due to future weather; however, the ESP methodology does not account for error associated with the model (e.g., uncertainty in the hydrologic state or model parameterizations and structure). Future weather variability decreases with time as forecasts approach the end of the forecast period (i.e., April through July for most CBRFC locations); as such, the probabilistic bounds can become unrealistically narrow and forecasters have relied on historical information to increase the probabilistic bounds late in the water supply forecast season. CBRFC hydrologists have made adjustments manually to the bounds of the official water supply forecasts, which is time consuming and, in some cases, a little arbitrary. Through the analysis of historical daily and annual error, the CBRFC developed an empirical distribution of model error for each forecast point. This distribution is then randomly sampled to account for and add error due to model uncertainty to the probabilistic bounds of CBRFC water supply forecasts (Figure 16).

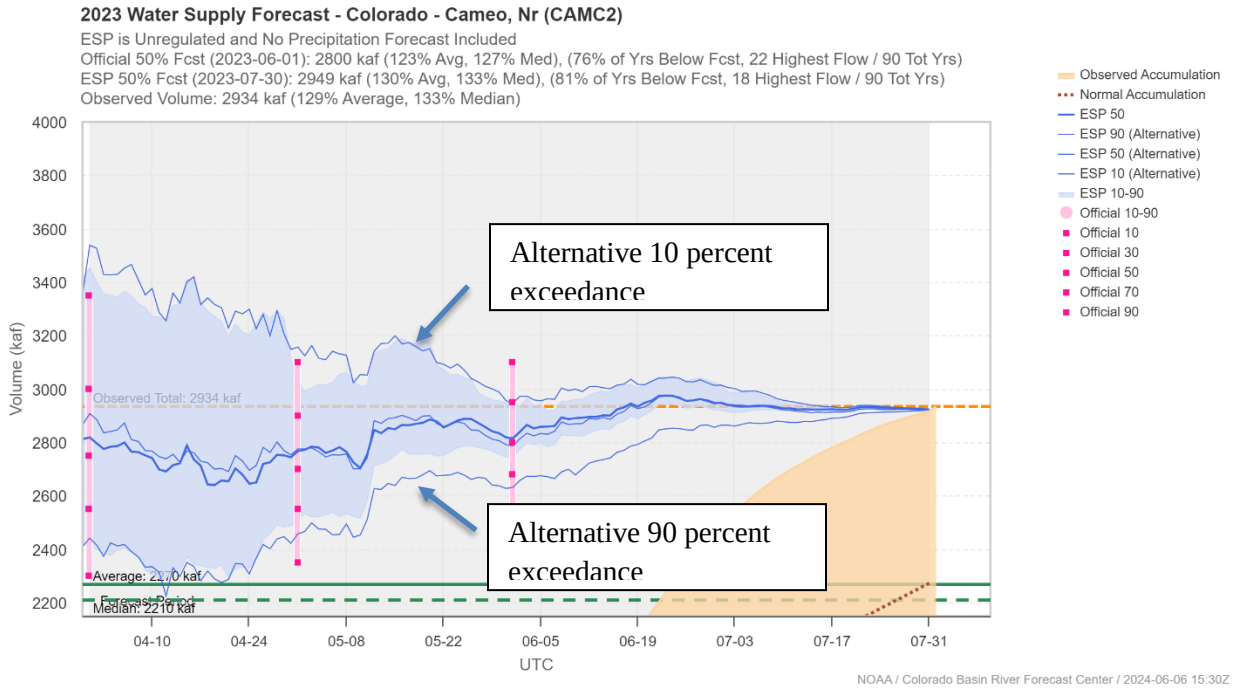

Figure 16: This example from the 2023 water supply season shows alternative 10 and 90 percent exceedance lines informed through the addition of model error.