CBRFC Water Year in Review

An Overview of Operational Changes, Improvements, and Investigations over the course of Water Year 2021

October, 2022

National Oceanic and Atmospheric Administration (NOAA)

National Weather Service (NWS)

Colorado Basin River Forecast Center (CBRFC)

Table of Contents

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 2021. An overview of the climate and significant weather events and patterns are 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 2021 Climate and Significant Weather Events

Persistent drought conditions dating back to 2000 have driven hydroclimatic conditions over the Colorado River Basin to historically dry conditions, and continued dry conditions over Water Year 2021 exacerbating strained water resources throughout much of the basin. Notably, the combined reservoir storage between Lake Powell and Lake Mead fell to 32% capacity by the end of Water Year 2021, the lowest combined storage since Lake Powell was initially filled in 1980 (Figure 1).

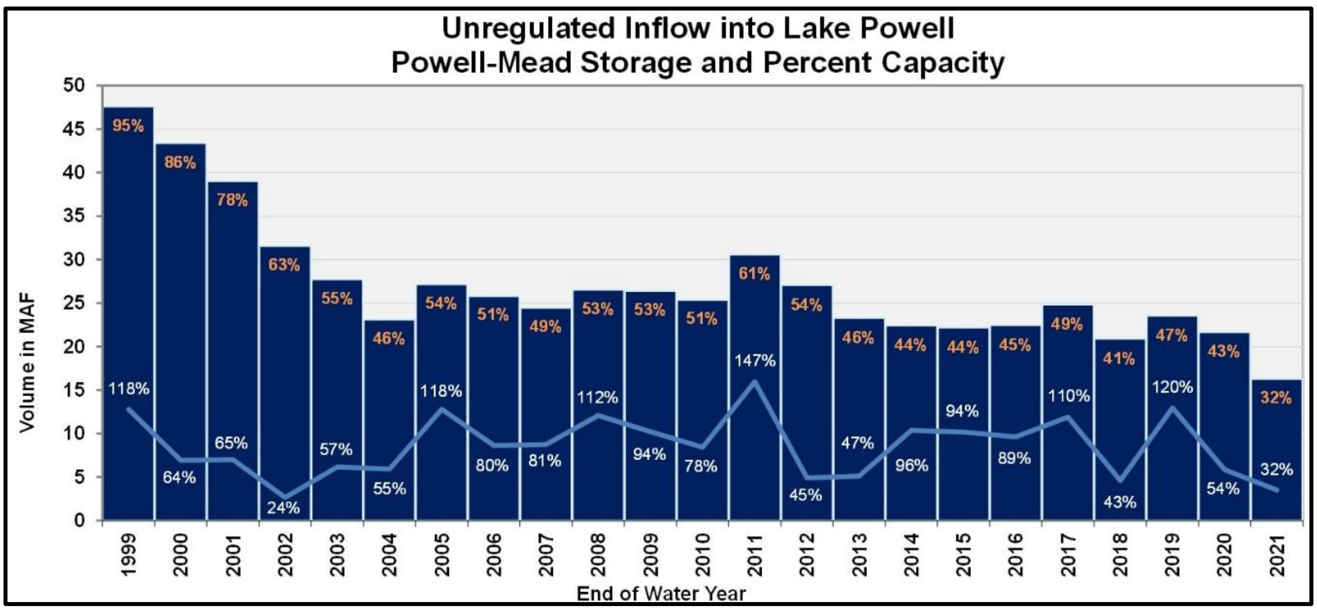


Figure 1: This figure, from the Bureau of Reclamation's Lower Colorado Region's Boulder Canyon Operations Office, shows the combined reservoir storage between Lake Powell and Lake Mead in blue columns. The percent capacity between the two reservoirs is in orange type. Unregulated inflow values, developed by the CBRFC, are illustrated in the light blue line with associated white text as a percent of the 1981-2010 average.

Water Year 2020 precipitation and streamflow conditions tended to be well below average over most areas in the Upper Colorado River Basin, and a historically dry monsoon period over the Lower Colorado River Basin contributed to dry antecedent soil moisture conditions over the CBRFC's area of responsibility (Figure 3). Modeled Fall 2020 (i.e. early Water Year 2021) soil moisture conditions were among the driest spanning the 1981 through 2020 period. Dry antecedent soil moisture conditions result in decreased runoff efficiency; a recent analysis by the CBRFC indicated that each 1.0% decrease in fall soil moisture conditions reduced annual runoff volume by approximately 0.5%[1]. Record dry modeled soil moisture conditions were particularly apparent over the San Juan River Basin and the Dolores River Basin.

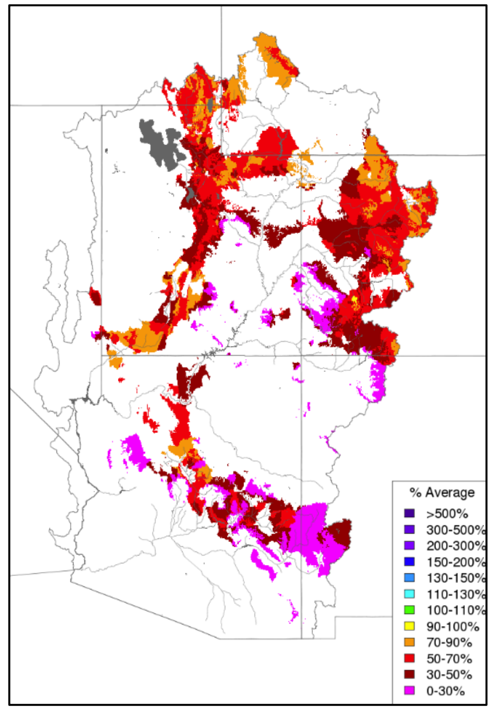


Figure 3: Historically dry Fall 2020 (November 15) soil moisture conditions were present throughout the CBRFC's area of responsibility. Dry soil moisture conditions decrease seasonal and annual runoff efficiency.

Water Year 2021 snowpack conditions were below normal throughout most of the Upper Colorado River Basin by January 1st. SNOwpack TELemetry (SNOTEL) stations maintained by the Natural Resources Conservation Service (NRCS) indicated slightly wetter conditions in the headwaters of the Colorado River Basin and portions of the San Juan River Basin, but snow water equivalent (SWE) values reported by NRCS SNOTEL stations were typically between 60% and 80% of normal (median) values (Figure 2). By April, water year to date precipitation was well below average throughout the CBRFC's area of responsibility (Figure 4). Model precipitation values were typically below 70% of average throughout the Upper Colorado River Basin and Great Basin regions; drier conditions were prevalent throughout the Lower Colorado Basin as model precipitation amounts rarely exceeded 50% of average.

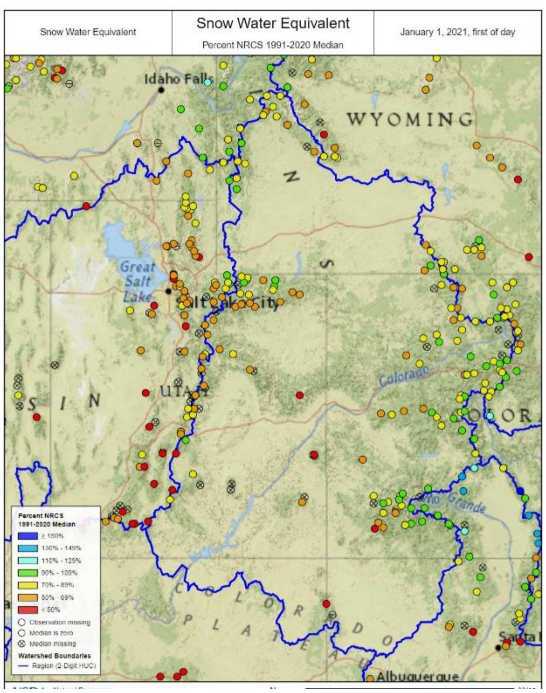


Figure 2: SWE values at NRCS SNOTEL locations throughout the Upper Colorado River Basin. Most values ranged from 60% to 80% of normal (median) on January 1st, 2021.

[1] See the CBRFC's Model Sensitivity Analysis, October 2020. Available at: https://www.cbrfc.noaa.gov/report/CBRFC_Model_Sensitivity_Analysis_2020.pdf

1.2.1 Historically Dry April

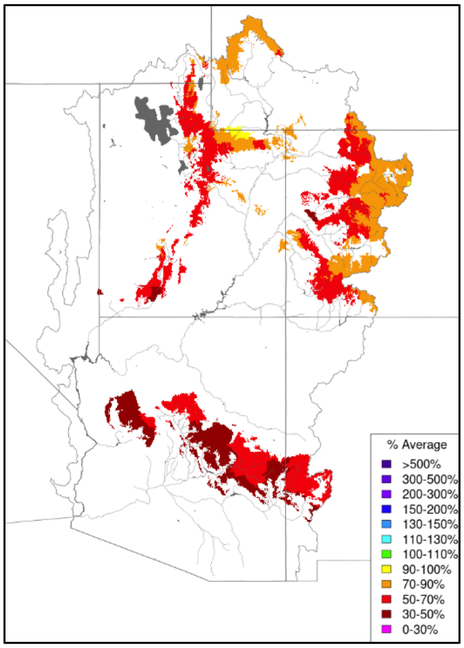


Figure 4: Water Year precipitation values through April over significant streamflow producing areas were well below average.

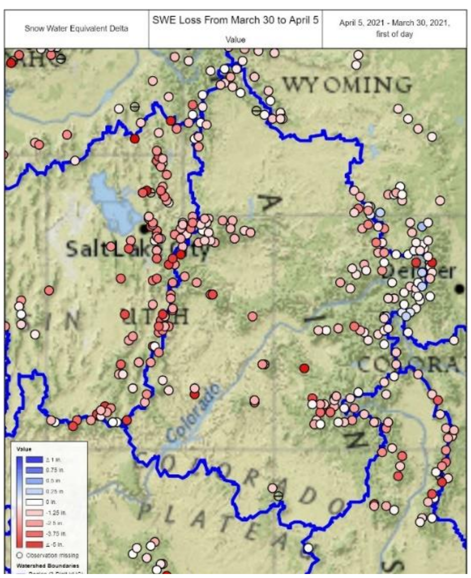


Figure 5: The first week of April saw significant snowpack lost at many SNOTEL gages throughout the Upper Colorado River Basin and the Great Basin. Numerous stations lost in excess of 3" during this time.

Near record temperatures (Figure 7) during the first week of April contributed to early season runoff throughout the Upper Colorado and Great Basin regions; by April 5th, some SNOTEL locations reported losses of SWE in excess of 3 inches since the end of March (Figure 5). This amount of snowmelt, particularly at middle and high elevations where SNOTEL stations are typically located, is unusually early in the runoff season.

Hydrologic conditions over April 2021 were historically dry; many SNOTEL sites throughout the basin reported the driest April over each gages period of record, which was further reflected in the CBRFC's hydrologic model (Figure 6). Near to record-high temperatures in Colorado initiated rapid snowmelt of an already limited snowpack (Figure 7).

Despite above average temperatures and snowpack losses at low and mid-elevations, unregulated streamflow volumes ranked at or near the lowest on historical record (Figure 8 and Table 1). Typically, even in relatively dry years, early season snowmelt would drive relatively higher flows in the early Spring months; however, due to the historically dry characteristics of 2021, early snowmelt and historically low streamflow volumes were only a precursor to the dry seasonal (April through July) volumes ahead.

Water year precipitation through July remained well below average. As a result primarily of historically low precipitation and snowpack amounts, seasonal unregulated streamflow volumes were consistently among the driest on record. The 2021 unregulated seasonal streamflow volume at Glen Canyon Dam at Lake Powell was 1.85 million acre feet, or 29% of the 1981 through 2010 average (Figure 9). It was the third driest on record

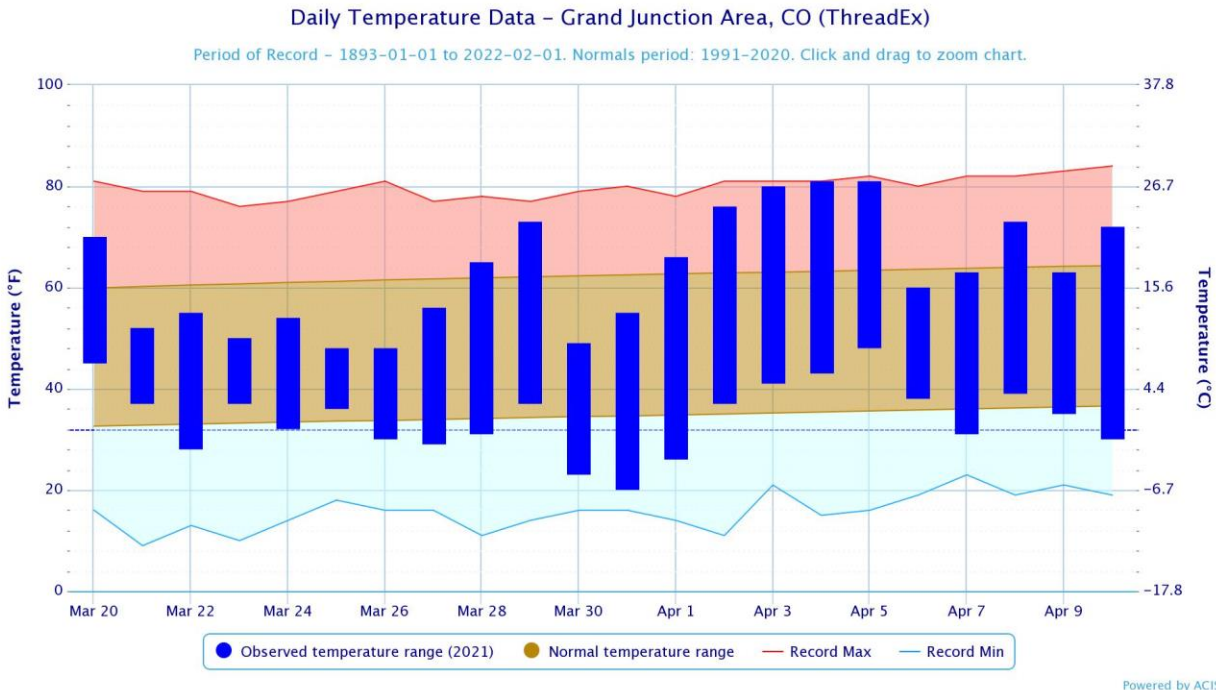


Figure 7: Near record temperatures in the Colorado River Basin contributed to early season melt of below normal snowpack conditions. Here, near record temperatures in early April are shown in the Grand Junction, CO area.

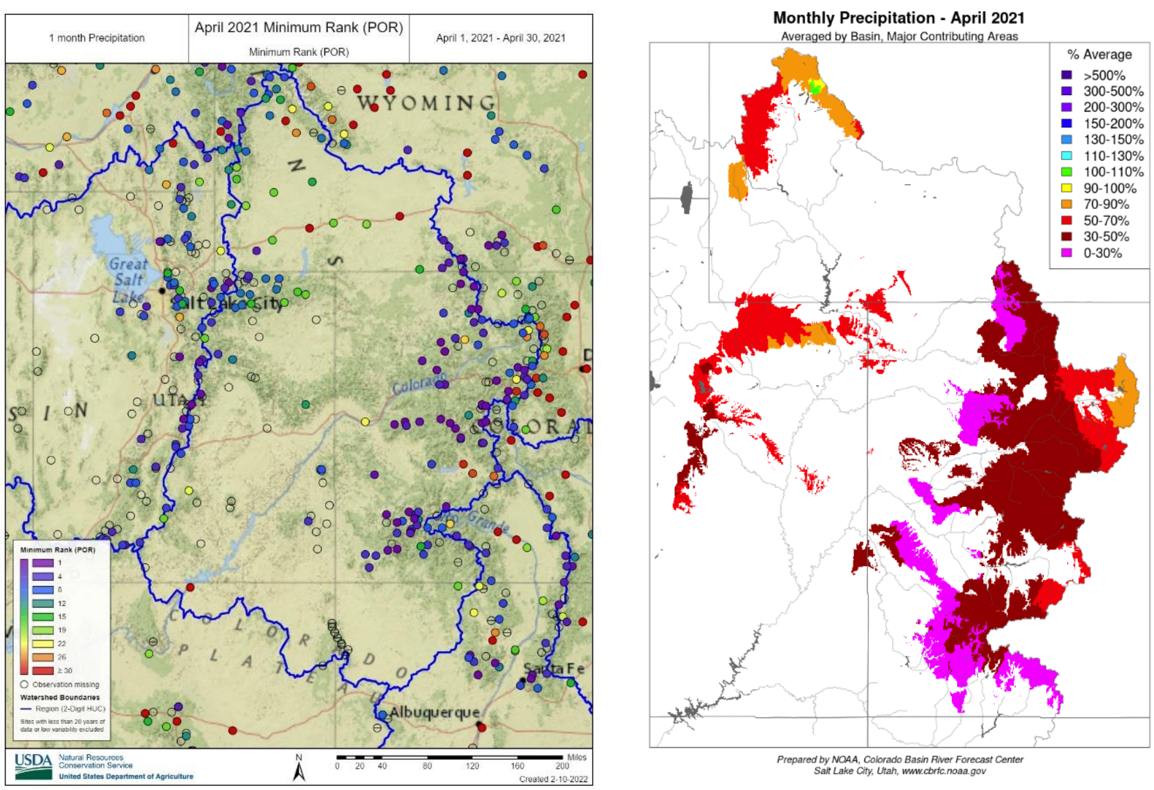


Figure 6: April 2021 was a historically dry month over the Upper Colorado River Basin. The picture on the left shows the Minimum Rank of April monthly precipitation over the period of record at NRCS SNOTEL stations. Many gages, particularly in the headwaters of the Colorado, Gunnison, and Yampa River indicated the driest April on record, or close to it. The picture on the right shows how that information translated into modeled precipitation over areas that significantly contribute to streamflow. These areas typically indicate less than 30% of average monthly precipitation over the Colorado River Basin.

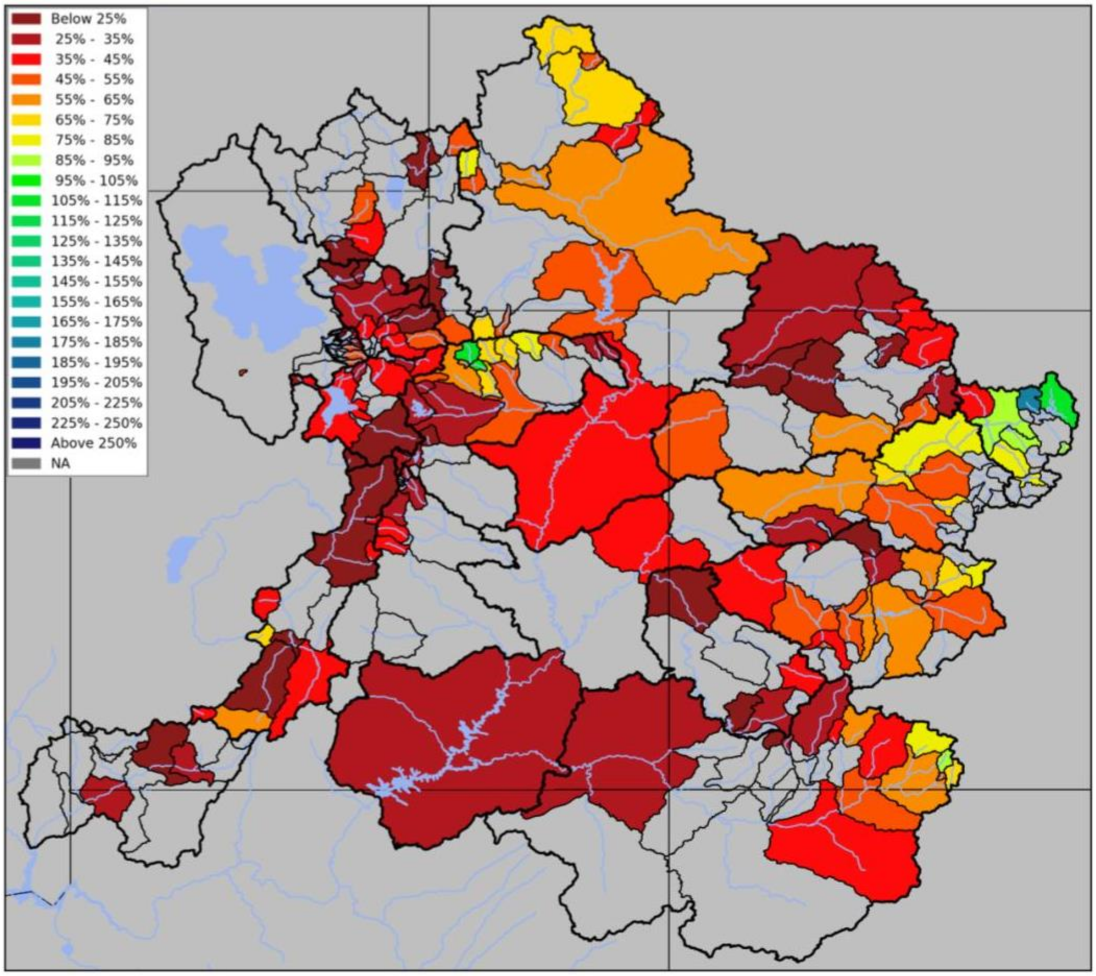


Figure 8: April unregulated streamflow volumes across the Upper Colorado River Basin and Great Basin were typically well below average; in many cases, flows were at or near historical lows.

Table 1: April unregulated streamflow volumes and their historical minimum ranks compared to their period of record. Most were at or near historical lows, except for the Willow Creek at Granby forecast point, where the contributing area was burned by the East Troublesome Fire.

Location	Historical Minimum Rank / Length of Record
Yampa River – Steamboat Springs	1 / 114
Yampa River – Maybell	1 / 105
Little Snake – Lily	2 /100
White River – Watson	1 / 93
Green River – Green River, Utah	2 / 116
Gunnison River – Grand Junction	2 / 105
Dolores River – Dolores	4 / 107
Animas – Durango	5 / 110
Willow Creek – Granby	91 / 102* *Burned by East Troublesome Fire

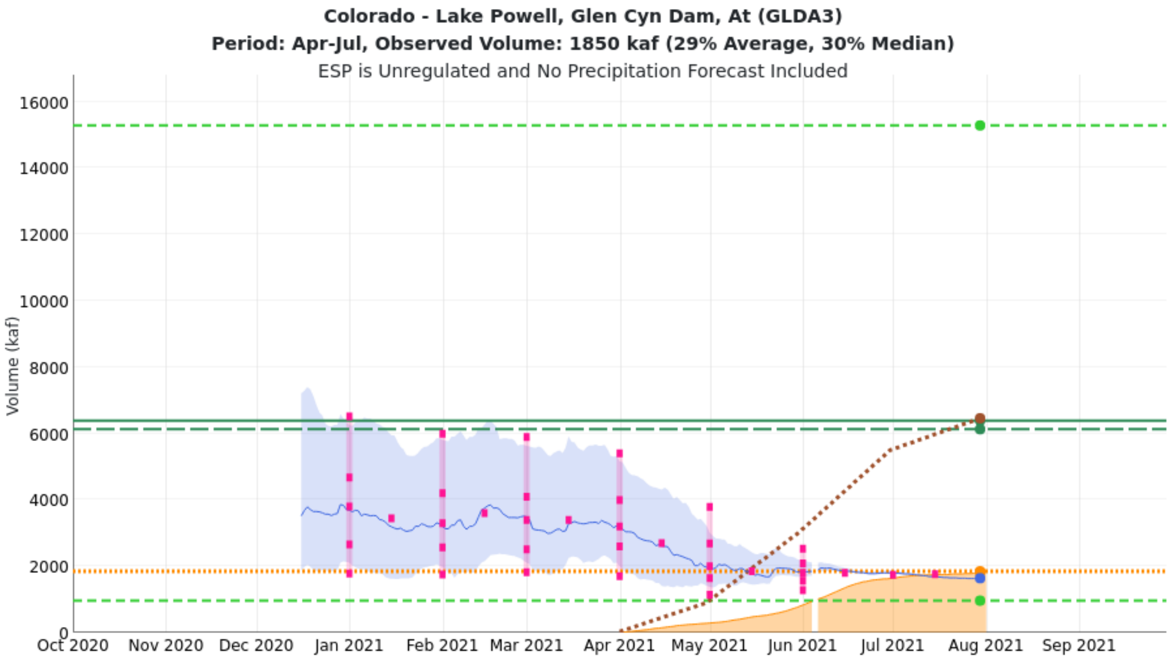


Figure 9: Unregulated seasonal streamflow volume was the 3rd driest on record for the Colorado River at Lake Powell at Glen Canyon Dam location.

1.2.2 Return of the Monsoon

Following the two driest monsoons on record (2020 and 2019), the 2021 monsoon was the wettest since 2014 and the 20th wettest since historical records began in 1895. According to the Phoenix Weather Forecast Office, average rainfall across the Southwest U.S. was 7.93", or 124% of the 1991-2020 average (6.39"). Figure 10 illustrates the spatial distribution of precipitation, and precipitation as a percent of average, over Arizona.

It is worth noting that even in monsoon years where well above average precipitation is observed, there is typically little impact to overall water supply conditions in the Colorado River Basin. However, active monsoon conditions improve antecedent soil moisture conditions in the area, which may improve runoff efficiency in water year 2022.

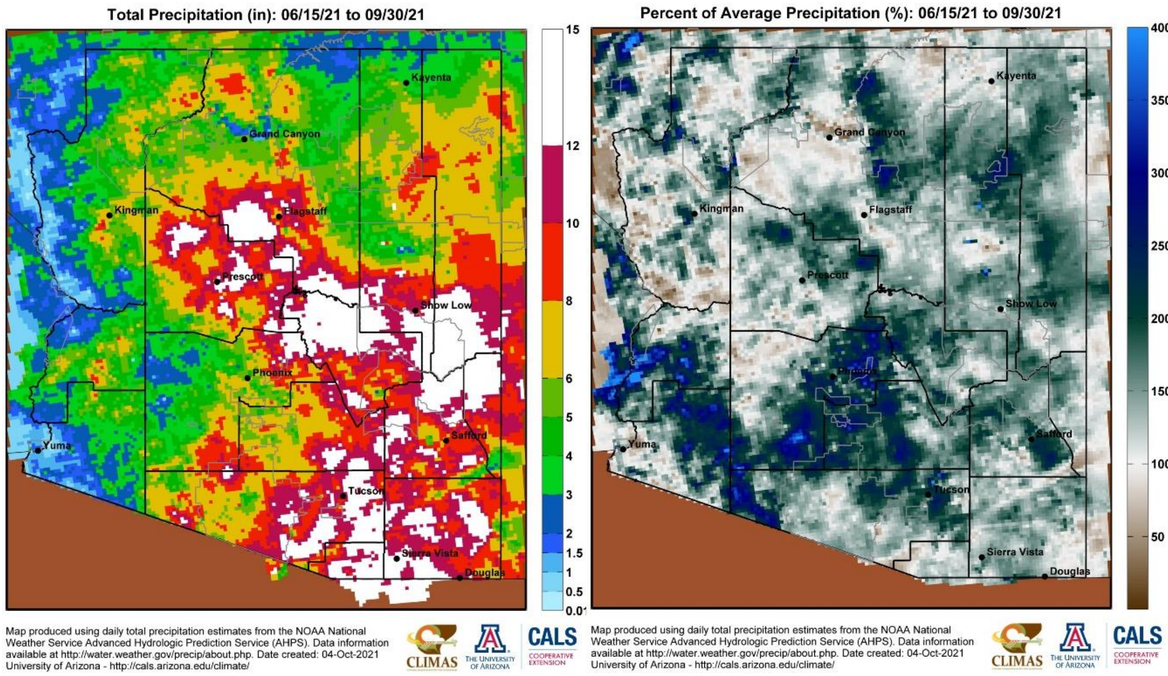


Figure 10: These plots, created by CLIMAS (Climate Assessment for the Southwest), a NOAA RISA, illustrate the total precipitation (left figure) and percent of average precipitation (right figure) over Arizona spanning the monsoon season of June 15, 2021 through September 30, 2021.

1.2.3 East Troublesome Fire Impacts to Willow Creek

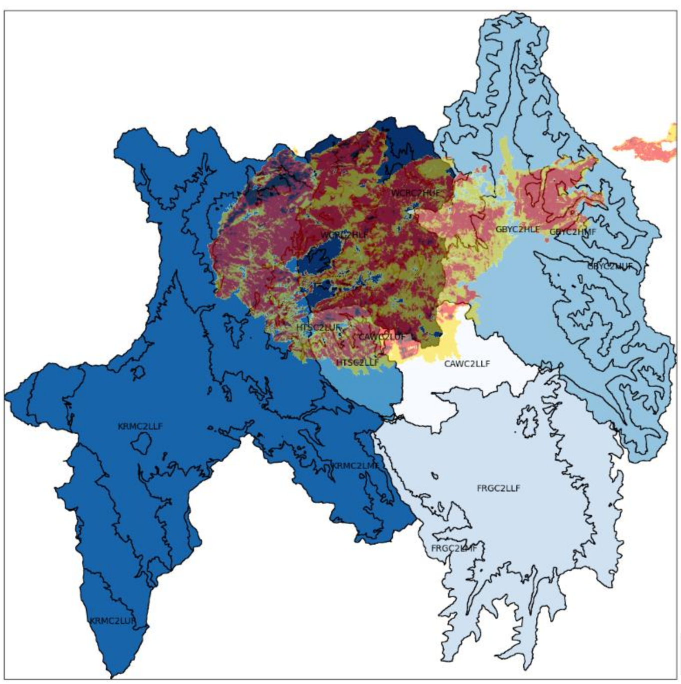
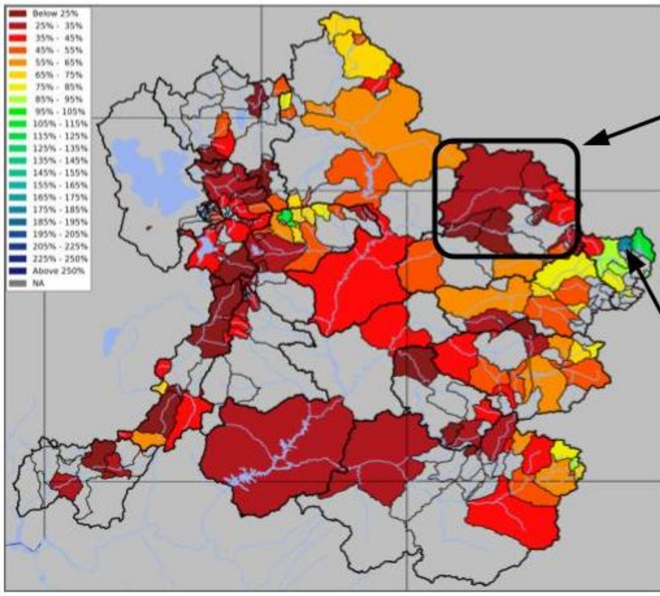


Figure 11: The East Troublesome Firre, represented here in shades of red, orange, and yellow, burned a majority of the Willow Creek Watershed. As a result, the CBRFC adjusted model parameters in the area to account for increased runoff due to resultant hydrophobicity.

In response to the Arizona 2020 fire season, the CBRFC developed a suite of tools to assess fire impacts to the hydrologic modeling process. Beginning on October 15th and spreading until its containment on October 28th, 2020, the East Troublesome fire burned through 193,812 acres of western Colorado and became the second-largest fire in Colorado's history. From a modeling perspective, the fire affected the majority of the area representing the Willow Creek watershed, which flows into the Willow Creek Reservoir near Granby (Figure 11).

The impacts of the fire were readily apparent, particularly when compared to surrounding areas in the Upper Colorado River Basin. In April, observed unregulated streamflow volumes were among the driest on record along the Yampa, Little Snake, White, Green, Dolores, and Animas Rivers; however, the observed unregulated April streamflow volume along Willow Creek was the 11th wettest over the 102 year period of record (Figure 12).



Location	Historical Rank / # of Years
Yampa River -Steamboat Springs	1 / 114
Yampa River- Maybell	1 / 105
Little Snake- Lily	2 / 100
White River- Watson	1 / 93
Green River- Green River, Utah	2 / 116
Gunnison River-Grand Junction	2 /105
Dolores River- Dolores	4 / 107
Animas - Durango	5 / 110
Willow Creek - Granby	91/102* *Burned by East Troublesome Fire

Figure 12: Record or near record dry April 2021 unregulated streamflow volumes were observed over much of the northeast portion of the Upper Colorado River Basin; however, observed April unregulated streamflow volumes were markedly higher in the Willow Creek watershed due to impacts from the East Troublesome Fire.

1.3 Water Supply Forecasting Challenges and Verification

Extreme dry and wet climate and weather patterns often challenge seasonal runoff forecasts. Historically dry antecedent soil moisture conditions and below normal snowpack accumulation in January 2021 resulted in well below normal forecasts. Forecasts continued to decline as dry conditions persisted, particularly in April when historically dry conditions brought forecasts to below January's 90 percent exceedance levels. Considering the historically dry conditions observed in April, where dry conditions, and observed volumes consistently ranked among the driest 10th percentile in the historical record, it would be expected that observed volumes fall below the January forecast of 90 percent exceedance values (Figure 9, for example).

Due to the impacts of the East Troublesome Fire in western Colorado, parameters within the CBRFC's hydrologic model were changed to better reflect the post-fire hydrologic characteristics of the basin. Soil moisture parameters were changed such that the basin's capacity to contain water within the soil was reduced, and parameters were further adjusted to accelerate snowmelt over this reach. Seasonal unregulated forecasts at Willow Creek were relatively unchanged over the course of the forecast season, and forecasts over the reach performed very well. These results provide the CBRFC with an important data point with regards to how the hydrologic model is adjusted after a fire and resultant model performance (Figure 13).

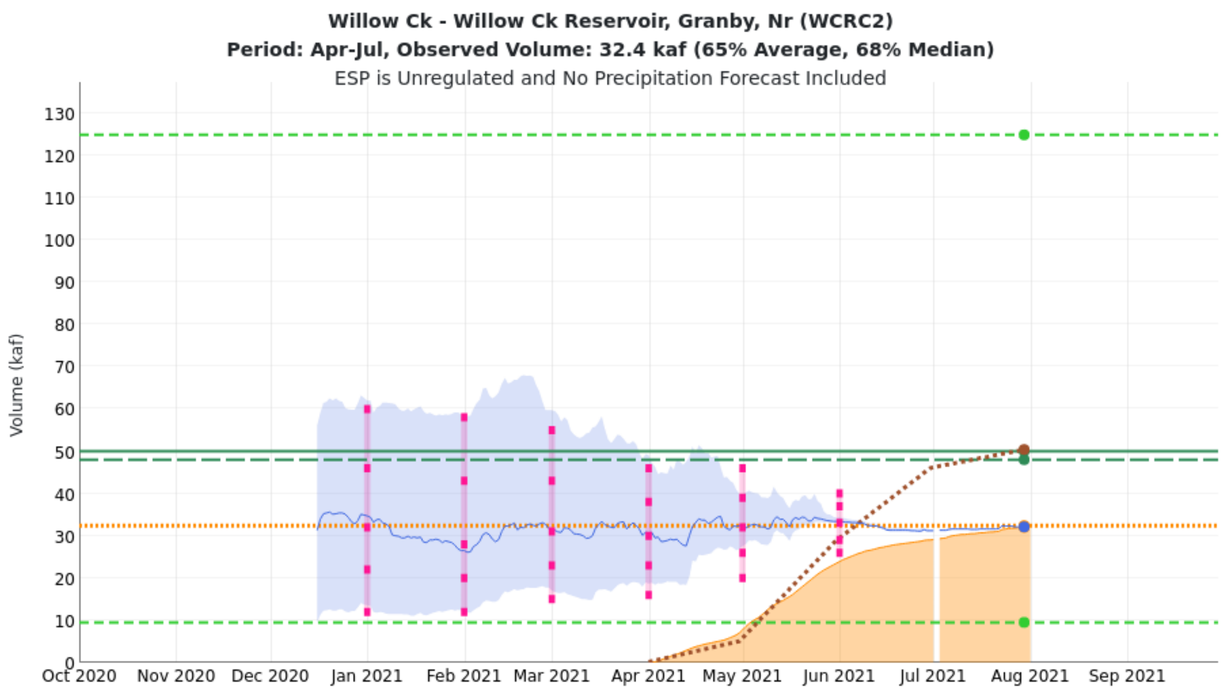


Figure 13: Seasonal water supply forecasts over the Willow Creek watershed after the East Troublesome Fire performed well after changes to parameters within the CBRFC's hydrologic model to account for post-fire impacts.

2 Summary of Major Water Year 2021 Improvements

The CBRFC constantly evaluates and works to improve its hydrologic model and methodology, including updating calibrations of specific forecast points when necessary. In addition, approximately every 10 years, the CBRFC devotes a significant amount of resources towards a thorough recalibration effort, impacting nearly every segment and forecast point in the CBRFC's hydrologic modeling paradigm. This recalibration effort is done to accomplish many goals, including, but not limited to:

- Conforming to World Meteorological Organization (WMO) standards, specifically updating the 30-year reference period to 1991 through 2020
- Acknowledge recent trends in observations and forecasts
- Provide an opportunity to thoroughly evaluate the CBRFC hydrologic model
- Add new data and methods

Section 3 will discuss the CBRFC's recalibration effort and normals update in greater detail.

In addition, and oftentimes complimentary to the CBRFC's extensive calibration effort, 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 and Enhanced Methods to Improve Forecasts (Section 4)
- Research, Investigations, and Collaborations (Section 5)
- Personnel Changes at the CBRFC (Section 6)

3 CBRFC Recalibration and Normals Update

3.1 Calibration Forcing History

Since 2000, there have been four distinctive 30-year forcing periods utilized at the CBRFC, including the latest one to be implemented. The first three forcing periods were:

- 1971 through 2000
- 1975 through 2005
- 1981 through 2010

These 30-year periods were selected to take advantage of data from the NRCS SNOTEL network, which started to become available around 1978 and minimize the use of estimated data. Use of the SNOTEL network has been critical to improving skill in CBRFC developed forecasts since its inception; as an aside, the CBRFC recently partnered with the U.S. Department of Interior Bureau of Reclamation (Reclamation) and RTI to fund research quantifying the impact of SNOTEL information to CBRFC forecasts (this is discussed in more detail in Section XX).

In 2017, the forcing period was extended by 5 years to span 1981 through 2015. The additional years were added to include record high (2011) and record low (2012) runoff years, while also expanding the range of weather patterns represented in the ensemble spread. During the use of the 35-year forcing period, the comparison period used to develop metrics such as percent of average and percent of median did not change, and remained the 30-year period spanning 1981 through 2010.

In 2021, the CBRFC undertook an extensive recalibration of the hydrologic model. In addition to including the years spanning 2016 through 2020, the reference period was updated to 1991 through 2020 to conform with World Meteorological Organization standards[2]. It is important to note that the hydrologic model was calibrated using the entire 40-year period of record from 1981 through 2020; however, water supply forecasts are developed from the 30-year period from 1991 through 2020 and refer to that same period when developing such metrics such as median

[2] The initial 30-year period of reference was set as a standard mainly because only 30 years of data were available for summation when the recommendation was first made. The early intent of normal swas to allow comparison among observations from around the world. The most significant of these changes was that the definition of a climatological standard normal changed, and it now refers to the most recent 30-year period finishing in a year ending with “0”. More information is available at: https://library.wmo.int/doc_num.php?explnum_id=4166

or percent of average. It is important to note that the vast majority of work to calibrate the model occurred in Water Year 2021, and was implemented in Water Year 2022.

3.2 Hydrologic Model Calibration Process

CBRFC hydrologic model calibration is a continuous process that includes forecaster knowledge and experience. Reliable calibrations of the underlying hydrologic models increase forecast certainty and lead-time, resulting in improved forecast service quality. The calibration goal is to reduce model error on all time scales (daily, monthly, seasonal, water year).

CBRFC hydrologic model calibration components include:

- Add/Remove Basins
    - Stakeholder forecast requests
    - Determine who maintains stream gage and status of future gage support funding
    - Remove basin if the stream gage has been discontinued
- Basin Research
    - Collect and quality control historical data
    - Basin delineation and basin elevation zone splits
    - Irrigation, diversions, etc.
- Model Forcings
    - Station (temperature/precipitation) quality control, selection, and weighting
- Model Calibration/Water Balance
    - Spatial consistency of hydrologic model parameters among nearby basins
    - Iterative process of refining parameters for hydrologic models including:
        - SNOW-17
        - SAC-SMA
        - UNIT-HG
        - CONSUSE
        - LAG/K
- Calibration Statistics
    - Biases, correlation, root-mean-squared error (RMSE) at various time scales
- Basin Implementation
    - Operational model, database, web, documentation, maintenance

3.3 CBRFC Hydrologic Model Calibration Updates and Highlights

3.3.1 CBRFC Hydrologic Model Segments Added

As part of the recalibration effort, the CBRFC added sixteen new forecast locations in an effort to better model streamflow over the Upper Colorado River Basin. Table 2 lists the new forecast points.

Table 2: New forecast segments added to the Upper Colorado River Basin in 2021

ID	DESCRIPTION	BASIN	NOTES
YAHC2	YAMPA - ELKHEAD CK- ABV- HAYDEN- NR	White/Yampa	
BAKC2	COLORADO - BAKER GULCH- BLO- GRAND LAKE- NR	UC Mainstem	Grand County Emergency Manager Request Implemented April 2021
SMRC2	COLORADO - SHADOW MTN RES- GRAND LK- NR	UC Mainstem	Grand Lake + Shadow Mountain Inflow
GORC2	GORE CK - MOUTH- MINTUR- NR	UC Mainstem	
HUTC2	HUNTER CK - ASPEN	UC Mainstem	Replacing HUNC2 (Gage Discontinued in 2016)
EMMC2	ROARING FK - EMMA- NR	UC Mainstem	
CMNC2	CIMARRON - SQUAW CK- BLO- CIMARRON- NR	Gunnison	
COWC2	COW CK - RIDGWAY RESERVOIR- NR	Gunnison	
UNBC2	UNCOMPAHGRE - UNCOMPAHGRE ROAD BRIDGE	Gunnison	
GRHC2	GROUNDHOG RESERVOIR	Gunnison	
RIOC2	RIO BLANCO - MOUTH- TRUJILLO- NR	San Juan	
VNBC2	VALLECITO CK - BAYFIELD- NR	San Juan	
LPAC2	LOS PINOS - VALLECITO RESERVOIR- ABV	San Juan	
ANBC2	ANIMAS - SILVERTON- BLO	San Juan	
CYKC2	CHERRY CREEK - MOUTH- RED MESA- NR	San Juan	
LPCC2	LA PLATA - CHERRY CK- BLO- RED MESA- NR	San Juan	

3.3.2 Utilization of Historical Consumptive Use Dataset in Colorado

The State of Colorado maintains an exhaustive database of consumptive water use data. This data is available on Colorado’s Decision Support Systems website developed by the Colorado Water Conservation Board and Department of Water Resources. This dataset was used to parameterize the CBRFC’s unmeasured depletion component of the CBRFC’s hydrologic model. The parameters influenced by the consumptive use dataset included irrigated acreage, irrigation efficiency, water demand, and return flow.

3.3.3 Lake Powell Unregulated Inflow

The update of the 30-year normal period is significant, particularly with regards to unregulated inflow at Lake Powell where the impacts of persistent drought over the Upper Colorado River Basin coalesce at Glen Canyon Dam. For the 30-year reference period spanning 1981 through 2010, the average seasonal (April through July) unregulated inflow volume into Lake Powell was 7.155 MAF; that value over the 30-year reference period spanning 1991 through 2020 is 6.392 MAF, or a reduction of 10.7%. Water year values were similarly impacted, showing an 11.3% decrease from 10.831 MAF using the 1981 through 2010 reference period to 9.603 MAF over the 1991 through 2020 period. Figure 14 shows the change in average monthly unregulated streamflow volumes comparing the two periods at Lake Powell.

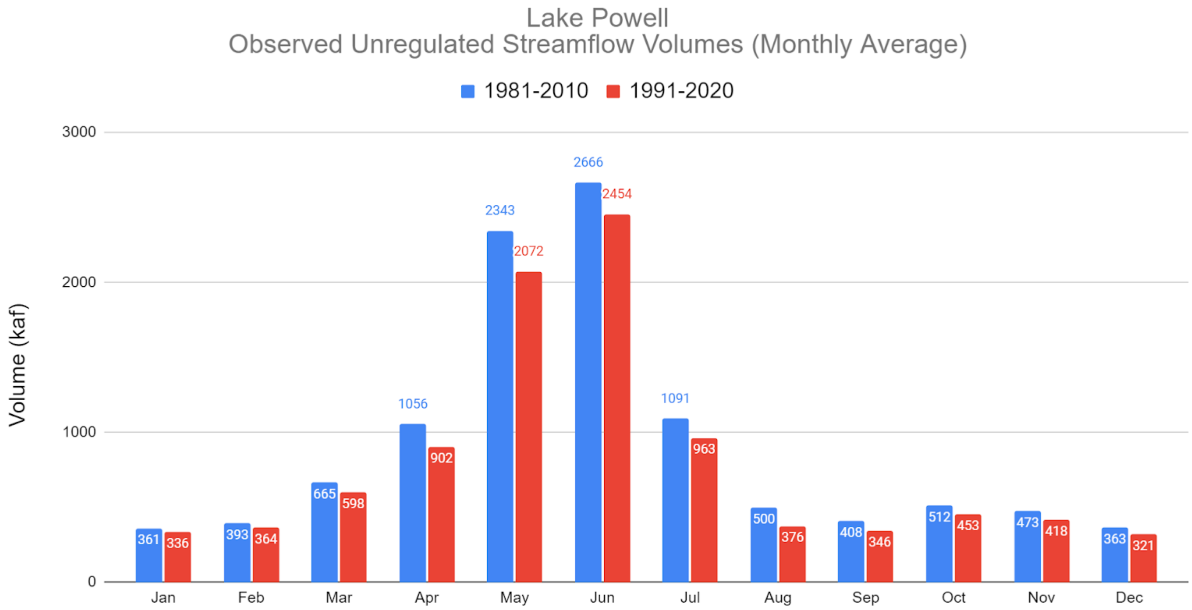


Figure 14: Comparison of average monthly unregulated streamflow volumes between the 1981 through 2010 and the 1991 through 2020 reference period. Over the seasonal and water year periods, average unregulated inflow volumes decreased approximately 11%.

It is important to understand the impact of the changing reference period to communicating and understanding runoff volumes. For instance, the seasonal unregulated inflow into Lake Powell for 2021 was 1.85 MAF, or 29% of the 1991 through 2020 average; had the reference period remained 1981 through 2010, it would have been 26% of average.

The impact of drought over the Colorado River Basin over the past 10 years is hard to understate. From 1981 through 1990, the average unregulated inflow into Lake Powell was approximately 12.8 MAF over the water year. These reference period years are replaced by 2011 through 2020 in the updated normal period. The average water year inflow into Lake Powell from 2011 through 2020 is 9.1 MAF, or a nearly 30% decrease from the decadal period being replaced in the reference period. Figure 15 shows the observed water year unregulated inflow volumes from 1981 through 2020 at Lake Powell.

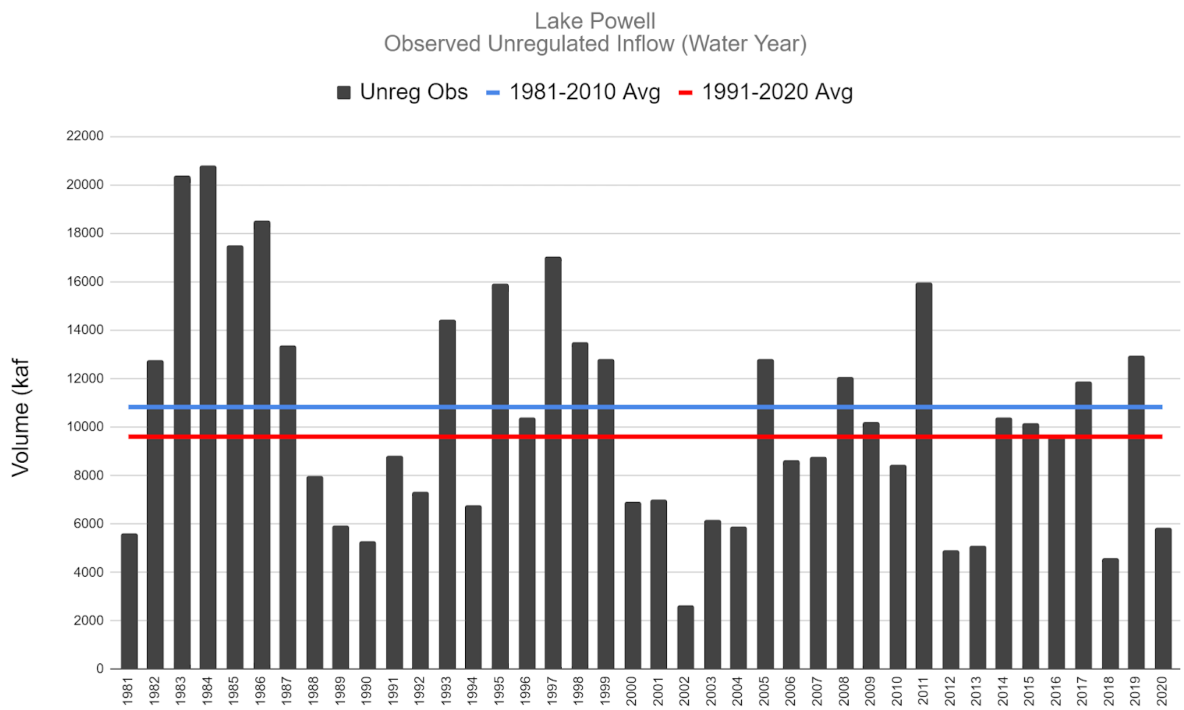


Figure 15: Observed water year unregulated streamflow volumes at Lake Powell and a comparison between the 1981 through 2010 reference period and the 1991 through 2020 reference period.

4 New and Enhanced Methods to Improve Streamflow Forecasts

The CBRFC is continually working to improve forecast accuracy, dependability, and scope of services. These efforts are often done in response to stakeholder needs, though the CBRFC is often evaluating new data, methods, and practices to improve forecast products and services in an effort to meet the mission and goals of the NWS and CBRFC.

4.1 Improved ENSO Weighting Method for Lower Colorado River Basin Water Supply Forecasts

Teleconnection information, such as that related to the El Niño Southern Oscillation (ENSO), has only been used to inform seasonal water supply forecasts in the Lower Colorado River Basin, where a statistically significant trend exists between water supply volumes and ENSO phases (i.e., El Niño or La Niña). However, past implementation of ENSO information in the Lower Colorado River Basin at the CBRFC has been subjective and lacked verification.

In June, the CBRFC conducted an analysis of available ENSO indices. These indices include:

- The Southern Oscillation Index (SOI) tracks the atmospheric part of the ENSO pattern. The SOI compares the difference from average air pressure in the western Pacific to average air pressure in the central Pacific[3].

- The Oceanic Niño Index (ONI) tracks the ocean part of the ENSO pattern. The ONI tracks a running 3-month average of average sea surface temperatures in the east-central tropical Pacific. The ONI is an indicator of how much cooler or warmer the sea surface temperatures are from average[4].

- The Equatorial SOI is similar to the SOI except that air pressures are compared between the eastern equatorial Pacific and an area over Indonesia.

- The Multivariate ENSO index (MEI) combines five different oceanic and atmospheric variables and is intended to provide real-time indications of ENSO intensity and provide context for ENSO's continually evolving conditions[5].

- The Pacific Decadal Oscillation is a collection of mostly independent climate phenomena influenced by ENSO and can be an indicator of ENSO conditions. The PDO consists of information related to the Aleutian Low, sea surface temperatures, and the Kuroshio Current[6].

For each of these indices, an average Fall (September – October – November) value is either used or calculated, with the exception of the MEI, where the September – October value is used. Over the 40-year ensemble spanning 1981 through 2020, analog years are identified for each index through a K nearest neighbors approach. To ensure an acceptable range of spread in each ensemble, the minimum number of members (i.e., neighbors) is set to 11. For each index in each sub-basin within the Lower Colorado River Basin, normalized weights are developed. These weights, and the resultant ensembles that are generated from them, are then used as the basis for official forecasts in the Lower Colorado River Basin.

This process is used whenever El Nino or La Nina conditions are met in the Lower Colorado River Basin and are reproducible. Verification in the Lower Colorado River Basin suggests that developing forecasts utilizing these ENSO indices produces more accurate forecasts.

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[3] For more information on the SOI visit: https://www.climate.gov/news-features/understanding-climate/climate-variability-southern-oscillation-index

[4] For more information on the ONI visit: https://www.climate.gov/news-features/understanding-climate/climate-variability-oceanic-ni%C3%B1o-index

[5] For more information on the MEI visit: https://psl.noaa.gov/enso/mei/

[6] For more information on the PDO visit: https://www.climate.gov/news-features/blogs/enso/going-out-ice-cream-first-date-pacific-decadal-oscillation

4.2 Updated and Added Diversion Estimates

CBRFC forecasters commonly evaluate information related to measured and projected diversions over various reaches and segments within the hydrologic model. Often, schedules of future diversions are provided by water users and these are incorporated into short-term (10 to 15 day) deterministic forecasts. In cases where future diversion schedules are unknown, the last measured diversion value is often extended through the forecast period; however this assumption can be incorrect. For guidance purposes only, an estimate of projected diversions is developed by computing the average monthly flow diverted based on available water in the reach. For instance, if a water user, on average based on the 30-year reference period of 1991 through 2020, uses 16% of the available water over a reach each August, then guidance is provided to the forecaster showing 16% of the available water over the forecast period. It is important to note that this is just guidance for the forecaster, and does not take into account additional considerations, such as the need to maintain a minimum environmental flow target, or capacity of a particular diversion; as such, the forecaster may deviate from this guidance using more information regarding operations over a particular reach or area. Over water year 2021, the historical monthly coefficients used to derive these guidance values were updated to be in synch with the updated reference period.

5 Research Investigations and Collaborations

The CBRFC is works with representatives from other agencies, academia, non-governmental organizations, and NOAA initiatives to investigate improvements to the CBRFC's current forecast development and communication paradigm. Much of this work is accomplished in direct collaboration with our stakeholders, and through efforts led by the Colorado River Climate and Hydrology Work Group (Work Group).

5.1 Investigation of Remotely Sensed Snow Products For Use In Operational Forecasting

Since 2013, the National Aeronautics and Space Administration's (NASA) Jet Propulsion Laboratory (JPL) Airborne Snow Observatory (ASO), and subsequently ASO Inc. in 2019, have flown low-flying aircraft utilizing LiDAR technology over portions of the Upper Colorado River Basin to provide estimates of Snow Water Equivalent (SWE) for use in operational forecasting. These estimates of SWE provide the opportunity to utilize SWE information over a spatial scale larger than a typical gage measurement could provide.

In 2018, the Work Group developed a project Scope of Work entitled, "Snow pack representation in the Colorado Basin River Forecast Center model SNOW-17: an evaluation with Airborne Snow Observatory SWE products." This project was labeled as "Project 8." The goals of this project were defined as:

- Demonstrate an improvement to the CBRFC's April 1 streamflow forecast for the April – July runoff period by incorporating higher resolution snow observing data into forecasting procedures.

- Facilitate reciprocal communication and data sharing between CBRFC and JPL.
- Document and evaluate the major obstacles impeding the integration of ASO data into CBRFC's forecast operations and identify data integration opportunities.

Data from NASA JPL and ASO Inc. span watersheds within several sub-basins over the Upper Colorado River Basin. These include the Gunnison River Basin, Upper Green River Basin, Upper Colorado Mainstem, and the Dolores River Basin. Data was provided to the CBRFC by NASA JPL ASO and ASO Inc. for the CBRFC to develop a methodology to compare forecasts based on the current forecasting paradigm, which uses SWE information computed by the CBRFC's SNOW-17 model, and forecasts using SWE information based on remotely sensed ASO information.

5.1.1 Limitations

The CBRFC recently conducted a sensitivity analysis[7] which indicated that precipitation, and specifically mountain snow that melts off during the spring and summer months, is the most impactful parameter when developing seasonal water supply forecasts. However, uncertainty associated with precipitation is not the sole source of uncertainty within the CBRFC's hydrologic forecasting process. On April 1st of any given year, the CBRFC expects that roughly half of the volume error is from unknown spring weather (i.e., the amount of precipitation observed between April 1t and July 31) (Figure 16). The other half of the uncertainty is due to model error which includes:

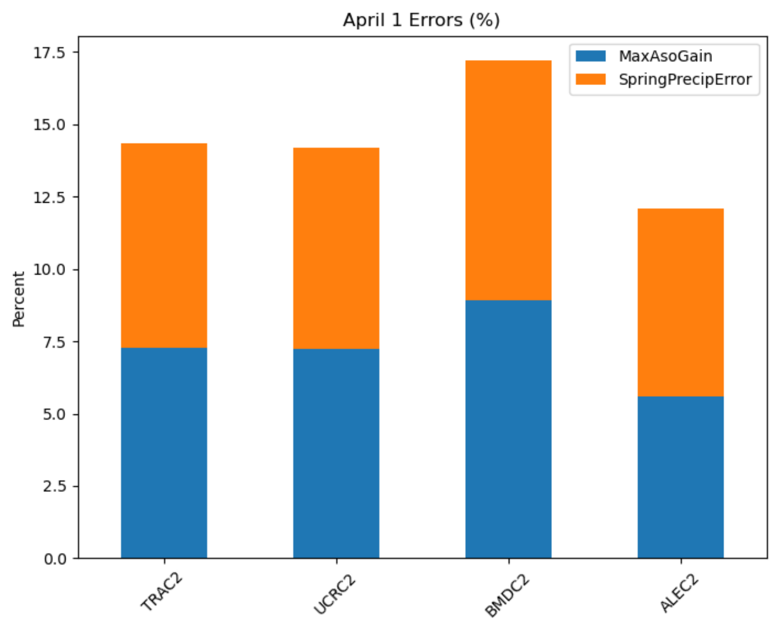

Figure 16: Model error compared to uncertainties in spring precipitation on April 1st at selected sites.

- Error in model soil moisture states
- Error in modeled snow pack and SWE
- Errors in model parameters
- Errors in model structure

Even under the false assumption that information from ASO is without uncertainty or error, the level of improvement to CBRFC water supply forecasts using ASO information is limited to the amount of uncertainty that can be potentially removed from errors associated with modeled snow

[7] See "Model Sensitivity Analysis: An Overview of CBRFC's Hydrologic Model Sensitivity to Changes in Precipitation, Temperature, Soil Moisture, and Evapotranspiration Perturbations" Available at: https://www.cbrfc.noaa.gov/report/CBRFC_Model_Sensitivity_Analysis_2020.pdf

pack and SWE information developed by SNOW-17. This is not to discourage the use or continued investigation of ASO information, but only acknowledge that any potential ASO improvements will not lead to perfect forecasts or address uncertainty in future weather.

5.1.2 Methodology

To compare seasonal water supply forecasts developed using the current CBRFC methodology with forecasts developed using SWE information provided by ASO, the CBRFC utilized a direct insertion method, where ASO SWE information was substituted directly into the CBRFC model; that is, SWE states developed using SNOW-17 were replaced with SWE values derived from ASO information. It should be acknowledged that the CBRFC's hydrologic model is calibrated using historical precipitation (and resulting model snowpack) developed primarily from gage information and not from SWE information, including SWE information developed from remotely sensed snow data. It is not expected that any model error (e.g., parameterization error which could potentially compensate for model SWE error) significantly impacted the results of the CBRFC's direct insertion method. In the development of water supply forecasts, SWE is the dominant driver of volumetric streamflow forecasts; as such, model SWE developed by the CBRFC or ASO-informed SWE will be the driving factor determining a seasonal water supply forecast. Uncertainty due to error in other parameters is relatively small compared to the initial SWE state. While small differences between CBRFC developed forecasts and ASO-informed forecasts could be due to model error, larger differences such as those shown in this document are the result of utilizing different SWE states. Additionally, there is an insufficient historical record associated with remotely sensed snow information to calibrate with.

5.1.3 Results

The following graphics compare CBRFC traditionally developed forecasts with forecasts developed using ASO SWE information. In general, performance of forecasts developed using ASO information are inconsistent. The following graphics are a representative sample of comparisons between traditional CBRFC forecasts and ASO-informed forecasts.

5.1.3.1 East at Almont (ALEC2)

Figure 17 shows official monthly and raw daily water supply forecasts developed by the CBRFC over the 2022 water year using its Ensemble Streamflow Prediction (ESP) methodology for the East River at Almont, CO location. Two instances of ASO data were available at this site; one in late April and one in mid-May. In both instances, ASO-informed median forecasts were too low.

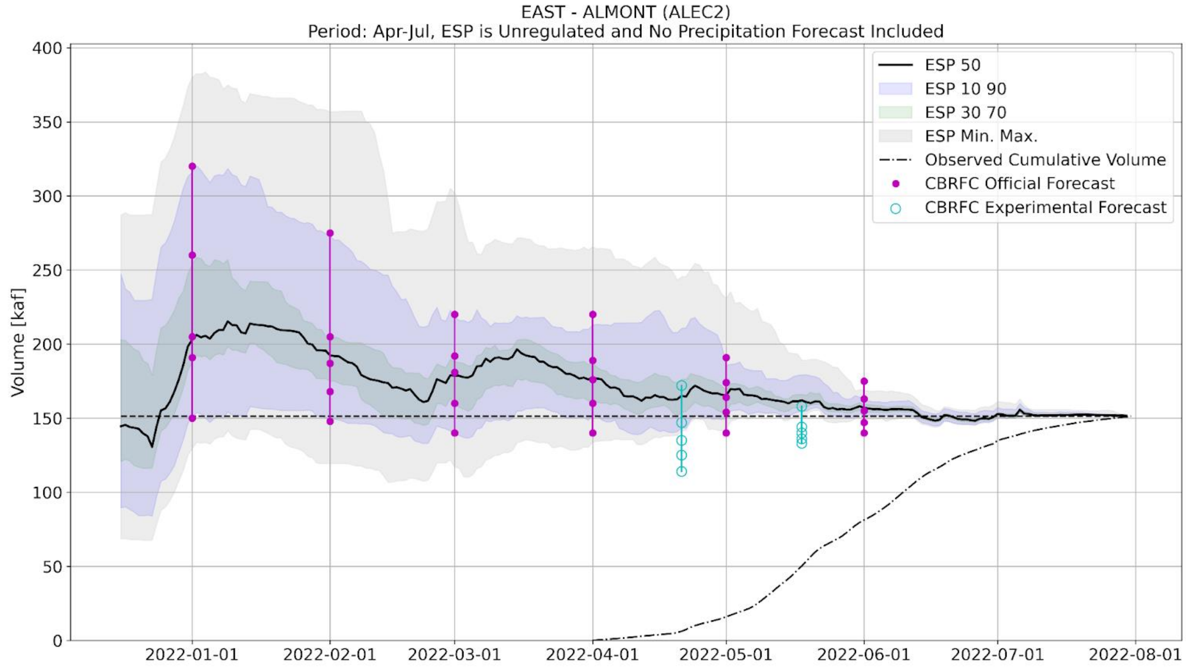

Figure 17: This figure shows CBRFC water supply forecasts (official forecasts are in purple) compared with ASO-informed forecasts (in light blue). In this instance, ASO-informed forecasts were too low.

5.1.3.2 Dolores River at Dolores (DOLC2)

Figure 18 illustrates CBRFC forecasts in the Dolores River Basin. Here, two ASO-informed instances would have produced forecasts that were too high.

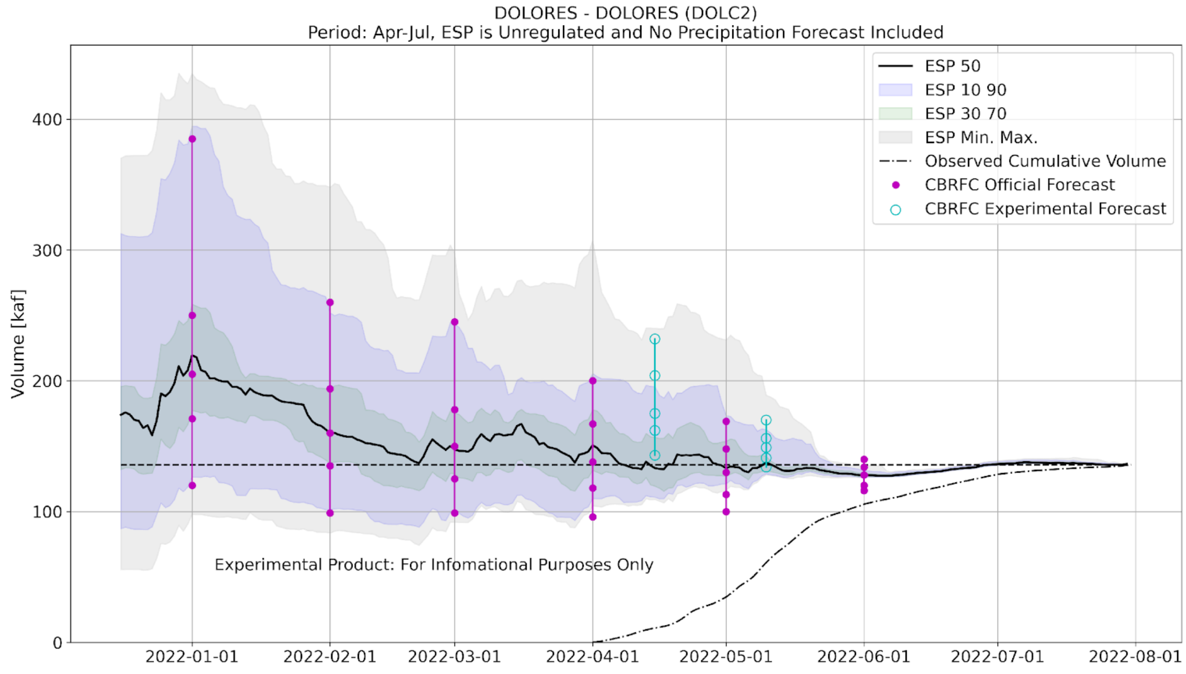

Figure 18: Here, ASO-informed forecasts were too high over the course of the runoff season.

5.1.3.3 Dillion Reservoir Inflow (DIRC2)

Figure 19 illustrates CBRFC forecasts for inflow into the Dillon Reservoir. Here, two ASO-informed instances would have produced forecasts that were similar to CBRFC forecasts.

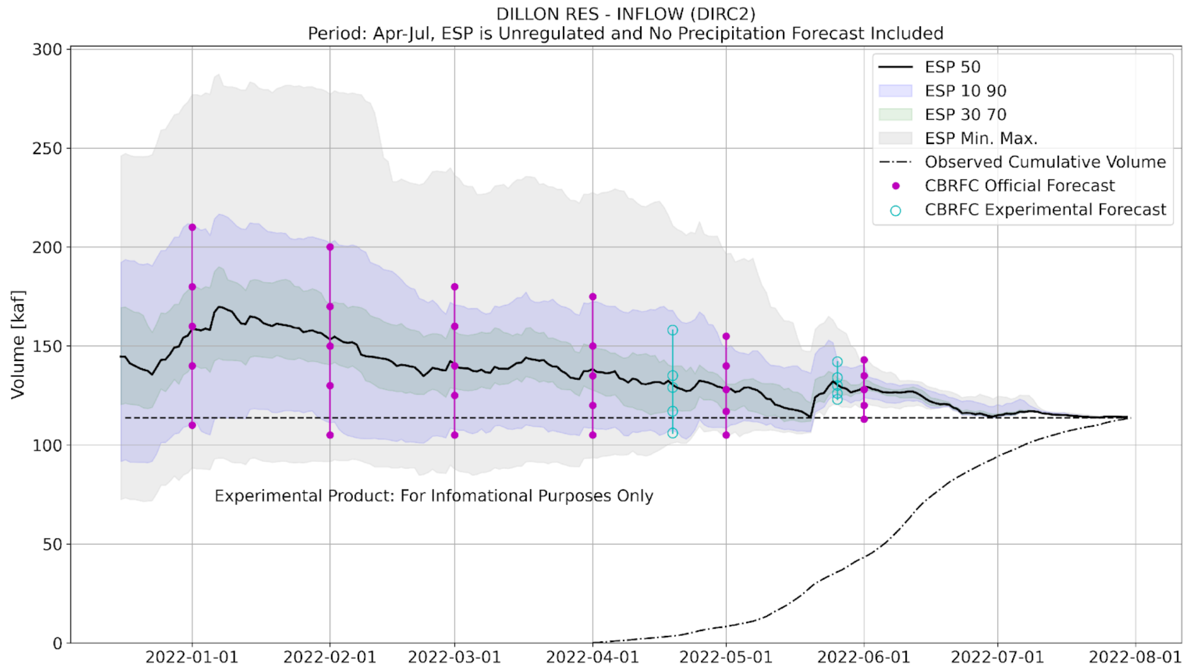

Figure 19: Here, ASO-informed forecasts were similar to CBRFC forecasts.

5.1.3.4 New Fork at Big Piney (BPNW4)

Figure 20 illustrates CBRFC forecasts for the New Fork River at Big Piney, WY, located in a data sparse region. Here, an ASO-informed instance yielded better forecast results.

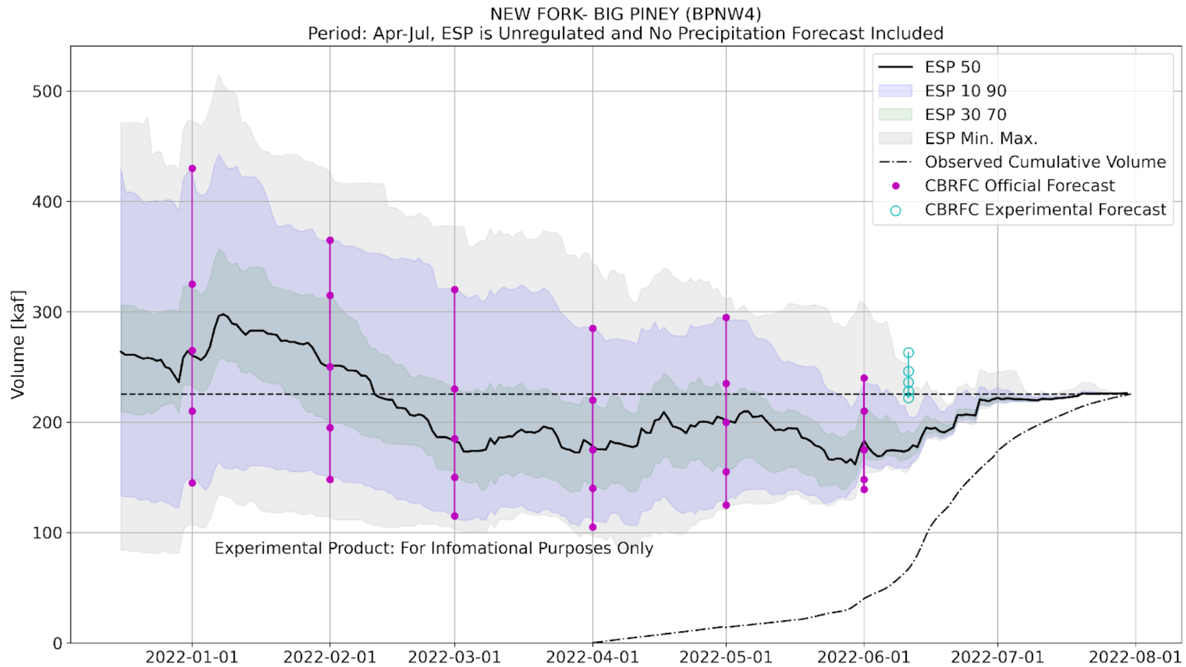

Figure 20: In this data sparse region in the Upper Green River Basin, ASO provided information that led to an more accurate forecast.

5.1.4 Conclusions

Remotely sensed snow observations by NASA JPL, ASO Inc., and others provide an unique opportunity to incorporate high resolution spatial data to inform a hydrologic model that has traditionally relied upon gage information to develop seasonal water supply forecasts. The CBRFC was able to compare seasonal forecasts developed using snow states derived from the SNOW-17 model that is coupled with the CBRFC's hydrologic model, to forecasts developed with ASO information. ASO-informed forecasts were developed by directly substituting SWE information from ASO into the CBRFC's modeling paradigm. In areas where the CBRFC has available information from nearby SNOTEL gages, ASO informed forecasts did not consistently improve seasonal water supply forecasts. At various instances, ASO-informed forecasts were comparable, under-forecasted, and over-forecasted when compared to CBRFC forecasts. ASO informed forecasts did show improvement over CBRFC forecasts in sparsely gaged areas, suggesting that added information from ASO in these areas could be beneficial for forecast development going forward.

As this project evolved the goals as defined by the original scope of work for Project 8 by the Work Group changed slightly. Adjusted project goals and responses may be characterized as:

- Compare CBRFC April – July runoff period forecasts with forecasts developed by incorporating higher resolution snow observing data into forecasting procedures.
    - The activities presented here show successful comparison between traditionally developed CBRFC forecasts and those forecasts informed using ASO data; improvement using ASO data was inconsistent.

- Facilitate reciprocal communication and data sharing between CBRFC and ASO Inc.
    - Channels of communication and data sharing between the CBRFC and ASO Inc. greatly improved over the course of this project.

- Document and evaluate the major obstacles impeding the integration of ASO data into CBRFC's forecast operations and identify data integration opportunities.
    - This summary document attempts to document the obstacles impeding the consistent integration of ASO data into operational forecasts. The primary obstacles are inconsistent results using ASO data, and lack of a historical record. However, there may be an opportunity to use ASO data in sparsely gaged areas in the future.

Due to the inconsistent results associated with using ASO informed forecasts, it is unlikely the CBRFC would implement consistent use of ASO data in the development of operational forecasts in the near future. Further consideration of using ASO data may center around sparsely gaged areas.

5.1.5 Next Steps

Despite the lack of consistent improvement to CBRFC forecasts using ASO information, the analysis did provide the CBRFC with the opportunity to develop a framework for comparing new datasets using a direct insertion method. The CBRFC has identified the following as next steps:

- Continue comparison of CBRFC forecasts with ASO informed forecasts as requested by stakeholders, noting that these would not be operational or "official" forecasts.

- Continued comparison of CBRFC forecasts and ASO informed forecasts in sparsely gaged areas, where added information from ASO could potentially be incorporated in the future operationally.

- Utilize the direct insertion methodology developed to compare ASO forecasts to compare other remotely sensed and modeled datasets, including non-SWE datasets.

- The CBRFC is actively investigating the use of distributed hydrologic and snow models, specifically a distributed version of the Sac-SMA hydrologic model and the iSNOBAL physically distributed snow model. As these investigations evolve, ASO information may be incorporated to evaluate its use in these environments.

5.2 Development of an Improved Methodology for Modeling Unmeasured Depletions in the Upper Colorado River Basin

The CBRFC utilizes observations of diversions and return flows whenever possible when modeling hydrologic conditions over the Colorado River Basin. However, many instances of water use are often reported infrequently or estimated in the absence of gages by water resource managers; as such, the CBRFC models the use of this water through a “consumptive use” model. It is important to note here that the term “consumptive use” can imply different components of the water balance over a particular area. For clarity and consistency, it is best to described the volume of water modeled by the CBRFC using its consumptive use model as “unmeasured depletions;” that is, water that is taken from the river, but is unmeasured (or data is not available to the CBRFC in a routine and timely manner). This water is not accounted for in the CBRFC’s development of unregulated inflow. A summary of important CBRFC terms and definitions is available here[8].

The CBRFC’s current consumptive use model simulates unmeasured depletions primarily as a function of temperature and irrigated acreage; as such, there is limited year to year variability in these uses. As an active member of the Work Group, the CBRFC and Colorado River Basin stakeholders identified the need for improved modeling of unmeasured depletions within the CBRFC’s hydrologic modeling framework. Phase 1 of this project began in November 2019. RTI International (RTI) was contracted to develop an improved consumptive use modeling methodology using robust data and records maintained in the State of Colorado by the Colorado Water Conservation Board (CWCB) Department of Water Resources (DWR). The project was funded by Work Group members from Arizona, Colorado, Nevada, California, and Utah, including additional funding from both the Lower and Upper Colorado Regions of Reclamation, and NOAA’s Oceanic and Atmospheric Research (OAR) Weather Program Office.

The goal of Phase 1 of this research effort was an improved consumptive use model that could be run from the CBRFC’s Community Hydrologic Prediction System (CHPS) framework over pilot basins in Colorado. RTI evaluated Colorado’s StateCU software for computing diversions and StateMod model for simulating diversions in addition to a robust analysis of historical diversion and water use data maintained by the CWCB DWR. RTI found that the existing Colorado models effectively simulated consumptive use without the need for significant adjustments. RTI developed CHPS transformations that behaved similarly to Colorado’s StateCU and StateMod; this included developing Penman-Monteith based estimates for evapotranspiration using temperature forcings to approximate many of the inputs needed for the Penman-Monteith method. While the Penman-Monteith method is what is utilized by the StateCU software, the framework developed by RTI is flexible where the Penman-Monteith method can be switched with another method if needed (e.g., a modified Blaney-Criddle approach). Figure 21 shows an

[8] For those unable to use the hyperlink: https://www.cbrfc.noaa.gov/wsup/doc/ConsumptiveUseDefinitions_forWeb_v1.pdf

overview of the computation workflow developed by RTI for estimating unmeasured depletions and total flow.

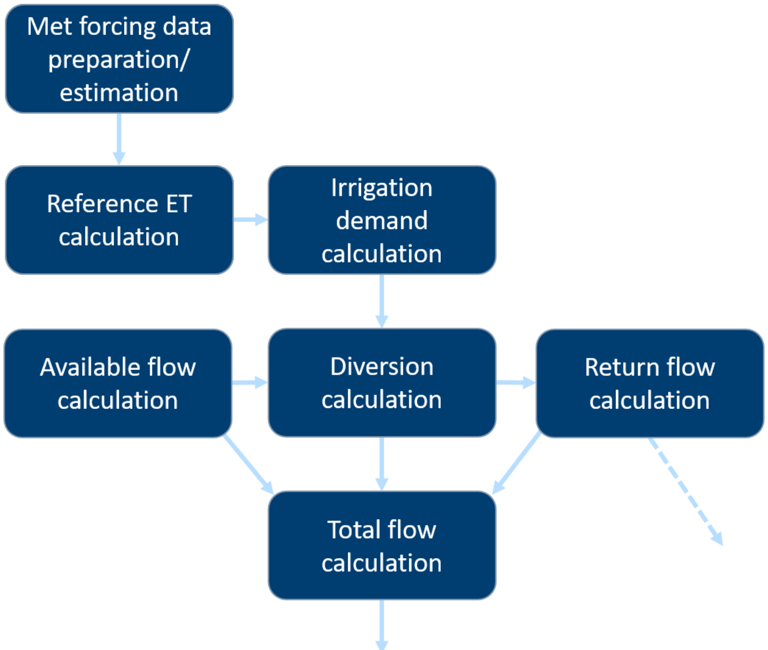

Figure 21: Flowchart describing how a new method for modeling unmeasured depletions and flow is developed. This work, identified by Work Group stakeholders as a priority, was done by RTI.

RTI tested and calibrated the methodology at the LOSC2 forecast point (Los Pinos River at La Boca, Colorado). The CHPS configuration files were delivered to the CBRFC in November of 2020, and were incorporated into a CBRFC evaluation (i.e., non-operational) model.

It is anticipated that the configuration will be fully implemented by the CBRFC in 2022 for forecast points in Colorado. The CBRFC and Work Group are currently exploring options to pursue future phases of this work, which would focus on the development of a methodology to model unmeasured depletions over areas outside of Colorado where water use data is not as widely available.

5.3 Submitted Proposals on Which the CBRFC is a Collaborator or Partner

The CBRFC partners with a broad range of stakeholders to address research needs with the goal of improving forecast products and services.

5.3.1 Western Water Assessment

Western Water Assessment (WWA) is a NOAA Regional Integrated Sciences and Assessments (RISA) program that partnered with the CBRFC to develop a proposal entitled, "Identifying Alternatives to Snow-based Streamflow Predictions to Advance Future Drought Predictability." This proposal was funded and work is expected to be completed in 2024.

5.3.2 Reclamation Science and Technology Grants

Reclamation's Science and Technology program funded three proposals in which the CBRFC is a collaborator one. The first funded proposal is entitled, "Quantifying the Value of the Natural Resources Conservation Service's SNOwpack TELemetry (SNOTEL) Network to Water Supply Forecasting and Data Planning." The goal of this work is to quantify the impact to the skill of CBRFC's water supply forecasts due to the implementation of the SNOTEL network. It is known that the CBRFC's forecasts are critically dependent on the NRCS's SNOTEL network, but the degree to which the CBRFC's forecasts are improved by the SNOTEL network has never been quantified. Further, this project will also identify areas where future SNOTEL stations may yield the most benefit to water supply forecasts in the future. RTI has been contracted to do this work. This project is expected to conclude in 2023.

The second funded proposal is entitled, "Exploring the Utility of CU-SWE Estimates for Water Supply Forecasting in the Colorado River Basin." This project aims to evaluate and fund the development of a gridded product developed at the University of Colorado describing snow water equivalent (SWE) values over the Upper Colorado River Basin. This proposal funds the development of a historical record of gridded SWE values at a monthly timestep over the Colorado River Basin. Future work will evaluate the data in the development of CBRFC water supply forecasts and continued development of the product into the future. This project is expected to conclude in 2024.

The third funded proposal is entitled, "Install New SNOTEL (SNOwpack TELemetry) sites within the Colorado River Basin." As the name implies, this project will fund the installation of additional SNOTEL stations in the Colorado River Basin and is expected to conclude in 2023.

5.3.3 NOAA's Physical Science Laboratory

NOAA's Physical Science Laboratory (PSL) is collaborating with the CBRFC on a Study of Precipitation, the Lower Atmosphere and Surface for Hydrometeorolgy (SPLASH), which would involve flying unmanned aircraft over the East River watershed to measure a number of hydrometeorologic variables in 2021 and 2022.

5.3.4 Proposed CBRFC Testbed through the Southwest Climate Adaptation Science Center

The CBRFC submitted a proposal in response to a call from the USGS's Southwest Climate Adaptation Science Center for research advancing science needs in the Colorado River Basin. In collaboration with the Southern Nevada Water Authority and Colorado State University (CSU), a proposal was submitted to establish a "CBRFC testbed" at the CBRFC. This testbed would utilize a post-graduate student from CSU at the CBRFC to analyze the impact to water supply forecasts from incorporating new and emerging datasets over the Colorado River Basin. This included, but was not limited to, remotely sensed snow information, remotely sensed soil moisture information, and the use of alternative models within the CBRFC's modeling paradigm (e.g., using iSNOBAL instead of SNOW-17 to model the accumulation and ablation of snowpack in the basin). This work was not accepted for funding.

5.3.5 Improved Snow Water Artificial Neural Network Tool Through the Use of Remote Sensing

The CBRFC supported a proposal submitted by the University of Arizona to NASA regarding the improvement of the Snow Water Artificial Neural Network (SWANN) tool through the use of additional remotely sensed information. This research was not funded.

5.3.6 Addressing Temperature Trends and Dynamic Evapotranspiration

Reclamation's Lower Colorado Regional Office is funding a research project entitled, "Improving Streamflow Forecasts and Reservoir Projections Through Temperature Detrending and Dynamic Evapotranspiration Modeling." This project will fund RTI to work with the CBRFC to accomplish two goals. The first is to investigate the impact of increasing temperature trends on seasonal streamflow forecasts. To this end, RTI will detrend historical mean areal temperature datasets to reflect contemporary temperature states. These detrended temperature datasets will be substituted for the CBRFC's historical temperature datasets to develop seasonal streamflow forecasts that could potentially be more representative of current temperatures.

The second goal of this project is to develop a dynamic evapotranspiration component for the CBRFC's hydrologic model that may be more skillful that the monthly, static coefficients the CBRFC currently employs in its model. These monthly coefficients are developed during model calibration and remain static, regardless of weather conditions; a dynamic evapotranspiration component may be more skillful.

6 Personnel Changes at the CBRFC

Owing primarily to the large degree of hydroclimatic variability and ever-changing advancements in hydrologic modeling and technology, newly hired personnel at the CBRFC can expect training to be at least two years. Personnel at the CBRFC learn to address a variety of decision support issues depending on stakeholder needs, hydroclimatic conditions, and modeling paradigms. Over the last year, CBRFC personnel have changed. While the loss of experience and knowledge is difficult to replace in the short-term, newly hired hydrologists and meteorologists bring new skillsets and perspective that will benefit the office and stakeholders in the long-term.