CBRFC Water Year In Review

An Overview of Operational Changes, Improvements, and Investigations over the course of Water Year 2020

March, 2021

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 2020. 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 2020 Climate and Significant Weather Events

Hydroclimatic activity towards the end of Water Year 2019 tended towards dry and hot, as partly indicated by the unusually dry and hot 2019 monsoon season (June through September). The 2019 monsoon season was the 9th driest and 3rd hottest on record, dating back to 1895. The dry monsoon season, combined with well below average precipitation conditions over the Upper Colorado River Basin during the Fall of 2019, resulted in antecedent soil moisture conditions that were below average throughout most of the Colorado River Basin and Great Basin areas (Figure 1). Although below average, these dry soil conditions benefited from relatively wet conditions over the 2019 runoff period and were an improvement over the historically dry conditions that preceded Water Wear 2019.

Active weather conditions characterized the first quarter of Water Year 2020 (Figure 2). In particular, December through January precipitation over much of the Upper Colorado River Basin and Great Basin were near to above average in areas that significantly contribute to spring runoff. This active weather pattern continued to bring above average precipitation amounts to parts of the Upper Colorado River Basin headwaters into February.

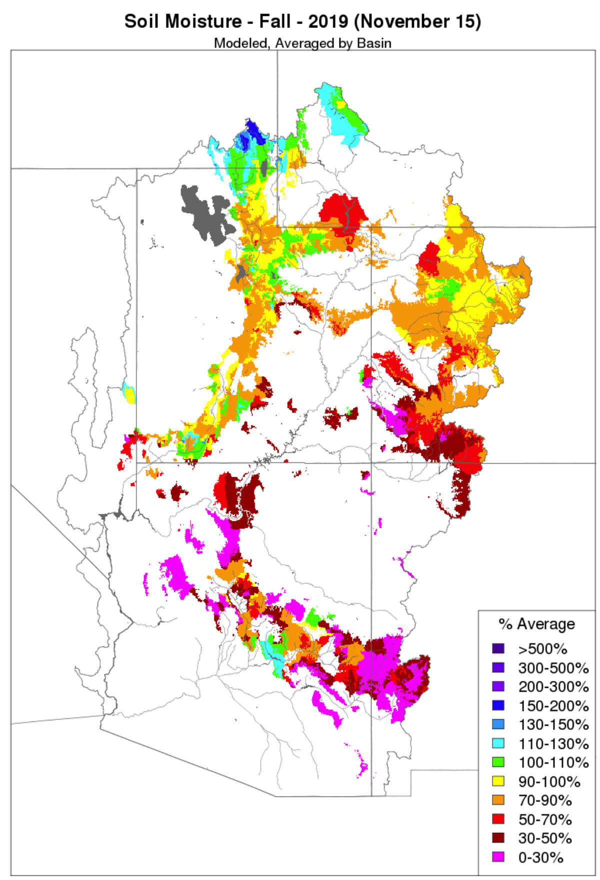


Figure 1: Dry Fall Soil Moisture conditions spanned much of the Colorado River and Great Basin regions. The impacts from the dry 2019 monsoon season were particularly prevalent throughout the Lower Colorado River Basin.

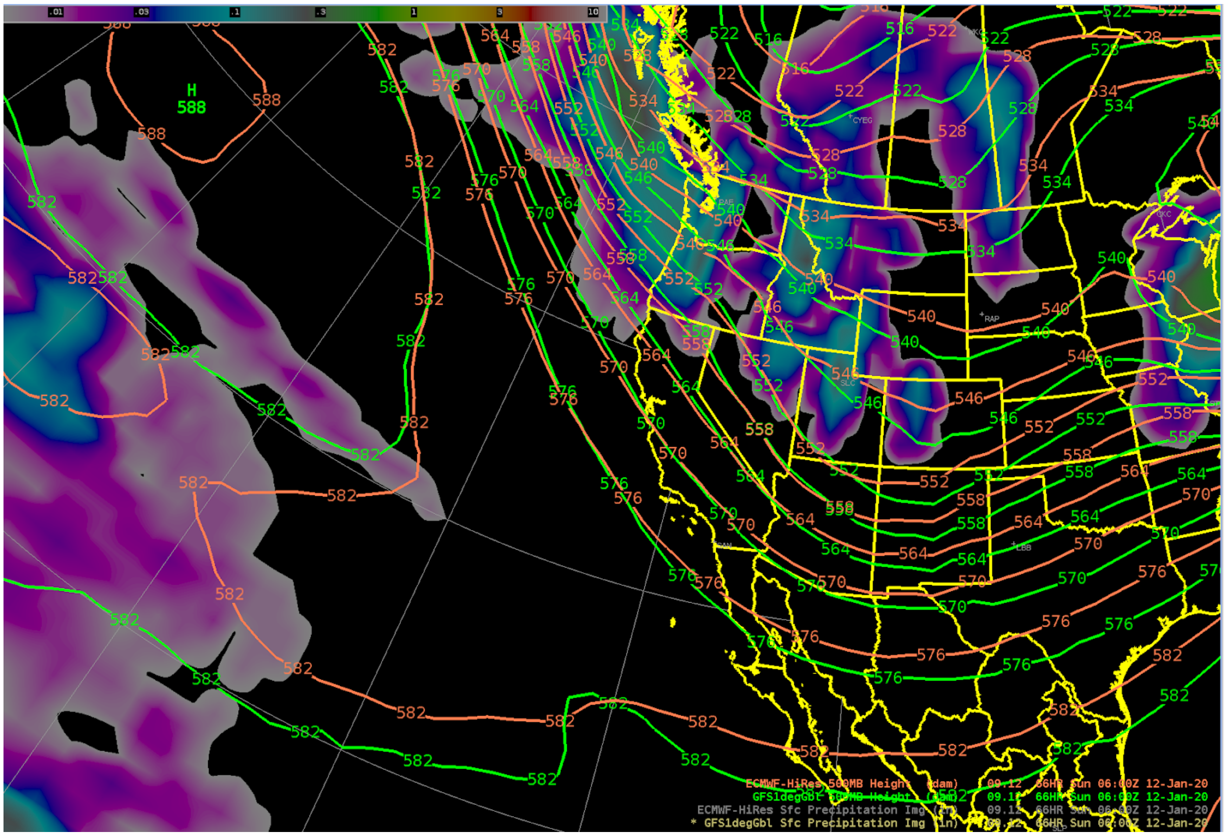


Figure 2: Active weather systems, like the one shown here in early January, brought significant mountain snow to mountains in Northern Utah, Wyoming, and Colorado. While there were brief dry periods between storms, these active weather patterns brought above average precipitation amounts to much of the mountainous areas of the Upper Colorado River Basin through early February.

As a result of near to slightly above average precipitation and dry antecedent soil moisture conditions, water supply forecasts in the Upper Colorado River Basin and Great Basin regions ranged from well below average in the San Juan River Basin to slightly above average in the Yampa River Basin and Sevier River Basin. The forecasted unregulated inflow into Lake Powell in early February was 80% of average (Figure 3). Table 1 shows winter (December through February) precipitation and snowpack amounts, as well as associated percentiles, at selected SNOwpack TELemetry (SNOTEL) stations in the basin. It is important to note that these stations are typically located at higher elevation areas and may not be representative of snowpack conditions in nearby valleys or lower elevation areas. It is interesting to note the difference between some precipitation percentile values and snowpack percentile values at some stations. The CBRFC uses precipitation information, combined with temperature and freezing level information, to model snowpack in its hydrologic model; typically, modeled snowpack information developed by the CBRFC corresponds closely to information observed at SNOTEL sites.

Table 1: Selected Winter (December through February) precipitation and snowpack amounts at SNOTEL stations in the Upper Colorado River Basin and Great Basin.

SNOTEL Station (NWS ID)	Precipitation (Percentile)	Snowpack (Percentile)
Trial Lake (TRLU1)	12.3” (51)	19.2” (63)
Little Warm (LTWW4)	4.8” (41)	9.2” (76)
Lake Irene (LKIC2)	13.1” (85)	21.5” (68)
Middle Creek (MDLC2)	7.0” (28)	13.5” (38)

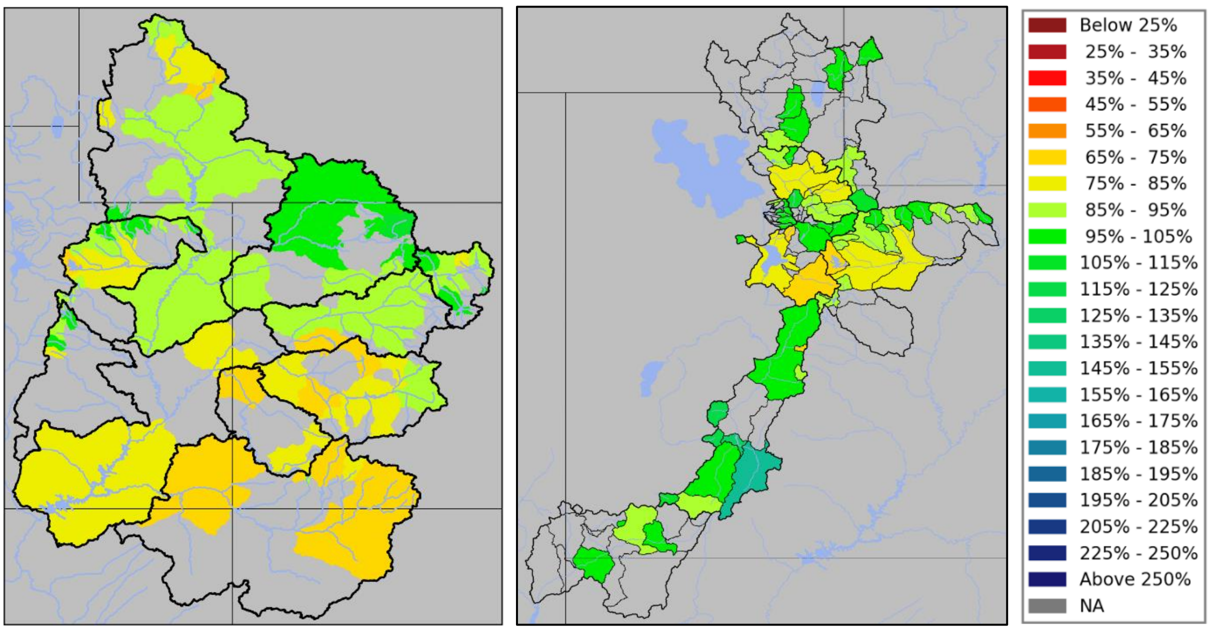


Figure 3: Early February water supply forecasts in the Upper Colorado River Basin (right map) and Great Basin (left map) typically ranged from well below average in the San Juan River Basin to slightly above average in the Yampa and Sevier River Basins.

The active weather observed during the early portion of the water year did not continue into spring. Precipitation throughout the Upper Colorado River Basin and Great Basin regions was well below average from March through June. In particular, May was among the driest on record in some areas, particularly in the San Juan and Gunnison River Basin areas (Figure 4). The combined April through May precipitation amounts were among the driest on record at many SNOTEL locations.

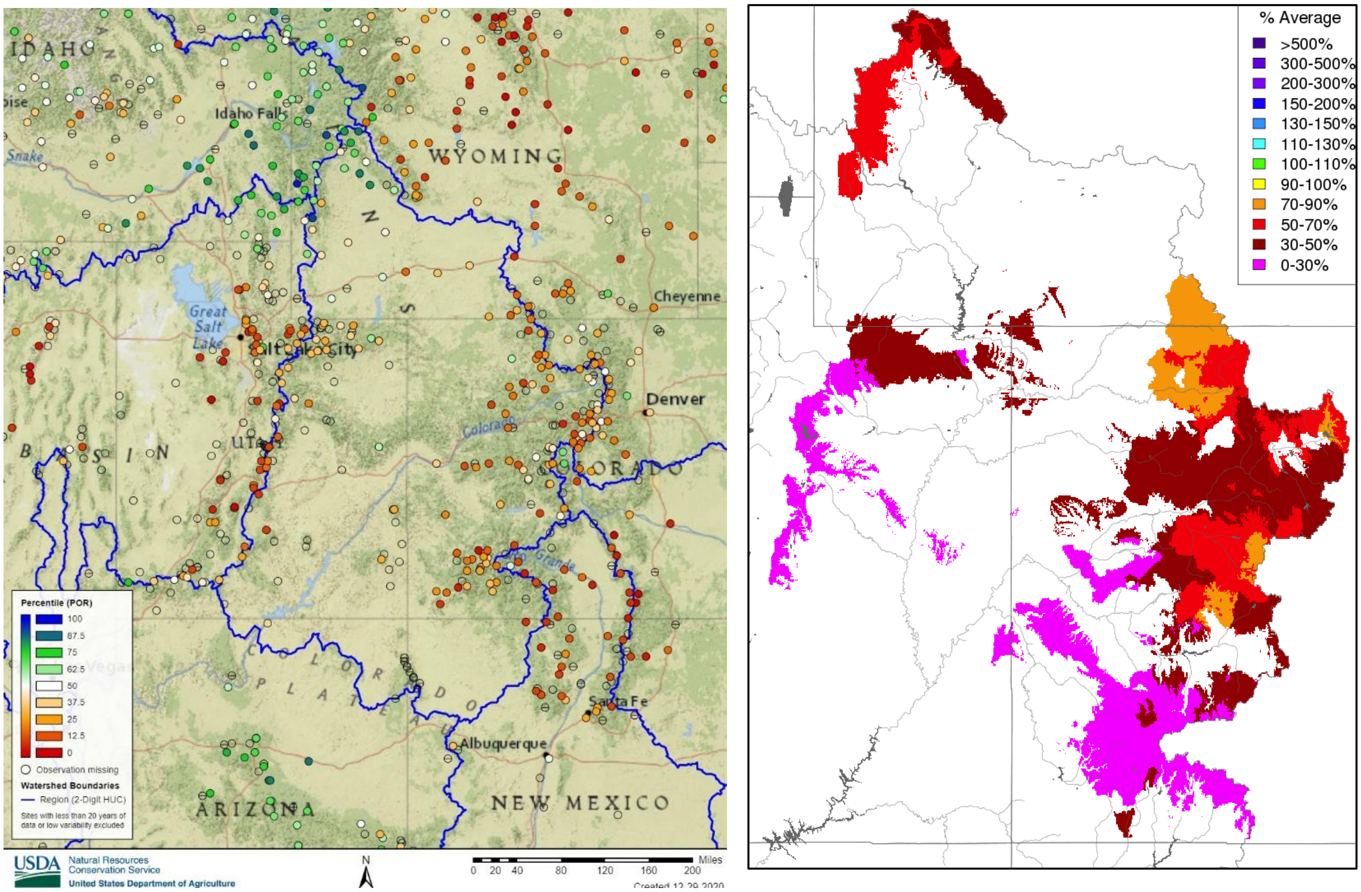


Figure 4: March through June was particularly dry over the Upper Colorado River Basin and Great Basin regions, negating near average precipitation observed at the beginning of the water year. Over these four months, observed precipitation at NRCS SNOTEL locations (right) were well below normal. In May, near record low precipitation was observed in the San Juan and Gunnison River Basins (left).

May and June temperatures were much above normal throughout the basin, which contributed to snowpack melting out earlier than usual at SNOTEL locations throughout the basin (Figure 5). Figure 6 shows the impact of well above average temperatures on modeled high elevation snowpack; here, the modeled high elevation snowpack for the Green River at Warren Bridge near Daniel, WY is near normal from September through April. In May, it is apparent that normal snowpack accumulation that continues through much of May did not occur, and above average temperatures in the area contribute to rapid melt and a sharp decline in snowpack.

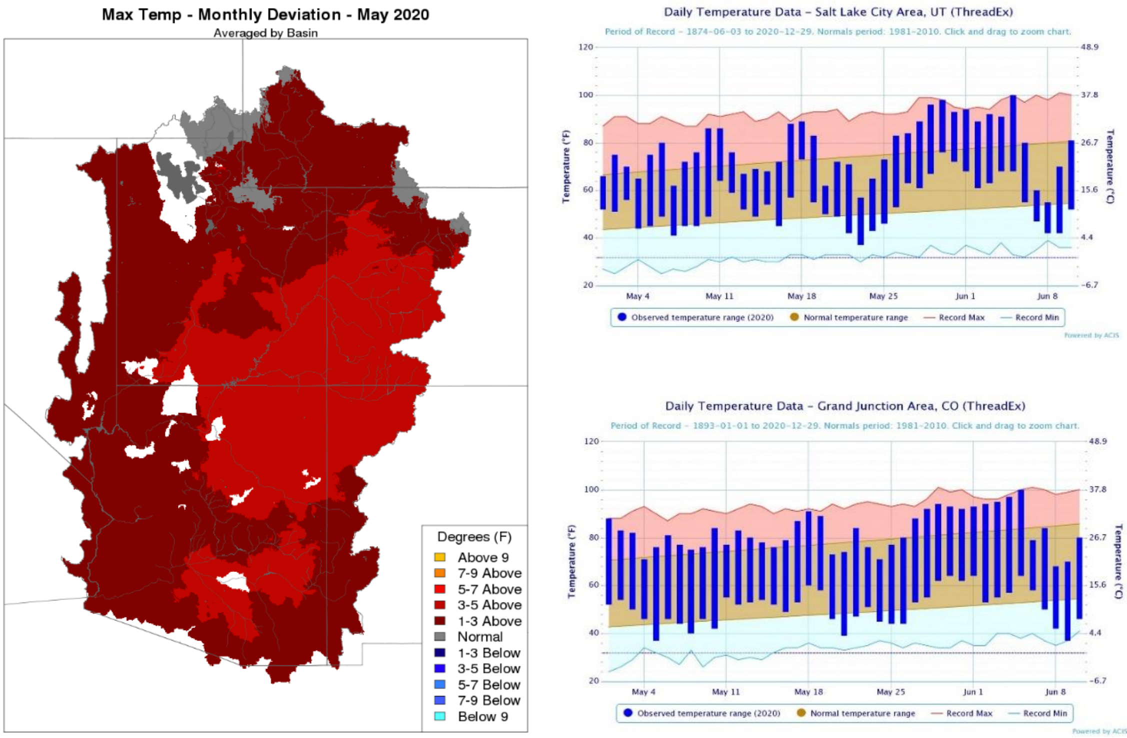


Figure 5: May temperatures were well above average through the Colorado River Basin and Great Basin areas. The map on the left shows the average monthly deviation from maximum temperatures over the CBRFC region. The graphs on the right show daily temperature values for Salt Lake City, UT (top) and Grand Junction, CO (bottom) from May 1st through June 10th. From late May through early June, new maximum temperature records were set in each area, accelerating melt from what little snowpack was left.

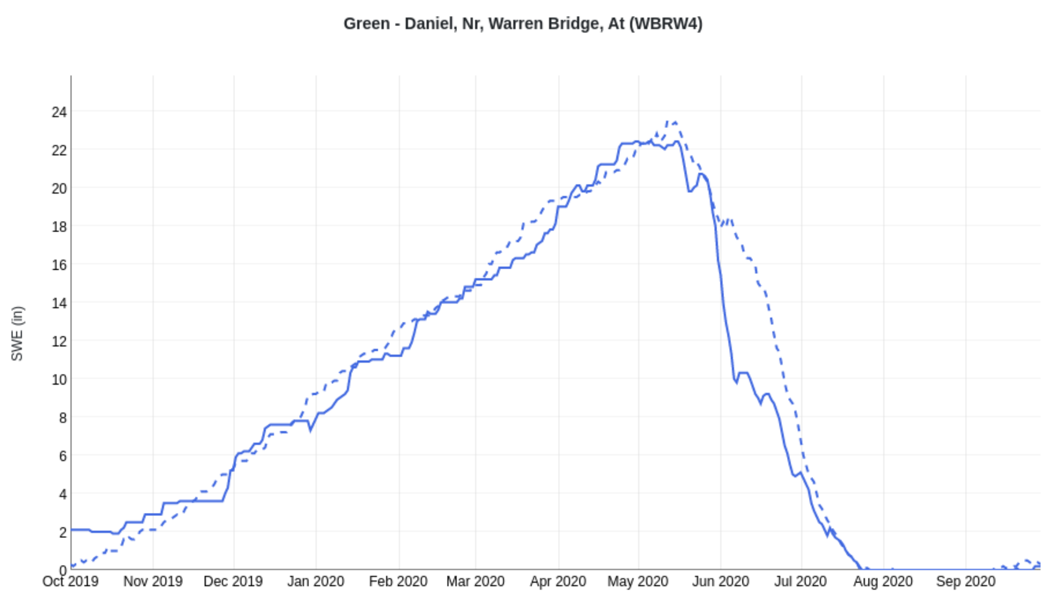


Figure 6: Modeled high elevation snowpack in the Green River Basin (solid line) is shown here compared to normal snowpack conditions (dashed line) over the course of Water Year 2020. Modeled conditions were near normal until May, when snowpack accumulation did not reach normal peak, followed by accelerated snowmelt in early June due to well above average temperatures.

Water Supply forecasts throughout the Upper Colorado River Basin and Great Basin tended to decline from March through the runoff season primarily due to the very dry spring. In January, when snowpack was near normal, the official forecasted seasonal unregulated inflow into Lake Powell was 5.9 million acre-feet (MAF) or approximately 82% of average. By the beginning of April, that forecast had only decreased 0.3 MAF. However, due to the extremely dry April and May conditions, the official June unregulated inflow forecast into Powell had decreased to 4.1 MAF (57% of average). Interestingly, the 90 percent exceedance value in January was 3.6 MAF. The final observed seasonal unregulated inflow into Lake Powell (3.76 MAF) nearly came in at the January 90 percent exceedance value (Figure 7).

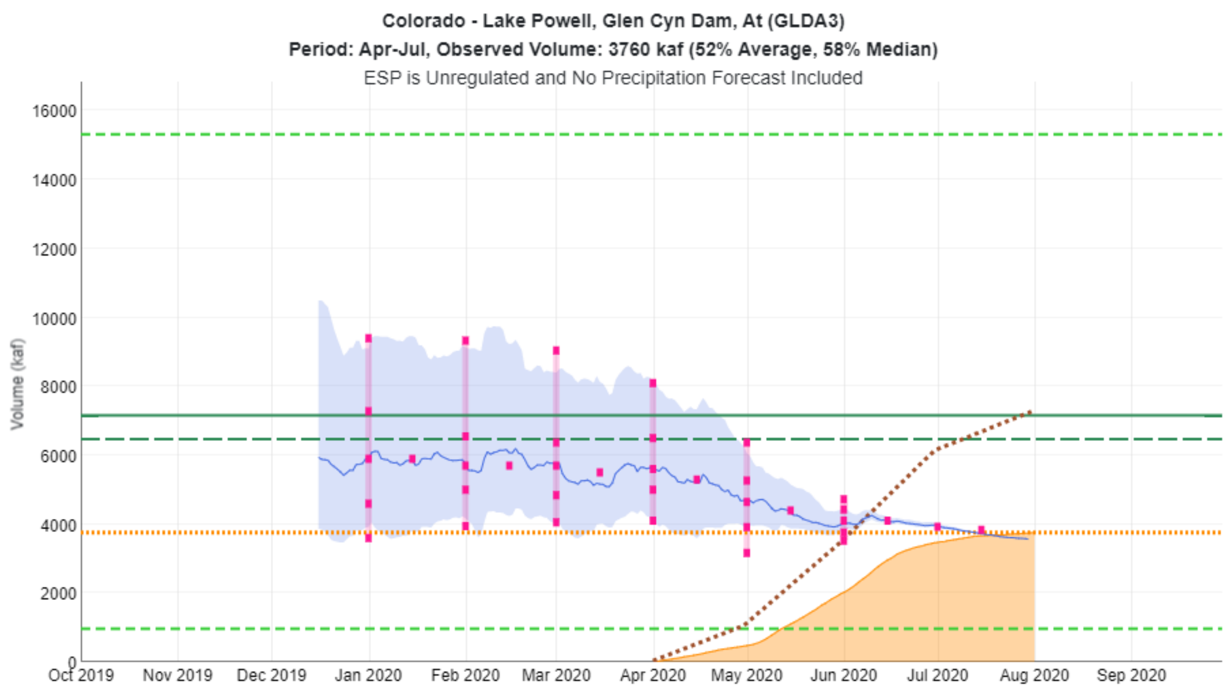


Figure 7: The evolution of model guidance, seasonal (April through July) unregulated inflow into Lake Powell for Water Year 2020 is shown in light blue, with official forecasts shown monthly in pink. Forecasts were relatively stable until a historically dry April and May period significantly decreased expected volumetric forecasts throughout the Upper Colorado River Basina and Great Basin regions.

Extremely dry conditions continued through the summer months; the April through September period was among the driest on record for much of the Colorado River Basin and Great Basin (Figure 8). For the second consecutive year, monsoon precipitation conditions were near or at record lows, worsening precipitation and soil moisture deficits through the beginning of fall. The dry monsoon season is discussed in more detail in Section 1.3.2.

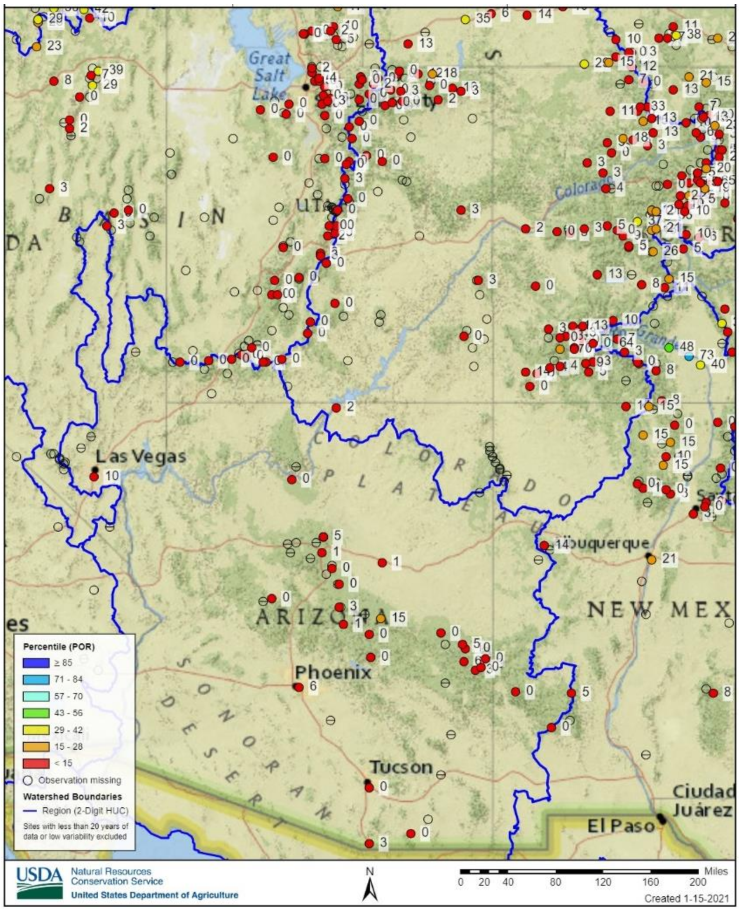


Figure 8: Precipitation percentiles over the Colorado River Basin and Great Basin regions for the April through September period. Many were at or among the lowest on record.

1.3 Water Supply Forecasting Challenges and Verification

The 2020 Water Year presented unique challenges in the communication and interpretation of model output and water supply forecasts. Despite near normal snowpack conditions early in the water year, many initial forecasts were below average, due in part to the near record dry 2019 monsoon season and dry fall soil moisture conditions. Additionally, the CBRFC's hydrologic model accounted for consistently below normal high elevation snowpack accumulation which, percentage wise, trailed low elevation snowpack conditions throughout the season (Figure 9). Unfortunately, the near average snowpack amounts observed at many SNOTEL locations throughout the Upper Colorado River Basin led to incorrect assumptions by the general public and media that snowmelt driven runoff would be near normal for much of the basin.

As mentioned in the previous section, seasonal unregulated inflow forecasts dropped sharply after the CBRFC's official April forecast issued near the beginning of the month due to the extremely dry April and May conditions. However, the April forecast, and those forecasts preceding it, should not be interpreted as poor forecasts. For instance, consider the forecasts made at McPhee Reservoir in the Dolores River Basin.

In early January, snowpack conditions at SNOTEL locations in the headwaters of the Dolores River Basin near the McPhee Reservoir were well above normal conditions. By April 1st, snowpack conditions at these same locations were still near to well above normal conditions

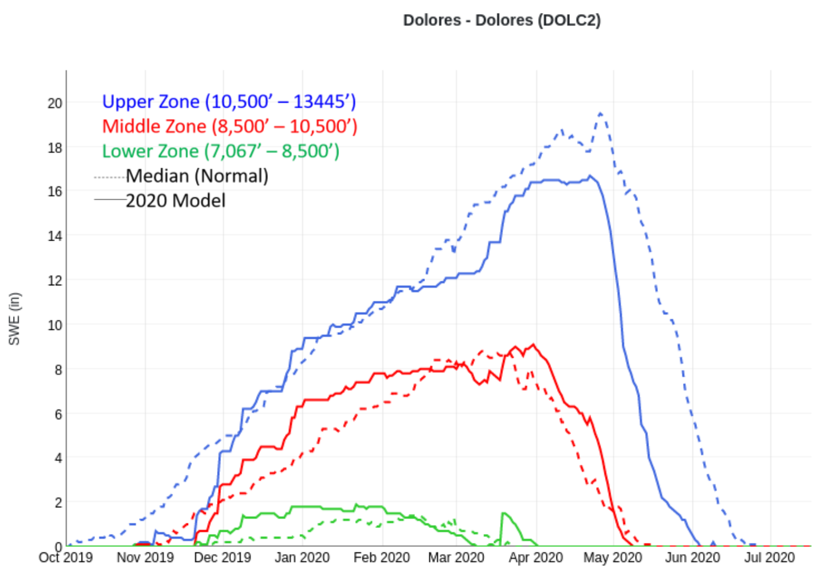


Figure 9: The character of high elevation snowpack was often different than low and mid elevation snowpack throughout the Colorado River Basin and Great Basin regions. Here, modeled low elevation snowpack (solid green line) was above normal simulated conditions (dashed green line). The solid and dashed red lines are similar for the mid elevation snowpack conditions. In contrast, high elevation model snowpack (solid blue line) began accumulating later than usual, then trended near normal for much of the Winter, though never reached normal peak conditions.

(Figure 10). Despite the above normal conditions at these SNOTEL locations, water supply forecasts developed at the CBRFC were consistently below normal; this was due, in large part, to the presence of dry soil moisture states and modeled high elevation snowpack in the Dolores River Basin that was below normal. Figure 11 illustrates the range of forecasts used to develop water supply forecasts at the McPhee Reservoir; the final observed seasonal flow volume was below the 90th percent exceedance value, or a 10% chance that flows could be lower until the May official forecasts. Due to the historically dry nature of April and May, it is reasonable that the final observed seasonal volume would fall below the 90% exceedance forecast. In other words, the CBRFC's hydrologic model and subsequent forecasts did not perform poorly despite initial forecasts being above the final observed seasonal volume for much of the year; rather, official forecasts indicated below average seasonal volumes despite well above snowpack conditions observed at gage locations due to dry model soil moisture conditions and below average modeled snowpack at high elevations. Further, historically dry conditions in April and May caused observed volumes to fall outside of the 90% exceedance forecast range which is where dry hydroclimatic extremes would be represented.

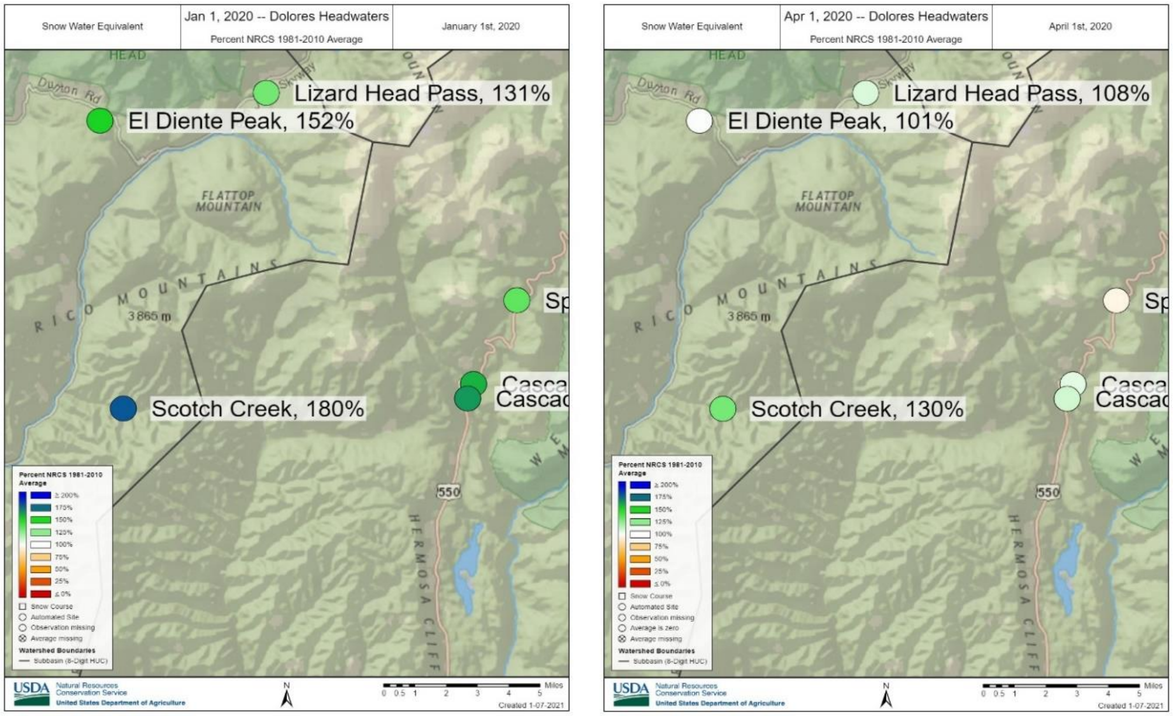


Figure 10: On January 1st (left) and April 1st (right), SNOTEL locations in the headwaters of the Dolores River Basin were consistently showing above normal conditions. Despite this, water supply forecasts developed by the CBRFC were below normal due to dry soil moisture conditions and modeled high elevation snow conditions that were below normal. For reference, Lizard Head Pass is located at 10,200', El Diente Peak is located at 10,000', and Scotch Creek is located at 9,100'.

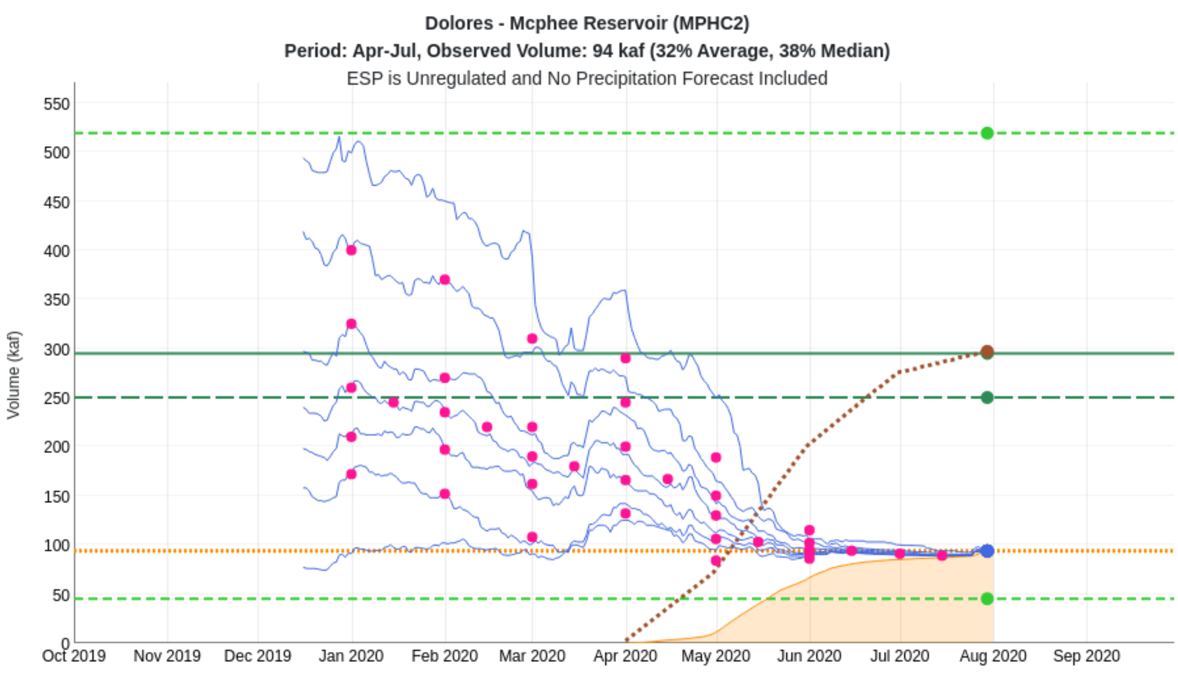


Figure 11: The ensemble of forecast traces developed by the CBRFC was consistently below average conditions (solid green line) despite well above snowpack conditions observed at area SNOTEL locations. Only the minimum trace (solid blue line at the bottom of the ensemble) was representative of what the final observed volume would be until March. Forecasts declined sharply after the historically dry April and May months. The traces shown here indicate the maximum and minimum of the ESP ensemble (top and bottom solid line, respectively). The intervening lines show the 10, 30, 50, 70, 90 percent exceedance values.

It is important to note the benefit of the CBRFC's hydrologic model, even during extremely dry years when, intuitively, model performance may not be viewed as accurate. The CBRFC's hydrologic model incorporates much more information to physically model the complex hydrology of the region; this is why well-above normal conditions at area SNOTEL stations did not equate to above normal water supply forecasts over the course of Water Year 2020. Among other factors and parameters, the CBRFC's model incorporates modeled soil moisture and modeled high elevation snow conditions, which play critical roles in the seasonal water supply volumes. In Water Year 2020, the CBRFC's model signaled drier conditions well ahead of the runoff period despite some gage observations indicating otherwise; further, the historically dry April and May conditions expectedly led to an observed volume that fell outside the range of the CBRFC's 90% exceedance forecasts. More succinctly, historically dry conditions, as opposed to model performance, was the primary driver of observed volumes falling outside the range of early CBRFC forecasts.

1.3.1 Distribution of SNOTEL Elevations

As mentioned in the previous section, observed snowpack conditions at SNOTEL locations are not always indicative of potential seasonal water supply volumes. While the SNOTEL network, maintained by the NRCS, is an invaluable and critical source of information into the CBRFC's hydrologic model, it is limited in that only 5% of the stations are located above 11,000 feet where a significant amount of high elevation snowpack accumulates and contributes to seasonal runoff (Figure 12). SNOTEL information, along with temperature and freezing level, is used to model the accumulation of snowpack at high elevation areas within the CBRFC's hydrologic model, where gage observations of snowpack are not typically available.

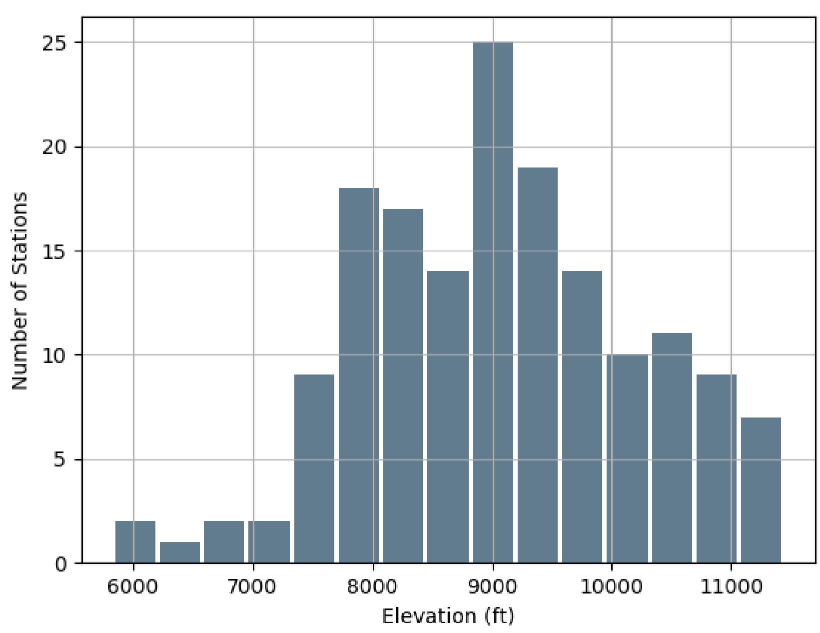


Figure 12: The distribution of SNOTEL stations over the CBRFC's area of responsibility. Only 5% of stations are located above 11,000 feet, where a significant amount of snowpack accumulation occurs and impacts seasonal runoff. CBRFC modeling efforts track snowpack accumulation at high elevation areas where gage observations are sparse.

As the snowpack begins to melt, the CBRFC utilizes other tools to assess the model's snow states correctly. Remotely sensed information, such as the Moderate Resolution Imaging Spectroradiometer (MODIS) snow covered area and grain size (MODSCAG) information provided by the National Aeronautics and Space Administration (NASA) Jet

Propulsion Laboratory (JPL) is currently being used qualitatively to inform the CBRFC's hydrologic model. Current efforts within the CBRFC focused on using remotely sensed snow information is discussed in more detail in Section 5.

1.3.2 "Nonsoon" Impacts to Soil Moisture

The southern portion of the Upper Colorado River Basin and Lower Colorado River Basin experienced one of the driest, if not the driest, monsoon seasons (July through September) on record in 2020 (earning the nickname "nonsoon" by numerous media outlets) depending on the location of interest. In the Tucson, Arizona area, the monsoon was the second driest on record, while in Flagstaff, Arizona, the monsoon was the driest on record, eclipsing the previous year's record setting dry conditions (Figure 13). These dry conditions extended into the Four Corners area, leading to dry fall soil moisture conditions throughout the Lower Colorado River Basin and Four Corners regions (Figure 1), which partly led to dry initial Water Year 2021 seasonal runoff forecasts in the San Juan River Basin. This was the second consecutive year that monsoon precipitation conditions throughout the basin were well below average.

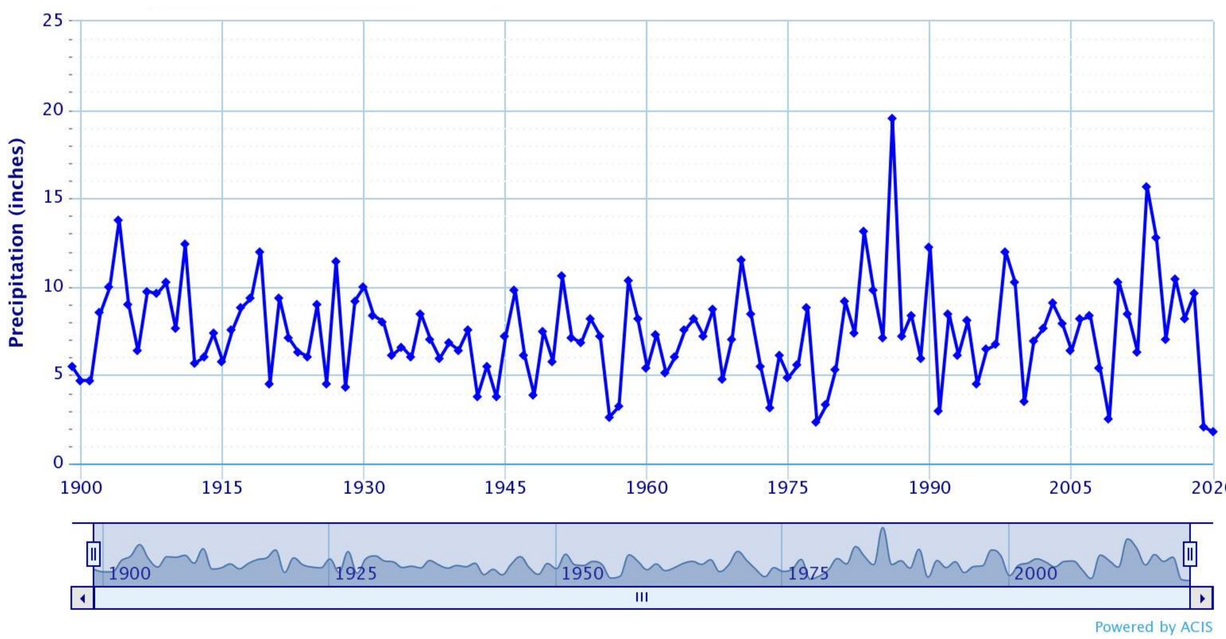


Figure 13: Monsoon conditions were the driest on record for the second consecutive year in the Flagstaff, Arizona area.

2 Summary of Major Water Year 2020 Improvements

There were several major 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:

- Expanded Services (Section 3)
- New and Enhanced Methods to Improve Forecasts (Section 4)
- Stakeholder Outreach and Support (Section 5)
- Research, Investigations, and Collaborations (Section 6)

The novel coronavirus of 2019 (COVID-19) grew to a global pandemic and impacted nearly every facet of life, including operations at the CBRFC. To this end, the CBRFC enacted working conditions to limit contact between CBRFC staff members and stakeholders. CBRFC personnel were divided into two "pods" so that in the event that one pod was exposed to COVID-19, the other pod could continue CBRFC operations. Additionally, the National Weather Service implemented the use of Virtual Private Networks (VPNs), and CBRFC staff was able to work remotely; on most days, only a single CBRFC staff member was physically present in the office, and coordinated operations among staff members from the home. All travel was cancelled, and the CBRFC was no longer able to meet with partners physically. Like everyone else, the expanded use of tools to meet virtually (e.g., GoToMeeting, WebEx, Google Meetings) allowed for CBRFC personnel to continue meeting operational goals and provide time sensitive decision support for stakeholders with very limited interruption or delays.

The most notable improvements by the CBRFC over water year 2020 are those done with the CBRFC's continued focus on providing decision support for its stakeholders. Significant and frequent fire events in Arizona necessitated the development of a methodology to begin assessing and incorporating post-fire impacts into the CBRFC's hydrologic model; in an odd sort of contrast, additional forecast points were added below Parker Dam in Arizona to address concerns from emergency managers in the area concerned about future potential high flows in the area that have not been seen since 1984. Additional efforts targeting improved decision support for Colorado River Basin and Great Basin stakeholders included participation for the improved management of a 15-mile reach of the river located in the Colorado River headwater region and participation in drought coordination efforts for the state of Utah.

Remotely sensed snow information has become a priority for many stakeholders within the Colorado River Basin. The CBRFC is interested and is actively engaging with partners developing both remotely sensed snowpack information and modeled snowpack information. Among the most prevalent datasets available is snowpack information developed from Airborne Snow Observatories, Inc. (ASO), formerly a division of the NASA JPL. Research investigating the impact of incorporating ASO information in the CBRFC's hydrologic model is currently ongoing, but preliminary results and trends in incorporating ASO data, and other snowpack information, is discussed in Section 5 of this report.

3 Expanded Services

The CBRFC consistently works to expand services through the addition of new forecast points, webpage improvements, and the introduction of new products and services to meet stakeholder needs. This section describes expanded services the CBRFC undertook in Water Year 2020.

3.1 Added SNOTEL to MPE for National Product

The CBRFC has always utilized hourly precipitation information from many gage networks such as the Automated Local Evaluation in Real Time (ALERT) network and from the Geostationary Operational Environmental Satellite (GOES) server, but hourly information from the SNOTEL network was not always utilized. In October, the CBRFC began feeding hourly precipitation information for all SNOTEL sites utilized by the CBRFC into its Multisensor Precipitation Estimate (MPE) tool; previously, hourly SNOTEL precipitation values were only fed to the MPE tool for select sites in the Lower Colorado River Basin. This was done to improve the winter precipitation map on the NWS's Advanced Hydrologic Prediction Service (AHPS) webpage[1]. This change did not impact how mean areal precipitation forcings used in the CBRFC's hydrologic model were developed; however, the Sevier River Basin areas which relied on hourly precipitation forcings derived from the precipitation grid developed using MPE were potentially impacted. It is expected that these impacts will improve the hydrologic model's performance in those areas, particularly with regards to snowpack modeling since SNOTEL information was not previously being used in those areas.

3.2 Additional CBRFC support during HUP Calls

The CBRFC works with Colorado River Basin Stakeholders to share and coordinate information regarding streamflow forecasts, reservoir operations, and irrigation plans over a 15-mile reach of the Colorado River just upstream of the Gunnison River confluence to the Grand Valley Diversion Dam at Palisade, Colorado. This reach has been identified as a critical stream reach for the recovery of endangered fish in the Colorado River by the U.S. Fish and Wildlife Service (FWS). The FWS has defined a suite of recommended flows, depending on hydrologic conditions, to encourage the recovery of the endangered fish. The Historic User Pool (HUP) Coordination Call strives to balance the needs of reservoir operations, irrigation, and endangered species goals.

In an effort to improve the coordination, transparency, and efficacy of river management during the HUP calls, the Bureau of Reclamation secured a 2-year Reclamation Science and Technology Grant to develop a decision support tool in which HUP call participants, through a web service, can submit both observed and forecasted streamflow information, reservoir operations, and irrigation plans to evaluate impacts to the river in real time. Over the first year of this project, HUP call participants have designed systems to load data from the Bureau of Reclamation, Wolford and Williams Fork reservoir, and CBRFC; have developed a routing model to the stream gage at Kremmling, Colorado; and have developed a beta version of the web service

[1] For those unable to access the hyperlink: https://water.weather.gov/precip/

(Figure 14). For its role in the project, the CBRFC configured its hydrologic model to output specific forecast timeseries to be ingested by the HUP routing model. In 2021, the project will incorporate data from additional entities along the reach, and further develop the hydrologic model to incorporate more information regarding proposed reservoir releases and diversion schedules for irrigation.

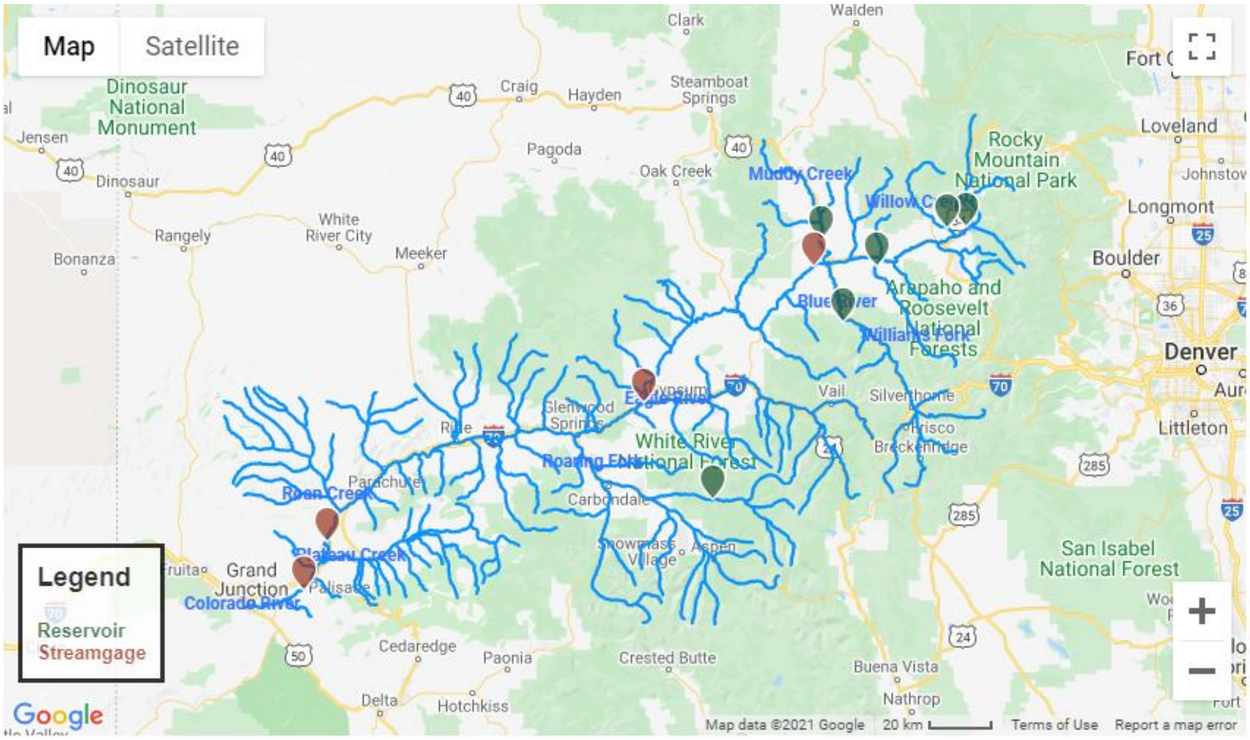


Figure 14: A beta version of the interactive web service for use during HUP calls has been developed and is available at: https://www.usbr.gov/lc/region/g4000/riverops/ecaodss.html. In 2021, the service will be expanded to cover the reach of river from Kremmling, CO to Palisade, CO.

3.3 Additional Forecast Points Added Below Parker Dam at Lake Havasu, Arizona

The CBRFC added forecast points below Parker Dam in the Lower Colorado River Basin (Figure 15) at the request of emergency managers in the area, who were concerned about potential future flooding on the order of what was last observed in 1983 (among the wettest years on record). The points added, and associated NWS Handbook 5 IDs, were:

- Colorado River at Water Wheel (CWWC1)
- Colorado River below Palo Verde Dam (CPVC1)
- Colorado River at Cibola (CQQC1)
- Colorado River below Imperial Dam (CIDC1)

Figure 15: The CBRFC added four points (CWWC1, CPVC1, CQQC1, and CIDC1) below Parker Dam to assist in the event of flooding on the mainstem of the Lower Colorado River Basin.

Observed data at these points are provided by the Bureau of Reclamation. Forecasted flows at these points are developed by routing forecasted releases from Parker Dam, also provided by the Bureau of Reclamation, and accounting for diversions from the Colorado River Indian Reservation Main Canal, Palo Verde Canal, Gila Gravity Main Canal, All-American Canal, and reservoir regulation at Senator Wash Dam. Inflow and storage information at Imperial Dam is not available, so releases from Imperial Dam are assumed to be constant into the future. It is important to note that forecasts at these locations are based solely on routed flows, and are therefore unaffected by weather or climate conditions in the area.

3.4 Virgin River model changes

The portion of the CBRFC's hydrologic model that represents the Virgin River Basin underwent substantial changes in an effort to improve hydrologic forecasts in the area. The basin's calibration was updated to use 3-hourly gage data spanning 2000 through 2020. In addition, the mean areal precipitation forcings that were calculated using station weights prior to 2000 were bias corrected using the common 2000 through 2010 period. This change was made so that the precipitation data used in the calibration process was more representative of the information being used operationally to force the CBRFC's hydrologic model. Table 2 summarizes the changes while Figure 16 illustrates the changes to the Virgin River Basin. Among the major changes to the Virgin River Basin model:

- Kolob Reservoir was added to the North Fork of the Virgin River (NFVU1) segment to account for increased Fall streamflows in the area.
- The Virgin River above LaVerkin Creek (VLLU1) segment was added. The Quail Creek Pipeline was also included in this segment.
- The Virgin River above Quail Creek near Hurricane (HUCU1) segment was added.
- Quail Creek Reservoir (QCRU1O) is now being modeled. Inflows include the natural flow as well as the flows from the Quail Creek Pipeline, less the water diverted to Sand Hollow Reservoir.
- The Santa Clara near Pine Valley (STCU1) segment has been corrected.
- Grass Valley Reservoir (GVRU1O) is now being modeled.
- The Santa Clara River above Baker Reservoir near Central (SCVU1) segment was added. Data from Baker reservoir is needed, but none has been found as of yet.
- The Santa Clara River near Gunlock (SCGU1) segment was removed since the USGS gage has been discontinued; however, the Gunlock Reservoir (GUUU1) segment was added in its place.
- The Beaver Dam Wash at Beaver Dam (BEAA3) USGS gage was discontinued; however, the segment will continue to be modeled using an ALERT gage in its place since it is an important point during flood events.

Table 2: Summary of changes to the CBRFC's model with regards to the Virgin River Basin

Action	Handbook 5 ID	Description	Note
Add	ASRU1	Ash Creek Reservoir	
Redefine	GUUU1	Gunlock Reservoir	Routing segment
Add	GVRU1	Grass Valley Reservoir	
Add	HUCU1	Virgin River Above Quail Creek near Hurricane	
Redefine	HURU1	Virgin River near Hurricane	
Add	LEEU1	Leeds Creek near Leeds, Utah	
Add	QCRU1	Quail Creek Reservoir	
Remove	SCGU1	Santa Clara at Gunlock	Gage discontinued December, 2013
Add	SCVU1	Santa Clara River above Baker Reservoir near Central	
Replace	VRMN2	Virgin River at Mesquite, Nevada	VRMN2 is replacing VMQN2
Add	VLLU1	Virgin River above La Verkin Creek near La Verkin	

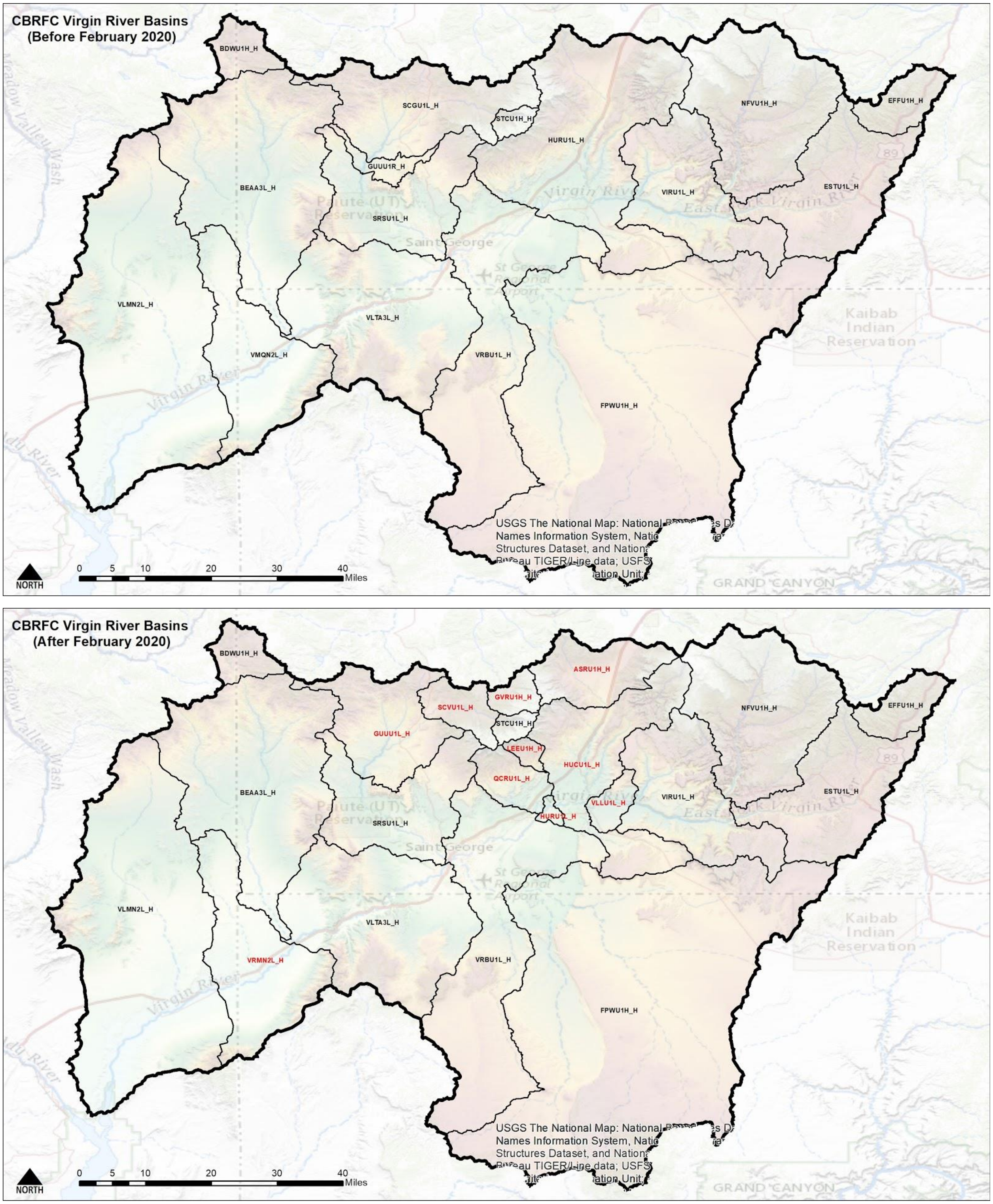


Figure 16: The above figure shows the delineation of areas as defined by the CBRFC's hydrologic model within the Virgin River Basin. The map at the top shows the Virgin River Basin before the model improvements were made. The map at the bottom shows the basin after the model improvements were made.

3.5 Development of CBRFC Fire Tool in response to Arizona Fires

There were over 50 wildfires that burned over 1,000 acres in Arizona alone over the 2020 fire season. Among the most notable of these fires were the Sawtooth Fire (nearly 25,000 acres burned), Bighorn Fire (nearly 120,000 acres burned), and the Blue River and Blue River 2 Fires (nearly 30,000 acres combined burned). In response to requests from Arizona Weather Forecast Offices, and the increased frequency of large-scale severe fire events within the CBRFC's area of responsibility, the CBRFC developed a tool to assess potential impacts of fire to CBRFC modeled subbasins and elevation zones and objectively make changes to the hydrologic model to capture the fire-driven hydrologic response in these areas.

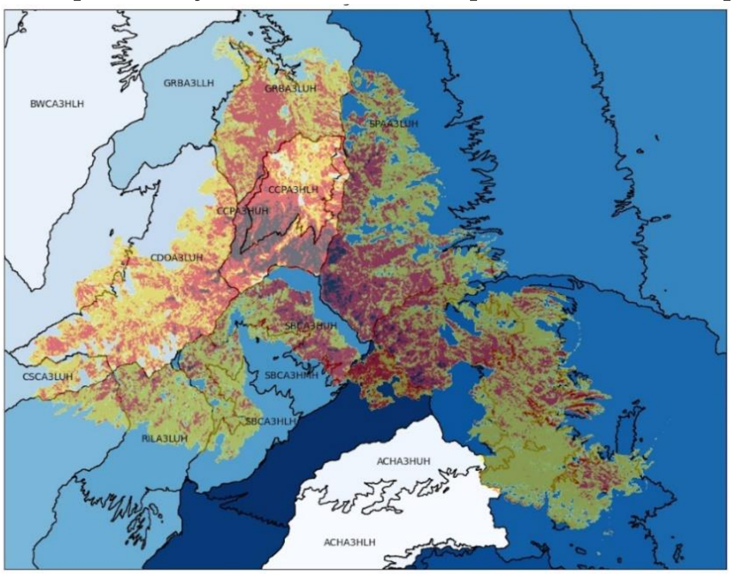


Figure 17: Sample output from the CBRFC's fire tool. Here, the burn area from the Bighorn fire is overlayed onto CBRFC modeled elevation zones in Southern Arizona.

In the past, fire information was incorporated ad-hoc into the CBRFC's hydrologic model; this information was incorporated inconsistently and somewhat subjectively. To improve how fire information is incorporated into the hydrologic model, the CBRFC developed a Python-based GIS fire tool to assess potential fire impacts to hydrologic model parameters. The tool uses burn area and/or severity maps to develop tables and maps (Figure 17) showing the percentage of elevation zones affected by fires in the CBRFC's area of responsibility. Based on the output from this tool, if less than 25% of a modeled area is burned, no changes are made to the hydrologic model. If between 25% and 50% of the modeled area is burned, then a new area is defined within the CBRFC's model with parameters representing increased impermeable area to simulate increased flow in the basin. When greater than 50% of the model elevation zone is burned, the hydrologic model parameters of that entire area are adjusted to increase the impermeability of the area. These thresholds are a first, subjective, estimate. As weather events provide information relating to the performance of these adjusted areas, the CBRFC intends to evaluate the thresholds and process in the future. Figure 18 illustrates the changes in the response hydrograph over Sycamore Creek due to impacts from the Bush Fire.

Over the course of this fire season, changes to modeled zone parameters were made in response to the Bush Fire at Sycamore Creek (SYCA3). In response to impacts from the Bighorn Fire, zone parameters at Canada Del Oro at Coronado Camp (CCPA3), Canada Del Oro near below Ina Road near Tucson (CDOA3), and at Canada Del Oro at Golder Road Bridge (GRBA3) were changed. Additionally, a new burn area was added at Sabino Creek near Tucson (SBCA3), also in response to the Bighorn Fire.

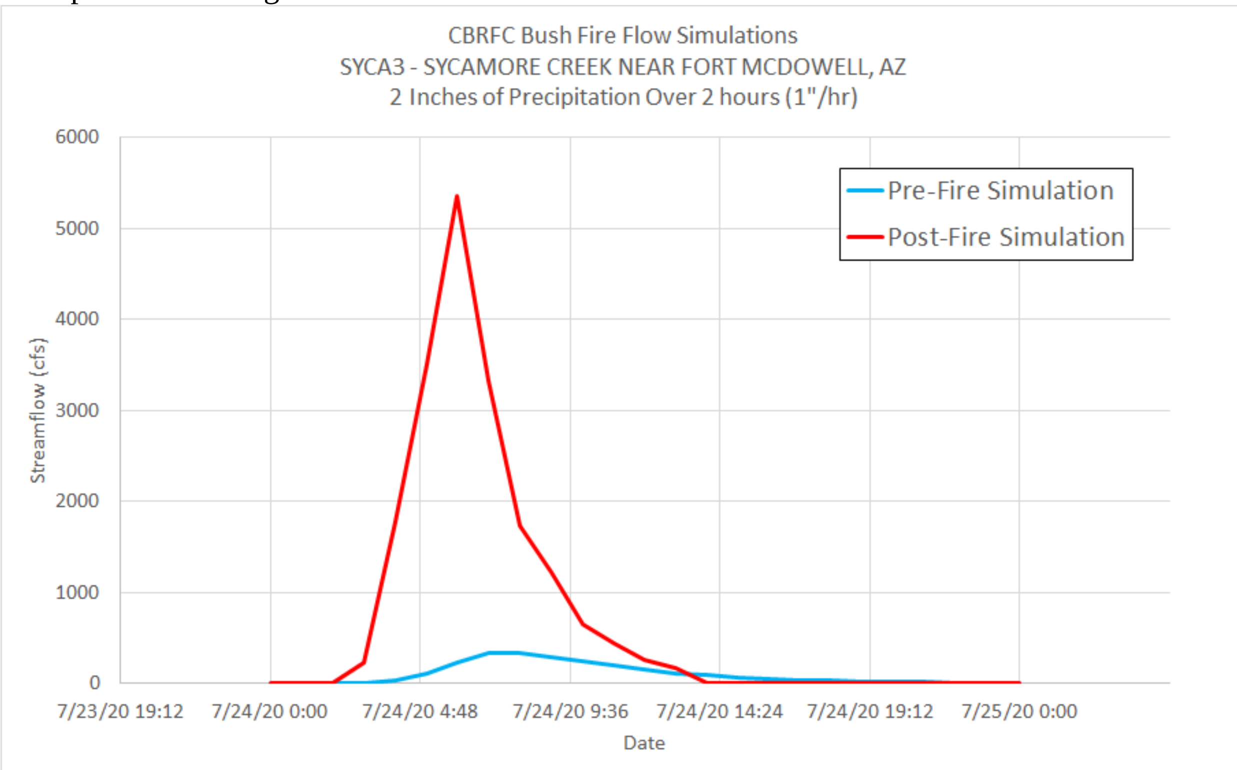


Figure 18: The Bush Fire affected portions of the Sycamore Creek watershed near Fort McDowell, Arizona. Based on information from the CBRFC's fire assessment tool, changes were made to the model parameters. The red line indicates the response hydrograph after 2 inches of rain over 2 hours in the area after changes to the model parameters; the blue line indicates the response hydrograph prior to the Bush Fire.

3.6 Monthly Utah Drought Meetings

In late 2018, the CBRFC was invited to participate in the development of a working group led by Utah Department of Natural Resources and Utah Department of Agriculture and Food charged with providing input from the State of Utah on drought conditions for the National Drought Monitor (Figure 19). Last year, the Utah Drought Monitor Advisory Workgroup began meeting biweekly to discuss and make recommendations to the National Drought Monitor regarding drought conditions over the state of Utah. The CBRFC is one of many agencies that provides information to the workgroup; information from the CBRFC is typically focused on seasonal water supply forecasts and short term streamflow forecasts and the primary drivers behind those forecasts. It is important to note that the CBRFC does not provide recommendations to the group regarding drought categories throughout the state.

Discussions from these drought meetings are intended to be open and transparent; slides from these meetings are available on the Utah Division of Water Resources drought website[2].

[2] For those unable to access the hyperlink: https://water.utah.gov/water-data/drought/

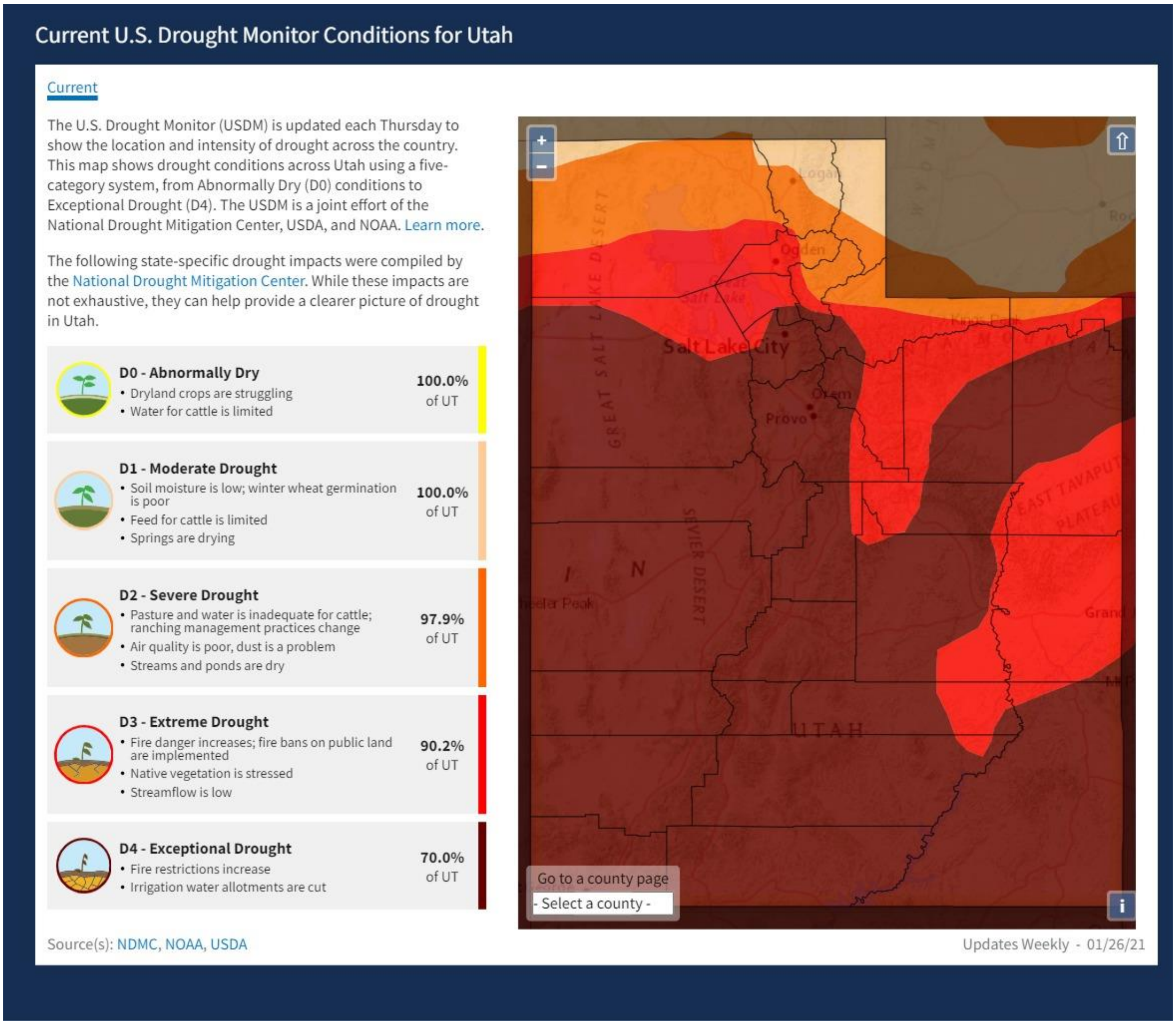


Figure 19: The United States Drought Monitor categorizes drought over the nation based on input from a variety of sources, including state and regional working groups. The Utah Drought Monitor Advisory Workgroup provides drought information and reccommendations to the National Drought Monitor for the state of Utah. The CBRFC presents information to this group to develop these recommendations.

4 New and Enhanced Methods to Improve 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 Calibration Update of Ruedi Reservoir, Fryingpan River Basin, and Roaring Fork River Basin

The calibration of six segments within the CBRFC's hydrologic model were updated to address a noticeably dry bias (under forecast) during the runoff season in the Colorado River Basin headwaters along the Fryingpan River and Ruedi Reservoir catchments, and the Roaring Fork River Basin; between 60% and 80% of the unregulated inflow into the Ruedi Reservoir comes from the Fryingpan River basin. The six segments were:

- Roaring Fork River near Aspen, CO (APNC2)
- Crystal River near Redstone, CO (RCYC2)
- Hunter Creek at Aspen, CO (HUNC2)
- Fryingpan River near Thomasville, CO (FPTC2)
- Inflow into Ruedi Reservoir (RURC2)
- Roaring Fork River at Glenwood Springs, CO (GWSC2)

Table 3 shows the changes to the percent bias after the recalibration effort for the inflow into Ruedi Reservoir segement (RURC2). Note the improvement in the hydrologic model simulation during seasonal runoff months, extending into August.

Table 3: The table compares calibration bias for inflow into the Ruedi Reservoir prior to and after recalibration efforts to address a dry bias.

Month	%Bias prior to recalibration	%Bias after recalibration
October	2.3	6.5
November	-0.5	6.3
December	-3.6	2.0
January	-6.6	0.2
February	-10.1	-2.0
March	-5.4	-0.4
April	3.8	1.5
May	6.7	4.1
June	-2.3	-2.6
July	-8.9	4.5
August	-13.1	-3.6
September	-4.9	2.4
Water Year	-1.8	0.9

As the CBRFC begins a major recalibration effort on its hydrologic model this year, the CBRFC will investigate using the Ivanhoe SNOTEL station (IVHC2), located in the headwater area of the Fryingpan River, which currently has a 28 year record and is located at elevation 10,400 feet.

4.2 Utilization of Snow Level Data from the NBM

In November, the CBRFC began to use observed and forecasted snow level data from the National Blend of Models (NBM). Traditionally, the CBRFC had used observed data from the Rapid Update Cycle (RUC) and forecasted freezing level data from the Global Forecast System (GFS) weather model to compute the rain-snow elevation This change was made because freezing level data is not used in the model calibration process; temperature data is used to calculate the rain-snow elevation during calibration. Using of the NBM snow level data should improve consistency within our hydrologic modeling paradigm since temperature forcings are also derived from the NBM.

An opportunity to somewhat compare the two methods occurred from November 6th through the 8th when a mix of rain and snow fell over the headwaters of the San Juan River Basin. The storm event brought over 2 inches of precipitation to the area and resultant forecasted streamflow impacts were highly dependent on accurate forecasts of the rain-snow elevation. Figure 20 illustrates an improvement to the model simulation at the San Juan River at Pagosa Springs, Colorado reach when using the NBM observed snow level data. Similar improvement was also observed at the Rio Blanco River near Pagosa Springs, Colorado (not shown).

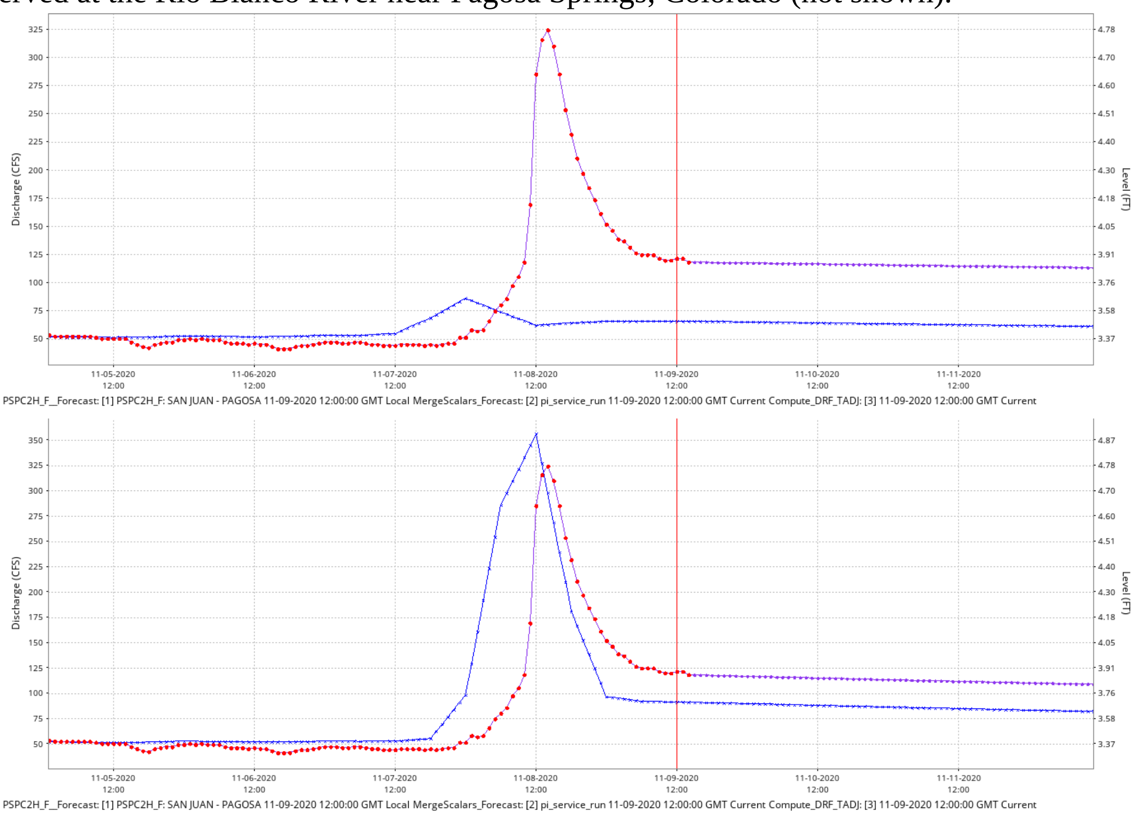


Figure 20: The figure above shows simulated (blue line) and observed (red line) flows at the San Juan River at Pagosa Springs, CO. The simulation at the top was derived using the CBRFC's legacy method for computing the rain snow elevation. The simulation at the bottom was derived using the NBM snow level data and compares more favorably to the observed data.

In contrast, utilization of the NBM snow level data over the Piedra River near Arboles, Colorado did not produce a better hydrologic simulation (Figure 21). The performance of the model showed no significant difference between the simulations over the Animas River at Durango, Colorado reach (not shown). It is important to note that this analysis did not compare the use of forecasted freezing level and forecasted snow level data; this analysis only compared model simulations using the different *observed* datasets and how they compared over a single event. While the CBRFC is using snow level information from the NBM as the default forcing, CBRFC forecasters continue to have the option to use freezing level information from the GFS, particularly in the development of short-term forecasts.

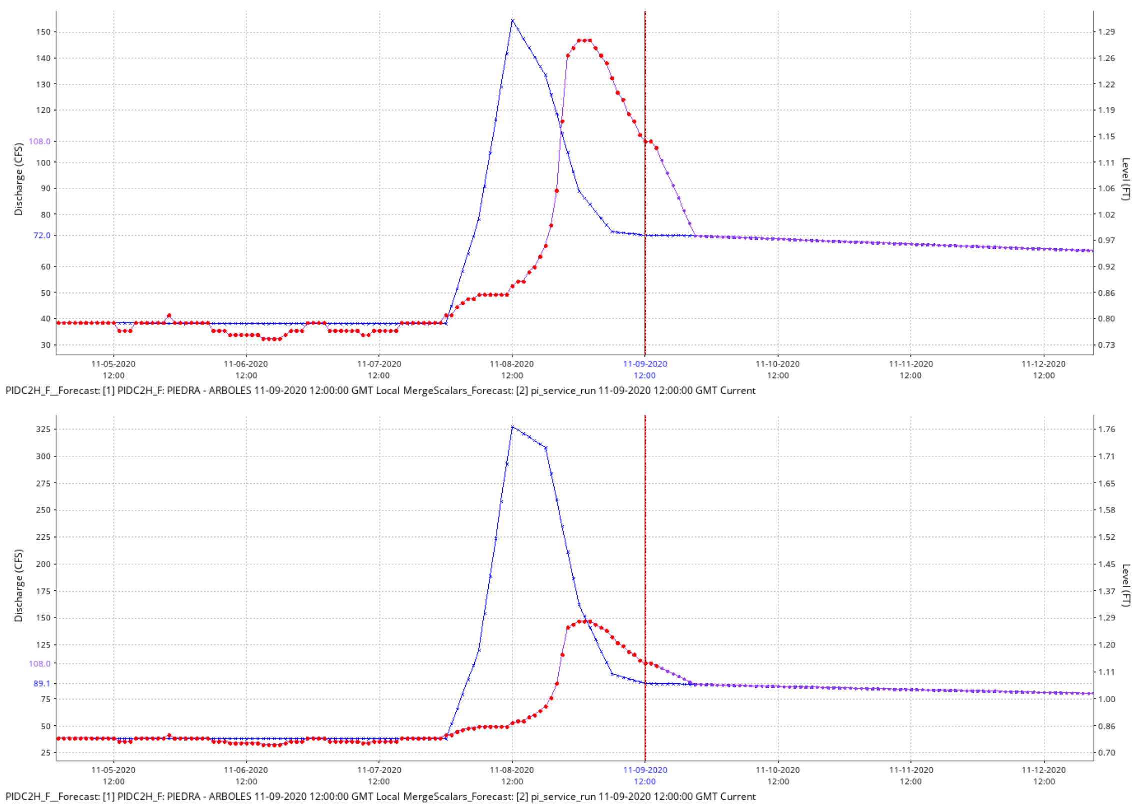


Figure 21: The figure above shows simulated (blue line) and observed (red line) flows at the Piedra River near Arboles, CO. The simulation at the top was derived using the CBRFC's legacy method for computing the rain snow elevation and compares more favorably to the observed data. The simulation at the bottom was derived using the NBM snow level data.

4.3 Extension of WPC QPF through Day 7 throughout the CBRFC's area of responsibility

Historically, the CBRFC has utilized 5 days of Quantitative Precipitation Forecast (QPF) information to force its hydrologic model. Since then, weather forecast models, and the science behind those models, have improved precipitation forecast skill at longer lead times. Last year, the CBRFC began using the QPF through 7 days for forecasts in the Lower Colorado River

Basin; further, the CBRFC began using the hourly QPF from the NBM for Day 1 of the forecast, followed by the QPF from the Weather Prediction Center (WPC) for subsequent days. The CBRFC conducted a robust verification of QPF over the Upper Colorado River Basin from the NBM, WPC, and the legacy RFC methodology, which additionally assumed zero QPF past Day 5. Verification statistics utilized by the CBRFC included:

- Equitable Threat Score (ETS), which measures the fraction of observed and/or forecasted events that were correctly predicted.
- Frequency Bias (FB), which measures the ratio of the frequency of forecast events to the frequency of observed events
- Mean Absolute Error (MAE), which measures the average magnitude of error in the forecast

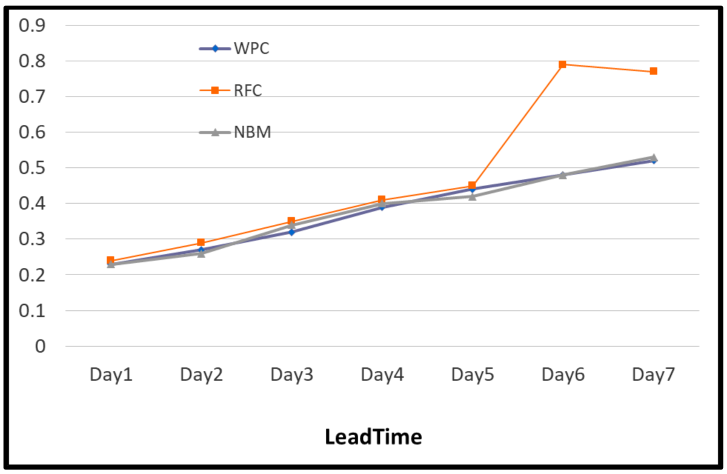


Figure 22: The MAE comparison between QPF information derived from WPC, NBM, and the legacy RFC methodology for precipitation events greater than 0.5 inches. MAE values between WPC and NBM are comparable and less than the legacy RFC methodology, particularly on Days 6 and 7.

MAE and FB statistics were very similar over the 7-day forecast window between the WPC and NBM QPF information, which made sense since the WPC QPF relies heavily on the NBM QPF for its first day of QPF. ETS for precipitation amounts greater than approximately 0.25 inches per hour, or greater than approximately 0.5 inches over 6 hours tended to show the benefits of utilizing QPF information from the NBM in Day 1. Figure 22 shows the MAE differences between various QPF sources for precipitation events greater than 0.5 inches. Most importantly, note the large jump in RFC MAE at Days 6 and 7 caused by using a QPF of zero at these longer lead times. As a result of this analysis, the CBRFC implemented the use of QPF information from the NBM for Day 1, followed by QPF from the WPC for Days 2- 7 throughout the entire CBRFC's area of responsibility in the Fall of 2020. It should be noted that while hourly precipitation values are used in the Lower Colorado River Basin, 6-hourly values are used in the Upper Colorado River Basin.

4.4 Intervening flow reforecast verification

Last year, the CBRFC began to develop a methodology for improving forecasts of intervening flow over the reach of the Colorado River and its surrounding tributaries downstream of Glen Canyon Dam and above Lake Mead. This effort is being done to specifically provide the Bureau of Reclamation with a forecast of intervening flow that can be used in operational decisions. Initial efforts used a 5-year period and was verified over 1- to 3-month lead times.

This year, the CBRFC developed a 30-year (1981-2010) reforecast dataset of intervening flows over 1- to 12-month lead times. Forecasts developed using the CBRFC's Ensemble Streamflow Prediction method, climatology, and an average of the two aforementioned methods were compared using monthly mean absolute error (MAE) and a running 3-month seasonal MAE. Over the course of a year, it was found that using the average of the two methods is typically the most accurate.

The CBRFC provided the Bureau of Reclamation with the 30-year reforecast dataset to use in their analysis of competing intervening flow forecasts for use in their operational models. Future work from the CBRFC may involve utilizing teleconnection information to improve intervening flow forecasts in the area.

5 Research, Investigations, and Collaborations

The CBRFC is open to working and actively 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.

5.1 Sensitivity Analysis Report

Through its participation in the Colorado River Climate and Hydrology Workgroup, it was identified as a high priority that the CBRFC would conduct a sensitivity analysis of its hydrologic model. The Scope of Work for the project was developed in cooperation with the Bureau of Reclamation and Southern Nevada Water Authority. The sensitivity analysis was part of a larger project which included the development and issuance of this annual report.

The CBRFC investigated four parameters within its hydrologic model: precipitation, soil moisture, evapotranspiration, and temperature. An ensemble of historical data spanning 1981 through 2015 was used in the analysis, although 1981 is not included in results as it was used as a model spin up year. The precipitation time series was perturbed by ±2.5%, ±5.0%, and ±10.0%. Temperature time series were perturbed by ±0.5 ^{o}F, ±1.0 ^{o}F, and ±2.0 ^{o}F. Monthly coefficients of evapotranspiration derived during the model calibration process were perturbed by ±2.5%, ±5.0%, and ±10.0%. Initial fall soil moisture states (i.e., the model soil moisture condition on October 1st of each year) were perturbed by ±2.5%, ±5.0%, and ±10.0%. It's important to note that these perturbations were only selected to induce a hydrologic response from the model; they are not representative of any sort of climate change scenario or a projection of future climate conditions. Six headwater basins within the CBRFC's hydrologic model were selected for this study; headwater basins were selected to isolate the impacts of the perturbations to the model parameters and avoid impacts due to routing or other model impacts. The sites selected were:

- Green River at Warren Bridge (WBRW4)
- Elk River near Milner (ENMC2)
- Crystal River at Redstone (RCYC2)
- East River at Almont (ALEC2)
- Animas River at Durango (DRGC2)
- Weber River at Oakley (OAWU1)

The report focused on impacts within the Colorado River Basin, so results from the Weber River at Oakley were not included in the report, though results presented in the report are representative of the results seen on the Weber River segment. Overall, the parameter with the largest impact to streamflow over the course of the year and during the runoff season was precipitation which showed an approximate 1.5% increase in annual runoff per 1% increase in precipitation. Although not intuitive, temperature perturbations had very little impact on overall streamflow volume and impacts were primarily to the timing of runoff in the model. Soil moisture and evapotranspiration impacts were, at times, impactful during the fall months when cooler temperatures and snowfall events are more prevalent. Figure 23 summarizes the results for each parameter for the Animas River at Durango basin. The entire report, as well as supplemental data including all raw data output, summary tables, and figures, is available on the CBRFC's website under the heading for 2020 Reports[3].

[3] For those unable to access the hyperlink: https://www.cbrfc.noaa.gov/report/reports.php

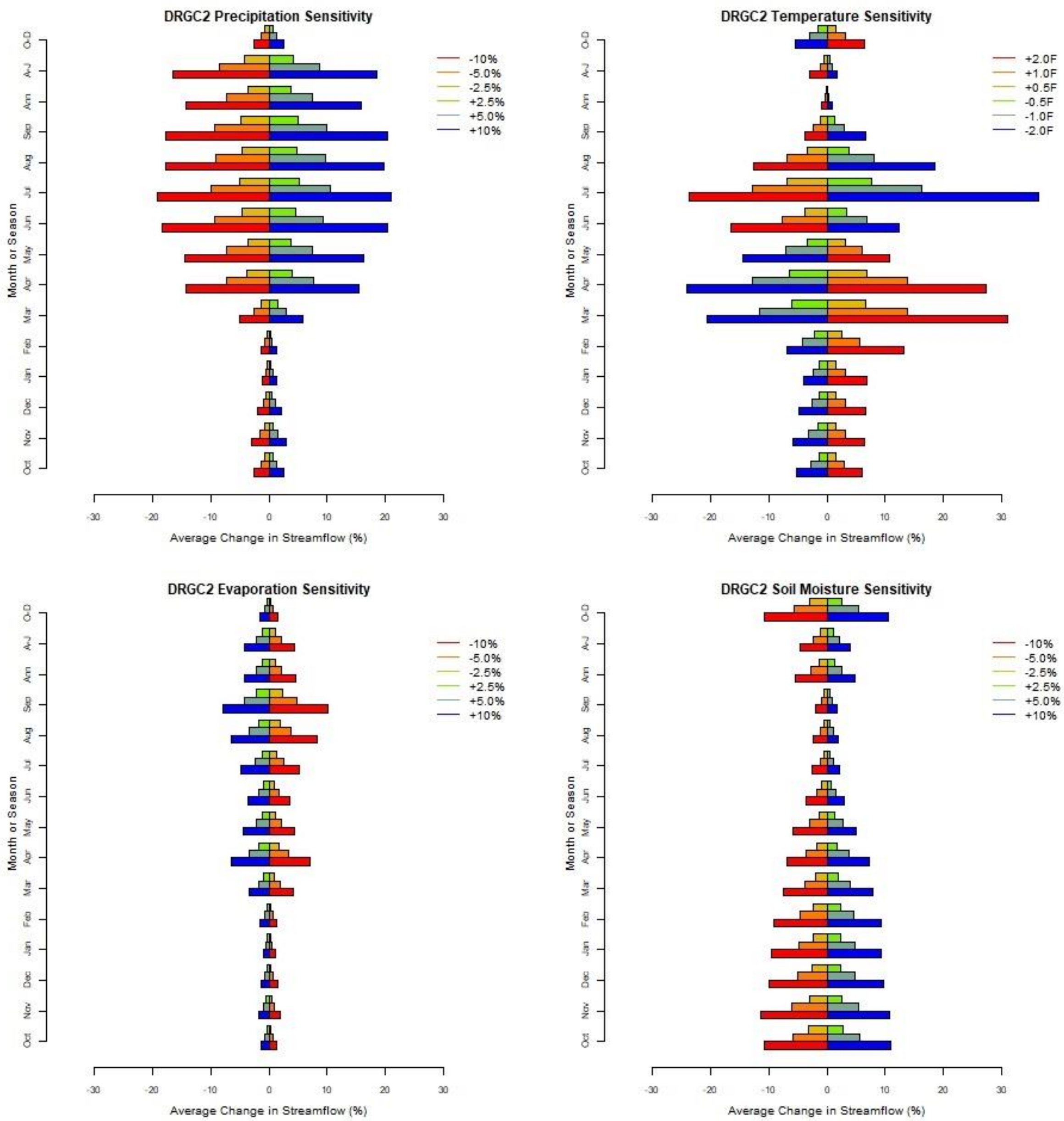


Figure 23: The above figure illustrates model sensitivity to perturbation to precipitation (top left), temperature (top right), evaporation (bottom left), and soil moisture states (bottom right) for the Animas at Durango (DRGC2) segment. These results are representative of other sites considered in this investigation.

5.2 Investigating the Potential Use of an Energy Balance Snow Model in CBRFC Operations

The CBRFC collaborated with Utah State University and RTi International (RTi) to investigate the use of an energy balance snow model, the Utah Energy Balance (UEB) snow model, in a distributed version of the CBRFC's hydrologic model. The distributed version of the CBRFC's hydrologic model is referred to as the Research Distributed Hydrologic Model (RDHM). The RDHM was calibrated over the Dolores River above McPhee Reservoir segment and the Blue

River above Dillon Reservoir segment; the SNOW-17 component was replaced with the UEB model. As opposed to the temperature-index based SNOW-17 model, the UEB model is a one-layer, distributed snow model that uses radiative, sensible, latent, and advective heat exchanges to calculate mass and energy balances. The goals of this project were to:

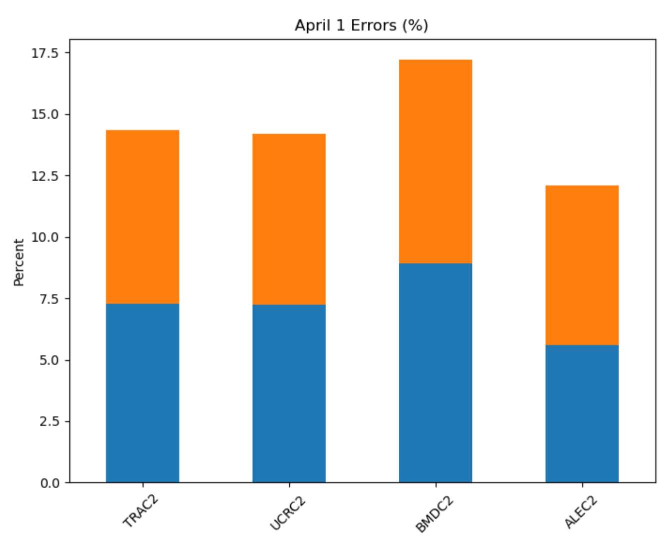
- Evaluate the performance of the UEB in CBRFC operations
- Implement the use of UEB if there is improvement in forecasts
- Evaluate the performance of RDHM in water supply forecasts

The RDHM was able to be run over the Animas River at Durango watershed, and did not include the UEB. RTi was able to implement snow data assimilation of SNOTEL data at the CBRFC test basins, but it is not currently being run operationally. Initial results showed that modeled streamflow simulations improved slightly over the Dolores River at Dolores, CO segment when using the RDHM with the UEB model integrated in place of SNOW-17. Modeled snow cover is also improved when using UEB when comparing results to snow cover derived from the MODIS satellite. Volumetric streamflows are similar between RDHM using SNOW-17 and RDHM using UEB. Researchers noted that bias in precipitation inputs negatively affected the performance of the UEB.

Snow data assimilation of SNOTEL snow water equivalent and MODIS snow covered area was successfully demonstrated for RDHM using SNOW-17 at the CBRFC during tech transfer activities. Due to difficulties in tech transfer, UEB and RDHM were never successfully run at the CBRFC. We continue to move forward with automation RDHM and SNOW-17 distributed modeling system as time permits.

5.3 Investigation of Externally-Produced Snow Products in Operations

The CBRFC is actively engaged with and investigating the use of remotely sensed snow information to improve daily streamflow and seasonal water supply forecasts. This includes snow information from the MODIS satellite and ASO. Over the past recent years, the CBRFC has developed methodologies to quantitatively incorporate dust-on-snow information from the MODIS Dust Radiative Forcing in Snow (MODDRFS) dataset, and is using



maximum improvement that remotely sensed snow data could contribute to water supply forecasts at these locations on April 1st.

MODSCAG information qualitatively.

While remotely sensed snow information has the potential to improve streamflow forecasts and provide critical information, uncertainty in spring precipitation plays a significant role in water supply forecasts. Uncertainty in water supply forecasts can be attributed to unknown future weather, and model error which includes errors in modeled soil moisture, errors in model snowpack, errors in model parameters, and errors in model structure. Separating out the individual impact of each of these model errors is difficult. Figure 24 illustrates the average volume error in April 1st water supply forecasts at four headwater basins in the Upper Colorado River Basin. On average, roughly half of the volume error on April 1st is due to the aforementioned model error, and the other half is due to uncertainty in future weather.

The CBRFC is actively working with ASO to assess and further the advancement of remotely sensed snow information and the use of that information operationally. To date, a robust assessment of ASO data is not possible due to the current spatial extent of data and number of years and observations collected within the CBRFC's domain. Currently, information from each ASO flight covers 3 to 6 of the CBRFC's modeled elevation zones, or roughly 1 or 2 basins. To date, there is a maximum of 2 years worth of data over the same basin. Preliminary results, while encouraging, are inconclusive. Table 4 shows the comparison between CBRFC SWE data and ASO SWE data derived over the East River at Almont, CO in the Gunnison River Basin in 2018 and 2019. 2018 was a dry year in the Gunnison River Basin and this particular segment was observed at 42% of average; in contrast, 2019 was a wet year and seasonal runoff was observed at 148% of average. In 2018, the CBRFC model oversimulated flows and model snowpack in the CBRFC's model was likely too high at higher elevations; in this case, use of ASO data would have resulted in a more accurate forecast. In 2019, the CBRFC model undersimulated flows and model snowpack in the CBRFC's model was likely too low in the middle elevations. Again, use of ASO data would have resulted in a more accurate forecast.

Table 4: This table compares SWE information from the CBRFC's hydrologic model and ASO over the East River in the Gunnison River Basin in 2018 and 2019. In 2018, the use of ASO information would have resulted in a more accurate seasonal forecast; in 2019, the use of ASO information would have resulted in a less accurate forecast.

	Volume (kaf)		Snow Water Equivalent (in)		
	Calibration	Observed	Zone	Calibration	ASO
Mar 31, 2018	89	77	11000'-14216'	18.6	15.0 ↓
	Over simulated	Dry year: 42% avg.	9500'-11000'	7.3	8.3
			8016'-9500'	0.8	1.6
Apr 7, 2019	235	269	11000'-14216'	36.7	36.6
	Under simulated	Wet year: 148% avg.	9500'-11000'	18.8	22.4 ↑
			8016'-9500'	9.4	9.1

The CBRFC remains committed to work with developers of external snow information and evaluating these products for use in operational forecasts in the future.

5.4 Snow Data Product Assessment Tools

New snow data products and datasets are becoming more widely available and accessible than ever before. These products range from remotely sensed datasets (e.g., MODIS satellite information and ASO derived data) to snow information derived using artificial intelligence models (e.g., SWANN). To assess and compare these snow products for possible use in the CBRFC's hydrologic forecasting paradigm, a suite of Python-based[4] tools have been developed to easily ingest and compare between different datasets, as well as compare to the CBRFC's modeled snow information. These tools have been used to begin initial investigations into the use of these datasets. Further, more robust analysis into the feasibility of utilizing these datasets in the development of streamflow forecasts is planned by the CBRFC.

5.5 2019 Annual AWRA Conference and Snow Water Mapping Session

As part of the American Water Resources Association 2019 Annual Conference held in Salt Lake City, UT on November 3rd through the 6th, the CBRFC partnered with the Southern Nevada Water Authority and Bureau of Reclamation to host a session entitled "Snow Water Mapping". The goal of the session was to present a broad perspective of snow products that had been recently made available, or were actively engaging with the operational community. The

[4] Python is a programming language that is widely used in the National Weather Service, as well as numerous other agencies and industries. More information can be found at www.python.org

CBRFC, SNWA, and Reclamation presented a brief overview of the importance of snow data to hydrologic forecasts and modeling. The following presentations followed:

- ***Presentation 1 – The National Snow Analysis: Past, Present, and Future***
  - Presenter: **Gregory Fall**, Office of Water Prediction, National Oceanic and Atmospheric Administration, Chanhassan, MN

- ***Presentation 2 – Integrating Satellite Data, Distributed Models, and SNOTEL Observations to Improve Real-time SWE Estimation in the Colorado River Basin***
  - Presenter: **Noah Molotch**, Center for Water Earth Science and Technology (CWEST), Institute of Arctic and Alpine Research, University of Colorado, Boulder, Boulder, CO (co-authors – **L. Lestak, K. Yang, K Musselman**)

- ***Presentation 3 – The Airborne Snow Observatory: Current State-of-the-Art for Instantaneous SWE Mapping in the Mountains***
  - Presenters: **K.J. Bormann**, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA; **J.S. Deems**, National Snow and Ice Data Center, Boulder, CO; **E.M. Carey**, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA; **T.H. Painter**, Joint Institute for Regional Earth System Science and Engineering, University of California, Los Angeles, Los Angeles, CA

- ***Presentation 4 – SnowView: A Satellite Data and Model Drive Decision Support Tool for Monitoring Snowpack, Precipitation, and Streamflow***
  - Presenters: **Patrick Broxton**, School of Natural Resources and the Environment, University of Arizona, Tucson, AZ; **Willem van Leewen**, School of Natural Resources and the Environment, University of Arizona, Tucson, AZ; **Joel Biederman**, Agricultural Research Service, U.S. Department of Agriculture, Tucson, AZ

The session produced a handout summarizing the various snow products discussed in this session. Presentations from the session and the associated handout can be found here under the 2019 Report heading[5].

5.6 Investigation of Modeled Snow Products by Summer Student

The CBRFC hosted a summer NOAA Pathways Master's student, Zach Butler, from Plymouth State University; Zach's research focused on the comparison of snow data from the Snow Water Artificial Neural Network (SWANN)[6] project with the CBRFC's modeled snow data derived

[5] For those unable to access the hyperlink: https://www.cbrfc.noaa.gov/report/reports.php
[6] For those unable to access the hyperlink: https://climate.arizona.edu/snowview/

using SNOW-17. In summary, SWANN uses in-situ and data from Oregon State's PRISM (Parameter-elevation Relationships on Independent Slopes Model) Climate Group to develop gridded SWE data at 1 km resolution in near real time with historical data generated back to 1982. Comparisons focused on the comparison between March, April, and May 1st SWE values at 11 CBRFC modeled basins. A comparison of model snow data developed with SNOW-17 with snow data developed with SWANN over the Green River at Warren Bridge basin is shown in Figure 25.

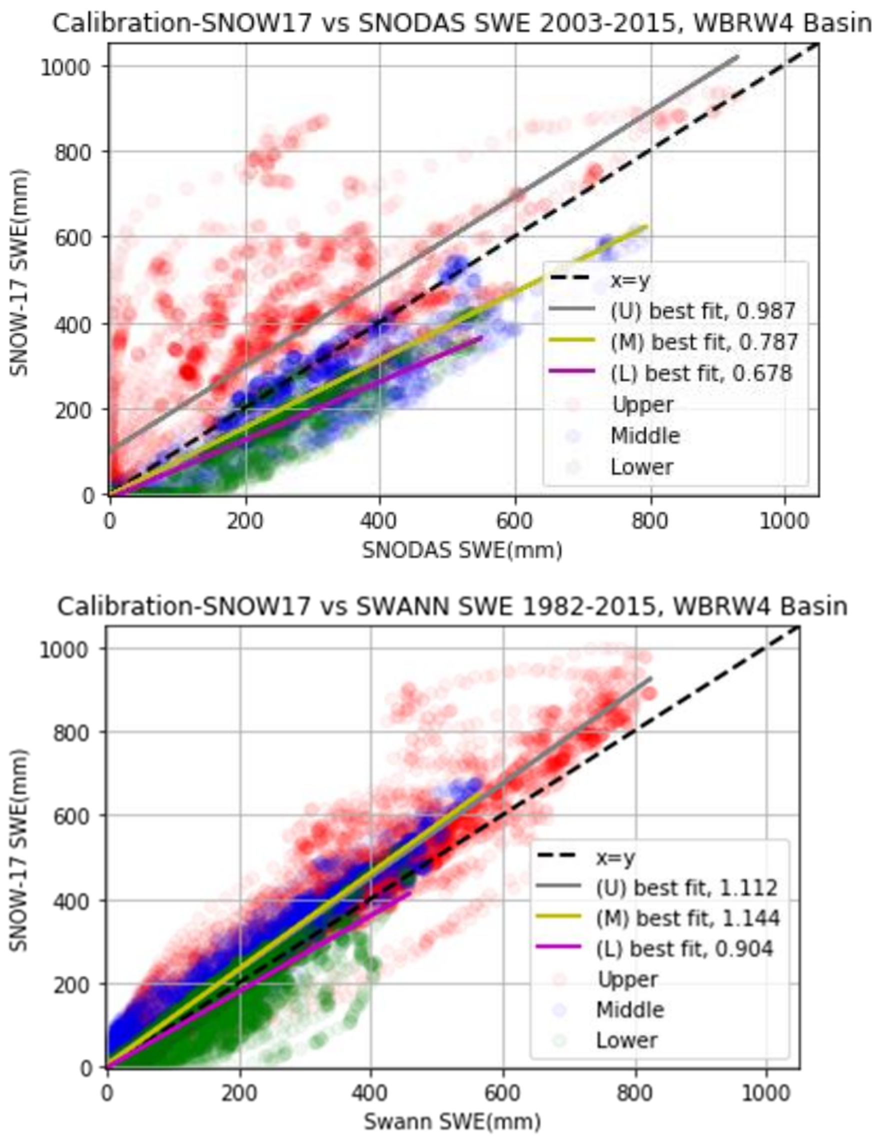


Figure 25: The correlation between modeled SWE information developed with SNODAS (top) and SWANN (bottom) with SNOW-17 is shown. Correlations between the datasets showed general agreement at all elevation zones within the CBRFC's hydrologic model.

Preliminary results indicate little value in including SWANN data into operational forecasts as improvement was inconsistent between basins and timeframes. However, performance of the SWANN datasets generally performed better in Lower Colorado basins, though not enough to warrant implementation in operational forecasting. It should be emphasized further that these results are preliminary and research is ongoing as part of Zach's graduate degree work at Plymouth State University. A final, more robust, report on this research is expected in 2021 as part of Zach's thesis and will include impacts to seasonal streamflow forecasts.