CBRFC Water Year In Review

An Overview of Operational Changes, Improvements, and Investigations over the course of Water Year 2019

April, 2020

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, the first of a new annual product from the Colorado Basin River Forecast Center, describes the forecasting activities, research, and improvements undertaken by the CBRFC over the course of Water Year 2019. 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 2019 Climate and Significant Weather Events

Water Year 2019 began with dry antecedent soil moisture conditions that typically ranged between 30% and 70% of average, including near record low levels in the San Juan and Gunnison River Basins (Figure 1). These dry conditions presented a challenge for CBRFC forecasters, as model behavior at historically extreme parameters can be difficult to verify. Streamflow rates at United States Geological Survey (USGS) sites at the beginning of the water year indicated record low flows at many sites within the Upper Colorado River Basin, providing physical evidence of low soil moisture conditions. Low soil moisture conditions often lead to reduced runoff efficiency and water supply forecasts that are initially (i.e., forecasts made early in the year) below average.

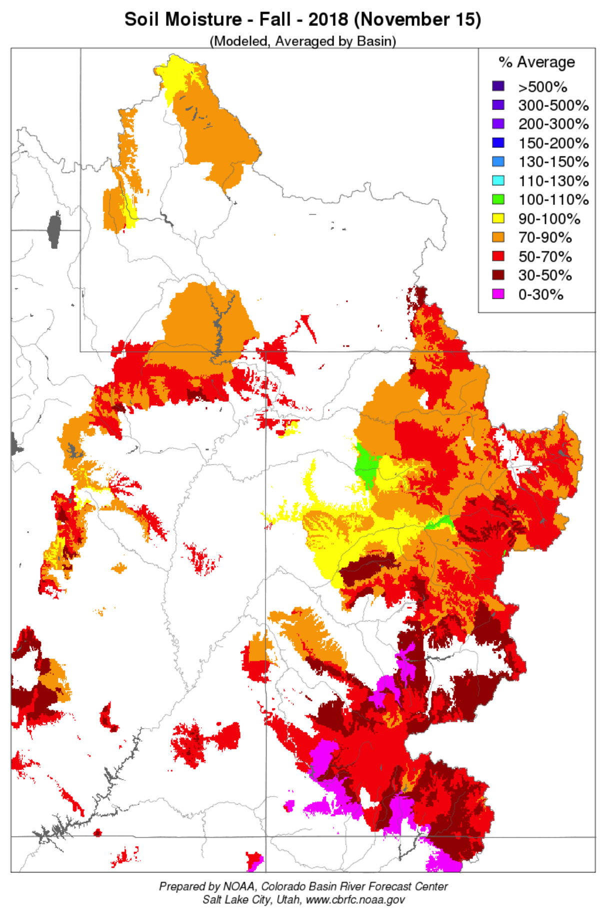


Figure 1: Dry Fall Soil Moisture conditions were prevalent at the start of water year 2019

In November, the mainstem of the Upper Colorado River received above average precipitation and below average temperatures were prevalent over most of the Upper Colorado River Basin. Snowpack accumulation in the Gunnison River Basin was apparent. Normal to below normal temperature conditions persisted through March, and precipitation was normal to slightly above normal throughout much of the Colorado River Basin in January.

Beginning in February and continuing through mid-March, an active, persistent trough (Figure 2) resulted in record precipitation over much of the Gunnison and San Juan River Basins (Figure 3).

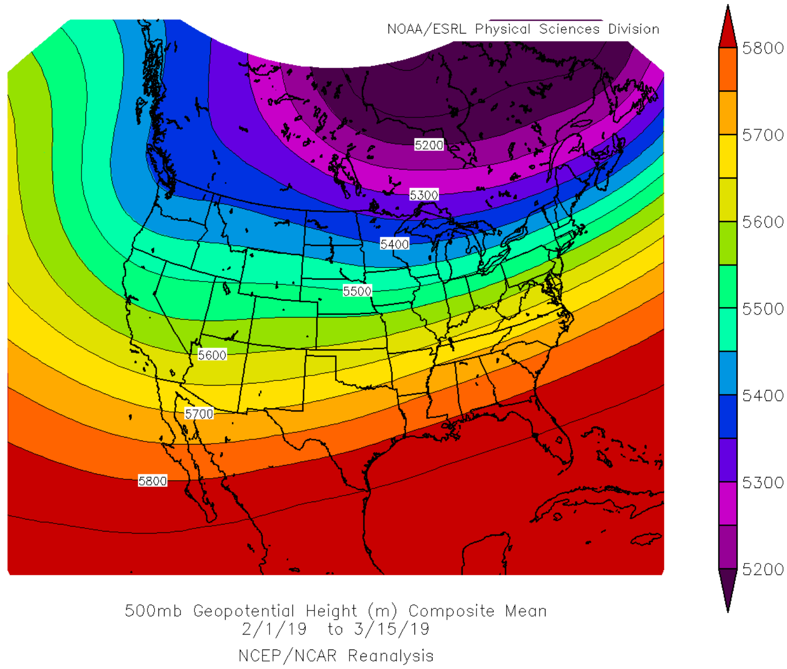


Figure 2: From February through mid-March, an active weather pattern brought record precipitation over the Gunnison and San Juan River Basins

Precipitation exceeded five times the monthly average in some areas in Arizona on Valentine's Day (February 14th), which resulted in widespread flash flooding over the state.

By April 1st, snow water equivalent (SWE) values in the headwaters of the Gunnison and San Juan River Basins were at or near historically high values. Many other SWE values, as measured by the SNOwpack TELemetry (SNOTEL) network, were in the top 10 of the historical record at each gage. Temperatures remained below average for much of the Upper Colorado River Basin through March, and modeled snowpack in the Upper Colorado River Basin was much above normal heading into the April through July runoff period. In particular, much above normal snowpack remained at low and mid elevation zones (Figure 4). During normal years, most low elevation snowpack has melted prior to the start of the runoff season and does not contribute to seasonal water supply volumes; however, a significant contribution to water supply volumes was made by snowpack at lower elevations during water year 2019.

As the runoff season began, below normal temperatures and active weather patterns slowed snowmelt rates, and forecasted water supply volumes began to rise as snow continued to accumulate in some portions of the basin. In particular, during the latter half of May, a deep trough came through the Western United States, dropping temperatures up to 20 degrees below normal and providing additional precipitation (Figure 5). Monthly May precipitation amounts at SNOTEL locations in Western

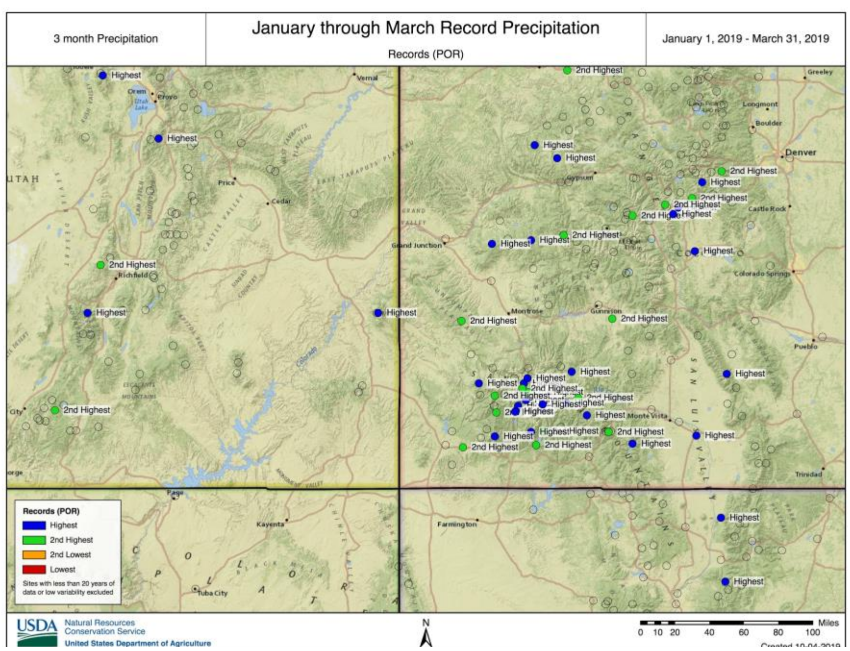


Figure 3: Record amounts of precipitation were observed over the Gunnison and San Juan River Basins by the end of March

Colorado were among the top 5 on record, and notable increases in water supply forecasts were observed.

Substantial high elevation snowpack remained through June due to continued cooler temperatures and snowpack accumulation, prompting concerns that sudden and persistent warming could lead to widespread flooding. However, June was marked by a pattern of warming temperatures followed by cooling temperatures, which created a pattern of multiple late season streamflow peaks (Figure 6) and reduced widespread flood events. Portions of the Yampa and Upper Colorado mainstem river basins received above average precipitation for the month; a snow storm in Steamboat Springs, Colorado received national media attention when approximately 20 inches of snow fell on the first day of summer (June 21st).

Due to historically high precipitation amounts and snowpack accumulation that continued through the Spring, water supply volumes throughout the region were above normal. Observed unregulated inflow into Lake Powell was 10.4 million acre-feet (MAF), or 145% of average.

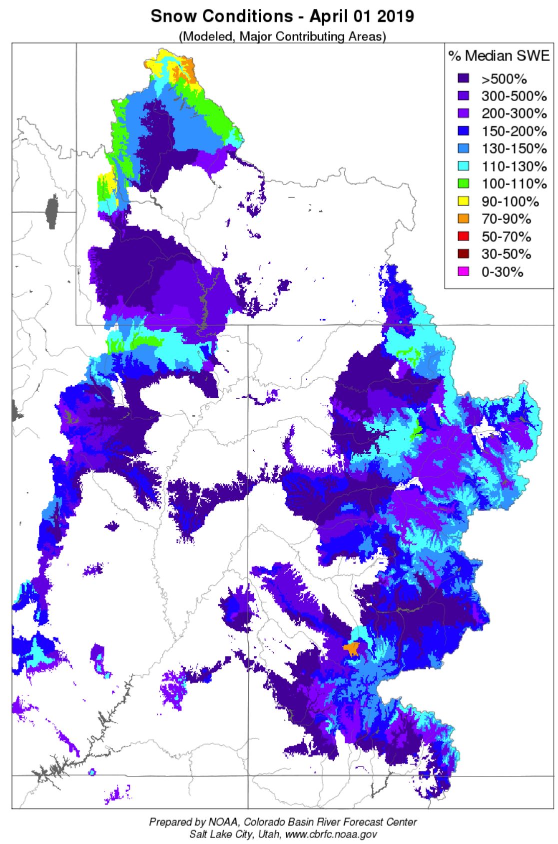


Figure 4: April 1st modeled snowpack was well above average, even at low and mid elevation zones

1.3 Water Supply Forecasting Challenges and Verification

The 2019 Water Year presented unique challenges to water supply forecasters due to the extremely dry antecedent soil moisture that gave way to historically wet conditions and persistent cool temperatures that delayed snowmelt, particularly at lower elevations. Record setting precipitation events in February, March, and May also contributed to lower skill in seasonal water supply forecasts. Figure 7 illustrates the spatial distribution of skill in January, April, and June water supply forecasts over the Upper Colorado River Basin and Great Basin. Generally, forecast skill was

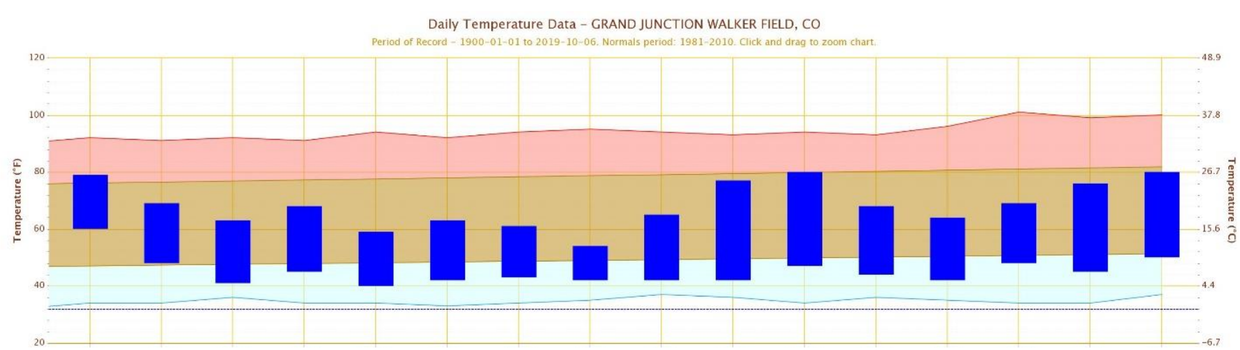


Figure 5: Cooler than normal temperatures were prevalent through mid-May

lower than usual, primarily due to the large, late season precipitation events previously discussed, in addition to other factors that are discussed further in this section.

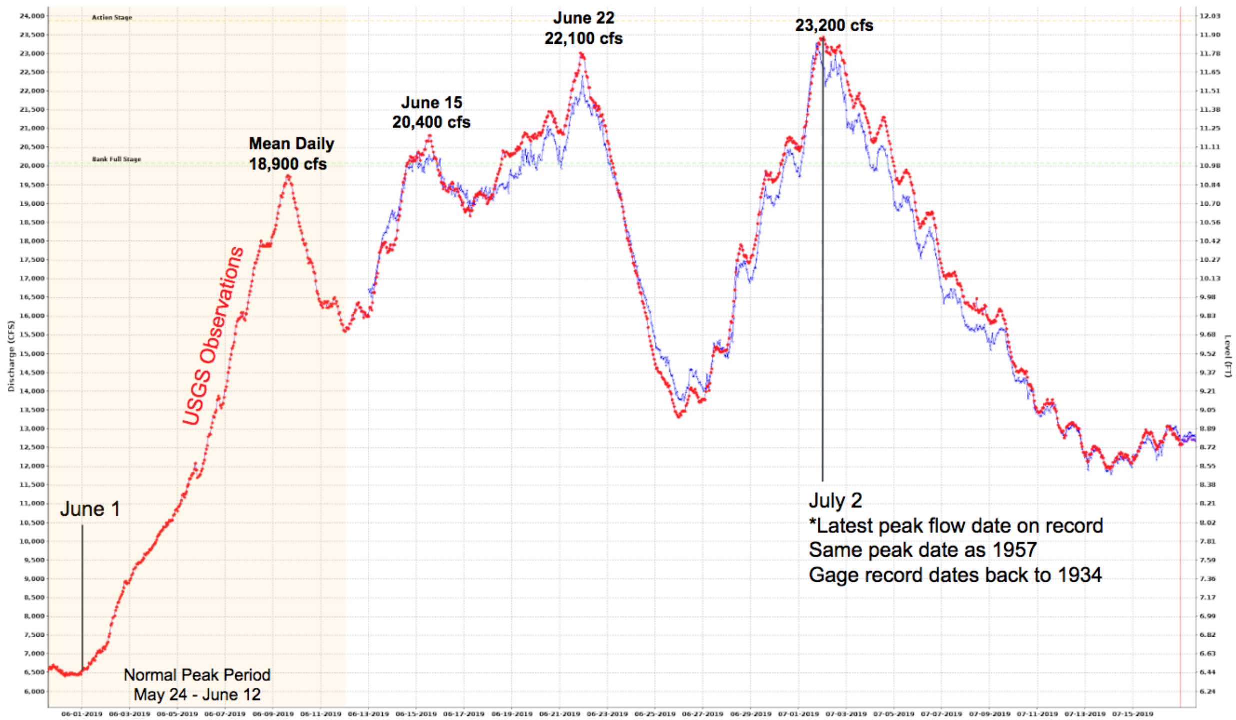


Figure 6: Temperatue fluctuations within the basin made for multiple peaking events throughout the Colorado River Baisin

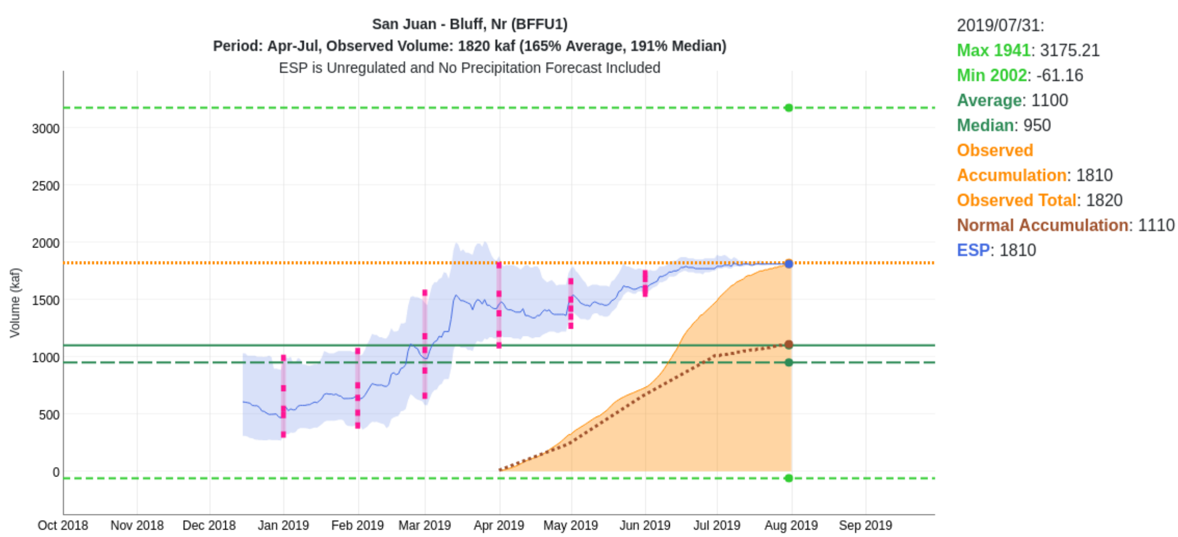


Figure 7: Dry soil moisture conditions drove low seasonal forecasts in January; by April, forecasts began to improve as a result of changing weather and climate conditions

1.3.1 Historically Dry Soil Moisture Conditions

Streamflow over the 2018 Water Year was well below average, particularly over the San Juan River Basin where observed unregulated seasonal streamflow was only 12% of average. As a result, historically dry soil moisture conditions were prevalent in the region and extending northward into the Gunnison River Basin (see previously mentioned Figure 1). These record low soil moisture levels in the region resulted in January seasonal water supply forecasts that were well below average. Initial water supply forecasts for the San Juan River at Bluff, New Mexico was only 50% of average. Despite the large soil moisture deficit, model guidance was near average by March, and the observed seasonal volume was just outside the forecast bounds by the April forecast (Figure 8).

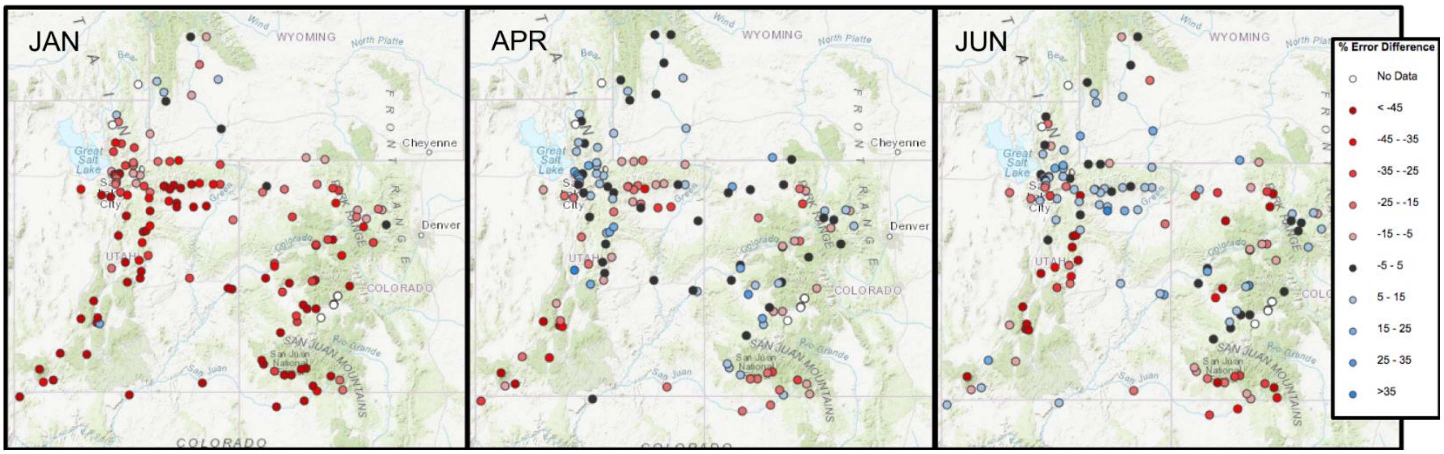


Figure 8: Forecast skill over the Upper Colorado River Basin improved as the year progressed; skill in January was lower than normal due to extreme weather events that followed in WY2019

1.3.2 Record Setting Precipitation Events

Record setting precipitation events in February, March, May, and June significantly contributed to snowpack accumulation and regional water supply. These events ultimately resulted in observed volumes that fell outside the bounds of early and late season water supply forecasts. Because of the record setting nature of these events, it is justifiable, and not unexpected, that the subsequent volumes of water fell above the 90th percentile (10% exceedance probability) of CBRFC forecasts.

A widespread precipitation event occurred on Valentine’s Day (February 14th), particularly impacting the Lower Colorado River Basin and Salt River Basin. Record amounts of precipitation were observed in Coconino County and the Salt River Basin, where flood stages were reached and water supply forecasts rose nearly 25% as a result of the event (Figure 9).

June is usually a relatively dry month over the Colorado River Basin; however, on June 21st, record precipitation fell over the Yampa River Basin and the Upper Colorado River mainstem. Snowpack accumulation was apparent at high elevations and increased water supply projections in the Yampa River Basin by approximately 10%. Smaller, but still significant, increases on the order of 5% were seen in areas of the Colorado River Basin headwaters.

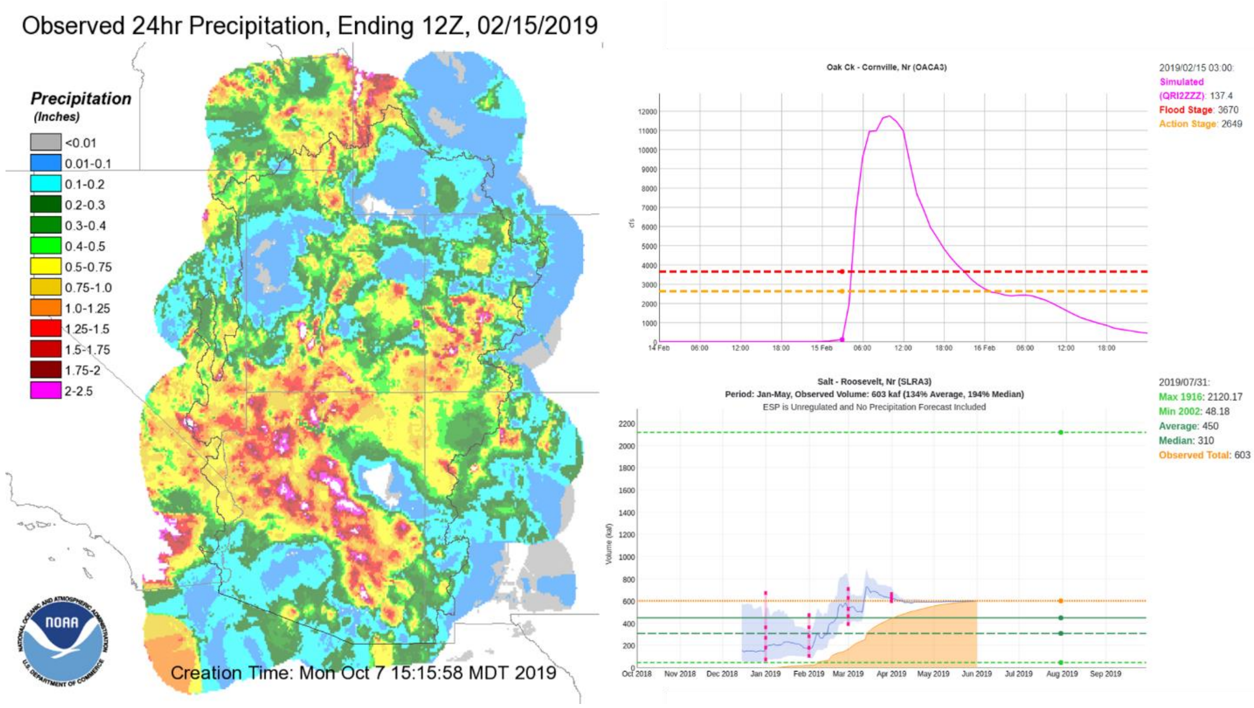


Figure 9: The 2019 Valentine's Day brought rain throughout the basin, particularly in Arizona (right). Flooding was observed over some reaches in Arizona (top left), and significantly increased water supply projections in the region (bottom right)

2 Summary of Major Water Year 2019 Improvements

There were several major operational improvements at the CBRFC that impact 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)

During the course of this water year, the CBRFC began to leverage information from the National Blend of Models (NBM). The NBM is an ensemble of National Weather Service (NWS) and non-NWS numerical weather model information that is blended together to develop initial gridded weather forecast information. The CBRFC is now using information from the NBM to inform both its Quantitative Temperature Forecast (QTF) and Quantitative Precipitation Forecast (QPF) that is used to force its hydrologic model. Additional information and details regarding the implementation of NBM data at the CBRFC is provided in Section 4.1.

In the Lower Colorado River Basin, a gridded historical precipitation dataset was developed for use in model calibration over the area. This dataset leverages hourly gage information, regardless of the period of record, to develop a spatially uniform calibration quality dataset that utilizes all the information available to the CBRFC. This dataset should improve the quality of the CBRFC calibration in the Lower Colorado River Basin moving forward. Additional information and details regarding the new gridded dataset is provided in Section 4.4. The CBRFC also developed a Lower Colorado Situational Awareness webpage that acts as a dashboard for summarizing soil moisture, snow, and monthly precipitation information. The webpage can be accessed at: https://www.cbrfc.noaa.gov/dash/az.php.

Water supply forecasts developed in WY 2018 through Ensemble Streamflow Prediction (ESP) by the CBRFC in the Upper Colorado River Basin utilized a 35-year period of record spanning 1981 through 2015. In WY 2019, the CBRFC began to use a 35-year period of record for water supply forecasts in the Great Basin as well. Extending the period of record that the ESP method uses allows for forecasters to leverage water supply information from 2011 through 2015 when developing a forecast. Additional information can be found in Section 4.2

In response to stakeholder needs, particularly those related to the timing of environmental flow releases, the CBRFC is now able to produce 15-day forecasts at CBRFC forecast locations on request. While there is increased uncertainty into the 15-day timeframe, some stakeholders have found the longer forecast lead time to be helpful. Additional information can be found in Section 3.3.

In an effort to provide more information regarding the amount of snowpack modeled within the CBRFC hydrologic modeling framework, the CBRFC has developed interactive snow graphics that allow users to see the current state and past evolution of modeled snowpack at elevation zones within a forecast segment. In addition to being able to see modeled snowpack data, users have the option of including SNOTEL information on the graphic. These plots can be accessed from any water supply evolution plot page by clicking the “Snow” link under the “Data” heading on the right side of the page underneath the water supply evolution plot. They can also be accessed from the CBRFC home page under the “Snow Conditions” heading to the right of the map. Additional information can be found in Section 3.2.2.

The CBRFC has partnered with other western area River Forecast Centers (RFCs) to further develop a Western Water Supply Forecast website, which can be accessed from the CBRFC homepage (www.cbrfc.noaa.gov, click on "Western Forecast Map" under the "Water Supply" dropdown menu) or directly at: https://www.cbrfc.noaa.gov/wsup/graph/west/map/esp_map.html. The Western Water Supply Forecast website (formerly named Water Resources Monitoring and Observation or WRMO) aggregates water supply forecasts from all three RFCs in the Western Region (Colorado Basin, California Nevada [CN], and Northwest [NW] RFCs) as well as water supply forecast point locations in the western portion of the West Gulf (WG), Missouri Basin (MB), and Arkansas Basin (AB) RFCs onto a single map so that stakeholders, particularly those in areas served by multiple RFCs, can quickly assess water supply conditions in their area (Figure 10). In the CNRFC and NWRFC, clicking on a point will direct you to the water supply forecast page for that particular point at the CNRFC and NWRFC websites; clicking on a point in the WGRFC, MBRFC, or ABRFC area will direct you to a water supply forecast page hosted by the CBRFC that illustrates a forecast with the same appearance and behavior as a water supply forecast point within the CBRFC's area. More information is provided in Section 3.2.4.

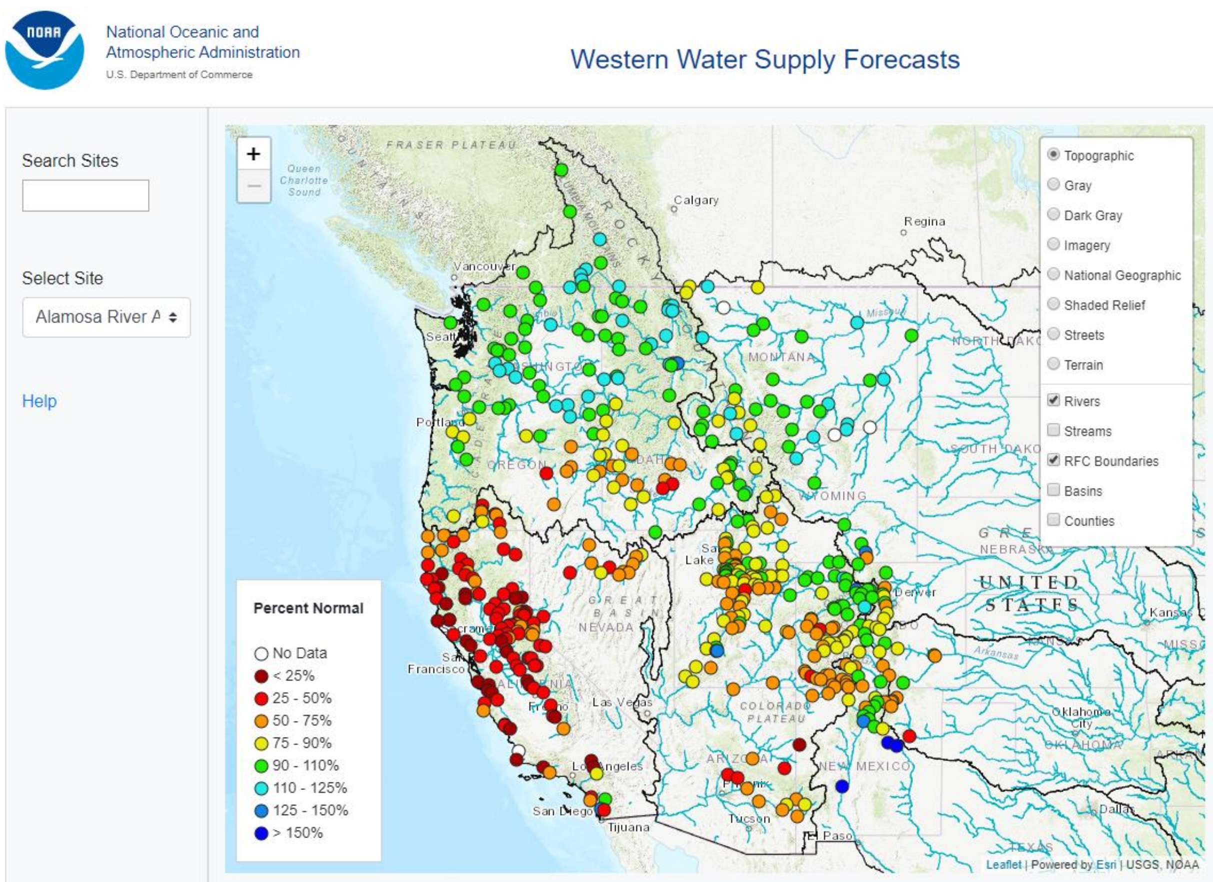
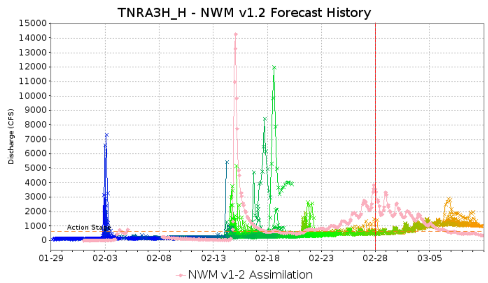
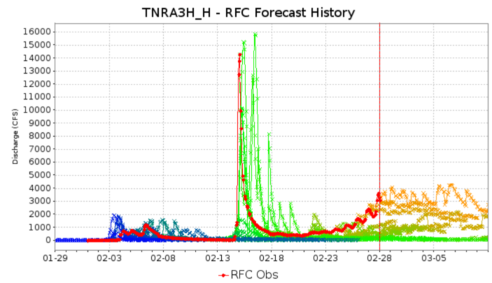


Figure 10: The Western Water Supply Forecasts page provides users with the ability to view water supply forecasts spanning multiple RFCs from a single map

The CBRFC is working closely with the National Water Center (NWC) to assess the performance of the National Water Model (NWM) within the CBRFC area of responsibility. For select forecast points, the CBRFC archives forecasts from the NWM and CBRFC for the past 30 days, which are then archived monthly. **At this point, the NWM generally does not provide consistently accurate, actionable information for CBRFC stakeholders.** Those interested in viewing the comparisons for a subset of points can do so at: https://www.cbrfc.noaa.gov/outgoing/nwm/ (Figure 11). Additional information is provided in Section 3.2.5.



NWM v1.2 Forecasts (-30 day to 10 day) Thresholds Report						
default	Bank	Action	Minor	Moderate	Major	Record
27	-	81	-	-	-	-



RFC Forecasts (-30 day to 10 day) Thresholds Report						
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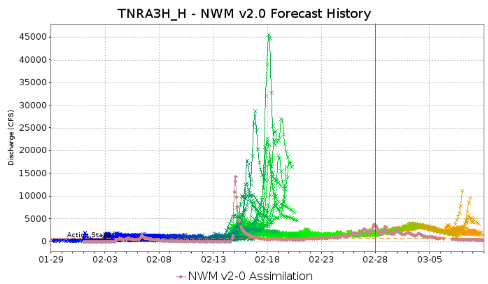

NWM v2.0 Forecasts (-30 day to 10 day) Thresholds Report						
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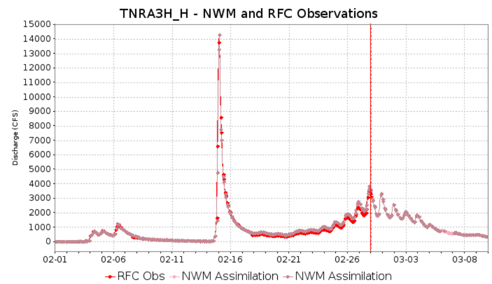


Observations (-30 day to 10 day) Thresholds Report						
default	Bank	Action	Minor	Moderate	Major	Record
-	-	1	-	-	-	-

Figure 11: Comparison of NWM and CBRFC model runs at Tonto Creek, Arizona over February 2019. Of particular interest may be that NWM forecasts signaled flow above action stage nearly 3 to 4 times more frequently than RFC forecasts

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 2019.

3.1 New Forecast Points

In water year 2019, the CBRFC added forecast points to the Verde River Basin. Points in the Verde River Basin were added to improve forecast skill, where the additional points allowed for improved routing to help decision makers meet environmental flow targets.

3.1.1 Verde River Basin

Granite Creek is a tributary to the Verde River whose headwaters originate in the Bradshaw Mountains near Prescott, Arizona. The segment "Granite Creek Below Watson Lake" was added with Handbook 5 ID of "GRWA3". The GRWA3 segment was primarily added to improve the hydrologic model simulation of flow at the segment "Verde River Near Paulden (VDPA3)" site (Figure 12).

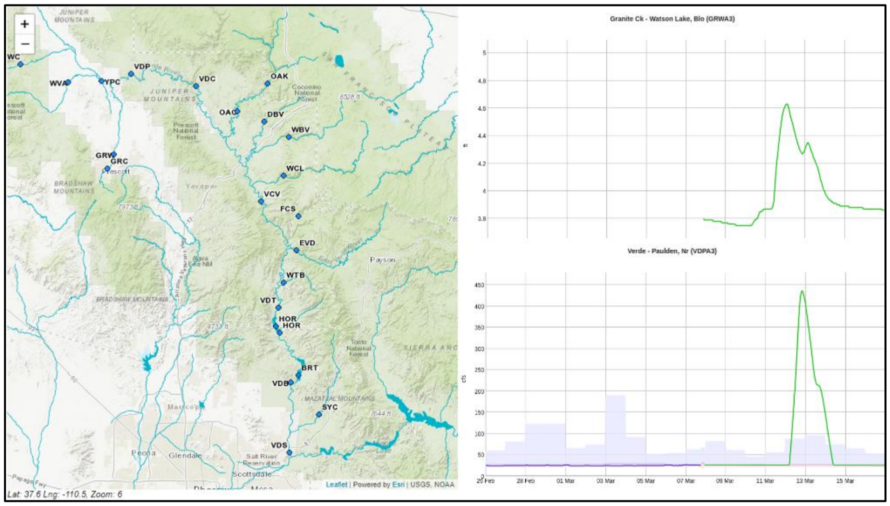


Figure 12: A new forecast point, GRWA3 was added to improve forecasted flow at VDPA3 in the Verde River System

3.2 Webpage Improvements

The CBRFC's primary method of information dissemination is through its webpage located at www.cbrfc.noaa.gov. As additional products and services are developed, the CBRFC strives to make this information accessible via its website. The following sections describe improvements to the CBRFC web services that were made in Water Year 2019.

3.2.1 Lower Colorado Situational Awareness Webpage

The CBRFC developed an Upper Colorado Situational Awareness Page in 2017 in response to stakeholders who wanted a concise tool to brief their upper level managers on current water supply conditions. As the popularity of this page grew, similar requests were made to synthesize information that spoke to the hydrologic conditions of the Lower Colorado River Basin. The CBRFC developed a Lower Colorado Situational Awareness page that highlights soil, snow, and precipitation conditions within the basin. It can be accessed by selecting "Lower Colorado Situational Awareness" from the "Water Supply" drop down menu from the CBRFC homepage. The direct link is https://www.cbrfc.noaa.gov/dash/az.php.

There are two graphics that speak to soil moisture conditions on the Lower Colorado Situational Awareness page. The first describes daily modeled soil moisture as a percent of average over the modeled portion of the basin that significantly contributes to water supply conditions. This information illustrates the efficiency to which snowpack may potentially run off, as drier soils necessitate more recharge (loss) from snowmelt during the runoff season. The second shows inches to soil saturation which identifies areas within the Lower Colorado River Basin where soil saturation levels are high (green colors correspond to wetter soils) and are more susceptible to surface runoff during active weather conditions. This graphic may identify areas that are more prone to flash flooding given an intense rainfall event (Figure 13).

Precipitation information is also presented on this page including: model snow conditions as a

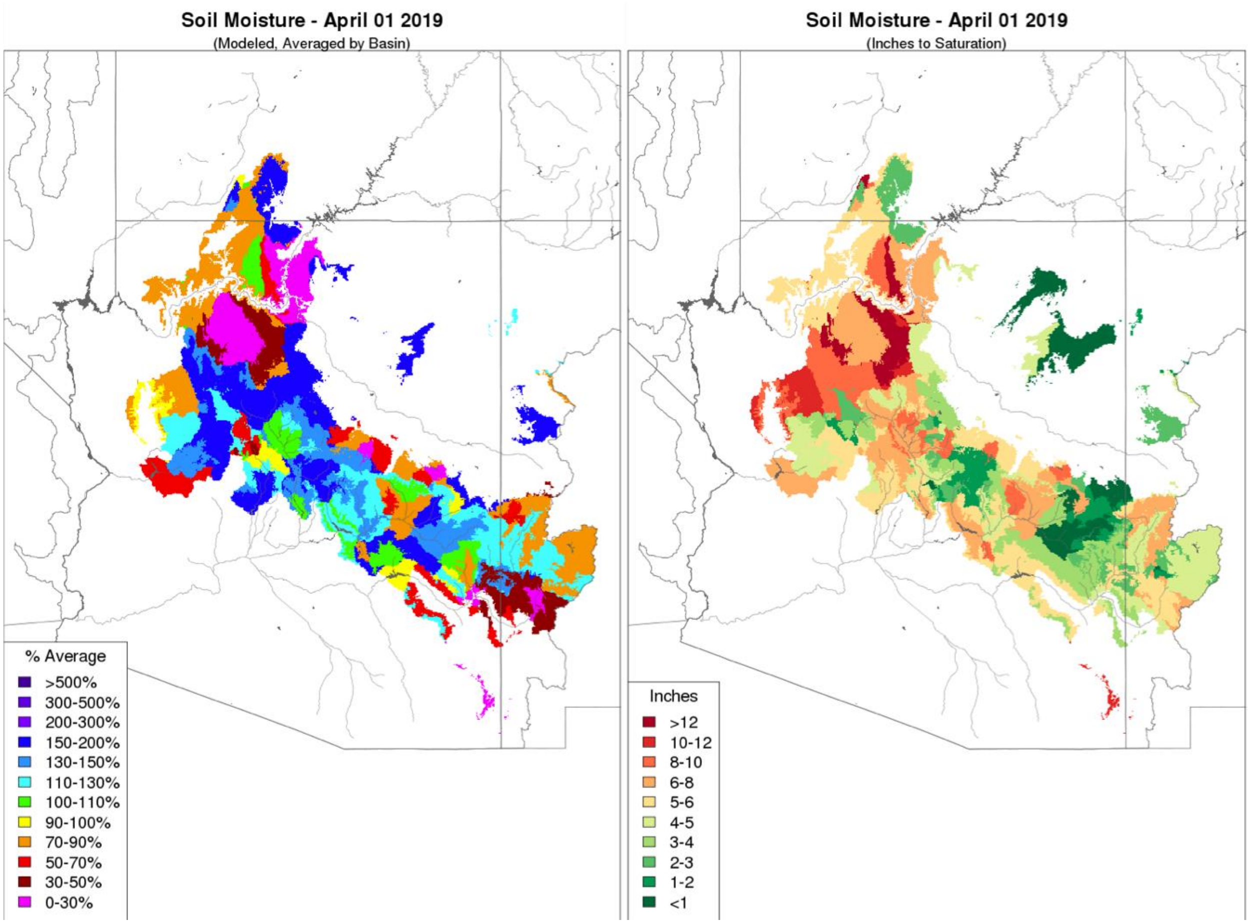


Figure 13: Lower Basin soil moisture information is one of the multiple parameters available on the Lower Colorado Situational Awareness Page

percent of normal (median) over the portion of the basin that contributes significantly to water supply conditions in the region, and water year precipitation and month-to-date precipitation in terms of percent of average.

3.2.2 Modeled Snowpack Information

The CBRFC heavily relies on precipitation information derived from the Natural Resources Conservation Service (NRCS) SNOTEL network. SNOTEL gages provide valuable, real-time information on precipitation and snowpack conditions at the site, and the CBRFC specifically utilizes precipitation information from the network to model snowpack accumulation. Since the CBRFC hydrologic model is forced by mean areal parameters, there is often a disconnect between snowpack conditions as observed at a SNOTEL site and the modeled snow that is a critical parameter within the CBRFC's hydrologic modeling framework.

In an effort to be more transparent about the states driving water supply forecasts within its hydrologic model, the CBRFC developed interactive graphics of modeled snow. Those graphics can be accessed from the CBRFC homepage (www.cbrfc.noaa.gov) by clicking on the "Snow" heading to get to the Snow Condition Map, and then clicking the "Model" tab to the right of the map. Click the "Show" check box and the "Hide Other Types" hyperlink to make the map selection clear. The model snow graphics are also accessible from the water supply evolution graphic at a specified point by clicking on Snow, under Data (lower right side of the page).

By clicking on any point, a pop-up dialog will provide a "View Graph" hyperlink that directs to an interactive webpage showing the modeled snow for the selected point. Stakeholders can view modeled snow at each elevation band and select options on the graphic that allow for the comparison of model snow to user selected SNOTELs and historical levels (Figure 14).

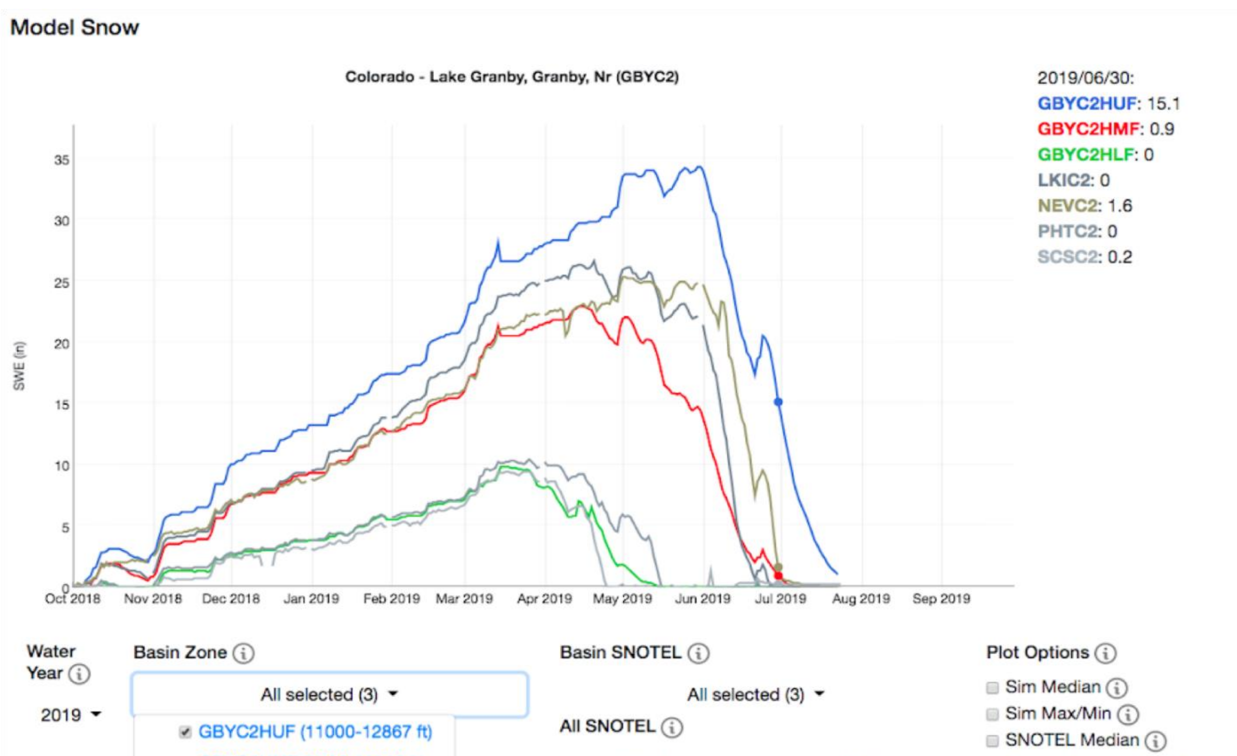


Figure 14: Model snowpack information is now available through the CBRFC website. This particular graphic compares modeled snowpack information at Lake Grandy with nearby SNOTEL site information

3.2.3 Improved Peak Flow Information Dissemination

In response to needs from the Weather Forecast Offices (WFO) and broader stakeholder communities, the CBRFC began to redevelop how peak flow information was disseminated. It is important to note that the underlying methodology for developing peak flow forecasts did not change, only how information regarding peak flows is being made available.

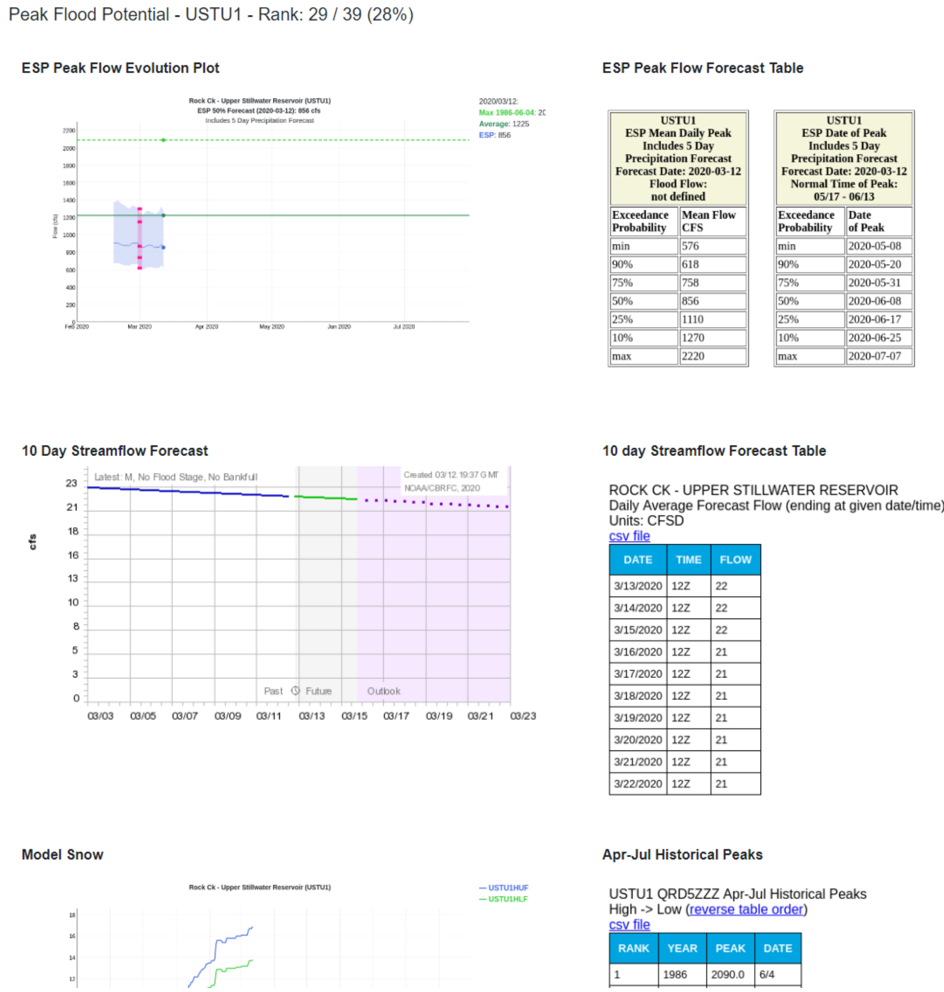


Figure 15: More information regarding peak flows is now available through the CBRFC website. In particular, daily guidance and peak timing information is now much more accessible to stakeholders

From the homepage, the option to view forecasted peak flow values by percentiles has been added. Prior to this year, only the probability of exceeding flood thresholds had been presented; by allowing the user the option to view by percentile, interested stakeholders can get a sense of how forecasted values compare to historical flow values. Further, by selecting one of the mapped points visible when the percentile option is active, additional information regarding the peak flow at the site is available. A peak flow evolution plot, very similar in format to commonly referenced water supply evolution plots, is now available making daily guidance regarding peak flows now available. Peak flow forecast tables provide information regarding the probability of exceeding particularly mean daily flow values and probabilities associated with the timing of seasonal peak flows. This page also provides a link to the 10-day forecast graphic and table, modeled snow conditions in the segment, and a table with historical seasonal peaks (Figure 15).

3.2.4 Western Water Supply Forecast Page Updates

The CBRFC has partnered with other western area RFCs to further develop a Western Water Supply Forecast website, which can be accessed from the CBRFC homepage (www.cbrfc.noaa.gov, click on "Western Forecast Map" under the "Water Supply" dropdown menu) or directly at: https://www.cbrfc.noaa.gov/wsup/graph/west/map/esp_map.html. The Western Water Supply Forecast website (formerly named Water Resources Monitoring and Observation or WRMO) aggregates all NWS produced water supply forecasts onto one map so that stakeholders, particularly those in areas served by multiple RFCs, can quickly assess water supply conditions in their area (Figure 10). The RFCs that produce those forecasts include CBRFC, CNRFC, NWRFC, WGRFC, MBRFC, and ABRFC. In the CNRFC and NWRFC, clicking on a point will direct you to the water supply forecast page for that particular point at the CNRFC and NWRFC websites; clicking on a point in the WGRFC, MBRFC, or ABRFC area will direct you to a water supply forecast page hosted by the CBRFC that illustrates a forecast with the same appearance and behavior as a water supply forecast point within the CBRFC.

3.2.5 National Water Model Graphical Verification Project

The CBRFC is working closely with the National Water Center (NWC) to assess the performance of the National Water Model (NWM) within the CBRFC area of responsibility. The CBRFC developed an online verification tool to monitor the performance of the NWM at key locations across the Colorado and Eastern Great basins, primarily for internal use but available for stakeholders to view via the web. Since March 2018, the CBRFC archives forecasts from the NWM and CBRFC for the past 30 days, which are then archived monthly and are accessible at: https://www.cbrfc.noaa.gov/outgoing/nwm/ (Figure 11). This verification website provides qualitative information and performance indicator statistics for CBRFC forecasts and the latest two versions of the NWM. At this point, the NWM generally does not provide accurate, actionable information for CBRFC stakeholders.

3.3 15-Day Deterministic Forecast

During peak runoff season, stakeholders within the Gunnison River Basin request 15-day deterministic forecasts (5-days longer than traditionally available forecasts) to improve the management of reservoirs in the basin, despite lower forecast skill at the extended lead times. These deterministic forecasts are forced with the same forcing data (i.e. precipitation and temperature) and developed exactly the same as other short term forecasts for days 1 through 10. For days 11 through 15, the model is forced with average temperatures from climatology, and zero precipitation amounts.

Extended daily forecasts are currently generated upon demand, during the runoff season, for the Gunnison and Yampa River Basins. Other areas can be implemented on request.

3.4 SLCRVFMCT Update

The SLCRVFMCT is a NWS internal product that transfers short range daily forecasts from the RFC to WFO databases for use in the watch and warning flood program. Until this year, this product would only be sent once all forecasts in the CBRFC domain were completed, leading to occasional situations where the WFO would be waiting for an update during high water or flood events while less active hydrologic regions were being worked on.

This process has been changed so that the SLCRVFMCT is sent to WFOs as soon as each forecast group is completed at the RFCs, allowing WFOs to receive updates more quickly. The SLCRVFMCT now also includes 7 day forecasts instead of the traditional 5-day forecast.

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 Implementation of NBM Information

Traditionally, forecasts issued by the NWS were largely influenced by and dependent upon the WFO responsible for the forecast. In an effort to become more consistent and objective nationally, the NWS has developed and begun to implement the National Blend of Models (NBM). The NBM is a nationally consistent and skillful suite of calibrated forecast guidance based on a blend of both NWS and non-NWS numerical weather prediction model data and post-processed model guidance. Guidance is provided on a plethora of forecasted weather parameters, including precipitation and temperature. The goal of the NBM is to create a highly accurate, skillful, and consistent starting point for the gridded forecast.

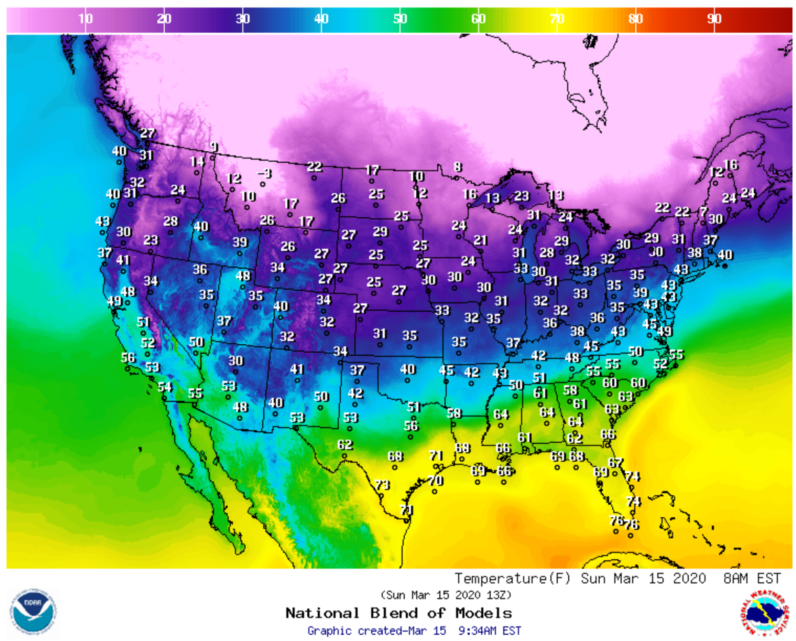


Figure 16: Placeholder picture for NBM temp or precip picture of CBRFC

Precipitation and temperature forecasts are the primary forcings that drive the CBRFC's hydrologic model. Similar to procedures at WFOs, temperature and precipitation forecasts were developed independently by the CBRFC and involved some degree of subjectivity by CBRFC forecasters. As a result, inconsistencies in the development of precipitation and temperature forecasts could arise and impact daily streamflow forecasts. The CBRFC has implemented the use of precipitation and temperature output from the NBM, ensuring more consistent, objective, and accurate forecasts (Figure 16). Further, the NWS has been developing and improving the NBM for use in all field offices, and has become widely used across WFOs as an initial point forecast development.

4.1.1 NBM for Temperature Forcings

The CBRFC conducted verification of the NBM temperature forecasts compared to the legacy CBRFC method, which used temperatures based on Global Forecast System (GFS) numerical model, which was calibrated using the Model Output Statistics technique from the NWS Meteorological Development Laboratory (MDL). A biased corrected version of the NBM (bcNBM) was also developed by bias correcting the raw NBM output with observed date as part of the verification project. The results showed that utilizing the CBRFC developed bcNBM was the best performing method, on average producing the most accurate (lowest Mean Absolute Error [MAE]) and consistent (lowest percent of significant change between successive issuances of the NBM) forecast.

Additionally, temperature forecasts developed using the product from the MDL generally have similar MAE to the raw NBM. However, as the MDL is derived from a single GFS model run, its forecasts are much more susceptible to inconsistency between model runs, especially at longer lead times (Figure 17). This inconsistency can result in inconsistent forecasts and hydrographs. The bcNBM was implemented operationally in March 2019.

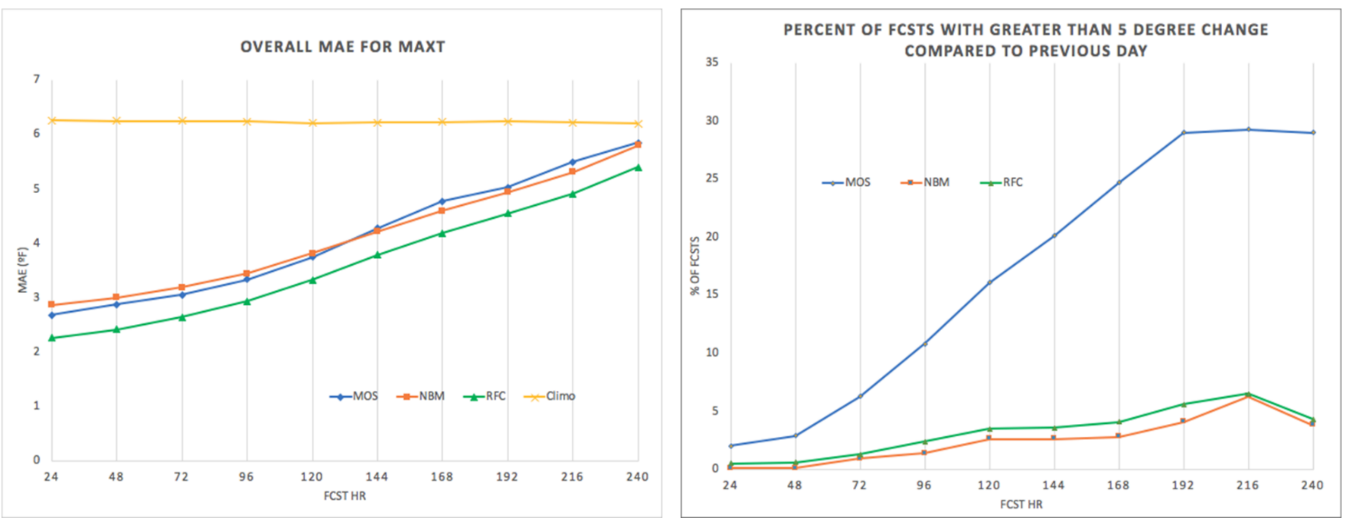


Figure 17: On the left, comparison of MAE between maximum temperature forecasts developed using information from the GFS MOS, raw NBM, bcNBM developed by the RFC, and climatology. On the right, a comparison of the degree of change between GFS MOS temperature forecasts, raw NBM, and bcNBM developed by the RFC.

4.1.2 NBM for precipitation

Five days of forecasted precipitation have traditionally been used to force the CBRFC's hydrologic model. Precipitation forecasts are initialized using information from the National Center for Environmental Prediction, Weather Prediction Center (WPC). Typically, these forecasts were adjusted by CBRFC forecasters depending on how WPC forecasts compared with numerical weather prediction models, WFO forecasts, and spatial distribution of the magnitude and intensity of storm events. As such, it was common for inconsistencies to arise between precipitation forecasts.

With continued improvements to the NBM and the High Resolution Rapid Refresh (HRRR) models, the CBRFC compared short-term (Day 1) forecasts from the NBM and HRRR to the forecasts derived from the WPC. It was found that precipitation forecasts from the WPC do well at lower precipitation thresholds (< 0.5 inch), but tend to under forecast higher precipitation amounts. The HRRR tends to over forecast all precipitation amounts, resulting in better skill scores at larger, high-impact events (> 1.0 inch). Further, the NBM, and particularly a combination of the NBM and HRRR, were most skillful at higher precipitation thresholds. The CBRFC also compared historical CBRFC precipitation forecasts with WPC, and found that WPC performs consistently better than CBRFC.

From this investigation, the CBRFC implemented the use of the precipitation forecast from the NBM for day 1, while utilizing the precipitation forecast from WPC for days 2 through 5 (through day 7 in Arizona). This change was made in July, 2019.

4.2 Great Basin, Sevier and Verde ESP Extension

The Ensemble Streamflow Prediction (ESP) methodology used to develop probabilistic seasonal water supply forecasts generates a range of forecast scenarios based on historical temperature and precipitation time series. These time series span water years 1981 through 2015 (35 years, or traces) in the Upper Colorado River Basin and were updated in 2018. This allows for water supply forecasts to include the latest climate information.

This past year, the historical years used in ESP in the Great Basin and Sevier River Basin were updated to include through water year 2015, identical to the range of traces used in the Upper Colorado River Basin. ESP traces in the Salt and the Verde River Basins were updated through water year 2017 (1981 through 2017, or 37 years).

4.3 Improved Intervening Flow Forecasts

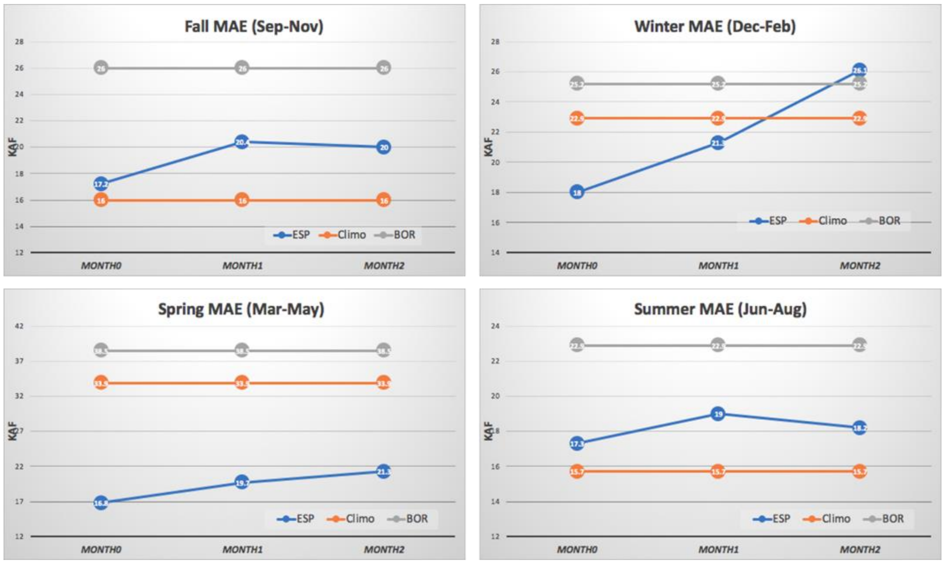


Figure 18: Results comparing MAE associated with different methodologies for developing intervening flow forecasts between Glen Canyon Dam and Lake Mead over the course of each season

The CBRFC has traditionally provided a forecast of the intervening flows (also known as side inflows) between Glen Canyon Dam and Lake Mead. Intervening flow is primarily driven by Colorado River tributaries: the Virgin River, Little Colorado River, Kanab Creek, Diamond Creek, Muddy River, and the Las Vegas Wash.

Over the past year, the Bureau of Reclamation (Reclamation) and Colorado River Basin stakeholders have been interested in understanding if this forecast of intervening flow can be used to help inform Reclamation's reservoir operations model (commonly referred to as the 24-Month Study).

Forecasters at the CBRFC reconciled differences between the methodologies employed by the CBRFC and Reclamation to develop intervening flow forecasts. In doing so, the CBRFC proposed an adjusted intervening flow forecast that could be used by Reclamation to drive their reservoir operations model, while also improving upon the forecast methodology to reduce the MAE in CBRFC forecasts. Based on the results of the study, the CBRFC now uses ESP to develop intervening flow forecasts in the winter and spring months (December through May), and then rely on historical climatology during the summer and fall months (June through November) (Figure 18).

Reclamation is currently in the process of evaluating the forecasts provided by the CBRFC for use in their reservoir operations model; the CBRFC expects to continue to provide support for this analysis as needed.

4.4 New 800m Gridded Precipitation and Temperature Data Sets

The CBRFC develops gridded datasets derived from gage, radar, and PRISM data to derive mean areal information that is used to drive its lumped hydrologic model. These grids are tailored for use in calibration, operations, and research efforts. Over the course of WY 2019, three different gridded datasets, at 800m resolution and covering the entire CBRFC domain, were developed for the uses described below.

4.4.1 800m Gridded Precipitation for the Lower Colorado River Basin

An 800m gridded precipitation dataset was developed using all available precipitation gage data, with a particular focus on the Lower Colorado River Basin, including the Virgin River Basin. That point data was closely quality-controlled before generating the 800m the dataset for water years 2000 through June 2019. The intent is to use this dataset for future calibrations in the Lower Colorado River Basin. This will align the calibration dataset with the one used operationally, though without radar information which is also used operationally.

4.4.2 800m Gridded Precipitation for the Upper Colorado River Basin

An 800m gridded precipitation dataset was developed to support a collaborative effort with RTI International to run the CBRFC's lumped hydrologic model as a distributed model. This gridded dataset uses only gage data from the calibration record, which have long records and well understood statistics. Quality control was primarily focused mostly over the Upper Colorado Basin. Grids were developed spanning water years 1988 through 2013. While available to CBRFC stakeholders for their own investigative efforts, there are no future plans to use this dataset at the CBRFC unless the use of distributed models becomes more widespread in the agency.

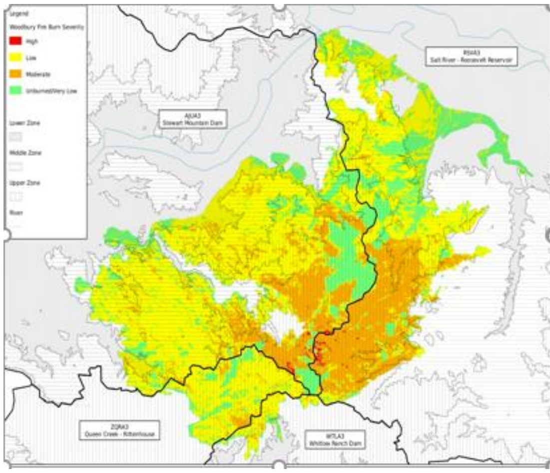
4.4.3 800m Gridded Temperature Data

An 800m gridded temperature dataset was developed using only gages from the calibration record for water years 1988 through 2013. This dataset can be used over the entire CBRFC domain, and will be used to calibrate the Lower Colorado River Basin in the future.

4.5 Woodbury Fire Support

From June 8th through July 15th, 2019, the Woodbury Fire burned over 120,000 acres in Arizona's Tonto National Forest. The resultant burn scar is located in the Salt River Basin within the Phoenix WFO's hydrologic service area; stakeholders in the area, including the WFO, were concerned about the potential impacts to hydrology as a result of the fire .

The CBRFC examined the impact of the Woodbury Fire to the area and catchments defined within the hydrologic model, including burn severity maps, and percentages of basins and sub-basins impacted by the fire (Figure 19). This information will allow forecasters to make adjustments to the CBRFC's hydrologic model during active hydrologic (i.e. rain) events.



		WOODBURY FIRE BURN SEVERITY									
		High		Moderate		Low		Unburned/Very Low		High+Moderate+Low	
Basin Zone	Area (mi2)	mi2	%	mi2	%	mi2	%	mi2	%	mi2	%
AJUA3LLH	199.8	0	0.0	0.6	0.3	6.4	3.2	3.2	1.6	7.0	3.5
AJUA3LMH	115.5	0	0.0	6.8	5.9	38.1	33.0	8.6	7.4	44.9	38.9
AJUA3LUH	71.4	0.4	0.6	14	19.6	14.7	20.6	9.8	13.7	29.1	40.8
RSVA3LLH	272.1	0	0.0	0	0.0	6.6	2.4	8	2.9	6.6	2.4
RSVA3LMH	251.1	0	0.0	5.1	2.0	15	6.0	6.6	2.6	20.1	8.0
RSVA3LUH	320	0.4	0.1	17.1	5.3	8.3	2.6	3.5	1.1	25.8	8.1
WTLA3HLH	76.9	0	0.0	0	0.0	0.1	0.1	0.2	0.3	0.1	0.1
WTLA3HUH	66.2	0	0.0	0.4	0.6	2.4	3.6	0.7	1.1	2.8	4.2
ZQRA3LLH	11.4	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0
ZQRA3LMH	76.5	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0
ZQRA3LUH	78.9	0	0.0	1.9	2.4	11.2	14.2	3.5	4.4	13.1	16.6

Figure 19: The CBRFC investigated the impacts of the Woodbury Fire to basin hydrology in the area. Results will inform future modelling efforts during active hydrologic events

4.6 Weekly Webinars During the Runoff Season

Seasonal runoff due to snowmelt in WY 2019 was higher and later than normal, continuing well into July. Most years, the CBRFC holds monthly water supply webinars through May to communicate information to interested stakeholders. This year, given the uncertainties associated with above average snowpack late in the runoff season, CBRFC forecasters held weekly webinars to provide updates on conditions through June. While weekly water supply webinars are not usually necessary, the CBRFC will adapt communication and products to meet the needs of stakeholders during hydrologically active seasons.

4.7 Stakeholder Engagement Forums

The CBRFC convenes a stakeholder engagement forum almost every year. Usually, meetings are held at the CBRFC office in Salt Lake City, UT. This year, the CBRFC held its stakeholder engagement forum in Grand Junction, CO. The decision to hold the CBRFC annual forum in Grand Junction was actually the result of visiting three cities (Denver, Phoenix, and Salt Lake City) in WY 2018 as part of a stakeholder engagement meeting "roadshow" to reach stakeholders that are not often able to attend the annual meeting in Salt Lake City and emphasize more regional issues. Stakeholders suggested also reaching out to the community near Grand Junction, CO during the roadshow and the CBRFC was able to partner with the Reclamation office in Grand Junction to host the meeting in WY 2019.

The goals of these meetings are to present services and methods, with an emphasis on enhancement, and listen to stakeholder needs and requests. Much of what CBRFC works on during the year is based on stakeholder feedback received at these meetings.

4.8 Support During Henson Creek Flooding

Figure 20: Debris from avalanche events line the banks of Henson Creek. Photo by Dean Krakel, published in The Colorado Sun on May 28, 2019.

Devastating avalanche events tore through a 20 mile section of Henson Creek, located in Hinsdale County near Lake City, CO in March. Debris from the avalanche events swept downstream during a flood event on May 13th, 2019. This enormous amount of debris in the creek caused water to build behind two abandoned, structurally unsound, concrete dams. To support emergency management operations in the area, the CBRFC began communicating peak flow information at the Lake Fork at Gateview (LFGC2) and Lake Fork below Lake San Cristobal (LFBC2) gages. Additionally, the CBRFC began to communicate information regarding Henson Creek via its WebCat tool, an internal NWS tool for alerting WFOs of hydrologic conditions (e.g., changing precipitation amounts and reservoir levels) that may cause concern.

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. Among the highlights from WY 2019 was what the CBRFC somewhat playfully termed, "CBRFC Summer Institute." The Summer Institute was a collection of highly motivated summer students who chose to work on CBRFC defined projects over the Summer. Three of the students were undergraduates in NOAA's Hollings Scholar program: Kirsten Jensen (University of Vermont), Bethany Murphy (Syracuse University), and Lauren Castanon (California State Monterey) worked on a variety of projects. Jensen worked on quantitatively assessing ESP sensitivity to QPF (Section 5.6), Murphy worked on interpreting and comparing data from NASA's Airborne Snow Observatory to snow information derived through CBRFC methods (Section 5.4), and Castanon worked on improving the CBRFC's understanding and methodology for distributing seasonal probabilistic volumetric forecasts (Section 5.5). These Hollings Scholars presented their research at a symposium hosted by NOAA in Washington D.C. before returning to school to continue their studies. Some of the students also presented this research at other conferences, including the conference of the American Geophysical Union (AGU).

Additionally, the CBRFC hosted a graduate student, Gabriela Morales from San Diego State University, whose work was supported by the NOAA Experimental Research and Training Opportunities (NERTO) Center for Remote Sensing Science and Technologies (CREST). Morales's work focused on evaluating how evapotranspiration is treated in the NWM (Section 5.3). Morales has since returned to school to complete her Master's program.

The CBRFC hosts summer student relatively infrequently, so having four students over the summer was unusual; however, the students' projects were widely successful and the CBRFC appreciated the quality of work that these students produced. The CBRFC hopes for future success in attracting more talented students.

5.1 Energy Balance Snow Model

The CBRFC partnered with RTI International and Utah State University to evaluate the effectiveness of an energy based, distributed, Utah Energy Balance (UEB) Model. The UEB incorporated a robust set of parameters (e.g., long and short-wave radiation, topography, etc…) to quantify snow accumulation and melt. Theoretically, a robust, distributed model quantifying snow accumulation and snowmelt could be coupled with the CBRFC's Sac-SMA model to provide an alternative to SNOW-17.

This project ended without definitive conclusions because the UEB model was unable to be run at the CBRFC. However, the CBRFC was able to calibrate and run the Research Distributed Hydrologic Model (RDHM) configured by RTi over a small scale (1 km), and was also able to improve the CBRFC's understanding of gridded forcing products.

5.2 Climate Prediction Center Sub-Seasonal (2-4 week) Forecasts

NOAA's Climate Prediction Center (CPC) and the Western Region River Forecast Centers (CNRFC, NWRFC, and CBRFC) agreed to collaborate investigating the potential improvement to water supply and flood forecast lead time. The CPC has demonstrated skill in precipitation and temperature forecasts 2 weeks out, and potentially 3 to 4 weeks out. The team working on this project was organized this year, but most of the work is planned to take place in WY 2020.

5.3 Evapotranspiration Processes in the NWM (Morales)

Modeling evapotranspiration (ET) within the CBRFC's hydrologic model framework is challenging due to a lack of appropriate current quantitative observations of ET. Indirect measurements of ET such as pan evaporation records exist, but do not accurately measure transpiration processes from plants. For the CBRFC's modeling efforts, ET is estimated using a water balance approach, in which ET typically decreases with elevation as a result of falling temperatures and the absence of vegetation above the treeline. ET simulations developed using a water balance produce reasonable, but simulated ET forcings are not able to respond robustly to seasonal anomalies and climate change scenarios.

The NWC has started producing nation-wide streamflow forecasts using the NWM. The NWM, unlike the CBRFC model, uses a land surface model in place of a water balance approach. The Noah land surface model with multiparameterization options (Noah-MP) operates within the NWM by incorporating complex representations of physical processes such as snowmelt and soil infiltration. Noah-MP works well at a broad spatial scale, but its performance within the NWM over a long period of time and in various ecosystems has not been assessed.

Using the Animas River at Durango, CO catchment, the NWM was run locally over an 8-year time period (2007-2015). The run resulted in a record of accumulated ET (ACCET) at a 6-hour timestep. The ACCET record was further aggregated to a daily timestep and tabulated into an accessible format. To get individual ET values for each day, a difference calculation for each grid cell was performed on the ACCET record. These gridded ET values were aggregated to elevation zones corresponding to those in the CBRFC's lumped model for comparison purposes.

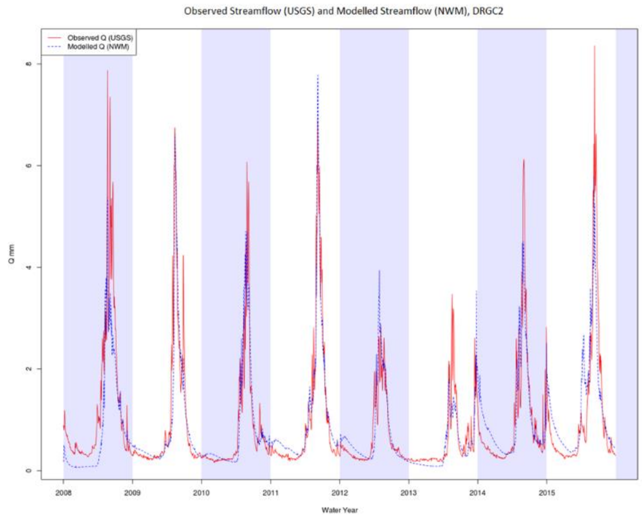


Figure 21: A comparison of USGS streamflow observations on the Animas River at Durango with NWM modeled streamflow.

The NWM had difficulty capturing seasonal streamflow recessions when compared to daily streamflow data from the USGS (Figure 21). It is possible that the NWM mistyped the character of fall precipitation (i.e. defining more rainfall, rather than snowfall, events) contributed to elevated baseflow conditions within the NWM. Further, the Noah-MP land surface model was consistent with land conditions described within the CBRFC's hydrologic model; however, vegetation cover in high elevation areas above the treeline over summer months are likely too high. Overall, the NWM showed the ability to model complex hydrologic processes accurately, but there seemed to be a need for more accurate model forcing information and improved calibration.

5.4 Investigation of Airborne Snow Observatory Data (Murphy)

In 2013, NASA's Jet Propulsion Laboratory (JPL) launched Airborne Snow Observatory (ASO), which utilizes imaging spectrometry and LIDAR information taken from plane flights to take snow measurements over the entire extent of a watershed. ASO captures snow depth measurements at high resolutions, which can be converted to SWE using snow density. The accuracy of the snow density estimates largely determines the accuracy of ASO reported SWE values. SNOTEL data in the surrounding area can be used as a proxy to understand snow densities in the basin.

Five ASO flights have been conducted in the Upper Gunnison River Basin in Colorado throughout late March 2018, late May 2018 and early April 2019. ASO used a constant snowpack density for the March conversions, density as a function of elevation for the May conversions, and density as a function of snow depth for the April conversion. The flight area corresponds to the East at Almont (ALEC2), Ohio Creek (OHOC2), Taylor Park (TRAC2), and Taylor Park Reservoir (TPIC2) basins modelled by the CBRFC. ALEC2 and OHOC2 are modelled using lower, mid, and upper elevation zones, while TRAC2 and TPIC2 are modelled with only lower and upper elevation zones.

It was found that ASO and SNOW-17 both show that SWE increases with elevation, but ASO shows this with much more detail, due to the gridded nature of the product. The ASO SWE values reach a maximum of 3.13 meters at a grid cell location, while SNOW-17 SWE values only reach a maximum of 0.48 meters over a lumped catchment area. Generally, SWE values derived from ASO were larger than SNOW-17 values at the highest elevations and smaller at lower elevations (Figure 22). One possible reason for this could be that PRISM-based climatology used by SNOW-17 may be overestimating monthly precipitation amounts above 11,000 feet.

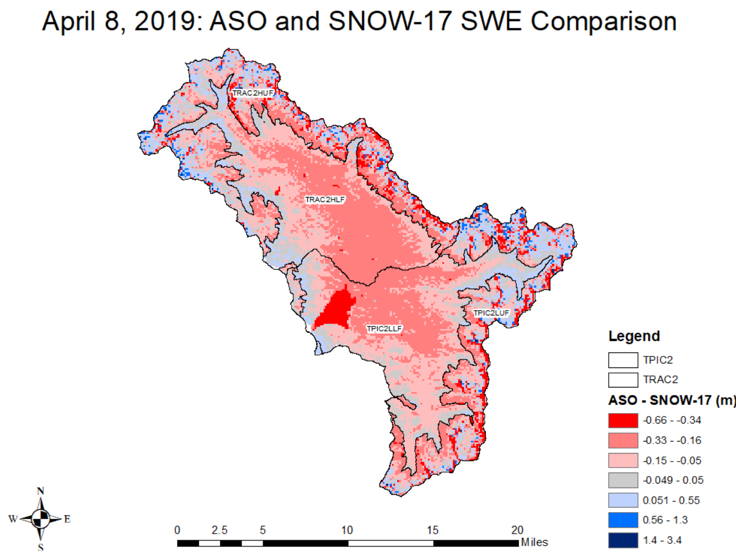


Figure 22: Difference between ASO and SNOW-17 derived SWE values from an April, 2019 ASO flight. ASO values are larger than SNOW-17 values at high elevations (blue shading) and smaller at lower elevations (red shading)

This project allowed for the CBRFC to better understand ASO products and services, as well as the complexities of snow distribution and snow density assessments. Future proposed research could use ASO data to address quantifying coniferous interception and subsequent sublimation in heavily forested areas. While a very important research effort, the data available for this study was very limited in quantity and area, making it difficult to draw conclusions from this effort. With more ASO data (more days, and over more basins), the CBRFC, and the greater research and operations community, could develop more conclusive insight.

5.5 Evaluation of Seasonal Runoff Distribution (Castanon)

The probabilistic nature of volumetric seasonal (i.e. usually April through July) runoff forecasts can, at times, make it difficult to provide a monthly breakdown of seasonal flow volumes. For instance, when providing a "maximum probable," or 10 percent exceedance forecast of April through July runoff, it is not mathematically correct to state that it is the sum of the 10^{th} percentile of each individual month. As a result, stakeholders resort to their own methodologies to distribute seasonal volumes into monthly amounts to force their own operational models. The CBRFC is interested in providing accurate monthly breakdowns of seasonal volumes for stakeholder use.

Additionally, stakeholders are often interested in how the climate of a particular year affects runoff distribution. It is commonly assumed that very wet years, or those often described by the maximum probable forecast, have associated runoff hydrographs that are skewed later in the season. Conversely, very dry years are assumed to have seasonal runoff hydrographs that are skewed earlier in the season. While these assumptions are generally accepted, little effort has been done to validate the assumption. Considering climate change impacts, stakeholders have been interested in how the distribution of seasonal runoff may be changing with time. The research effort taken here is intended to address these questions.

5.5.1 Changing Distribution of Runoff Over Time

To address the issue of changing runoff distribution over time, the center of seasonal runoff volume for March through July was determined, and correlated with annual runoff. As often cited and understood by researchers within the Colorado River Basin, streamflow runoff has been decreasing over time, and drier than average years are occurring more frequently. The CBRFC further investigated how monthly runoff has been trending over time; as expected, March, April, and May, are overall seeing increased runoff over time. Conversely June and July are seeing decreased runoff over time (Table 1).

Table 1: Summary of trends of the percentage of runoff occurring each month. A cell with a green plus demonstrates that runoff is increasing during that month for that site. A cell with a red minus demonstrates that runoff is decreasing during that month

Siteid	March	April	May	June	July
ALEC2	+	+	-	-	-
ASHU1	-	-	+	-	+
DOLC2	+	-	+	-	-
DRGC2	+	+	+	-	-
FCNU1	+	+	-	-	-
LILC2	+	-	-	-	+
MBLC2	+	+	+	-	-
NEUU1	+	+	+	-	-
OAWU1	+	+	+	-	-
PSPC2	+	+	+	-	-
STMC2	+	+	+	-	-
WBRW4	+	+	-	+	-
WRMC2	+	+	+	-	-
WTRU1	-	-	-	0	+

+	increasing runoff over time
-	decreasing runoff over time

Historical runoff data was split into thirds, separating the driest third, wettest third, and middle third of the data. Further, data was also split into fifths. This was done to compare the distribution of runoff between varying degrees of dry and wet years. Visual inspection of the runoff distribution at each site (Figure 23) showed that drier years ran off earlier than wetter years.

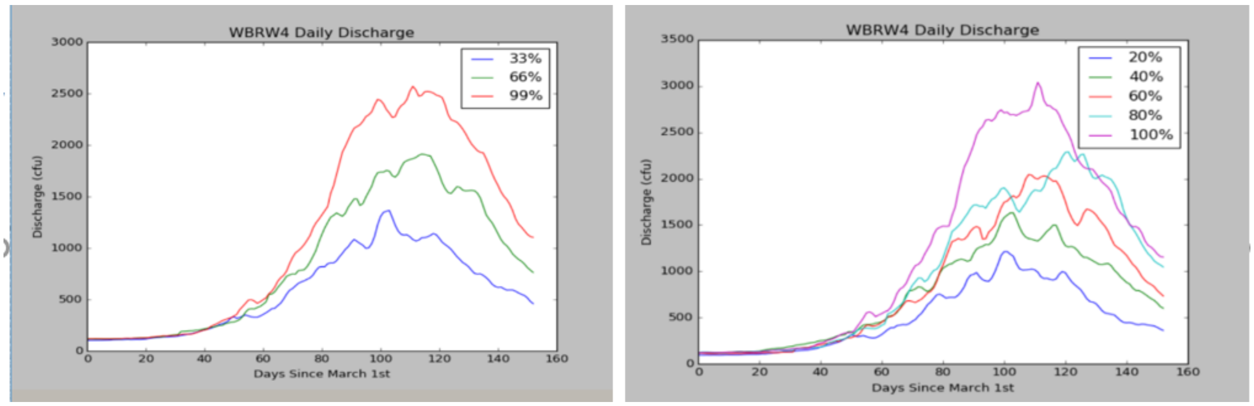


Figure 23: Comparison of runoff distribution between varying degrees of dry and wet years

Plotting the runoff distribution at each site with respect to the total volume of runoff over the course of the year indicated that it was necessary to determine whether the trend of earlier runoff was due to a greater occurrence of drier years in the past 20 years or to the earlier melt due to another effect such as rising temperatures. Splitting the data into fifths (driest, dry, med, wet, wettest), and plotting the percentage of total runoff versus the year also demonstrated that the distribution of runoff throughout the March – July period was changing differently between these groups. Results are summarized in Table 2.

In the dry 20% of years (i.e. the flows falling in the 20th to 40th percentile), runoff appears to be occurring earlier in the water year, with the percentage of runoff increasing in March, April, and May, and decreasing in July. In the wettest 20% of years runoff appears to be unaffected by the general trend of increasing runoff earlier in the water year. The driest 20% of years does not appear to follow a trend of running off earlier or later in the year, which may be attributed to very low amounts being relatively unaffected.

Table 2: summarizes the change in runoff distribution over time for each site during the 20% of dry years. As a trend, runoff is increasing in the months of March – May and decreasing in July over time

Siteid	March	April	May	June	July
ALEC2	-	+	-	+	-
ASHU1	-	-	+	+	-
CIVU1	+	+	+	-	-
DOLC2	+	+	+	-	-
DRGC2	+	+	+	-	-
FCNU1	+	-	+	+	-
LILC2	+	-	+	-	+
MBLC2	+	-	+	+	-
NEUU1	-	-	+	-	+
OAWU1	-	-	-	+	-
PSPC2	+	+	-	-	+
STMC2	-	-	-	+	+
WBRW4	+	+	-	+	-
WRMC2	+	+	+	-	-
WTRU1	-	-	-	-	+

+	increasing runoff in this month
-	decreasing Runoff in this month

The results indicate the distribution of runoff in the Colorado Basin is changing over time. Earlier runoff over the last 20 years is due to at least two effects. The first being that there have been more dry years which melt out earlier compared to wet years. Secondly, rising temperatures are contributing to earlier runoff. Dry runoff years are showing the most pronounced changes in distribution. Dry years are likely most affected by changes in distribution because in dry years there is a lesser volume of snow which is more vulnerable to earlier melting in response to higher temperatures. Wet years are less affected by this trend because the greater volume of snow in these years is more resistant to early melting. The driest years did not follow a consistent trend as their distribution is often dependent on the occurrence of precipitation events.

5.5.2 Seasonal Runoff Distribution

To determine how seasonal runoff distribution may be changing depending on basin hydrology, the 10th (wettest) and 90th (driest) percentile of data was analyzed, in addition to the 10% of flows closest to the historical median. For each set, the percentage of runoff within each month was averaged for analysis. Table 3 below shows the data, and shows that runoff occurs at different rates in dry, wet, or near median years, but most often the majority of the runoff occurs in June.

Table 3: Estimated percentage of the April - July forecast which will run off each month. The estimates are split by site, and wet, dry, and median years

	Dry				Med				Wet			
Siteid	April %	May %	June %	July %	April %	May %	June %	July %	April %	May %	June %	July %
ALEC2	4	27	46	24	9	31	44	17	8	30	44	18
ASHU1	3	34	48	14	4	47	33	16	9	42	36	13
CIVU1	14	44	32	10	22	46	26	6	24	46	24	6
DOLC2	13	40	36	11	20	42	30	8	22	44	26	8
DRGC2	9	29	42	19	15	37	34	13	10	31	40	19
FCNU1	7	49	38	6	12	59	23	6	18	53	22	6
LILC2	14	40	37	8	19	48	29	4	23	47	26	4
MBLC2	12	38	38	11	18	41	34	7	15	41	34	9
NEUU1	2	17	54	27	4	27	46	23	5	29	44	23
OAWU1	6	27	49	18	9	34	45	12	9	29	46	15
PSPC2	12	30	41	17	16	36	39	9	21	41	30	8
STMC2	9	32	45	13	16	39	38	7	15	39	38	7
WBRW4	5	22	46	27	6	24	42	29	9	25	39	27
WRMC2	8	26	45	20	12	35	40	13	13	34	40	14
WTRU1	3	20	52	25	5	33	42	20	9	39	38	15

There is a difference in the ratio of the monthly volumes to the total April - July runoff volume between dry, medium and wet years. Future work will involve using this information to help better inform splitting the minimum and maximum probable forecast volumes into monthly values.

5.6 ESP Sensitivity to Quantitative Precipitation Forecasts (Jensen)

In an effort to better understand the influence of lead time, start dates, and variation in precipitation on the skill of seasonal water supply forecasts, and determine at what point the skill and predictability of the forecast benefits from longer lead times, the CBRFC investigated the impact of changing QPF on ensemble streamflow forecasts. The project used reforecast and observed data to analyze the accuracy of modeled predictions.

Over the course of a forecast season (January 1st through the end of June), ensemble streamflow forecasts were developed using 1, 2, or 4 weeks of observed data starting at the first of each month to represent a "perfect" QPF or QTF. Using this information, it could be determined what forecast lead times, and during what portion of the year it would be most beneficial to have accurate, longer-lead precipitation and temperature forecasts.

In general, it was demonstrated that there is a correlation between skill of prediction and variation in precipitation (Figure 24). Peaks in skill correspond to months with the highest variation in precipitation within the forecast lead time. This essentially indicates that being able to forecast extreme events generally gains a significant amount of skill for end of year water supply predictions. However, in some cases, there may be a great deal of precipitation in the lead period with significantly less precipitation for the rest of the season. This would lead to an over forecasted prediction and a low skill count. This indicates that correctly forecasting extreme precipitation events does not guarantee an improvement in skill, though in general, it does improve predictions.

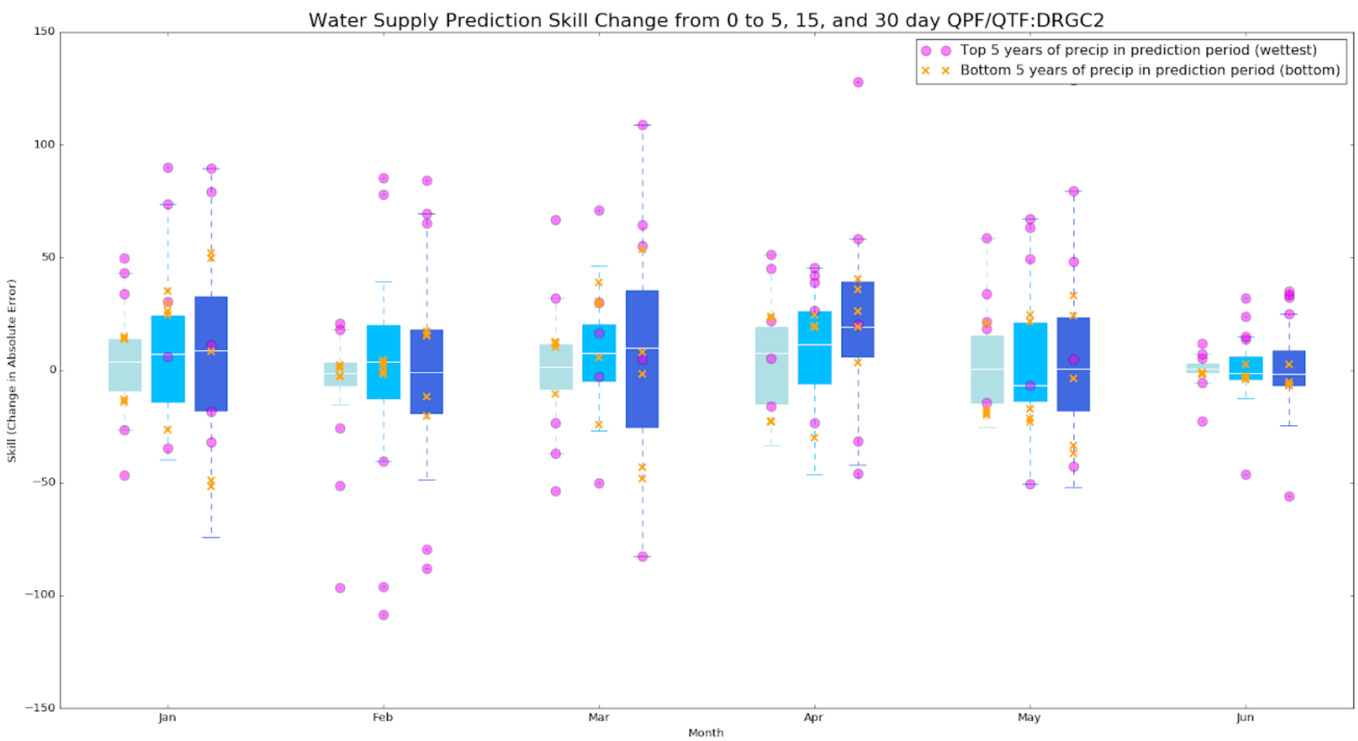


Figure 24: Change in forecast skill with improved QPF and QTF lead time

The data almost always indicated that end of year volume forecasts improve with longer lead times and later start dates. It is important to note the decrease in predictability over time. Though having an accurate QPF/QTF for a longer period of time significantly improves the accuracy of the end of year forecast, the ability to predict temperature and precipitation decreases over time. Beyond approximately 2 weeks, temperature and precipitation forecasts generally have low skill.

Because of this, this project aimed to find an intersection where the predictability and skill of the forecast are at their highest. More specifically, it was important to determine whether the skill improvement from 5 to 15 days of QPF/QTF is significant enough to pursue more accurate 2 week temperature and precipitation forecasts. The findings of this project would indicate that this skill increase is significant, particularly when there is an above average amount of precipitation in the prediction period.