Challenges in Forecasting the 2011 Runoff Season in the Colorado Basin

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ABSTRACT

Historically large snowpack across the upper Colorado basin and the Great Basin in 2011 presented the potential for widespread and severe flooding. While widespread flooding did occur, its impacts were largely moderated through a combination of sustained cool weather during the melt season and mitigation measures based on forecasts. The potential for more severe flooding persisted from April through the first part of July as record-high snowpacks slowly melted. NOAA's Colorado Basin River Forecast Center (CBRFC) is the primary office responsible for generating river forecasts in support of emergency and water management within the Colorado River basin. This paper describes the 2011 runoff season in the basin and examines the skill of CBRFC forecasts for that season. The primary goal of this paper is to raise awareness of the research and development areas that could, if successfully integrated into the CBRFC river forecasting system, improve forecasts in similar situations in the future. The authors identify three areas of potential forecast improvement: 1) improving week two to seasonal weather and climate predictions, 2) incorporation of remotely sensed snow-covered area, and 3) improving coordination between reservoir operations and forecasts.

1. Introduction

This paper describes the 2011 peak streamflows in the Colorado basin and the Great Basin in an attempt to illuminate the forecasting efforts of the NOAA Colorado Basin River Forecast Center (CBRFC). A recent National Research Council (2012) report highlighted the difficulties in transferring research results into operational river forecasting as a major impediment to improving forecasts. The primary goal of this paper is to highlight three areas where research is most needed to improve river forecasts in years with large snowpacks similar to 2011: 1) improving week two to seasonal weather and climate predictions, 2) incorporation of remotely sensed snow-covered area, and 3) improving coordination between reservoir operations and forecasts. A description of water year 2011 conditions is followed by a description of the forecast methods employed by CBRFC. The results of a verification analysis are then presented to motivate the discussion on research needs.

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2. Event overview

Historically large snowpacks throughout the upper Colorado basin and the Great Basin in Utah, Wyoming, and much of western Colorado characterized the 2011 water year (WY), presenting challenges for forecasters, emergency managers, and water managers. Much of the seasonal snowpack was a result of two extreme precipitation events, one on 17–23 December 2010 and a second, more prolonged event in April–May 2011. Both events produced above-normal precipitation, leading to flooding in lower elevations and additional snow accumulations in upper elevation basins.

The 17–23 December 2010 precipitation event featured precipitation several times the average monthly value over a swath of the region running roughly from southern California northeast through Utah (Fig. 1). The event was driven by a tropical moisture feed consistent with literature on the atmospheric river phenomena (e.g., Ralph et al. 2004), with much of the precipitation falling in the last few days of the event. Rivers in low elevation areas below ~2000 m responded and flooding was observed along many reaches of the Virgin and Muddy Rivers in southwestern Utah and southern Nevada.

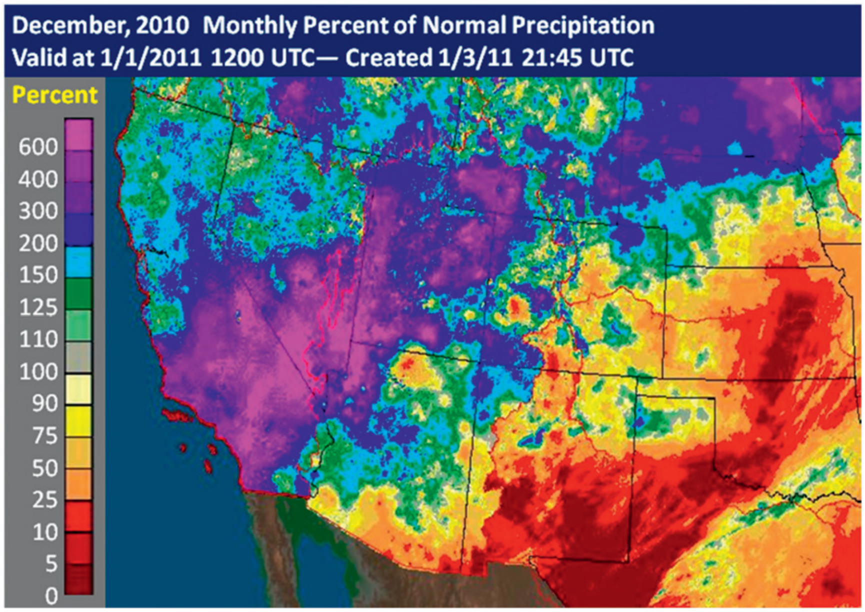


FIG. 1. Analyzed precipitation anomalies for December 2010 expressed as a percentage of normal. Image courtesy of the Advanced Hydrologic Prediction Service.

Streamflow on the Virgin and Santa Clara Rivers exceeded 8000 cfs in many areas, causing major damage to nearby homes, businesses, and roadways. Figure 2 shows the streamflow response on the Virgin River in southwestern Utah from this precipitation event.

Precipitation for this event was well forecasted 5–10 days in advance, allowing for skillful river forecasts with similar lead times. However, seasonal forecasts were largely consistent with the coinciding La Niña signal and failed to predict December's above-average precipitation (CPC 2011; Fig. 3). Typically, La Niña is associated with below-average precipitation in the southern portions of the Colorado basin, including the area most affected by the 17–23 December 2010 event (Cayan 1996; McCabe and Dettinger 1999; Pulwarty and Melis 2001).

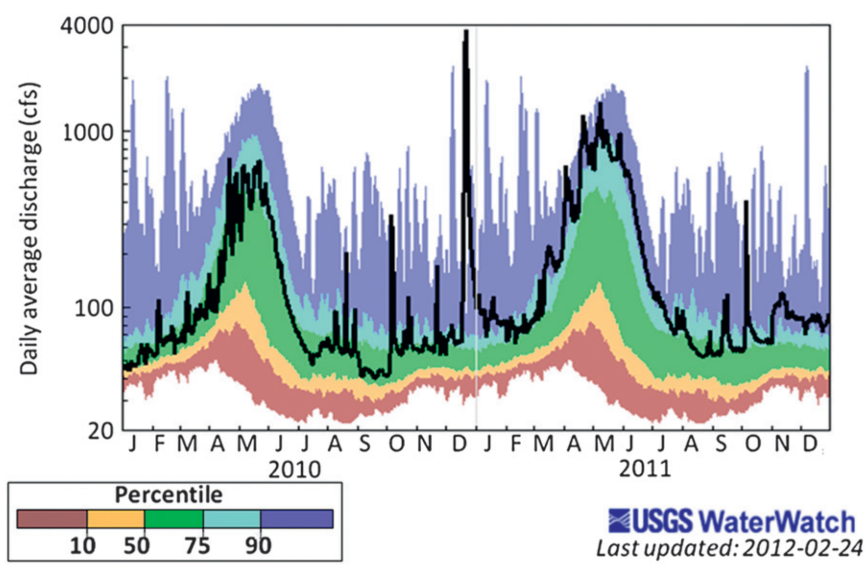


FIG. 2. Duration hydrograph of daily average streamflow for the North Fork Virgin River (2010–2011). Image courtesy of the U.S. Geological Survey.

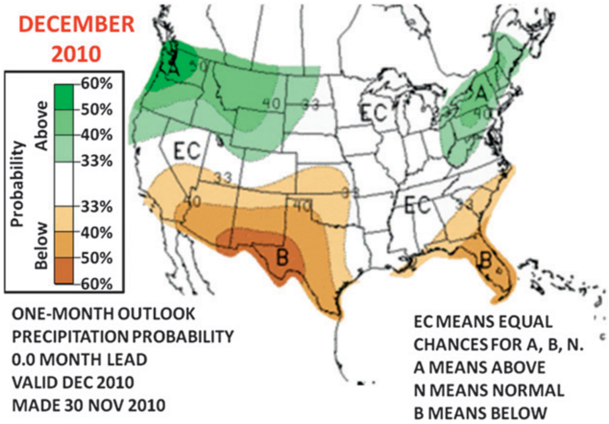


FIG. 3. Official Climate Prediction Center (CPC) monthly precipitation outlook for December 2010 issued on 30 November 2010. Image courtesy of the CPC.

Conditions returned to normal for January–March, followed by an extremely wet and cool period during April–June in the northern part of the basin. A series of late winter storms contributed to well above average precipitation totals and record-high snowpacks in April and May (Figs. 4a,b). In some instances, particularly in the Yampa, upper Colorado mainstem, and Duchesne basins, the snowpack nearly doubled the 30-yr average snow water equivalent (SWE). One example of this was the Tower Snowpack Telemetry (SNOTEL) site in the upper Yampa River basin that peaked at 79.9 in. SWE compared to 70.4 in. SWE in 1986, the next highest year on record. Furthermore, peak SWE values, which are typically recorded in late April or May at mountain sites, were significantly delayed because of the persistent storm activity. Daily temperatures remained well below normal for most of April, May, and the first three weeks of June, with the exception of a few brief (1–3 days) warming periods (Fig. 5). It was not until the last week of June that a sustained period of near-normal—and by that time, very warm—temperatures was observed. Had temperatures during the first three weeks of June been closer to normal, the above-average snowpack might have melted rapidly, resulting in record widespread flooding. However, most of the upper Colorado basin experienced gradual warming tempered by sporadic cool periods, helping to mitigate runoff in all except the highest elevation basins of the upper Colorado basin. Only these highest basins with considerable snow coverage and water equivalent toward the end of June produced near record-high peak flows. As with the December precipitation event, climate outlooks at all lead times largely failed to capture this prolonged wet and cool event (Fig. 6).

While the magnitude of the peak flows was moderated by the long duration of the melt event, runoff volumes were not. In many cases, the much-above-average snowpack caused record-high runoff volumes. The Yampa River and its tributaries saw some of the most extreme values within the larger basin. The Elk River near Milner, Colorado, for example, reported 742 kac-ft between April and July, besting the previous record of 552 kac-ft set in 1917. Similar volume runoff records were broken or nearly broken across the upper Colorado headwaters, including sites in the Yampa basin, the Duchesne basin, and the upper Colorado River mainstem. Runoff volumes decreased to near average farther south in the San Juan and Dolores basins.

3. Streamflow forecast and verification methodology

a. CBRFC forecast modeling and operations summary

The CBRFC generated both long- and short-lead forecasts throughout the duration of the 2011 runoff season at more than 400 locations using the hydrologic modeling system maintained and operated in real time at the CBRFC. The modeling system incorporates both the Sacramento Soil Moisture Accounting Model (SAC-SMA) and the Snow-17 models. The SAC-SMA model is a conceptual water balance model first developed in the 1970s to support National Weather Service (NWS) streamflow forecasting (Burnash and Ferral 1973). The Snow-17 model is a temperature-index model used by the NWS to model snow accumulation and melt (Anderson 1973). Model parameters for both models are determined through a calibration process periodically conducted by CBRFC staff. Model states are maintained in real-time, accounting for precipitation, snowmelt, and other physical and anthropogenic processes as part of the daily forecasting operations at the CBRFC.

CBRFC generates three basic types of forecasts: long-lead volume forecasts, long-lead peak flow forecasts, and daily streamflow forecasts. The long-lead forecasts are issued on a monthly and as-needed basis during the winter and spring seasons. These forecasts specify a probability function of likely outcomes (either volumes or peak flows) generated by exercising the forecast model in an ensemble mode (Day 1985). Long-lead forecasts are generated using deterministic (single-valued time series) forecasted temperature (10 days), precipitation (5 days), and ensemble historical time series from the 30-yr calibration period to fill out the forecast period. Volume forecasts typically describe the accumulated unregulated streamflow (e.g., in absence of reservoirs and diversions) and are generated for a subset of forecast points of interest to water management,

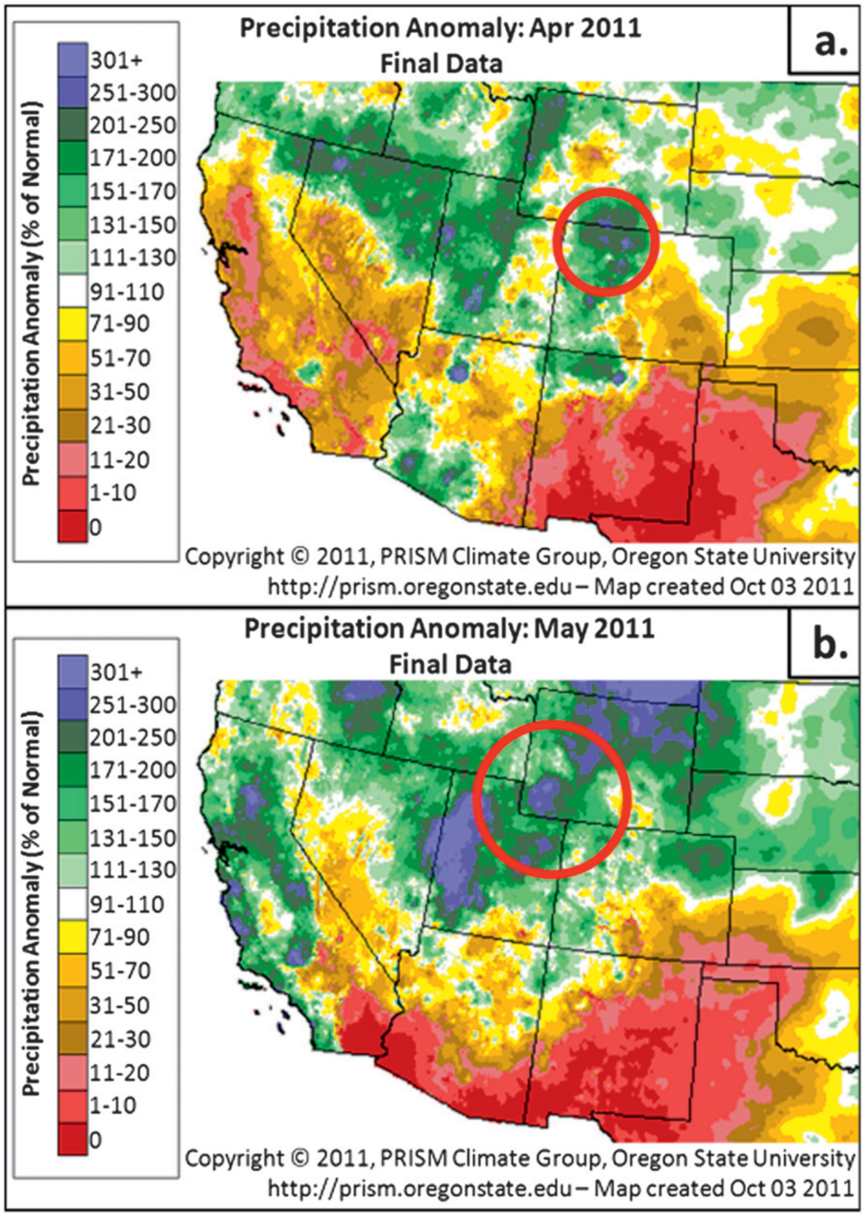


FIG. 4. Analyzed precipitation anomalies expressed as percent of normal for (a) April and (b) May 2011. Images courtesy of the PRISM Climate Group, Oregon State University (http://www.prism.oregonstate.edu).

primarily reservoir operators. Peak flow forecasts describe the maximum likely streamflow and are generated for a subset of forecast points requested by emergency management and/or recreation interests.

In contrast to long-lead forecasts that are probabilistic, daily forecasts describe a single, most likely, streamflow time series 10 days into the future. These forecasts are based on a combination of 1) quality-controlled inputs of recent, real-time precipitation and temperature analyses; 2) forecasted precipitation and temperature over the next 5–10 days; 3) known reservoir and diversion operations both in the recent past and scheduled in the future; and 4) forecast model adjustments made by the forecaster to simulate recent observed streamflow.

b. Verification

As interest in streamflow forecasts has increased in recent years, demand for information about the error characteristics of the forecasts has become more important (NRC 2006). The NWS has called for increased

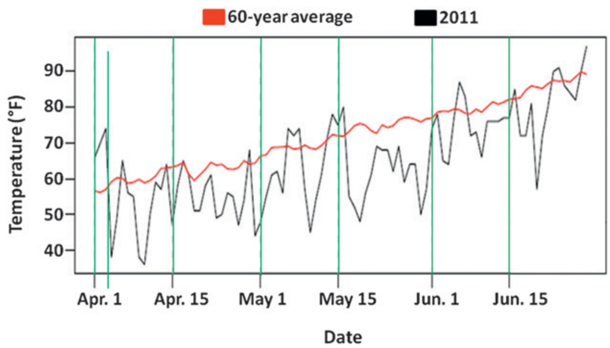


FIG. 5. Observed and 60-yr average (black and red lines, respectively) daily maximum temperatures for Salt Lake City for April–June 2011.

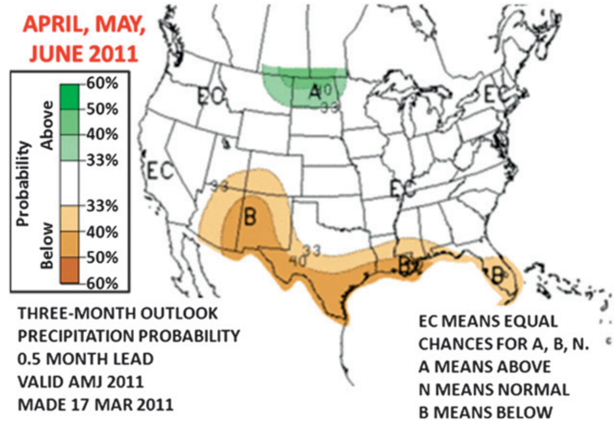


FIG. 6. Official CPC seasonal precipitation outlook for April–June 2011 issued on 17 March 2011. Image courtesy of the CPC.

capacities for verifying streamflow forecasts (Demargne et al. 2009). The 2011 WY is an important opportunity for analyzing streamflow forecasts in extreme conditions.

Long-lead and daily streamflow forecasts are verified using plots of observations and 5-day deterministic forecasts and three metrics: mean error, mean absolute error, and mean relative absolute error. The mean error is defined by

$$\text{mean error} = \frac{1}{n}\sum_{i=1}^{n} F_i - O_i,$$

where F is the forecast, O is the observation, and n is the number of time steps. The mean absolute error is defined as

$$\text{mean absolute error} = \frac{1}{n}\sum_{i=1}^{n} |F_i - O_i|.$$

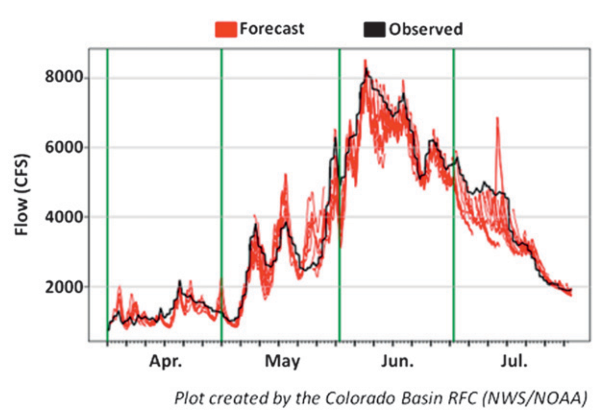
Finally, the mean relative absolute error is simply the mean ratio of the absolute error to the observations as shown by

$$\text{mean relative absolute error} = \frac{1}{n}\sum_{i=1}^{n} \frac{|F_i - O_i|}{O_i}.$$

Forecasters visualize forecast tendency and accuracy through the verification plots, which overlay 5-day deterministic streamflow forecasts with streamflow observations (Fig. 7). The metrics then provide a more concrete comparison of streamflow forecast skill on different lead days. However, the metrics do not differentiate between normal flow periods and extreme flow events, so care should be taken in interpreting these values, as the forecast skill during an extreme flow event is likely very different from the forecast skill during a normal flow period. Extreme flow events are, by their nature, more difficult to forecast and more likely to have large forecast errors than normal flow periods. Peak flow forecasts are verified using a similar methodology of plotting peak flow forecasts against their corresponding observations (Fig. 8).

4. Results

Long-lead volume forecasts were generally too low throughout the winter before centering their probability on the forecast target, as the April–May extreme precipitation was observed and accounted for in the model. Figure 9 shows the 2011 actual and forecasted April–July inflow into Lake Powell. As with most of the northern tributaries, most of the Lake Powell inflow forecast



	DAY 1	DAY2	DAY3	DAY4	DAY5	OVERALL
Mean Error(cfs):	-148.1	-257.4	-305.8	-340.8	-383.1	-287
Mean Absolute Error(cfs):	279.4	409.5	497.4	525.9	571.9	456.8
Relative Absolute Error (%):	8.4	11.4	14.1	13.9	15.2	12.6

FIG. 7. Forecast and observed (red and black lines, respectively) streamflow for inflows to Blue Mesa Reservoir in 2011. Forecasts are issued at least once per day. The first 5 days of each forecast are plotted on the graph.

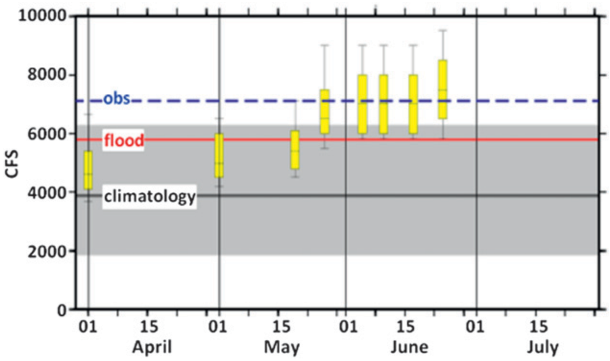


FIG. 8. Forecast (yellow rectangles with whiskers) and observed (blue dashed line) peak flow for the Elk River near Milner in 2011. The box and whisker position on the ordinate corresponds to the forecast issue date. Flood stage is the red line. The blue line is climatology with the gray shading showing the range of historical mean daily peaks for the gauge record.

probability for the winter season forecast issuances was well below the observed inflow of 12.9 maf. By 1 May, the range of inflows described by the forecast probability was nearer to the actual inflow because the storm activity in late April (and early May) was included in these forecasts.

While the peak flows were moderated somewhat by the sustained cool temperatures, high flows were observed in many locations, including the Elk River, which experienced record-high flows (Fig. 8). Like the volume forecasts, the peak flow forecasts were generally too low in March and early April prior to the inclusion of the wet, cool pattern at the end of April to the streamflow forecasts. Once that pattern was accounted for, peak flows were generally well within the forecasted 10%–90% spread. In some cases, such as the Elk River, most of the forecast distribution was above the previous record level.

Spring weather is very important in determining peak flows. As such, weather prediction is an important source of forecast skill as well as forecast error in both long-lead peak flow and daily forecasts. Throughout the spring, the forecasted daily streamflow time series reflected the forecasted weather time series. As weather forecasts consistently indicated atmospheric ridging in the long-range (e.g., 5–10 day) forecast during the months of May and early June, daily streamflow forecasts reflected that warm bias with high streamflow forecasts. This effect was greatest in the middle- and higher-elevation basins that retained above-normal snow amounts through the month of May. In addition to the temperature forecast

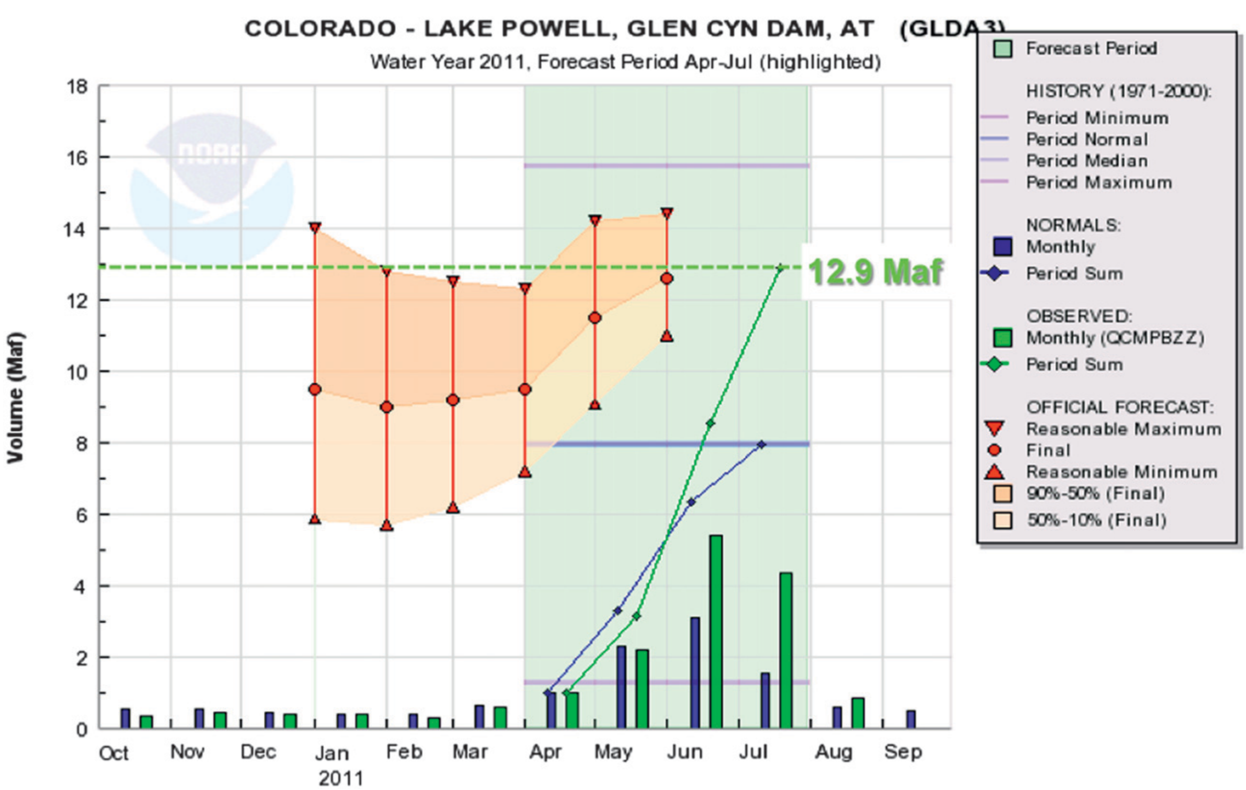


FIG. 9. Forecast (red vertical lines) and observed (green dashed line) April–July inflow volumes to Lake Powell in 2011.

uncertainty, the daily snow information available through the SNOTEL network provides an indispensible, yet limited, understanding of the snow conditions across a particular watershed. Additional forecast uncertainty comes from reservoir regulation, variable snow albedo, and changes in the physical characteristics of the basin, such as vegetation.

Based primarily on forecasting experience, we identify the following three factors that negatively affected streamflow forecast skill: 1) climate outlooks, 2) weather forecasts, and 3) reservoir regulation plans.

Climate outlooks for both the 17–23 December 2010 and the April–May 2011 periods were problematic in their near total lack of advance indication of the extreme precipitation that was about to occur in both the upper Colorado basin as well as the Great Basin (Figs. 3 and 6, respectively). Early-season long-lead streamflow predictions indicated high probabilities of above-normal volumes and flows. However, these forecasts were well below the observed values until the late April forecast issuances. Likewise, 1 December 2010 climate forecasts did not suggest the extreme precipitation event that occurred later that month. These two instances illustrate the lack of skill in seasonal predictions when and where it is most needed, during extreme events. They also illustrate the potential importance of skillful long-lead forecasts. While climate outlooks are not used directly in long-lead streamflow forecasts, CBRFC forecasters do follow both the forecasts and, especially, their skill. Should forecast skill improve in the upper Colorado River basin, climate outlooks would provide an important source of skill.

Weather forecasts, while clearly skillful at short lead times, consistently indicated atmospheric ridging in the second week of the forecast that did not materialize. This created a warm bias in the temperature predictions that were used to produce streamflow forecasts.

Finally, streamflow forecasts for sites downstream of reservoirs are heavily influenced by reservoir operations. The amount of water released by a reservoir directly contributes to the streamflow at downstream sites. The CBRFC receives reservoir release schedules intermittently (daily, weekly, and monthly) from some reservoir operators, but in some cases schedules change or are not available at all, causing major errors at downstream forecast points.

5. Improving streamflow forecasts

Extreme runoff situations such as those observed during the 2011 WY present opportunities for identifying areas of research and/or development to improve streamflow forecasts. The primary goal of this paper is to suggest areas of potential improvement to encourage research and development work in these areas to improve forecast skill. A recent study by the National Research Council (2012) identifies the state of hydrologic science employed by the NWS as significantly lagging behind the state of the science in the larger community. The primary cause of this disparity is the barrier in translating research to NWS operations. This paper addresses this barrier through presenting the experience with forecasting in 2011.

Fully addressing these improvement areas is beyond the scope of both this paper and an operational River Forecast Center. We identify three areas of potential improvement where research efforts and research to operations efforts could have improved 2011 forecasts here: 1) improving week two to seasonal weather and climate predictions, 2) incorporation of remotely sensed snow-covered area, and 3) improving coordination between reservoir operations and forecasts.

As previously discussed, many of the observed problems with streamflow forecasting stem from inaccurate weather and climate forecasts. We understand that this is a problematic area for improvement given the inherent difficulties in long-lead weather prediction and climate prediction in areas with low ENSO correlation such as the upper Colorado basin. However, the application potential of long-lead forecasts with incremental improvements to skill is large.

Snow-covered area and snow water equivalent are also important variables in streamflow forecasting, especially during the melt period. Currently, CBRFC models and manually adjusts both snow-covered area and snow water equivalent based on average melt rates, observed streamflow, and qualitative comparisons with snow analyses such as those produced by the National Operations Hydrologic Remote Sensing Center (Barrett et al. 2001; Bitner et al. 2002). A more highly resolved dataset could enhance snow-covered area in the current snow model used by CBRFC, thus improving the quality of model-produced streamflow forecasts. This is particularly true for satellite-based snow-observing products (e.g., Dozier and Painter 2004), which, unlike in situ snow observations, are not currently integrated at all into streamflow forecasting. The in situ SNOTEL network is used by CBRFC for point-based measurements of precipitation and snow water equivalent. There are no in situ data available to CBRFC for snow-covered area. Therefore, CBRFC is undertaking efforts to improve its snow modeling through evaluation and possible incorporation of snow-covered area from these datasets.

Finally, streamflow in rivers downstream of reservoirs depend heavily on reservoir operations. As discussed previously, changes in flow along these reaches are determined primarily by changes in releases from the upstream reservoir more so than by physical processes that the CBRFC models. Although the CBRFC maintains and operates a reservoir model, this model is only as accurate as the consistency between the model's input for reservoir operations and actual operations of the reservoir. CBRFC engages reservoir operators to receive reservoir release schedules (daily, weekly, and monthly). But oftentimes these release schedules do not incorporate forecast inflow (O'Connor et al. 2005). Even in cases where reservoir schedules do consider forecasts and are updated frequently, the impact of forecast errors work in nonlinear and inconsistent ways to influence actual changes in reservoir releases. Although previous studies have identified the potential benefits of effectively linking reservoir operations to streamflow forecasts (e.g., O'Connor et al. 2005; Pulwarty and Redmond 1997), optimally connecting forecasts to improve reservoir operations remains a ripe area for future work.

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