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NOAA's Colorado Basin River Forecast Center: "Climate Services on the Colorado River: Capabilities, Gaps, and Chasms"

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1. Introduction

NOAA has a long history of providing forecasts on the seasonal time scale for the Colorado River through the Colorado Basin River Forecast Center (CBRFC). As water demand has increased over recent years, so too has the thirst for information and forecasts to better inform decision-making on this scarce natural resource. This talk first described the physiogeographic and policy characteristics of the basin. Next, the current forecast services provided by the CBRFC were described including developmental activities aimed at improving those services in the future. Finally, information gaps between the current suite of services and what stakeholders are asking for were discussed. In contrast to most CTB talks, this was a non-technical talk.

2. Colorado River primer

The Colorado River drains portions of seven US states as well as portion of Mexico before it drains into the Gulf of California. In modern times, nearly the entire river has been diverted such that by the time it enters the Gulf of California, there is very little water left in the natural channel. The naturalized mean annual discharge at the Lees Ferry Gauge below Lake Powell is approximately 15.0 million acre-feet (MAF) when averaged over the past century. In contrast, the unregulated inflow to Lake Powell over the 1971-2000 period is 12.1 MAF. Approximately 85% of this runoff originates in a relatively small area above 9000 feet of elevation, where winter temperatures are cold enough that the watersheds store winter precipitation as snowpack. The strong snow accumulation and melt cycle and its variability from year to year are extremely important to both modeling and managing streamflow on the river.

Humans have been using the water resources on the Colorado since prehistoric times. However, it wasn't until the 20th century that legal frameworks began to take shape to prescribe the usage of its fresh water resources. The major governing document on the river is the 1922 Colorado Compact. This compact divided the water resources equally among the upper basin and lower basin states allocating each group 7.5 MAF per year. The geographic division between upper and lower basin states (the "compact point") was established at the river location of the Lees Ferry gauge. The Compact further allocated a maximum annual withdrawal for each state to be averaged over a

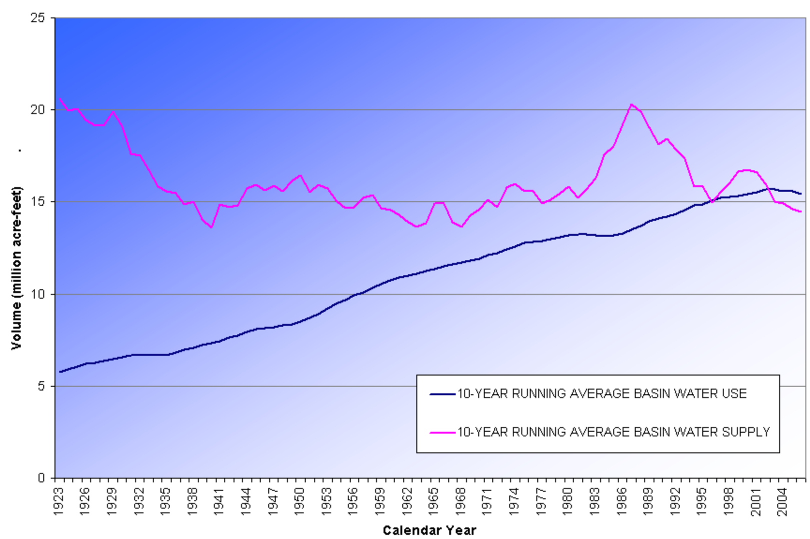

Figure 1 Long term water supply (purple) and demand (blue) for the entire Colorado Basin (USBR 2010). Note that these figures include tribuary contributions below the Lees Ferry compact point that are not included in the states' allocations.

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ten year period. Subsequently, in 1944, the US and Mexico signed the Mexican Water Treaty which allocated an additional 1.5 MAF per year to Mexico, bringing the total annual allocation on the Colorado River to 16.5 MAF. As the lower basin states began to develop their water rights fully, California and Arizona entered into litigation to determine whether inflows to the river below the compact point counted as part of a state's allocation. In 1964, the US Supreme Court decided Arizona v. California, determining that inflow below the compact point is not to be counted as part of a state's allocation (1983). In practice, this meant that the 12.1 MAF at the compact point has been over-allocated at 16.5 MAF. As the upper basin states have continued to develop toward their full allocations, the river has become fully used. Increased water demand coupled with reduction in water supply associated with the drought in the 2000s (Figure 1) motivated the creation of an interim operating agreement that is in place through 2026 to govern any shortages or surpluses on the system (USBR 2007).

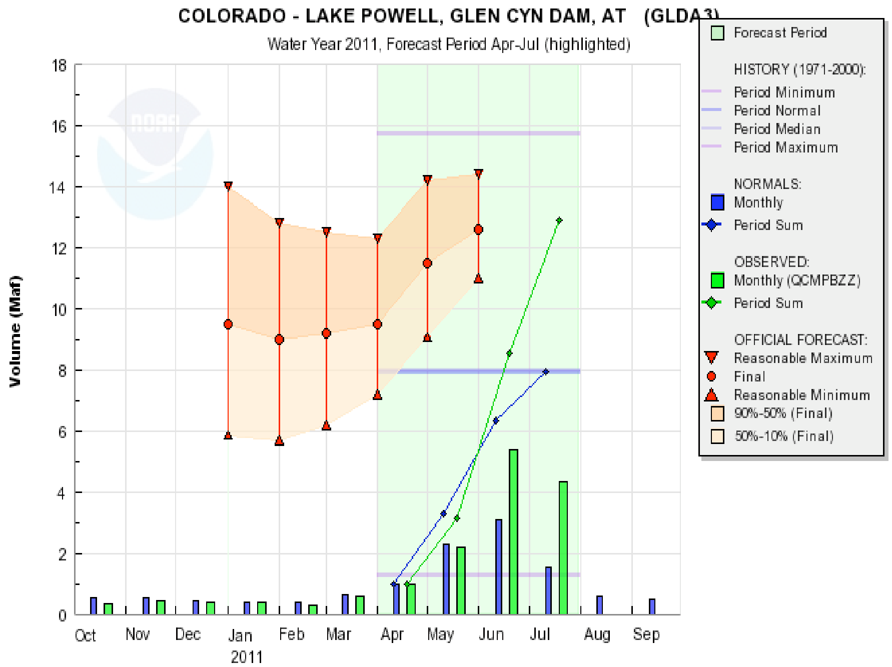

Figure 2 Lake Powell inflow (green) and forecasts (red) for 2011. Source: wateroutlook.nwrfc.noaa.gov

3. Water supply forecasting for the Colorado

The CBRFC has been issuing seasonal water supply forecasts on the Colorado River for over seven decades. These forecasts predict the volume of the spring runoff at many locations important to water management throughout the basin. Since the 1970s, these forecasts have been coordinated with the USDA/NRCS National Water and Climate Center. Figure 2 shows an example of the forecasts for Lake Powell inflow in 2011. The major source of forecast skill (runoff predictability) is the snowpack on the ground at the time of the forecast issuance, though soil moisture plays a lesser role in predictability. Many studies and years of experience have shown that in the upper Colorado River basin, climate predictability associated with the El Nino Southern Oscillation (ENSO) is weak. Figure 3 shows the correlation between upper Colorado water supply streamflow volume and the concurrent Nino 3.4 index of the ENSO phenomenon.

Forecasts are generated through two primary methods at the CBRFC – statistical and dynamical. Statistical prediction relies on equations that relate predictors – typically snow water readings at snow courses or SNOTELs, accumulated water year precipitation measured at NWS Cooperative Observer stations, and occasionally observed streamflow – and the predictand, the runoff volume at the forecast point. Both the CBRFC and the USDA/NRCS National Water and Climate Center use a similar form of statistical forecasting called principal components regression (Garen, 1992). The technique is applicable to the incorporation of climate forecasts, but due to their weak skill, such forecasts are not used in practice. At CBRFC, statistical prediction is only used for once-monthly predictions between January and June, when the snow predictors have significant values.

The second water supply prediction method employed by CBRFC is ensemble streamflow prediction (ESP). ESP makes use of the hydrologic simulation model that is also used for daily streamflow prediction operations to support flood warning and short term reservoir management. CBRFC uses the Sacramento Soil Moisture Accounting Model (Sac-SMA; (Burnash and Ferral 1973)) and the SNOW-17 temperature index model (Anderson 1973). Each of these models is calibrated to simulate observed streamflow over a 30 year historical period (1981-2010). The temperature and precipitation time series inputs to the models from this calibration period are used as a climate forecast ensemble inputs to generate a forecast ensemble of streamflow. Forecasts start from the simulation model variable states (e.g., snow water equivalent, soil moisture) that reflect the current conditions in the basin's watersheds (Day 1985). ESP forecasts may be updated at any frequency.

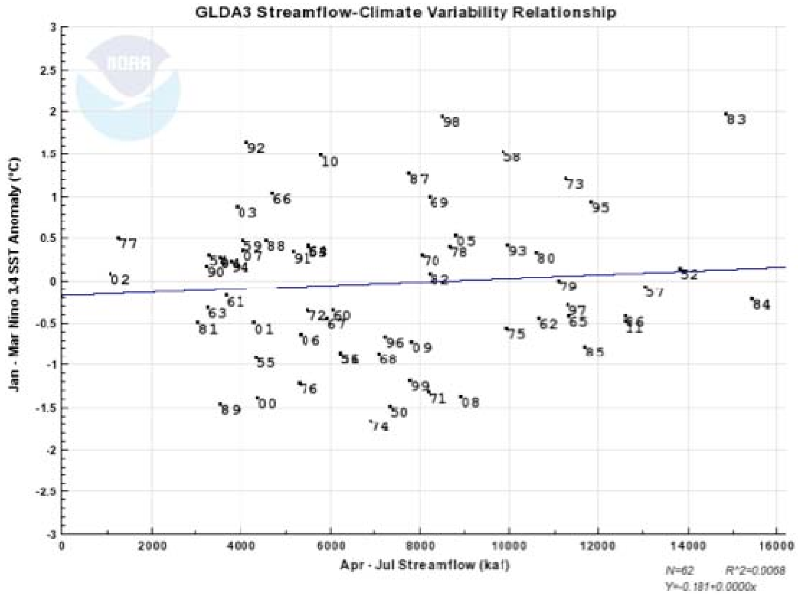

Figure 3 Lake Powell April-July inflow vs January-March Nino3.4 index (NWS 2011).

Forecasts are currently used by users such as the US Bureau of Reclamation (hereafter Reclamation), Denver Water and PacifiCorps (water and energy utilities) as input to reservoir operations management and planning models. Reclamation uses the "24-month study" model, which as the name suggests, helps plan monthly reservoir releases 2 years into the future using a combination of ESP and official water supply forecasts. This model is run once per month but only three times per year using the 10^{th} and 90^{th} percentile forecasted monthly runoff volumes. Stakeholders have expressed concerns that the projections from this model, particularly in the 2nd year of the forecast, have low skill, and observed that the 10^{th}-90^{th} percentile outputs to bracket a range of uncertainty does not provide sufficient probabilistic information to support risk-based decision making in their own resource management activities that depend on Colorado River water allocations.

4. The future: progress and challenges

Stakeholder demand for increased information and forecasts has led both CBRFC and Reclamation to undertake major research and development initiatives to improve forecasts and information available to stakeholders. CBRFC has launched a seasonal to year-two forecast intercomparison effort that is supported by collaborative research with academic partners who are assessing methods for statistical climate and flow prediction, and workshops to bring together stakeholders, researchers and forecasters, and a water-management oriented testbed to focus intercomparison efforts on streamflow predictions that have the most impact on Colorado River management. CBRFC has also implemented an ensemble forecast technique developed at the NWS Office of Hydrologic Development to create meteorological forecast ensemble (hence streamflow ensembles) based on weather and climate variable outputs from global numerical weather and climate prediction models. This meteorological forecasting technique is similar to a technique developed at CBRFC in the early 2000s (Werner, Brandon *et al.* 2005). It is also a centerpiece of the nascent NWS Hydrologic Ensemble Forecast Service (HEFS), and is described in Schaake *et al.* (2007) and Wu *et al.* (2011). CBRFC began running this technique in an experimental mode in 2010. Figure 4 shows an example of this ensemble forecast for Lake Powell inflow.

At the same time, Reclamation has invested in upgrading their modeling system from the 24-month study to the Mid-Term Operations Model (MTOM). MTOM is an objective, ensemble based operations model used for planning reservoir operations in an ensemble (probabilistic) mode. It is based on a 24 month long ESP forecast for monthly inflow volumes to the major Reclamation reservoirs in the Colorado Basin. MTOM began running in an experimental mode in 2010, in parallel its current operations.

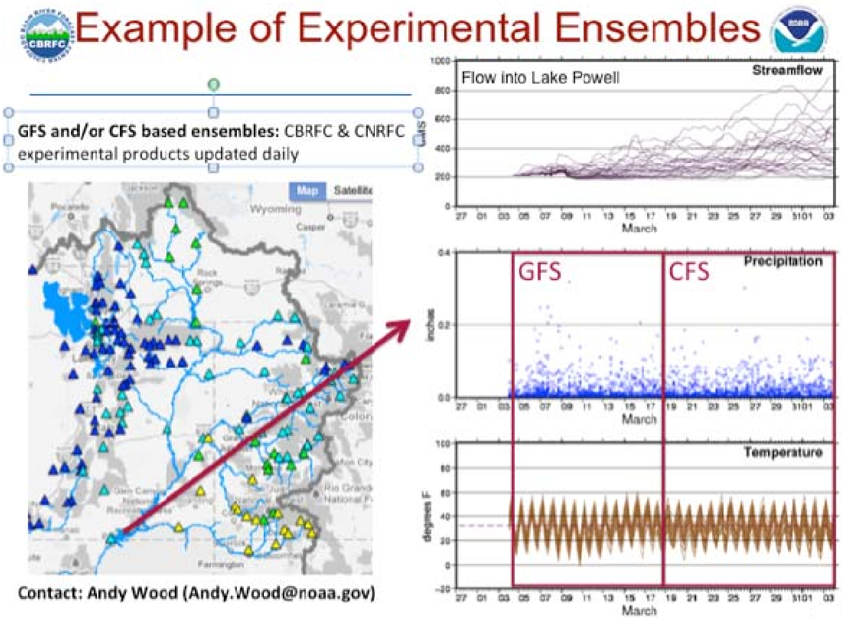

Figure 4 Example of ensemble streamflow forecasts for Lake Powell inflow based on ensemble weather and climate predictions (CBRFC 2011).

The new collaborative activities, forecast inter-comparison testbeds and forecasting and operations models at CBRFC and Reclamation present possibilities for addressing both long standing and more recent stakeholder requirements. Foremost among these is the new incorporation of climate predictions out to two years (ultimately out to five years) as input to the CBRFC streamflow forecast system. The large storage to annual flow ratio (approximately 4:1) and the high economic value of Colorado River water resources implies great potential for benefit from seasonal climate forecasts even if there is minimal skill in the climate predictions. Given the very low correlation between Lake Powell inflow and ENSO (*e.g.* Figure 3), developing skillfull climate forecasts for this region is difficult.

Both the science and stakeholder communities have inquired about or articulated other areas for attention that could lead to improvements in streamflow forecasting in the Colorado Basin. These include:

- The 'dust-on-snow' phenomenon, which has shown large inter-annual variability (*e.g.* Painter, Barrett *et al.* 2007) and influences snow-melt timing and potentially magnitude.
- Beetle kill of various species of pine forests, which has affected major swaths of land area in the Rocky Mountains.
- Reliable ensemble climate and streamflow forecasts on time scales from hours to years
- Water demand and evapotranspiration forecasts and analysis
- Improved stakeholder interactions to match forecast and information needs with stakeholder operational requirements
- A transition toward more transparent and objective methods for streamflow prediction
- An upgrade of NWS hydrologic prediction systems from the legacy NWS River Forecast System to a new state-of-the-art platform called the Community Hydrologic Prediction System (CHPS), designed to facilitate collaboration and partnerships and greater flexibility in forecasting approaches.

Ultimately, NOAA's mission "to understand and predict changes in the Earth's environment … to meet our Nation's economic, social, and environmental needs" (NOAA 2009) should guide both science and service activities to meet the needs of the various water resources stakeholders in the Colorado basin. Accordingly, the CBRFC has recently begun to play an active if not central role in spurring the development of new and improved scientific and operational approaches that support this mission. These have come in the form of internal research and development efforts as well as the forging of partnerships with external research and operations groups both in NOAA, in water management agencies, in academia, and in stakeholder communities. Though many of these activities are still in early phases, they hold great potential to deliver a significant improvements in the quality of CBRFC's hydrologic predictions and associated benefits for stakeholders and the nation.

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