

Development of a Seasonal Climate and Streamflow Forecasting Testbed for the Colorado River Basin

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1. Motivation

Many groups have documented a consistent need for climate forecasts from one season to two years lead time to support a variety of applications, and particularly for streamflow forecasting for water, energy and agricultural management. Forecasts across these relatively long time scales are particularly valuable in the Colorado Basin (Figure 1) where the reservoir capacity is approximately four times the mean annual discharge of the river. Yet the Colorado River basin (CRB) presents a challenge due to the limited forecast skill that can be harnessed from traditional sources (*e.g.*, ENSO indices) even at shorter lead times for runoff-generating headwaters in the upper basin, the source of most of Colorado River flow. Nonetheless, management and planning objectives related to the larger reservoirs that the U.S. Bureau of Reclamation (hereafter Reclamation) manages apply streamflow projections for lead times up to two full years. Motivated to improve these forecasts, Reclamation has funded university research that has shown some promise for developing climate and streamflow predictions in the CRB based on a more expansive range of climate system indices and state variables. Other federal and state-funded research focused on the western US shares these goals and complements the Reclamation effort.

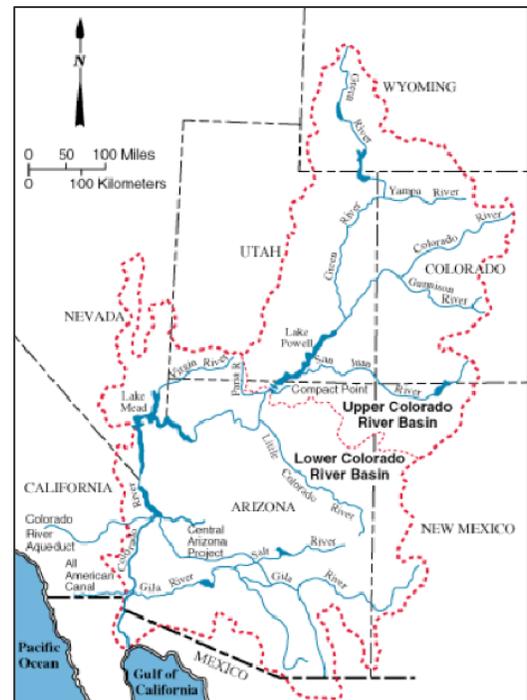


Fig. 1 Colorado River Basin

The NOAA/NWS Colorado Basin River Forecast Center (CBRFC) is the primary official provider of streamflow forecasting information products to Reclamation and other water management entities in the CRB, in some cases as a result of legal agreements between the seven western states that use Colorado River water. Reclamation and other agencies are unlikely to produce streamflow forecasts operationally, but rather depend on NOAA river forecast centers to provide forecasts that serve as input to their water operations and management activities. Consequently, the primary avenue for leveraging such research activities to support CRB water management is to evaluate the findings with respect to water management relevant watersheds, in comparison to current practice (the baseline), and where warranted, operationalize the new techniques into CBRFC streamflow forecasting efforts.

2. CBRFC streamflow forecasting

Operational forecasts that support reservoir management include one-week and peak flow predictions to manage high flows and recreation, but major water allocation decisions in the large storages of the CRB (Lakes Mead and Powell) depend primarily on “water supply forecasts”, *i.e.*, predictions of runoff volumes into the major reservoirs of the upper CRB (listed in Table 1) at lead times of 1 to 24 months into the future. Water supply forecasts (WSF) currently rely on two primary techniques, statistical water supply (SWS)

prediction and Ensemble Streamflow Prediction (ESP). The former relates predictors such as observed snow water equivalent (SWE), water year precipitation and runoff to date to future runoff, and is practiced in both the NOAA NWS RFCs and the NRCS National Water and Climate Center (NWCC). SWS methodology has remained essentially unchanged over the past half-century, despite two notable upgrades: (a) the deployment of the automated snow telemetry (SNOTEL) network for remote, real-time monitoring of SWE and precipitation, starting in the late 1970s (complementing manual snow course measurements); and (b) the upgrade of the statistical method from multiple linear regression to principal components regression (PCR, Garen 1992). ESP is an ensemble forecast approach that uses a continuous conceptual hydrologic model. ESP was introduced in the late 1970s (Twedt *et al.*, 1977), but was not widely used in NWS until the 1990s. Like SWS, ESP forecast skill derives primarily from the snowpack observed on the ground at the time the forecast is made. For the CRB, CBRFC subjectively merges its SWS and ESP WSFs into a preferred NWS forecast, and then subjectively coordinates with NWCC's SWS forecasts to arrive at an official WSF. During this process, forecasters from both agencies also discuss the current and forecast conditions and adjust the forecast in consideration of other factors deemed relevant. The resulting official forecast describes a probability distribution using the 90th, 50th, and 10th percentiles (non-exceedence probabilities).

Neither agency currently uses a climate forecast in the forecast process for the upper CRB, although both agencies are technically capable of doing so (*i.e.*, the software or approaches can admit a climate forecast as input). Short term weather forecasts (1-5 day QPF and 1-10 day temperature forecasts) are occasionally incorporated into the CBRFC ESP, at the subjective discretion of the forecaster, but not into the SWS from either agency. The primary reason that CBRFC and NWCC do not use climate forecasts (*e.g.*, CPC Official climate outlooks or ENSO indices) for prediction is that such forecasts have been found to have low to non-existent skill in the upper CRB. That the intermountain region of the western US exhibits low climate predictability has been well documented by agency investigation and academic research over the last decade.

3. CBRFC Climate and Streamflow Prediction Testbed

A workshop funded by the Colorado Water Conservation Board (CWCB) and co-sponsored by NIDIS was held at CBRFC in March, 2011 to discuss (1) research on seasonal to year 2 climate and flow predictability within the CRB and (2) formation of a testbed for comparing research results with the operational forecasts generated by CBRFC and used by Reclamation. The climate and research methods of interest from external researchers were primarily statistical, leveraging large-scale climate system information (*e.g.*, SST and geopotential height patterns), climate system indices, and other predictors to estimate future

Watershed Name	NWS ID	USGS ID	Drainage Area (km ²)
Gunnison R abv Blue Mesa	BMDC2	09124800	9,092
San Juan River nr Navajo Res Archuleta	NVRN5	09355500	8,476
Green R at Flaming Gorge Res Flaming Gorge Dam	GRNU1	09234400	11,076 (50,310)
Gunnison R at Morrow Point Res	MPSC2	--	--
Taylor R at Taylor Park Res	TPIC2	09107000	332
Green R Nr Fontanelle Res Fontanelle	GBRW4	09211200	11,128
Gunnison R at Crystal Res	CLSC2	09127800	--
Los Pinos Nr Vallecito Res Bayfield	VCRC2	--	--
Major Upper Colorado River Basin Areas			
San Juan R nr Bluff	BFFU1	09379500	59,800
Green R nr Green R	GRVU1	09315000	116,610
Gunnison R nr Grand Junction, CO	GJNC2	9152500	19,958
Colorado R at Lake Powell Glen Cyn Dam	GLDA3	--	637,000

Table 1 The watershed data in the table above encompass the drainage areas of the 8 major river basins that directly support Reclamation probabilistic forecasting. The last four drainage areas are additional areas of interest: the outlets of three major tributaries above Lake Powell, and the entire Lake Powell drainage.

climate and streamflow in the Colorado River area. Typical methodologies in this genre are described in Bracken *et al.* (2010), Grantz *et al.* (2005; 2007), Moradkhani and Meyer (2010), Najafi *et al.* (2011), Switanek *et al.* (2009) and Wang *et al.* (2009). *The primary goal of the testbed is to focus collaborative efforts to improve prediction for the management of Colorado Basin water resources on the key climate and flow datasets involved in this enterprise.* The central testbed website is located at

http://www.cbrfc.noaa.gov/testbeds/si_y2/.

A basin-oriented focus

A guiding principle of the climate and flow forecasting testbed is that the evaluation of climate forecasts must be oriented toward river basins, and in particular, basins which are important to water management in the upper CRB. Climate forecasts are typically and sometimes exhaustively analyzed by forecast producers, but at space and time scales, and in a separate rather than covariational framework, that often does not offer clear connection to their potential for streamflow prediction. The complex connection of climate to hydrologic forecast outcomes is illustrated in Wood & Lettenmaier (2008), which shows the varying influences of initial hydrologic state and future climate on future streamflow. In a nutshell, *every hydrologic anomaly has a story line*. As a water year progresses, for instance, past weather and climate are incorporated into the hydrologic initial conditions. In the CRB, for water supply forecasts, these initial conditions provide increasing signal to the runoff prediction, while the importance of future climate diminishes. Hydrologic extremes often involve pattern persistence (e.g., a sequence of wet months), but can arise from more complicated, multi-variate climate phenomena, as illustrated in Figure 2.

Basin-oriented climate forecast evaluation means assessing climate variable predictions not only with respect to catchment areas of interest, but also with consideration of times of interest – *i.e.*, periods that are important for hydrologic response. For instance, predictions of precipitation anomalies during winter (*i.e.*, snow accumulation season) and of temperature anomalies during spring (*i.e.*, snow melt season) are more critical for water prediction purposes than at other times. Forecast accuracy can be more important if hydrologic conditions are anomalous (*i.e.*, during extreme years) for some users, than in normal years. The testbed will stress such considerations, in addition to evaluating the translation of climate prediction into streamflow predictions that improve over existing operational baselines. Although the temporal focus of the testbed evaluations must still be determined, the watersheds of interest are the drainages of the key upper CRB flow locations forming inputs for Reclamation reservoirs that influence water allocation decisions between the upper and lower CRB each year. These are listed in Table 1 and illustrated in Figure 3.

Testbed components and constraints

The testbed will contain the following elements, which are being populated as time permits by the lead author of this article.

- hindcast results sufficient to establish the current operational baseline for prediction skill
- timeseries that define the climatologies of the variables of interest – primarily precipitation, temperature and streamflow
- experimental forecast results in tabular and graphical form
- documentation of current forecast methods (e.g., equations used for SWS)
- forecast evaluation metrics that are relevant to CBRFC operations (e.g., the error metrics associated with April-July streamflow volume).

The current operational baseline for climate forecasting at CBRFC is essentially the use of historical climatologies of precipitation and temperature for the watershed areas for which CBRFC predicts flow. The

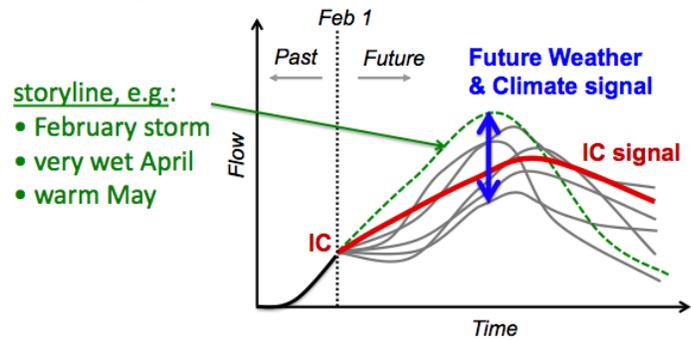


Fig. 2 Illustration of the signal components in a water supply streamflow forecast, which vary in importance throughout the year and may involve combinations of climate variables.

baseline for streamflow prediction at different lead times and for different predictands is the ESP approach, forced with the baseline (historical) precipitation and temperature inputs. For some predictands, the SWS water supply forecasts also form an operational baseline.

Two experimental climate and flow prediction approaches are now being developed CBRFC for seasonal/interannual lead times. One is the use of the CPC objective consolidation forecasts that are produced operationally in support of the official monthly CPC climate outlook. The other is the use of NCEP Climate Forecast System (CFS, soon to be CFSv2) precipitation and temperature, downscaled and calibrated to the watershed scale via statistical methods documented in Seo *et al.* (2006) and Wu *et al.* (2011).

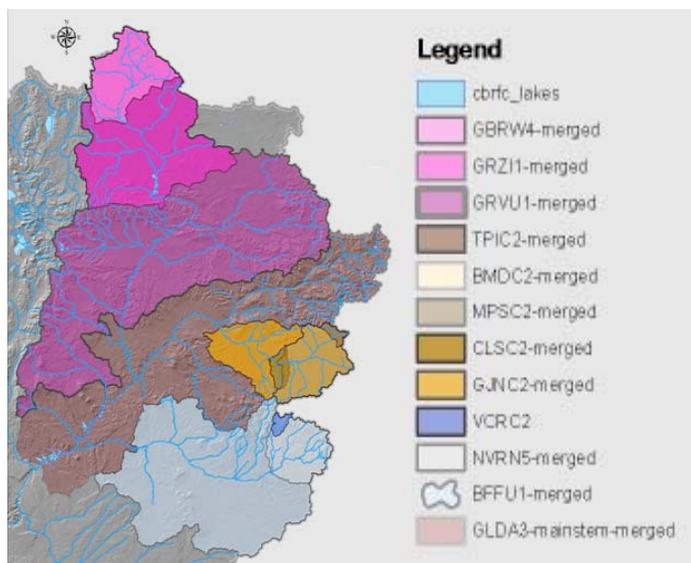


Fig. 3 Testbed watershed areas

A number of avenues for translating climate forecasts into streamflow forecasts exist. For instance, improved climate forecasts can be translated to streamflow forecast via a trace-weighting of ESP ensembles, in which the weightings for each trace (corresponding to a historical meteorological sequence) are derived from a climate forecast (*e.g.*, Werner *et al.*, 2004). Another approach might involve the modification of historical precipitation and temperature forecast time series to match climate forecast characteristics before input to ESP. More elaborate approaches involving, *e.g.*, synthetic weather generation and hydrological modeling, are under development by NOAA-funded collaborators (such as Dr. Balaji Rajagopalan at the University of Colorado). Climate predictors can also be related directly to predicted streamflow characteristics.

While CBRFC continues to populate the testbed from within, researchers are encouraged to train statistical climate forecast technique using historical data (observations or hindcasts) from one or more of the key watersheds provided, and for one or more forecast initialization dates (*e.g.*, October 1). The specific challenges raised in the testbed are to demonstrate that new climate prediction approaches:

- provide superior climate forecast skill (precipitation and/or temperature) relative to baseline forecast approaches available to CBRFC
- lead to improved long lead streamflow forecast skill, *i.e.*, when implemented via trace-weighting or alternative approach.

CBRFC will be focusing on applying the climate forecasts that warrant attention (via positive performance and abide by the constraints listed below) to streamflow predictions, though researchers are welcome to tackle that part of the challenge as well. Because an RFC is an operational center providing real-time climate and water information services, the testbed includes several constraints:

- The source datasets must be available with low enough latency to support a real-time prediction.
- The methods must be reasonably automatable, and configuration or setup steps must be "teachable" rather than arcane.
- The methods must ultimately (though not for prototyping) use non-proprietary software: *e.g.*, R is preferred to Matlab.

4. Discussion

The S/I to Year 2 Climate and Flow Forecasting Testbed is a CBRFC-led effort to engage and educate external research collaboration toward improving water management via advanced climate and streamflow forecasting in the western U.S. Although CBRFC is not a funding entity, this goal has been prominent in the

objectives of a number of federal and state grant opportunities, thus CBRFC seeks to attract collaborators to the testbed both by leveraging existing funded projects and by pursuing new ones through joint (co-investigative) proposals. While CBRFC has some capacity to engage in new research and development toward the objectives of the testbed, and can lean on some assistance from NWS and NOAA laboratories, integrated efforts that team CBRFC personnel with external groups is an ideal way to build capacity in CBRFC, educate external groups about operational forecasting, and ensure that applies research effort toward ostensible operational uses is properly focused and evaluated.

Although the major results of the SI/Y2 testbed are still evolving, the concept of a water-oriented climate and streamflow prediction testbed have broad advantages beyond the Colorado River basin. Water is a primary sector in which benefits from improved climate forecasting can be derived, and the evaluation of climate prediction through the prism of relevance to water prediction can add a valuable context for climate forecast producers, and a compelling demonstration for climate forecast users in the water sector. One can envision a nationwide testbed of this type as a framework to integrate researchers and forecasters from climate science to hydrology to water resources. The literature is full of research results that claim to have potential to advance water management, yet have never been implemented operationally – this gap may arise from a failure of integration that the testbed effort is designed to address.

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