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Exploring the use of temperature to understand recent drought and project future conditions in the Colorado River Basin

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BOR's midterm projections of Colorado River Basin reservoir operations are based on data that do not account for recent warming. This study combined temperature predictions and statistical modeling to generate experimental forecasts that showed moderate skill improvements.

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Colorado River Basin, temperature predictions, midterm streamflow forecasts

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Mission Statements

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The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

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This study was performed from July 2019 to June 2021. Forecast products and Reclamation modeling practices may have been updated since publication of this report.

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Final Report No. ST-2021-19264-01

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Peer Review

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Contents

Executive Summary

Reclamation provides midterm (2- to 5-year) reservoir operations projections for the Colorado River Basin (CRB) that are important to both Reclamation's and stakeholders' planning. One data source Reclamation uses to develop the projections is the Colorado Basin River Forecast Center's Ensemble Streamflow Prediction (ESP) forecast, which, at the time of this investigation, used data from 1981 to 2015. Despite the observed increase in temperatures since the late-1980s (Lukas and Payton, 2020) and the ongoing CRB drought, ESP weighs observations from cool years and warm years equally in their projections. Results from Baker et al (In Review) show that ESP did not provide any more skill at projecting midterm streamflows or operations than using climatology (average monthly observed streamflow).

Recent studies have shown that warm temperatures have reduced streamflow periodically throughout the observed record (Woodhouse et al., 2016), and that recent decades have shown a significant trend of temperature-induced streamflow declines (McCabe et al., 2017), but this information has not yet been incorporated into midterm projections. Newly developed methods using decadal predictions from Global Climate Models (GCMs) to generate midterm temperature predictions offer an avenue for incorporating temperature information (Towler et al., 2018). Towler et al (In Press) recently generated these GCM-based temperature predictions for the Upper CRB (UCRB). This study seeks to operationalize an approach to integrating temperature predictions, historical data, and advanced statistical modeling to generate temperature-conditioned streamflow forecasts.

This study has three main components: 1) an exploration of historical relationships between precipitation, temperature, and streamflow; 2) statistical modeling to generate midterm streamflow forecasts; and 3) operational modeling to compare the skill of the new forecasts to that of currently used forecasts. Analysis of historical data confirmed that UCRB runoff efficiency, or the amount of streamflow generated for a given amount a precipitation, has a clear relationship with temperature on an annual basis, and also showed that this relationship is even more pronounced when analyzing multi-year means. After evaluating multiple approaches, the Random Forest (RF) statistical modeling technique was chosen to generate multi-year streamflow forecasts based on temperature predictions and historical multi-year mean runoff efficiencies. This represents a novel use of RF. The RF forecasts were moderately skillful at capturing observed multi-year streamflow averages and showed greater skill than ESP in projecting reservoir elevations at three or more years into the future. At shorter lead times, ESP was more skillful.

This work demonstrates a proof of concept for using historical and predicted temperature information to improve skill of midterm streamflow forecasts and reservoir operations projections. It also contributes a novel application of RF in the field of hydrologic forecasting. The moderate skill improvements resulting from this method suggest that it should continue to be evaluated using Reclamation's Colorado River Basin Operational Prediction Testbed (Baker et al, In Review).

Main Report

Introduction

Reclamation provides midterm (2- to 5-year) reservoir operations projections for the Colorado River Basin (CRB) that are important to both Reclamation's and stakeholders' planning. One data source Reclamation uses to develop the projections is the Colorado Basin River Forecast Center's Ensemble Streamflow Prediction (ESP) forecast, which, at the time of this investigation, used data from 1981 to 2015. Despite the observed increase in temperatures since the late-1980s (Lukas and Payton, 2020) and the ongoing CRB drought, ESP weighs observations from cool years and warm years equally in their projections. Results from Baker et al (In Review) show that ESP did not provide any more skill at projecting midterm streamflows or operations than using climatology (average monthly observed streamflow).

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Research Activities

This research was performed in three main steps:

1. Exploring the historical relationship between temperature, precipitation, and streamflow
2. Developing a statistical model that uses GCM-derived temperature predictions and historical data to generate temperature-informed streamflow forecasts
3. Using the new forecasts in a reservoir operations model to evaluate their potential to benefit Reclamation's midterm projections

Historical data and forecasts were examined and generated based on the UCRB only. Lees Ferry, AZ, is the gage that represents the downstream aggregation of the climate and hydrology of the UCRB. Observed hydroclimate data including precipitation and minimum and maximum temperatures are from the Parameter-elevation Regressions on Independent Slopes (PRISM) model (Daly et al., 1994)

Historical Relationships

The relationships between temperature, precipitation, and streamflow (here called "runoff depth") in the UCRB were explored on both an annual basis and using 5-year averages, shown in Figures 1 and 2.

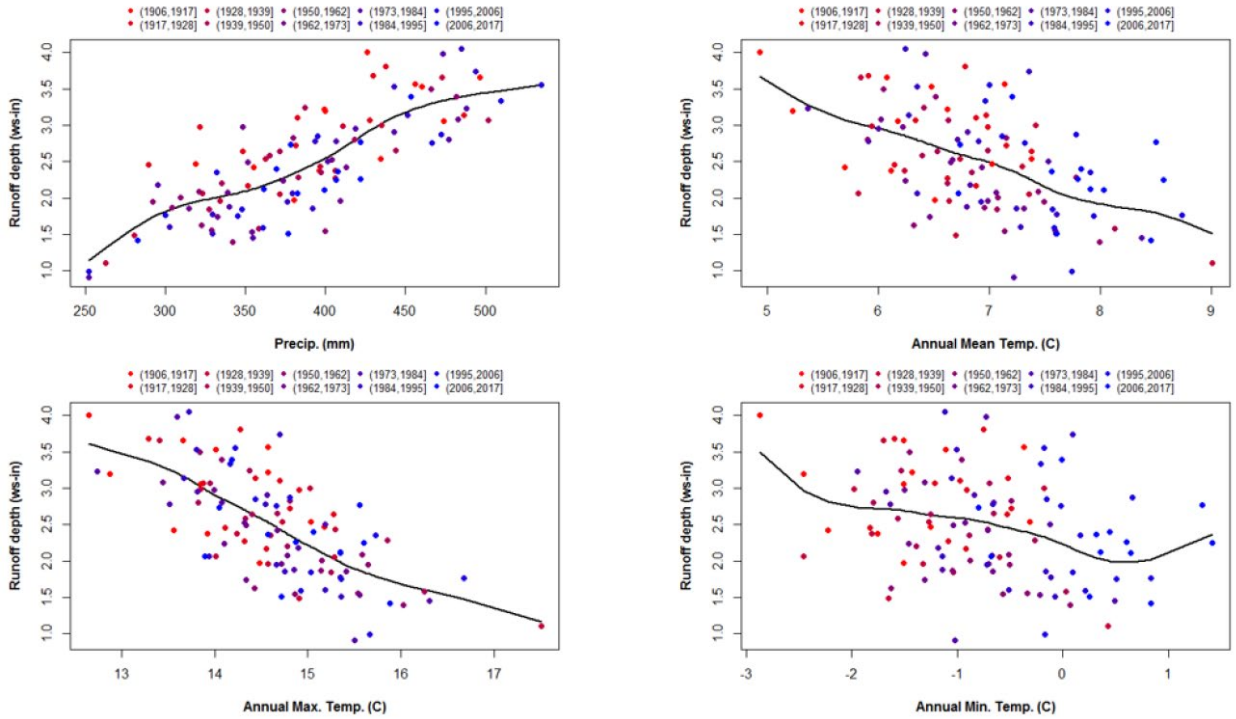

Figure 1. Relationships between annual streamflow (runoff depth) and annual precipitation, annual mean temperatures, annual maximum temperatures, and annual minimum temperatures. The black line is a cubic spline fit of the data, and colors correspond to historical year (redder colors are early 20th century and bluer colors are 21st century).

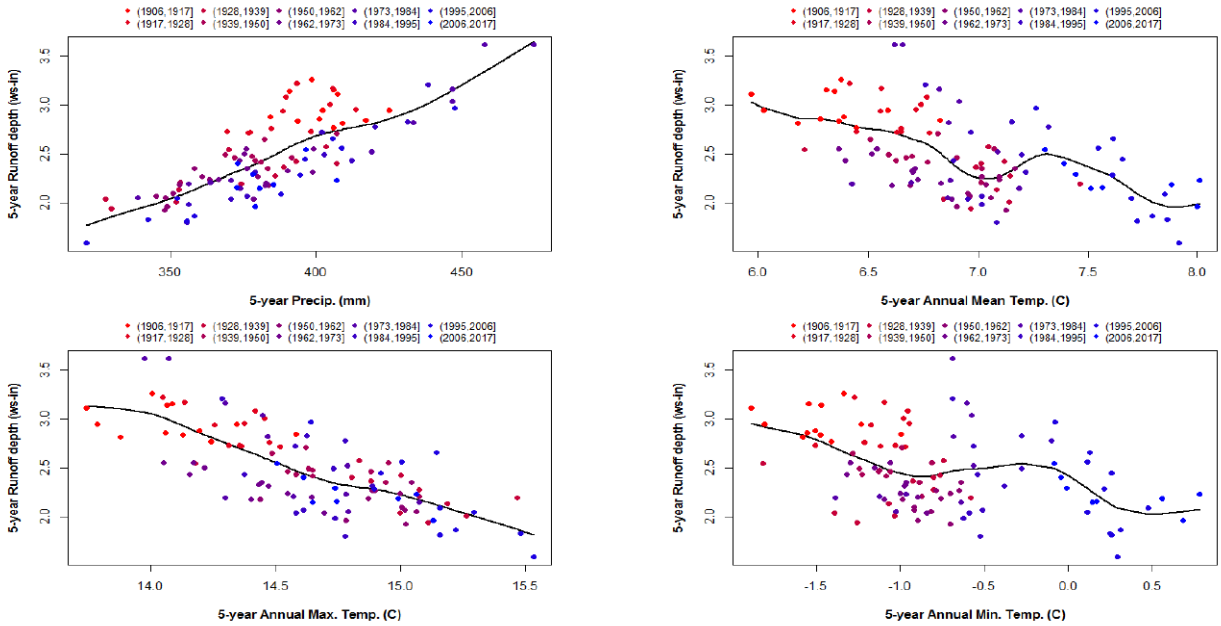

Figure 2. Relationships between 5-year mean streamflow (runoff depth) and 5-year mean precipitation, 5-year mean temperatures, 5-year mean maximum temperatures, and 5-year mean minimum temperatures. The black line is a cubic spline fit of the data, and colors correspond to historical year (redder colors are early 20th century and bluer colors are 21st century).

The annual and 5-year data show the same relationships, but the tighter fit of the points around the cubic spline line in the 5-year data indicate that there are stronger relationships in this data. This is consistent with the fact that averaging reduces variance and strengthens the signal. In the UCRB, which has very high interannual variability, there is greater potential to gain skill from forecasting multi-year averages than attempting to predict specific annual values.

The relationship between precipitation and streamflow is often described in terms of "runoff efficiency", or the percent of streamflow generated for a given amount of precipitation. Runoff efficiency captures the effects that temperature and watershed features have on streamflow. Because higher temperatures dry out soils, lengthen growing seasons, and increase evapotranspiration, they reduce the amount of precipitation that ultimately becomes streamflow, thus reducing runoff efficiency. Figure 3 shows the relationships between annual runoff efficiency and precipitation and temperature in the UCRB.

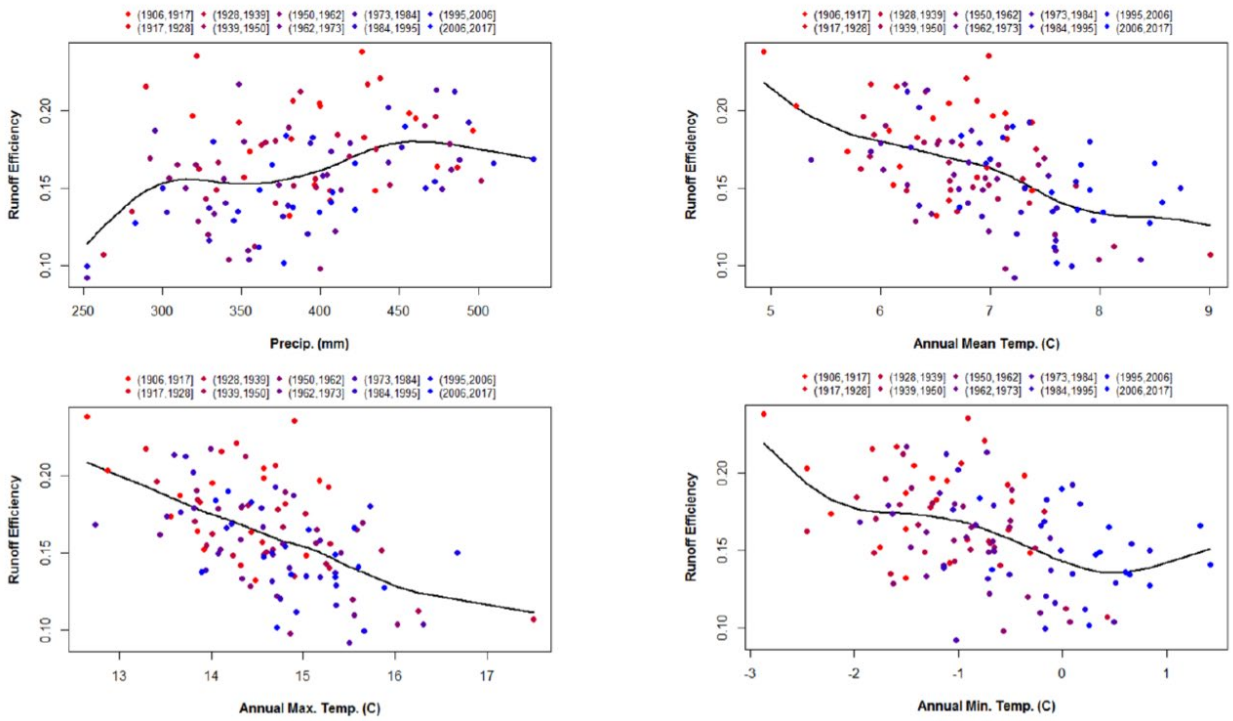

Figure 3. Annual relationships between runoff efficiency and precipitation, mean temperatures, maximum temperatures, and minimum temperatures. The black line is a cubic spline fit of the data, and colors correspond to historical year (redder colors are early 20th century and bluer colors are 21st century).

Figure 3 shows that temperature has a strong negative correlation with runoff efficiency in the UCRB.

Statistical Modeling to Generate Forecasts

This study used a variety of data to generate temperature-conditioned streamflow forecasts. Because the main purpose of the study was to identify a scientifically defensible way to capitalize on the observed and continuing warming trend, skillful temperature predictions from GCMs that were generated by Towler et al (In Press) played a critical role. While the historical relationships presented above show that precipitation is strongly linked to streamflow, there are no skillful sources of precipitation predictions for the UCRB. However, using temperature predictions to sample historical runoff efficiency provides a way to capture precipitation signals and watershed characteristics in a forecast.

After exploring multiple statistical modeling approaches, this study determined that Random Forests (RF) were a promising method because they showed skill, they naturally generate ensemble forecasts to represent uncertainty, and because their application in this context is a novel research contribution. RF was used to generate different multi-year mean Lees Ferry streamflow values using multi-year temperature predictions from Towler et al (In Press) and varying multi-year averages of historical runoff efficiency as covariates. In general, the RF ensembles were skillful at capturing observed multi-year average flows, especially beginning in the early 2000s when warming temperatures became prevalent.

A manuscript containing pertinent data and results pertaining to the statistical modeling and operational projections produced by this study has been finalized and submitted to a refereed journal. The principal investigator of this work will update Appendix A to include the submitted manuscript once the journal peer review process has been resolved and information is ready for public dissemination.

Operations Modeling

The multi-year average RF forecasts for Lees Ferry were disaggregated in space and time based on historical proportions so that they could be used in Reclamation's CRB midterm operations model. The Colorado River Midterm operations Modeling System (CRMMS, formerly called the MidTerm probabilistic Operations Model, or MTOM) is a basin-wide model that uses hydrology and demand inputs along with operational rules to project how reservoirs would operate under a range of potential future conditions. This study compared reservoir projections generated from CRMMS using the RF forecasts to those based on ESP forecasts and compared both to the observed end-of-water-year reservoir elevations at Lakes Powell and Mead to determine if the new forecasts offered more skill than the product currently used by Reclamation. In general, ESP performed better than RF forecasts when the projection horizon was less than 24 months into the future, but RF forecasts outperformed ESP at longer lead times.

A manuscript containing pertinent data and results pertaining to the statistical modeling and operational projections produced by this study has been finalized and submitted to a refereed journal. The principal investigator of this work will update Appendix A to include the submitted manuscript once the journal peer review process has been resolved and information is ready for public dissemination.

Summary Findings and Future Plans

This study integrated temperature predictions, historical data, and advanced statistical modeling to generate midterm streamflow projections that account for observed and projected warming in the CRB. Multi-year RF streamflow forecasts showed overall moderate skill at capturing observed multi-year averages, with increasing skill in more recent, warmer years. Reservoir projections generated by using the RF forecasts to run Reclamation's midterm operations model show that the RF forecasts are more skillful at longer project lead times than the standard ESP forecasts, but less skillful at shorter lead times. Because the new forecasts could only be compared against a relatively short observed record, Reclamation sees value in continuing to generate these forecasts for ongoing evaluation via the Colorado River Basin Operational Prediction Testbed (Baker et al, In Review).

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Appendix A – Journal Article (in review)

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Appendix B – Research Products

This Appendix provides a complete list of the research products for each component, including papers, presentations, outreach, and links to data and models used and generated.

Data

The data used and generated by this study is publicly available on GitHub at the following location: GitHub - Dave-Woodson/CRB-Decadal-Projections

Journal Article

A manuscript describing this study has been submitted to the journal Water Resources Research. This text will be updated upon final publication.

Outreach

Presentation Title	Forum	Date
Mid-term, Temperature Conditioned Flow Projections	Colorado River Climate and Hydrology Work Group S&T Meeting	12-Nov-19
Temperature informed streamflow forecasts for the Upper Colorado River	AGU Hydrology Days	13-Apr-20
Generating and evaluating temperature conditioned Colorado River Basin streamflow ensembles	Colorado River Climate and Hydrology Work Group S&T Meeting	11-Jun-20
Midterm Projections of Colorado River Streamflow and Water Resources Operations Conditioned on Temperature Projections	American Geophysical Union Fall Meeting	9-Dec-20
Multi-Year Forecast of Colorado River Flows Using a Random Forest Model	American Geophysical Union Fall Meeting	15-Dec-20
Comparing Experimental Streamflow Forecasts and Operational Projections using the Colorado Basin Streamflow Forecast Testbed	Reclamation webinar	10-Jun-21
Stochastic Decadal Projections of Colorado River Streamflow and Reservoir Pool Elevations Conditioned on Temperature Projections	Colorado Mesa University's Upper Colorado River Water Forum	4-Nov-21 (expected)

Stochastic Decadal Projections of Colorado River Streamflow and Reservoir Pool Elevations Conditioned on Temperature Projections	American Geophysical Union Fall Meeting	Dec-21 (expected)