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Development of Streamflow Projections Under Changing Climate Conditions Over Colorado River Basin Headwaters

W. P. Miller
wmiller@usbr.gov

Thomas C. Piechota
University of Nevada, Las Vegas, thomas.piechota@unlv.edu

S. Gangopadhyay
Technical Service Center

T. Pruitt
Technical Service Center

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Development of streamflow projections under changing climate conditions over Colorado River Basin headwaters

W. P. Miller[1,2], T. C. Piechota[2,3], S. Gangopadhyay[4], and T. Pruitt[5]

[1]United States Bureau of Reclamation, Lower Colorado Region, Boulder City, NV, USA
[2]Department of Civil and Environmental Engineering, University of Nevada Las Vegas, Las Vegas, NV, USA
[3]Director of Sustainability and Multidisciplinary Research, Office of the Urban Sustainability Initiative, University of Nevada Las Vegas, Las Vegas, NV, USA
[4]Water and Environmental Group, Technical Service Center, Bureau of Reclamation, Denver, CO, USA
[5]Water Resources Planning and Operations Support Group, Technical Service Center, Bureau of Reclamation, Denver, CO, USA

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Correspondence to: W. P. Miller (wmiller@usbr.gov)

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Abstract

The current drought over the Colorado River Basin has raised concerns that the US Department of the Interior, Bureau of Reclamation (Reclamation) may impose water shortages over the lower portion of the basin for the first time in history. The guidelines that determine levels of shortage are affected by forecasts determined by the Colorado Basin River Forecast Center (CBRFC). While these forecasts by the CBRFC are useful, water managers within the basin are interested in long-term projections of streamflow, particularly under changing climate conditions. In this study, a bias-corrected, statistically downscaled dataset of projected climate is used to force a hydrologic model utilized by the CBRFC to derive projections of streamflow over the Green, Gunnison, and San Juan River headwater basins located within the Colorado River Basin. This study evaluates the impact of changing climate to evapotranspiration rates. The impact to evapotranspiration rates is taken into consideration and incorporated into the development of streamflow projections over Colorado River headwater basins in this study.

Additionally, the CBRFC hydrologic model is modified to account for impacts to evapotranspiration due to changing temperature over the basin. Adjusting evapotranspiration demands over the Gunnison resulted in a 6% to 13% average decrease in runoff over the Gunnison River Basin when compared to static evapotranspiration rates.

Streamflow projections derived using projections of future climate and the CBRFC's hydrologic model resulted in decreased runoff in 2 of the 3 basins considered. Over the Gunnison and San Juan River basins, a 10% to 15% average decrease in basin runoff is projected through the year 2099. However, over the Green River basin, a 5% to 8% increase in basin runoff is projected through 2099. Evidence of nonstationary behavior is apparent over the Gunnison and San Juan River basins.

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1 Introduction

The Colorado River Basin is currently experiencing the worst drought over the observed record (e.g., Timilsena et al., 2007). At the beginning of water year 1999 (October 1998), water storage in the Colorado River Basin was at 94% capacity; in particular, the two largest reservoirs within the system, Lake Powell and Lake Mead, were at 98% and 91% capacity, respectively. Since 1999, water storage in the Colorado River Basin has decreased to 56% capacity; Lake Powell and Lake Mead are currently at 44% and 58% capacity, respectively. The current drought has increased concerns on the ability of United States Department of the Interior, Bureau of Reclamation (Reclamation) to continue to meet water delivery requirements (Barnett and Pierce, 2008; Barnett and Pierce, 2009; Barsugli et al., 2009; Rajagopalan et al., 2009) and the impacts of climate change to hydroclimatology over the Colorado River Basin and the American West (e.g., Balling Jr. and Goodrich, 2007; Brekke et al., 2008; Christensen and Lettenmaier, 2007; Fassnacht, 2006; Matter et al., 2010; Maurer, 2007; Meko et al., 2007; Miller and Piechota, 2008). Previous research indicates warming temperature trends over the Colorado River Basin region and corresponding changes in the timing of streamflow within the basin (e.g., Christensen and Lettenmaier, 2007; Hamlet et al., 2005; Hamlet and Lettenmaier, 2007; Hidalgo et al., 2009; Kalra et al., 2008; Miller and Piechota, 2008; Regonda et al., 2005; Timilsena and Piechota, 2008).

Traditionally, Reclamation has used historical data to project future streamflow conditions and associated reservoir operations. Implicit in this practice is the assumption that the distribution of past data (e.g., mean, variance, standard deviation) is representative of future conditions. Under changing climate conditions, the past may no longer be representative of the future (e.g., Brekke et al., 2008). Climate change caused by anthropogenic influences has influenced global climate and hydrology such that past hydroclimatic means and extremes are no longer representative of expected hydroclimatology (Solomon and Intergovernmental Panel on Climate Change, Working Group I, 2007). Milly et al. (2008) defines stationarity as the idea that natural systems fluctuate

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within an unchanging envelope of variability. As such, the assumption of hydroclimatic stationarity over the Colorado River Basin under climate change may not be correct.

Streamflow in the Lower Colorado River Basin has been shown to exhibit signs of nonstationarity and correspondence with climatic teleconnection phases such as the AMO, PDO, and SOI (e.g., Thomas, 2007; Timilsena et al., 2009). Drier conditions in the American West have persisted since 1999. In contrast, 6 of the 10 warmest years occurred between 1986 and 2000 and have continued to persist throughout the southwest. Streamflow conditions are representative of nonstationary behavior in the precipitation and temperature record and have decreased with drier, warmer conditions. These results are supported by later studies indicating nonstationary behavior in the streamflow record using nonparametric statistical tests (i.e., Kendall's τ and Spearman's ρ) to changes in climate teleconnection indices (e.g., AMO, PDO, SOI) (e.g., Thomas, 2007). Under changing climate conditions, the Colorado River Basin exhibits nonstationary behavior in temperature and precipitation characteristics, contributing to a hydrologic deficit in the basin, especially in the southwest.

Water managers have traditionally relied on the assumption of hydroclimatic stationarity to efficiently manage water resources and environmental operations. The timing and magnitude of runoff events is of particular importance, as actual and forecasted runoff events can impact the operation of reservoirs; however, climate change and anthropogenic alterations to basin characteristics increase the difficulty in accurately projecting streamflow conditions within hydrologic systems (e.g., Villarini et al., 2009). Raff et al. (2009) developed a methodology to assess flood risk and runoff projections using projections of future climate. Raff et al. (2009) utilized temperature and precipitation data from 112 GCMs within the World Climate Research Programme (WCRP) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset (Meehl et al., 2007) subjected to statistical downscaling and bias-correction (Maurer et al., 2007) to drive the National Weather Service (NWS) River Forecasting System (RFS) hydrologic model. Each of the four basins investigated in Raff et al. (2009) exhibited the potential for increased flood frequency under changing climate conditions, although the

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authors did acknowledge the need for further study to more fully understand these results. Other recent studies have developed alternative methodologies for incorporating temperature and precipitation patterns over the Upper Colorado River Basin (Matter et al., 2010). The models and data sources presented in Raff et al. (2009) are very similar to the models and data sources utilized in this focus of the study.

The development of a methodology to develop streamflow projections for use in Reclamation river and reservoir management models is described. An important contribution of this work is the evaluation of the impact of changing climate based on changing evapotranspiration rates. The need to address evapotranspiration rates in climate studies over the Colorado River Basin has been documented by Brekke and Prairie (2009). The impact to evapotranspiration rates are taken into consideration and incorporated into the development of streamflow projections over Colorado River headwater basins in this study. Here, 112 projections of future climate conditions over the Colorado River Basin are integrated with projections of future evapotranspiration to develop projections of streamflow conditions throughout the Gunnison, Green, and San Juan River headwater basins. Projections of streamflow are further investigated for evidence of nonstationary behavior.

Figure 1 illustrates how these models and data sets were derived and integrated to produce the projections of unregulated streamflow presented in this study.

1.1 Study area

Projections of streamflow are developed over the Gunnison, Green, and San Juan River Basins (Fig. 2). Collectively, the three basins contribute nearly 66% of the average annual water year natural flow in the Upper Colorado River Basin. The basins in this study provide an opportunity to cover a broad latitudinal range of the Upper Colorado River Basin and compare results to other research efforts in the area. Each of these headwater basins have been subject to previous study and are accompanied by significant and interesting water issues. The Gunnison River Basin has been the subject of numerous studies, particularly for the application of downscaled climate

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projections (e.g., Brekke and Prairie, 2009; McCabe Jr., 1994; Raff et al., 2009; US Department of the Interior, Bureau of Reclamation, Upper Colorado Region, 2009). Research on the impacts of teleconnection events on drought and streamflow conditions in the Green River Basin have provided some insight as to the role of climate variability over the Colorado River Basin (Tootle and Piechota, 2003). Pursuant to the National Environmental Protection Act (NEPA) of 1969, an Environmental Impact Statement (EIS) and Record of Decision (ROD) were published in 2006 defining the operations of the Navajo Reservoir within the San Juan River Basin to aid in the conservation of endangered fish species, habitat, and continue to meet Reclamation's obligations to water delivery requirements and Native American water rights (US Department of the Interior, Bureau of Reclamation, Upper Colorado Region, 2006).

1.2 Data

1.2.1 Bias corrected spatially downscaled precipitation and temperature data

Reclamation, in cooperation with Lawrence Livermore National Labs (LLNL) and Santa Clara University (SCU), has made available BCSD precipitation and temperature data from the WCRP CMIP3 dataset over the continental United States (available at: http://gdo-dcp.ucllnl.org/downscaled_cmip3_projections). This climate data has been downscaled to 1/8th degree (approximately 12 km or 7.5 miles) grid cell resolution, making it more useful for regional hydrologic analysis. As previously described, this data have been downscaled using the BCSD technique described in Wood et al. (2004) and is available at a monthly timestep. Statistically downscaled data derived using the Bias Corrected Spatial Downscaling (BCSD) method developed by Wood et al. (2004) is used. The method is documented in numerous peer-reviewed academic studies (Cayan et al., 2007; Christensen et al., 2004; Hayhoe et al., 2004, 2007; Maurer and Duffy, 2005; Maurer, 2007; Payne et al., 2004; VanRheenen et al., 2004; Wood et al., 2004) and produces downscaled temperature and precipitation data that statistically matches the historical period.

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Reclamation is also currently developing streamflow projections over the Upper Colorado River Basin using the Variable Infiltration Capacity (VIC) model and the WCRP CMIP3 dataset described in this study within the Colorado River Basin Water Supply and Demand Study (US Department of the Interior, Bureau of Reclamation, Lower Colorado Region, 2009). The VIC model being used by Reclamation is being run at a daily timestep; as such, temporal disaggregation of data from the monthly WCRP CMIP3 dataset over the Colorado River Basin is required. Temporal disaggregation of the monthly data was accomplished by scaling historical daily precipitation or shifting historical daily temperature data to match monthly time series data (Wood et al., 2004). Daily precipitation and temperature time series have been derived for the entire spatial and temporal extent of the monthly Reclamation, LLNL, SCU dataset, and are archived at the Department of Energy (DOE) National Energy Research Scientific Computing (NERSC) Center.

1.2.2 Emissions scenarios

Climate projections for each of the 112 model runs available from the WCRP CMIP3 dataset are developed using emissions scenarios identified by the Intergovernmental Panel on Climate Change (IPCC) (Nakićenović and Intergovernmental Panel on Climate Change, 2000). The IPCC has developed a broad range of scenarios based on future projections of greenhouse gas emissions in response to global demographic, socio-economic, and technological change and development. There are four sets of emissions "families", and each family contains one or more groups of emissions scenario storylines. The families are defined as A1, A2, B1, and B2. In this study three storylines are considered: A2, B1, and A1B (a group within the A1 family). The A2 storyline describes a heterogeneous world in which global population is continually growing. Economic and technologic advancement varies regionally with no emphasis placed on the sharing or exchange of information. For this study, it may be interpreted as the most pessimistic storyline and more apparent increasing temperatures.

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The B1 storyline describes a more homogeneous world in which population increases until the mid-century, at which point it declines and levels. This storyline describes a world where there is a socio-economic culture shift towards the sharing and exchange of information and the rapid introduction of resource-efficient technology. This storyline may be interpreted as the most optimistic storyline in which climate change due to greenhouse gas emissions are addressed at a global scale.

The A1B storyline is a subset of the A1 family which describes a global world similar to that in the B1 storyline and increased economic growth. In the A1B group, technological advancements in resource management are balanced between fossil fuel intensive and non-fossil fuel intensive energy sources. Greenhouse gas emissions in the A1B storyline are between those higher emissions within the A2 storyline and those lower emissions within the B1 storyline.

1.2.3 Projections of evapotranspiration

Changes to evapotranspiration rates with changing climate have seldom been considered when using hydrologic models and projections of climate data (Brekke and Prairie, 2009). Projections of evapotranspiration rates over the Colorado River Basin at 1/8th degree resolution were derived through use of the VIC model employed by Reclamation. Average rates of evapotranspiration change per degree temperature change observed in the VIC model are incorporated into the National Weather Service (NWS) Colorado Basin River Forecast Center (CBRFC) River Forecasting System (RFS). The VIC model computes evapotranspiration through use of the Penman-Montéith equation to estimate evapotranspiration. The Penman-Montéith equation is defined as:

$$E = \frac{1}{\lambda}\left[\frac{\Delta A + \rho_a c_P \frac{D}{r_a}}{\Delta + \gamma\left(1 + \frac{r_s}{r_a}\right)}\right] \tag{1}$$

where E is evapotranspiration in mm/d, Δ is the gradient of the saturated vapor pressure with respect to temperature, A is the energy available for partitioning into latent

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or sensible heat, D is the vapor pressure deficit, r_a is the aerodynamic resistance, r_s is the surface resistance of land cover, and γ is the psychrometric constant in kPa/°C and defined by:

$$\gamma = \frac{c_P P}{\epsilon \lambda} \times 10^{-3} \tag{2}$$

where c_P is the specific heat of moist air, P is the atmospheric pressure, ϵ is the ratio of the molecular weight of water vapor to that of dry air, and λ is the latent heat of vaporization of water (Maidment, 1993; Xu et al., 1994). The VIC model assumes that evapotranspiration occurs at the potential evapotranspiration rate for a saturated area, and at a percentage of the potential evapotranspiration rate when an area is partially saturated. For bare soil, evapotranspiration is only calculated from the uppermost VIC layer, typically about 10 cm thick. Projected evapotranspiration rates under the same climate change conditions described in this study are being investigated over the Columbia River Basin (Hamlet and Elsner, 2009).

Evapotranspiration rates were derived by increasing the minimum and maximum daily temperature within the VIC model by 1 °C and computing the relative change in evapotranspiration in the model. That is:

$$\mathrm{ET_R} = \frac{(\mathrm{ET_1} - \mathrm{ET_0})}{\mathrm{ET_0}} \tag{3}$$

where $\mathrm{ET_R}$ is a ratio representing change in evapotranspiration demand per degree Celsius. $\mathrm{ET_1}$ is the evapotranspiration rate calculated by the VIC model after the increase in temperature, and $\mathrm{ET_0}$ is the original evapotranspiration rate prior to the change in temperature parameters. Results were then averaged over a monthly timestep. In practice, monthly evapotranspiration rates are adjusted as a calibration parameter in the RFS by the CBRFC. Although this study was unable to use the calibration model used by the CBRFC, calibration of streamflow projections was achieved through the use of a ratio method in post-processing of streamflow output (see Sects. 2.5 and 3.2).

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2 Methodology

2.1 Hydrologic model

Reclamation relies on streamflow forecasts by the CBRFC for input into operational and policy models. The CBRFC develops these streamflow forecasts through use of the NWS RFS (National Oceanic and Atmospheric Administration, National Weather Service, 2005) applied over the Colorado River Basin. The NWS RFS incorporates numerous models to develop unregulated inflow forecasts. The primary models within the RFS and utilized over the Colorado River Basin are the Sacramento Soil Moisture Accounting (SAC-SMA) model (Burnash et al., 1973) and the Snow Accumulation and Ablation Model (SNOW-17) (Anderson, 1973; Anderson, 2006). The NWS RFS model used here was provided by the CBRFC and is run in calibration mode; that is, the model is run without the calibration model that is typically run in parallel with the model at the CBRFC. This calibration model is run to calibrate streamflow output from the RFS to observed streamflow from gage records.

The NWS CBRFC RFS model incorporates mean areal temperature (MAT) and mean areal precipitation (MAP) input files. Over the water year 1976 through water year 2005 calibration period, the CBRFC derives these files through the use of gage measurements provided by a variety of sources (e.g., National Oceanic and Atmospheric Administration (NOAA), National Resource Conservation Service (NRCS), National Climatic Data Center (NCDC), United States Geological Survey (USGS), and Reclamation). In this study, MAT and MAP files are developed using BCSD, temporally disaggregated climate data from the WCRP CMIP3 dataset.

The NWS RFS model provided by the CBRFC relied on values of evapotranspiration demand unique to each month; that is, evapotranspiration demand in any given month is identical throughout the length of the model run. This evapotranspiration demand, though reasonable and comparable to evapotranspiration measurements over any given area, was derived through the use of a separate calibration model to more closely align forecasted streamflow output with observations of streamflow over the

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calibration period. In this study, evapotranspiration is a function of monthly average projected temperature. As such, a third input file describing mean areal evapotranspiration (MAE) was derived in this study.

The NWS RFS is a lumped hydrologic model. Basins within the Colorado River Basin are divided into catchments which may each be solved individually using the NWS RFS. Each catchment may then be divided into up to three elevation bands. Headwater catchment input is primarily temperature and precipitation through the MAT and MAP input files. Catchments that are downstream from headwater and other catchments, described as "local" catchments, incorporate runoff from headwater catchments and other upstream local catchments in addition to precipitation and temperature input.

2.2 Derivation of MAT input files

The NWS CBRFC RFS requires temperature input at a 6-h timestep. The CBRFC derives 6-h temperature values using an empirical relationship between daily maximum and minimum temperature values. This practice is common between river forecasting centers, though the empirical relationship is unique to each river forecasting center. Empirical relationships are applied over all years and all seasons. For the CBRFC, the empirical relationships derived over the Colorado River Basin are as follows:

$$\begin{aligned} 00{:}00\mathrm{Z} &= 0.950 \cdot T_{\mathrm{min}} + 0.050 \cdot T_{\mathrm{max}-1} \\ 06{:}00\mathrm{Z} &= 0.400 \cdot T_{\mathrm{min}} + 0.600 \cdot T_{\mathrm{max}} \\ 12{:}00\mathrm{Z} &= 0.025 \cdot T_{\mathrm{min}} + 0.925 \cdot T_{\mathrm{max}} \\ 18{:}00\mathrm{Z} &= 0.670 \cdot T_{\mathrm{min}} + 0.330 \cdot T_{\mathrm{max}} \end{aligned} \tag{4}$$

where Z denotes Coordinated Universal Time (UTC, sometimes referred to as Zulu time), T_{min} is the minimum daily recorded temperature, T_{max} is the maximum daily recorded temperature, and $T_{\mathrm{max}-1}$ is the previous day's maximum recorded temperature (Greg Smith, 2009, personal communication).

Using geographic information system (GIS) software, gridded, 1/8th degree tem-

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perature values were overlaid with elevation data from 30 m resolution digital elevation maps (DEMs) downloaded from the USGS National Map Seamless Server (Available from the USGS, EROS Data Center in Sioux Falls, SD and http://seamless.usgs.gov). The elevation at the center of each 1/8th degree cell was derived from the DEM and assumed to be representative of the elevation over each cell. This elevation was used to classify temperature values over each elevation band within each catchment.

Each catchment is divided into three elevation bands as defined by the CBRFC. For each catchment and elevation band within that catchment, a daily time series of minimum and maximum temperature data was derived by taking the average of daily minimum and maximum temperature values from each 1/8th degree grid cell from the BCSD, temporally downscaled WCRP CMIP3 dataset. By applying the empirical formulations described in Eq. (4), a time series of 6-h temperature values was derived for each elevation band within each catchment. A MAT file containing this information for each elevation band within each catchment is used as input for the NWS CBRFC RFS.

2.3 Derivation of MAP input files

Similar to temperature data, the NWS CBRFC RFS requires precipitation input at a 6-h timestep. Precipitation data was separated by elevation band and catchment using a method identical to that used to separate 1/8th degree temperature data. Unlike temperature data, the CBRFC currently uses observations of precipitation at the 6-h timestep and there are no empirical formulations to translate daily precipitation values to a 6-h timestep.

Time series of precipitation at a 6-h timestep were derived by first comparing the daily rainfall depth from the BCSD, temporally disaggregated WCRP CMIP3 dataset to the 30-yr calibration period (1976–2005) of aggregated daily observations of precipitation used by the CBRFC. The aggregated daily precipitation event occurring in the same month and nearest to the daily precipitation event from the BCSD, temporally disaggregated WCRP CMIP3 dataset was then identified. The daily precipitation

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value from the BCSD, temporally disaggregated WCRP CMIP3 dataset was then disaggregated to a 6-h time step proportional to the identified event within the CBRFC observed dataset. A MAP file containing this information for each elevation band within each catchment is used as input for the NWS CBRFC RFS.

2.4 Derivation of MAE input files

Daily evapotranspiration data was derived by first averaging the rate of evapotranspiration change per 1 °C derived through the use of the VIC model over each elevation band within each catchment for each month over the 30-yr calibration period. In addition, 12 base average temperatures were derived for each month using the 30-yr calibration period.

The original evapotranspiration demand within the NWS CBRFC RFS model was used as a base evapotranspiration value. For each month over the model run (1950–2099), an average monthly temperature was derived. This monthly average temperature was then compared to the base temperature derived over the same month over the 30-yr calibration period. The original evapotranspiration value was then adjusted based on the difference between average monthly temperature and the base monthly temperature:

$$\mathrm{ET}_t = \mathrm{ET}_{\mathrm{orig}} + (T_{\mathrm{t}} - T_{\mathrm{base}})\overline{\mathrm{ET}_{\mathrm{R}}} \tag{5}$$

where ET_{t} is the adjusted monthly evapotranspiration demand at a given time, $\mathrm{ET}_{\mathrm{orig}}$ is the original evapotranspiration demand employed by the CBRFC, T_{t} is the average temperature over any given month in the derived time series, T_{base} is the 30-yr calibration period average temperature for any given month, and $\overline{\mathrm{ET}_{\mathrm{R}}}$ is the average ET_{R} over each elevation band within each catchment as derived through use of the VIC model.

Daily evapotranspiration demand was assumed to be constant and uniform over the course of any given month. A MAE file containing this information for each elevation band within each catchment is used as input for the NWS CBRFC RFS.

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2.5 Post-run bias correction

This study uses a ratio method to adjust streamflow projections such that the long term mean over the CBRFC calibration period is equal to the long term mean derived through the use of the BCSD, temporally disaggregated WCRP CMIP3 dataset over the calibration period.

Twelve monthly average streamflow projections over the 30-yr calibration period were derived using data from the CBRFC. Additionally, twelve monthly average streamflow projections over the 30-yr calibration period were derived using data from the BCSD, temporally disaggregated WCRP CMIP3 dataset. The ratio of these two values was computed and applied to streamflow projections derived using the temporally disaggregated BCSD dataset.

Numerous data sets were created and integrated to produce projections of streamflow under changing climate conditions. In addition, two models, the NWS CBRFC RFS and the VIC model, were utilized to develop unregulated streamflow projections and relative changes to evapotranspiration with respect to temperature, respectively.

3 Results of RFS model runs

3.1 Impact of evapotranspiration incorporation

Figure 3 illustrates the impact of taking into account climate change impacts to evapotranspiration. Whereas the 10th and 90th percentiles over the 90 yr projection period are approximately equal, the mean of the 112 climate projections is different. Over the 2010–2039 time period, adjusting evapotranspiration in response to temperature change results in a decrease of approximately 149 million m^3 (mcm) (121 000 acre-feet or approximately 6%) than projections made without an adjustment to temperature. This difference increases over time, with a decrease of approximately 258 mcm (209 000 acre-feet or approximately 10%) and approximately 329 mcm (267 000 acre-feet or approximately 13%) over the 2040–2069 and 2070–2099 time periods, respectively.

Evapotranspiration and associated impacts to projections of streamflow over the Gunnison River Basin is spatially distributed (Fig. 4). Adjusting evapotranspiration with changing temperature impacts the Gunnison River Basin across all catchments, particularly those in the southern portion of the basin which is typically characterized by flatter topography and contributes less flow to the Gunnison River tributary.

Streamflow projections are derived for each of the three headwater basins with evapotranspiration adjusted for temperature changes. Recent studies of climate change impacts to streamflow over the Colorado River Basin typically indicate decreasing flow within the basin between 10% and 20% (e.g., Barnett and Pierce, 2009; Christensen and Lettenmaier, 2007; Hamlet et al., 2007; Hoerling and Eischeid, 2007). When evapotranspiration is taken into consideration, these results support those findings.

3.2 Post bias correction

For each of the 112 climate projections within the temporally disaggregated BCSD dataset, the average streamflow projection associated with each month over the 30-yr calibration period was calculated. A bias correction factor for each climate projection was defined and applied over the projected time series such that the average streamflow over the 30-yr calibration period is exactly equal to that derived by the CBRFC. Summary statistics comparing pre- and post-bias corrected streamflow projection data are presented in Table 1. It is important to note that the mean for each climate projection was bias corrected to match the calibration period; that is the average for each of the 112 climate projections is equal to the mean of the results over the CBRFC calibration period. In contrast, the pre-bias corrected mean presented in Table 1 is the average of all mean streamflow derived using the 112 climate projections.

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3.3 Streamflow projections

3.3.1 Gunnison River Basin

The Gunnison River Basin contributes approximately 16% of the Upper Colorado River Basin's annual natural flow to the Colorado River. Over the 30-yr calibration period, the average runoff from the Gunnison is approximately 2690 mcm (2.18 MAF). Each of the 112 climate projections was used to force the NWS CBRFC RFS (Fig. 5). Over the model run period (1950–2099), average streamflow from the Gunnison River Basin is approximately 2530 mcm (2.05 MAF). Table 2 summarizes the results of the streamflow projections over the Gunnison River Basin. Reclamation operates the Blue Mesa, Morrow Point, and Crystal Dams and Reservoirs, collectively known as the Aspinall Unit, as part of the Colorado River Storage Project (CRSP) (US Department of the Interior, Bureau of Reclamation, Upper Colorado Region, 2009). Reclamation manages the CRSP to meet downstream flow requirements, hydroelectric power needs, and provide for endangered fish and their habitat, along with other approved uses.

On average, streamflow over the Gunnison River Basin decreases over future multi-decadal periods. Of interest, one climate projection results in a streamflow projection in excess of 14 800 mcm (12.0 MAF) in the year 2030. This projection is made by the Canadian Centre for Climate Modeling and Analysis GCM (Flato and Boer, 2001) under an A1B emissions scenario, which, on average, is the more moderate emissions scenario considered in this study. The minimum annual flow projection is approximately 540 mcm (0.44 MAF) in 2071. This minimum flow is a product of the GCM from the Institut Pierre Simon in Laplace, France (O et al., 2005); more intuitively, this projection falls under the A2 emissions scenario which describes, on average, a more aggressive warming trend. Figure 6 separates streamflow projections over the Gunnison River Basin by emission scenarios included in this study.

As shown in the right side of Fig. 4, the southern portion of the Gunnison River Basin exhibits the greatest percent reduction in projected streamflow from the calibration period. This area encompasses the southern portion of the Rocky Mountains. Previous

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work has shown that snowpack in this area has declined with warming trends over the Colorado River Basin and contribute decreased streamflow in the region (Mote et al., 2005; Mote, 2006).

3.3.2 Green River Basin

The Green River Basin contributes approximately 36% of the Upper Colorado River Basin's annual natural flow to the Colorado River. Reclamation manages two reservoirs, Fontenelle and Flaming Gorge, to regulate flow along the northern-most tributary to the Colorado River. Reclamation operates the Flaming Gorge reservoir to meet downstream water delivery and hydroelectric power needs. Like the Aspinall Unit, Flaming Gorge operations allow for Reclamation to protect and assist in the recovery of endangered fish within the Colorado River Basin.

Over the 30-yr calibration period, the average runoff from the Green River Basin is approximately 2380 mcm (1.93 MAF). Each of the 112 climate projections was used to force the NWS CBRFC RFS (Fig. 7). Over the model run period (1950–2099), average streamflow from the Green River Basin is approximately 2370 mcm (1.92 MAF). On average, streamflow over the Green Basin increases slightly over future multi-decadal periods.

As shown in Fig. 8, much of the central portion of Green River Basin exhibits slightly increased streamflow when compared to the calibration period. This is somewhat consistent with results noted by Mote (2006). Mote (2006) describes increasing trends in SWE when using a regression describing SWE in terms of precipitation and temperature. The SNOW-17 model derives snowpack conditions in a similar fashion (Anderson, 2006). Under these climate conditions, increased model snowpack conditions would yield increased runoff throughout the basin.

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3.3.3 San Juan River Basin

Since 1992, Reclamation has been working in collaboration with the San Juan River Basin Recovery Implementation Program to protect the Colorado pikeminnow and the razorback sucker and their respective habitat (US Fish and Wildlife Service, 2006). Reclamation operates the Vallecito and Navajo reservoirs within the San Juan River Basin to manage approximately 14% of the annual runoff to the Colorado River. Reservoirs within the San Juan River Basin are also part of the CRSP.

Over the 30-yr calibration period, the average runoff from the San Juan River Basin is approximately 2,230 mcm (1.81 MAF). Each of the 112 climate projections was used to force the NWS CBRFC RFS (Fig. 9). Over the model run period (1950– 2099), average streamflow from the San Juan River Basin is approximately 2,060 mcm (1.67 MAF).

On average, streamflow over the San Juan River Basin decreases over future multi-decadal periods. Of interest, one climate projection results in a streamflow projection in excess of 11 100 mcm (9.00 MAF) in the year 2030. Like the Gunnison River Basin, this projection is made by the Canadian Centre for Climate Modeling and Analysis GCM (Flato and Boer, 2001) under an A1B emissions scenario. The minimum annual flow projection is approximately 123 mcm (0.10 MAF) in 2091. This minimum flow is also a product of the GCM from the Institut Pierre Simon in Laplace, France (O et al., 2005) under the A2 emissions scenario.

As shown in Fig. 10, the vast majority of the San Juan River Basin exhibits reduced streamflow when compared to the calibration period. Reduced streamflow in the region results in less flexibility in the management of Reclamation's reservoir system. With reduced flows, it is more difficult for Reclamation to manage reservoir releases to protect endangered fish in the area, particularly as it relates to the regulation of river temperatures and the protection of habitat area.

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4 Stationarity in projected streamflow forecasts

The definition of stationarity, particularly with regards to climate change, is often under debate (e.g., Matter et al., 2010; Milly et al., 2008; Raff et al., 2009; Villarini et al., 2009; Wilby et al., 1999). The KS–Test is a nonparametric test for determining if the distributions of two samples are the same. The KS–Test compares empirical distributions of two sample sets of data and determining the maximum distance between the two sets of data (DeGroot, 1975; Georgakakos, 2003). This maximum distance is a value from which the hypothesis that the underlying distribution is the same for both samples may be rejected if the value of the maximum distance exceeds a critical value defined by the size of the samples. The KS–Test has been used to compare ensemble streamflow projections between lumped and distributed hydrologic models (Carpenter and Georgakakos, 2006) as well as detecting changes in the probability distributions associated with precipitation and streamflow events (Wang et al., 2008). In this study, the KS–Test is utilized to compare probability distributions of multi-decadal streamflow projections.

4.1 Gunnison River Basin results

Summary statistics for streamflow projections over the Gunnison River Basin are presented in Table 3. While there is an appreciable change in summary statistics between multi-decadal periods, these changes may be attributed to natural hydroclimatic variability within the Colorado River Basin as evidenced by tree-ring reconstructions over the region (e.g., Meko et al., 2007; Woodhouse and Lukas, 2006; Woodhouse et al., 2006). The cumulative distribution functions (CDF) of streamflow, regardless of emission scenario, tend to be close, though separation is more apparent over the time period spanning 2070–2099.

The KS–Test was first applied between streamflow projections derived by the CBRFC over the calibration period and streamflow projections derived using climate data from the 112 temporally downscaled BCSD dataset over the same period. As would be expected, the test statistic derived using the KS–Test was less than the critical test statistic. Thus, the null hypothesis that the data comes from the same distribution could not be rejected. When streamflow projections derived from the 112 temporally downscaled BCSD dataset were separated by emission scenario over the calibration period, the result was the same.

The KS–Test was then applied between streamflow projections derived by the CBRFC over the calibration period and streamflow projections derived using climate data from the 112 temporally downscaled BCSD dataset over the period from 2010 to 2099. In this case, the test statistic derived using the KS–Test was greater than the critical test statistic. Thus, the null hypothesis that the data comes from the same distribution could be rejected and may be indicative of nonstationary behavior.

The KS–Test was then applied between streamflow projections derived by the CBRFC over the calibration period and streamflow projections derived using climate data from the 112 temporally downscaled BCSD dataset over the period from 2010 to 2099, separated by emissions scenario and multi-decadal period. For each emissions scenario and projected streamflow over the period spanning 2010 to 2039, the test statistic was less than the critical value and the null hypothesis could not be rejected. However, for each emissions scenario and projected streamflow over the period spanning either 2040 to 2069 or 2070 to 2099, the null hypothesis could be rejected. Table 4 summarizes results of the KS–Tests performed over the Gunnison River Basin.

4.2 Green River Basin results

Unlike the Gunnison River Basin there is not an appreciable change in summary statistics between multi-decadal periods over the Green River Basin. There is less deviation from the 1976–2005 mean over each multi-decadal period than that observed over the Gunnison River Basin.

KS–Test results were developed in an identical fashion to those over the Gunnison River Basin. The results of each KS–Test indicated that the null hypothesis could not be rejected; that is, each multi-decadal period did not come from a statistically

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different distribution. As a result, it is not possible to state that streamflow projections statistically exhibit nonstationary behavior. The topography of the Green River Basin is generally more mountainous and at higher elevations than those in the San Juan and Gunnison River Basins. As warming temperature impacts are more prevalent at lower elevations, projected climate over the Green River Basin may exhibit more stationary characteristics since climate change impacts are not as realized at higher elevations and latitudes (e.g., Mote et al., 2005; Mote, 2006). Table 4 summarizes the results of the KS–Tests over the Green River Basin.

4.3 San Juan River Basin results

Similar to the Gunnison River Basin, there is an appreciable change in summary statistics between multi-decadal periods over the San Juan River Basin. KS–Test results were developed in an identical fashion to those over the Gunnison and Green River Basin. Results over the San Juan River Basin were slightly different from those results derived over the Gunnison and Green River Basins. For the period spanning 2010–2039, the A1B emissions scenario exhibits a test statistic greater than the critical value such that the null hypothesis could be rejected. Like the Gunnison River Basin, all emissions scenarios and projected streamflow spanning the period over 2040 to 2099, the test statistic was greater than the critical value and the null hypothesis could be rejected. Other KS–Test results were qualitatively identical with those observed over the Gunnison River Basin. Overall, the topography of the San Juan River Basin is at lower elevations than those in the Green and Gunnison River Basins. As warming temperature impacts are more prevalent at lower elevations, projected climate over the San Juan River Basin may exhibit nonstationary characteristics sooner than those projected in the Green and Gunnison River Basins. Table 4 summarizes results of the KS–Tests performed over the San Juan River Basin.

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5 Discussion

In this study, a methodology for incorporating BCSD climate data into a hydrologic streamflow forecasting model was developed. This methodology utilized data from large scale GCMs that had been bias corrected and spatially downscaled such that the data would be useful in regional hydrologic studies. This study also proposes and incorporates a methodology to integrate impacts to evapotranspiration under changing climate conditions, as there has been limited research addressing this topic. This research further represents a methodology and progress towards the ability to incorporate climate change projections into Reclamation's existing operations plans and river and reservoir management studies.

Evapotranspiration under changing climate conditions is not trivial in hydrologic modeling efforts or water resource management studies. A major contribution of this study is that by adjusting evapotranspiration with temperature, catchment streamflow projections better reflect the potential impacts of climate change. The CBRFC currently adjusts evapotranspiration demand within the SAC-SMA model within the NWS RFS to calibrate the model to observed streamflow in the basin. This methodology highlights both the importance and uncertainty regarding evapotranspiration in hydrologic modeling studies. Evapotranspiration is a sensitive and important parameter that must be accounted for; however, due to limited observational data, it is often implicitly calculated through calibration efforts or as part of a mass balance formulation. Under changing climate conditions, this uncertainty increases. This study presents a progressive methodology through which changes to evapotranspiration may be addressed when dealing with uncertainty associated with climate change. Previous studies have presented progressive automated calibration schemes but do not address evapotranspiration (e.g., Hogue et al., 2000, 2006; Sorooshian et al., 1993). Regardless, under changing climate conditions, accurate estimates and measurements of evapotranspiration will become increasingly important.

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Under the definition of stationarity presented in Milly et al. (2008), lower latitude Colorado River Basin headwaters (i.e. the Gunnison and San Juan River Basins) investigated in this study will exhibit nonstationary characteristics with changing climate conditions. This is important to water resource managers, particularly in Reclamation, where past observations of streamflow are assumed to be representative of future conditions. Future study may investigate the presence on nonstationarity at the seasonal scale to determine potential shifts in the timing and magnitude of streamflow runoff under changing climate conditions.

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Table 1. Statistics of streamflow projections pre- and post-bias correction. Values are presented in mcm.

Statistic	CBRFC streamflow projection (1976–2005)	Average of 112 climate projections (1976–2005) pre-bias correction	Average of 112 climate projections (1976–2005) post-bias correction
Mean	2690	2230	2690
Average median	2670	2120	2530
Average standard deviation	1000	780	1050
Average variance	810	510	910
Average maximum	4850	4190	5410
Average minimum	860	1000	1130
Average skew	320	870	1010

1 maf is approximately 1233.48 mcm.

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Table 2. Average streamflow projections from the Gunnison River Basin. Projections are separated by SRES emissions scenarios and future multi-decadal periods.

Average streamflow projection (mcm) from the Gunnison River Basin				
Time period	All	A2	B1	A1B
2010–2039	2550	2590	2580	2490
2040–2069	2360	2330	2370	2370
2070–2099	2260	2170	2340	2250

1 maf is approximately 1233.48 mcm.

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Streamflow projections under changing climate conditions

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Table 3. Gunnison River Basin summary statistics.

Summary statistics of streamflow projections over the Gunnison River Basin (mcm)												
	1976–2005			2010–2039			2040–2069			2070–2099		
Statistic	A2	B1	A1B	A2	B1	A1B	A2	B1	A1B	A2	B1	A1B
Min	670	750	780	750	790	580	600	750	630	530	650	620
1st Quantile	1920	1940	1940	1750	1750	1620	1490	1600	1540	1410	1550	1490
Median	2540	2570	2540	2360	2360	2260	2100	2130	2090	1900	2060	2020
Mean	2690	2690	2690	2590	2580	2480	2330	2370	2360	2170	2340	2250
3rd Quantile	3270	3280	3240	3160	3120	3020	2900	2840	2960	2660	2850	2730
Max	8260	6910	6770	8290	9080	15 630	8380	8880	8870	8990	8700	11 180

1 maf is approximately 1233.48 mcm.

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Table 4. Summary of results of the KS–Test performed in this study. Shaded boxes indicate significantly different distributions from the calibration period. Unshaded boxes indicate reflect not enough evidence to make a determination.

Time period/ emissions scenario	Gunnison River Basin			Green River Basin			San Juan River Basin		
	A1B	A2	B1	A1B	A2	B1	A1B	A2	B1
1976–2005	□	□	□	□	□	□	□	□	□
2010–2039	□	□	□	□	□	□	■	□	□
2040–2069	■	■	■	□	□	□	■	■	■
2070–2099	■	■	■	□	□	□	■	■	■

1 maf is approximately 1233.48 mcm.

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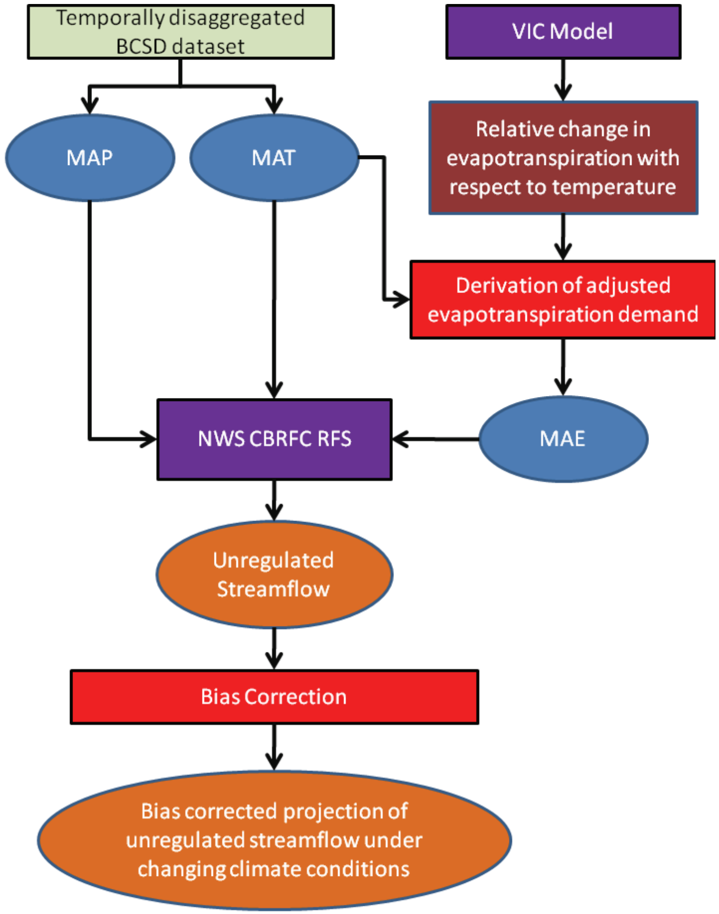

Fig. 1. This flow chart illustrates how the NWS CBRFC RFS and VIC model are utilized with multiple climate datasets to derive projections of streamflow.

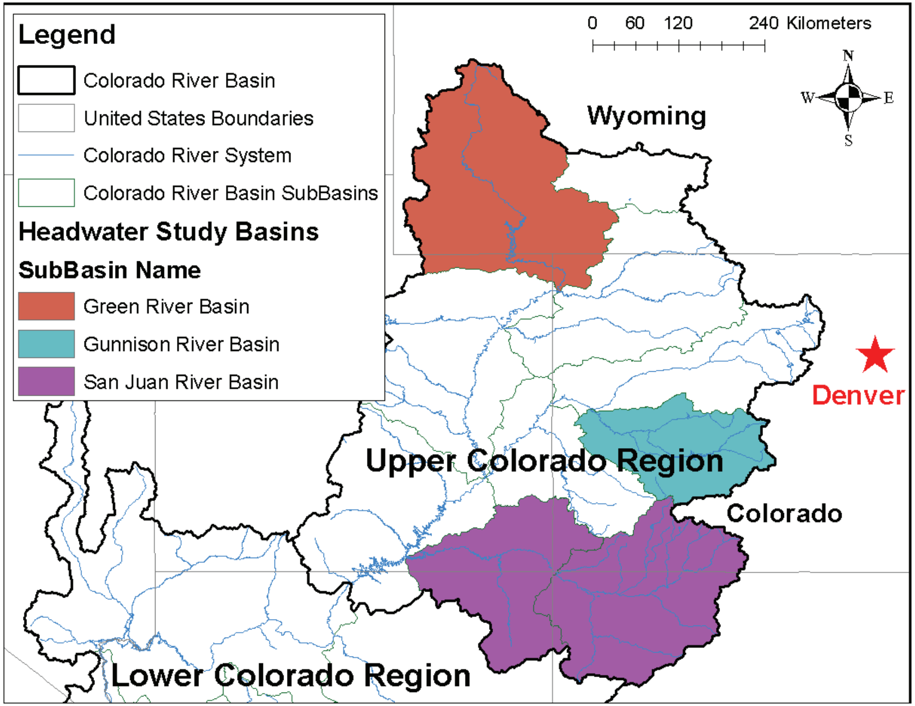

Fig. 2. The Colorado River Headwater Basins considered in this study encompass a broad range of the Upper Colorado River Basin. For reference, the city of Denver, Colorado is located at 39° 44′ 21″ N, 104° 59′ 5″ W.

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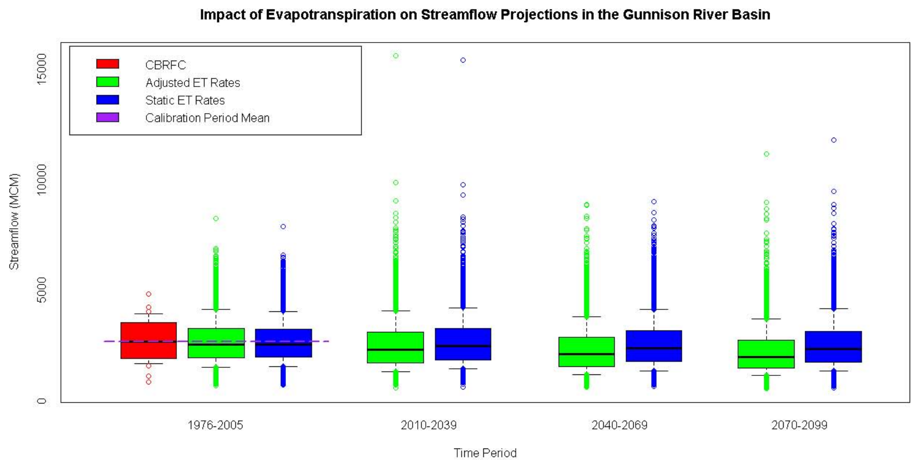

Fig. 3. Modified boxplots illustrating the impact of incorporating climate change impacts to evapotranspiration rates in the Gunnison River Basin. Boxplots in this study define the outer whiskers at the 10% and 90% exceedance values. The red boxplot illustrates results derived using data from the CBRFC over the calibration period. Green boxplots illustrate results derived using the temporally downscaled BCSD dataset and adjusting evapotranspiration in response to temperature change. Blue boxplots illustrate results derived using the temporally downscaled BCSD dataset without adjusting evapotranspiration in response to temperature change.

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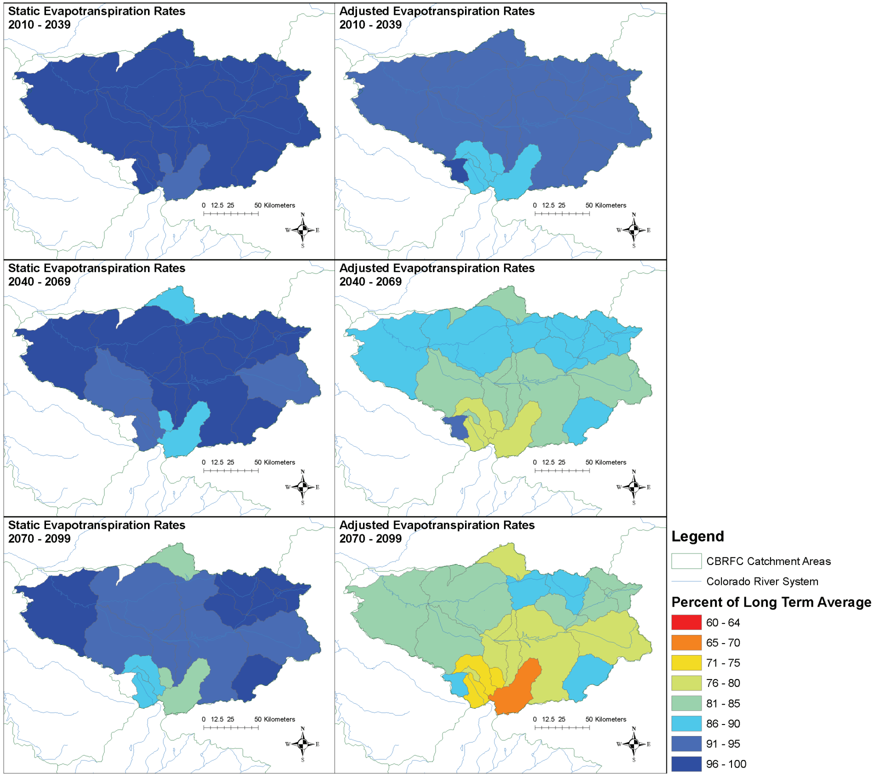

Fig. 4. Impact of adjusting evapotranspiration with changes in temperature at the catchment scale over the Gunnison River Basin. Panels on the left reflect average model output when evapotranspiration is not adjusted with temperature over the 2010–2039 time period (top left), the 2040–2069 time period (middle left), and the 2070–2099 time period (bottom left). Panels on the right reflect average model output when evapotranspiration is adjusted with temperature over the 2010–2039 time period (top right), the 2040–2069 time period (middle right), and the 2070–2099 time period (bottom right).

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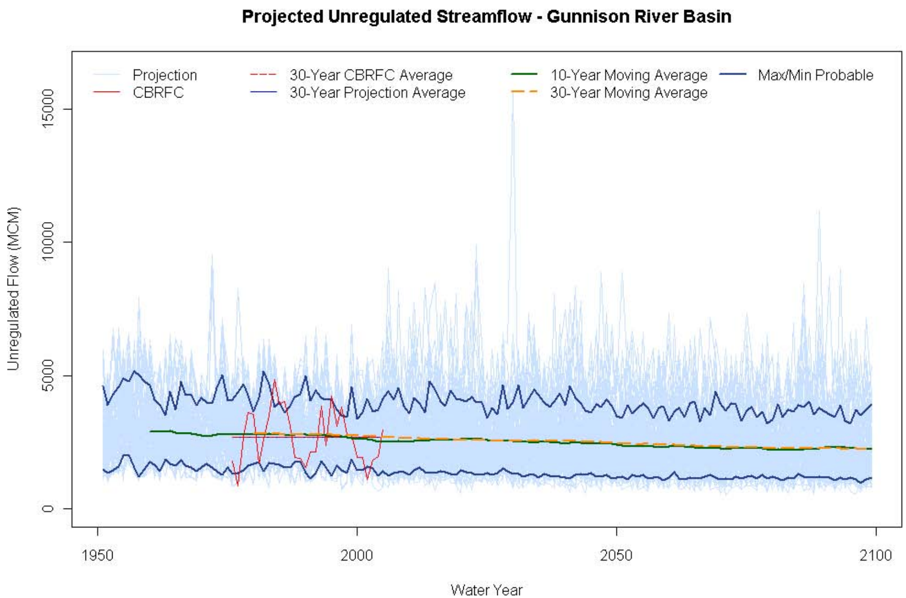

Fig. 5. Streamflow projections from each of the 112 climate projections over the Gunnison River Basin. Results from the CBRFC's calibrated model are included as well as long-term averages. The blue lines in bold indicate the Maximum and Minimum Probable flows, defined by the CBRFC as the 10% exceedance and 90% exceedance values, respectively.

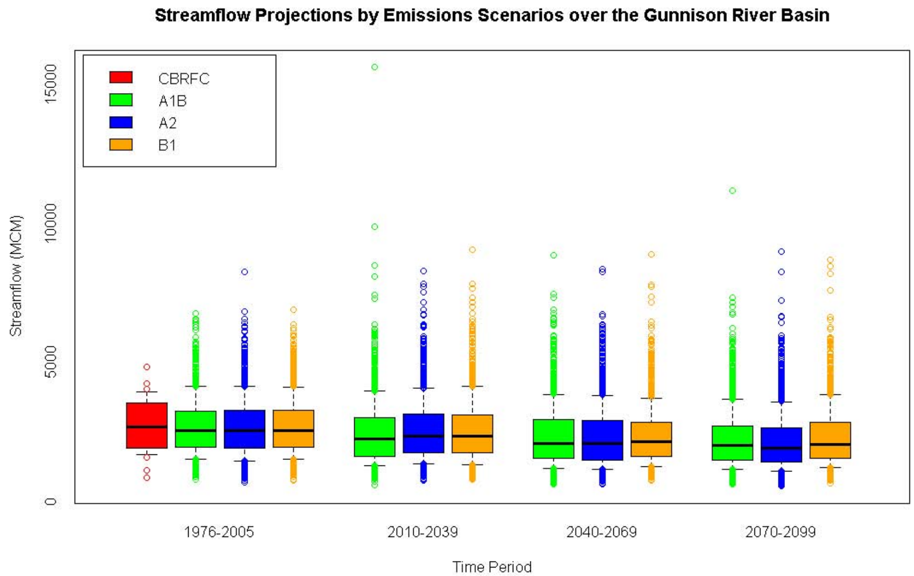

Fig. 6. Streamflow Projections over the Gunnison River Basin separated by emissions scenarios and by climatology used by the CBRFC.

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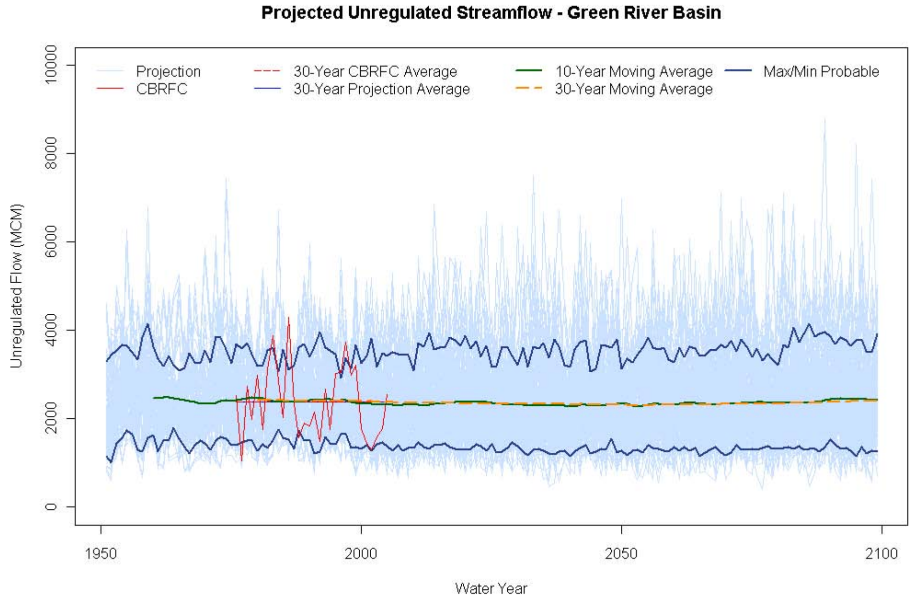

Fig. 7. Streamflow projections from each of the 112 climate projections over the Green River Basin. Results from the CBRFC's calibrated model are included as well as long-term averages. The blue lines in bold indicate the Maximum and Minimum Probable flows, defined by the CBRFC as the 10% exceedance and 90% exceedance values, respectively.

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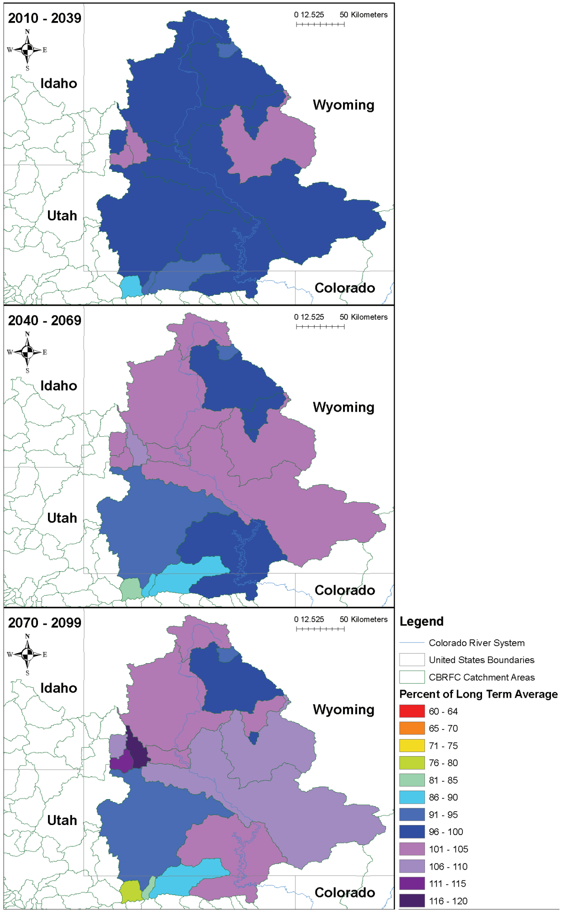

Fig. 8. Multi-decadal averages of streamflow projections over the Green River Basin.

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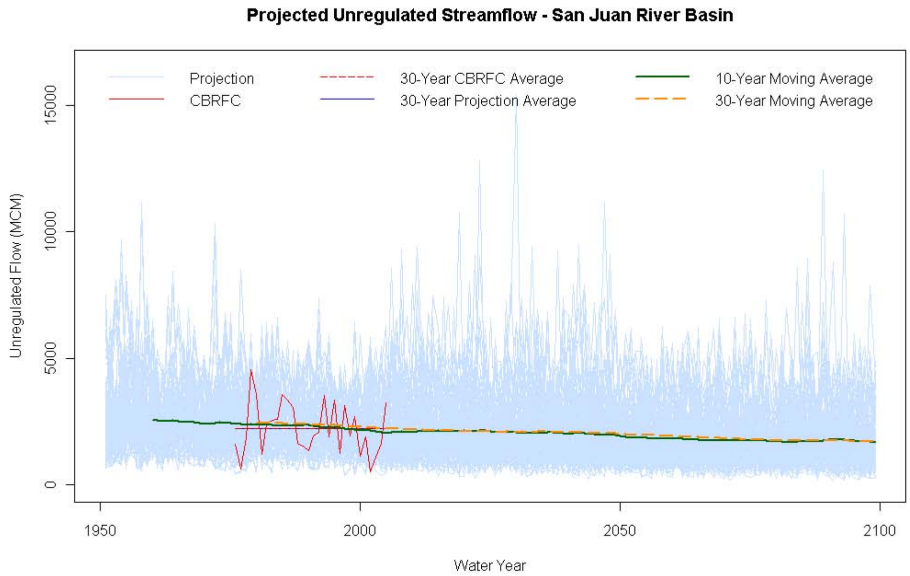

Fig. 9. Streamflow projections from each of the 112 climate projections over the San Juan River Basin. Results from the CBRFC's calibrated model are included as well as long-term averages. The blue lines in bold indicate the Maximum and Minimum Probable flows, defined by the CBRFC as the 10% exceedance and 90% exceedance values, respectively.

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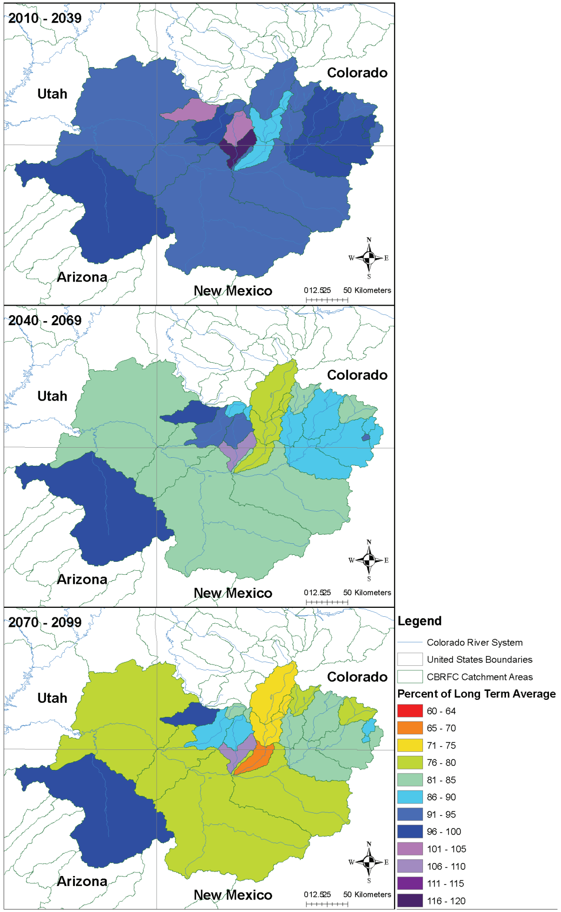

Fig. 10. Multi-decadal averages of streamflow projections over the San Juan River Basin.

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