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# Climate-change impacts on water resources and hydropower potential in the Upper Colorado River Basin

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ABSTRACT

**Study region:** The Upper Colorado River Basin (UCRB), comprised of the Colorado and Gunnison River basins, is the prime water source for much of the western United States.

**Study focus:** Future climate change models were used to drive a hydrologic model of the UCRB to evaluate future water resources and hydropower potential of the basin, using three different climate projections. The Intergovernmental Panel on Climate Change (IPCC) emission scenarios, the A2-business as usual, and the B1-reduced emissions scenarios were evaluated. More than 4500 water diversions and 17 reservoirs were incorporated into the hydrologic model.

**New hydrological insights for the region:** Precipitation projections from climate models vary up to 16%; flow projections revealed greater differences, up to 50%. The climate models projected increase in temperature at low elevations with extreme seasonality at high elevations, although summer temperatures increased at all elevations. The models projected a 60% decline in precipitation at lower elevations and a 74% increase at high elevations, although precipitation declined during the summer months at all elevations. Using the A2 scenario an overall decrease in annual flow was predicted, attributed to a reduction in precipitation and increasing temperature trends; however, this was not consistent during the winter months,

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which showed an increase in precipitation at high elevations and a modest temperature increase during the winter and resulted in an increase in stream flow. The responses to climate change on reservoir levels varied basin-wide due to variability in precipitation, evapotranspiration, and stream flow. Simulations indicated that water levels in Blue Mesa Reservoir (the largest reservoir in the UCRB) would decline by more than 70% with increasing annual temperatures. Reservoirs with smaller surface areas to the volume ratio were not significantly impacted by evapotranspiration. Our results indicate that hydropower management strategies in the UCRB must adapt to potential climate change, but the required adaptations are dependent on several factors including reservoir size and location.

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## 1. Introduction

Potential impacts of climate change on water resources are usually assessed by applying climate projections (temperature and precipitation) derived from global circulation models (GCM) using a hydrologic model. In this study we investigate the impact of global climate change on water resources and reservoir levels (as related to hydropower potential) on the Upper Colorado River Basin (UCRB) using state-of-the art climate projections and an integrated hydrologic model. The Colorado River is critical to the water resources of the southwestern United States. Already almost wholly allocated (Christensen et al., 2004), water management and supply issues of the basin are projected to be exacerbated by climate change (Nash and Gleick, 1991). Multiple studies have shown that the UCRB will respond to a temperature increase with an increase in the rain-to-snow ratio, increased winter runoff, and earlier spring snow melt. Although precipitation predictions vary, most studies agree in the overall reduction of runoff in the basin (Barnett and Pierce, 2009). A previous study on the basin by Christensen et al. (2004), demonstrated that there will be a 10–30% reduction in stream flow. These changes have already resulted in reduced storage levels of two significant reservoirs downstream, Lake Mead and Lake Powell, and are expected to impact the management of flow and reservoir regimes. Christensen et al. (2004) compared the impact of climate change on the Colorado River Basin using three 105-year future climate scenarios based on a "business-as-usual" (BAU) greenhouse gas (GHG) emission scenario to a static 1995 GHG simulation using the Variable Infiltration Capacity (VIC) model. The study concluded there would be a 0–10% increase in flow in the northwest portion of the river in Arizona. Christensen and Lettenmaier (2007) used an ensemble approach to characterize the hydrologic response to climate change using the Colorado River Reservoir Model (CRRM). They employed 11 GCMs and A2 and B1 climate scenarios. A2 is a business as usual (BAU) scenario that evaluates untamed $CO_2$ levels (850 parts per billion) until the year 2100, whereas B1 assumes a considerable effort to minimize emissions to achieve a moderate atmospheric carbon dioxide concentration of about 550 parts per billion. Although the authors used 11 GCMs, only 11 diversion points were considered to model the most critical junctures, in contrast to the over 4500 diversions considered in this study. The authors determined that an average increase in temperature of approximately 3–4 degrees Fahrenheit (°F), combined with a decrease in precipitation between 1% and 2%, resulted in a decrease in mean runoff to about 11%. Under the B1 scenario, it was predicted that there will be an average increase in temperature of approximately 2.52 °F, a change in precipitation between −1% and 1%, and a decrease in mean runoff up to 8%. McCabe and Wolock (2007) used a water balance model to describe streamflow changes and their impacts on long-term water sustainability of the Southwest. Only considering the warming effects of a changing climate, they concluded that the Colorado River Basin (CRB) will experience future water supply shortages. The United States Bureau of Reclamation (USBR) recently analyzed the basin under varying future scenarios, emphasizing the impact of evapotranspiration (ET). Using bias-corrected statistically downscaled data (BCSD) and changes in ET rates, they predicted a

6–13% decrease in runoff for the Gunnison River (Miller et al., 2011). Raff et al. (2009) used a statistically downscaled monthly precipitation model, temporally disaggregated into 6-h weather forcing at 1/8° spatial resolutions for flood frequency analysis. They concluded a cumulative increase in future predictions of annual flood due to an increase in extreme events. Raff et al. (2009) also noted a need for more studies to benefit from recent advances in GCM data. Rasmussen et al. (2011) analyzed runoff and snowfall trends over Colorado using higher-resolution models to better simulate "orographic precipitation, snowpack accumulation, ablation, evaporation and runoff processes". These authors used the Weather Research and Forecasting (WRF) weather and climate model for regional analysis with the Pseudo Global Warming (PGW) approach at 2 km grid spacing with SNOTEL observations. Results indicated an increase in snowfall at higher elevations, due to the presence of more moisture, with a 10–15% increase in precipitation at the Colorado River headwaters due to the rain shadow effect.

Our current study analyzes changes in precipitation, temperature, streamflow and reservoir storage using current GCM and downscaling approaches (discussed later) with a watershed and reservoir analysis model. Our work considers both the Colorado River and the Gunnison River basins with contrasting climactic conditions and topography, allowing simultaneous assessment of climate change and climate change impacts across different elevations and regions. To the best of our knowledge, our study is the first to account for over 4500 stream diversions, which provides a more robust model for future water rights assessment. Our study shares some common methods used in prior work; we use multiple GCMs and climate scenarios with a physically based hydrologic model that includes an integrated 2D reservoir model. Yet our work on the UCRB differs from previous studies in that it uses the results from a newly developed downscaling method Bias-Corrected Constructed Analogues (BCCA) from three climate models (MIR, MIROC3.2, and CGCM3.1) under two climate scenarios to drive our hydrologic model, which provides a broader and better insight about the impacts of climate change in stream flow and reservoir levels given the uncertainties in the climate models.

### 1.1. Description of study area

The Upper Colorado River basin (UCRB), shown in Fig. 1, includes the Colorado River Basin in the North and the Gunnison River basin in the South. It is a mountainous plateau ranging from 4850 to 13,000 feet in elevation, comprised of valleys, canyons, and mountain ranges. The UCRB has a total drainage area greater than 17,800 square miles with a mean flow of over 3000 cfs. The mean flow is approximately split equally between the Colorado River and the Gunnison River. The Colorado River supplies water to seven states and two nations, and irrigates more than 3 million acres of farmland (Barnett and Pierce, 2009). Most of the supply originates as snowmelt in the headwaters. The river is extensively managed to provide reliable water supply for farming and cities; thus, our model included over 4500 diversions and 17 reservoirs. The UCRB has an arid to semi-arid climate, with more pronounced periods of drought in the last half of the 20th century. Under future climate projections, snow accumulation and precipitation volume are projected to decline, while temperatures are expected to increase, thus increasing regional aridity. It is widely agreed that the UCRB will experience a 2–4 °C increase in upcoming years (Christensen et al., 2004), but precipitation projections are not as certain; many studies note the variability in precipitation trends, ranging from no change to reductions of about 10% basin-wide (Nash and Gleick, 1991; Christensen et al., 2004; Christensen and Lettenmaier, 2007; Skoulikaris and Ganoulis, 2011). Warming in the basin has exceeded all other regions of the United States (NAS, 2007) and is projected to increase even more. Water resources of the UCRB are highly sensitive to snowfall and snowmelt timing and thus may be severely impacted by a changing climate.

Over 75% of the streamflow is currently generated in the high elevation mountains from snowmelt (Nealon, 2008). A receding snowpack will alter runoff regimes and timing of peak spring flows, leading to more extreme events of flood and drought in both timing and frequency (Skoulikaris and Ganoulis, 2011). Regional water security and resiliency is determined by low-flows, which have already shown to be unsustainably low in summer especially with extreme flow conditions (both low and high) projected to increase under future climate scenarios.

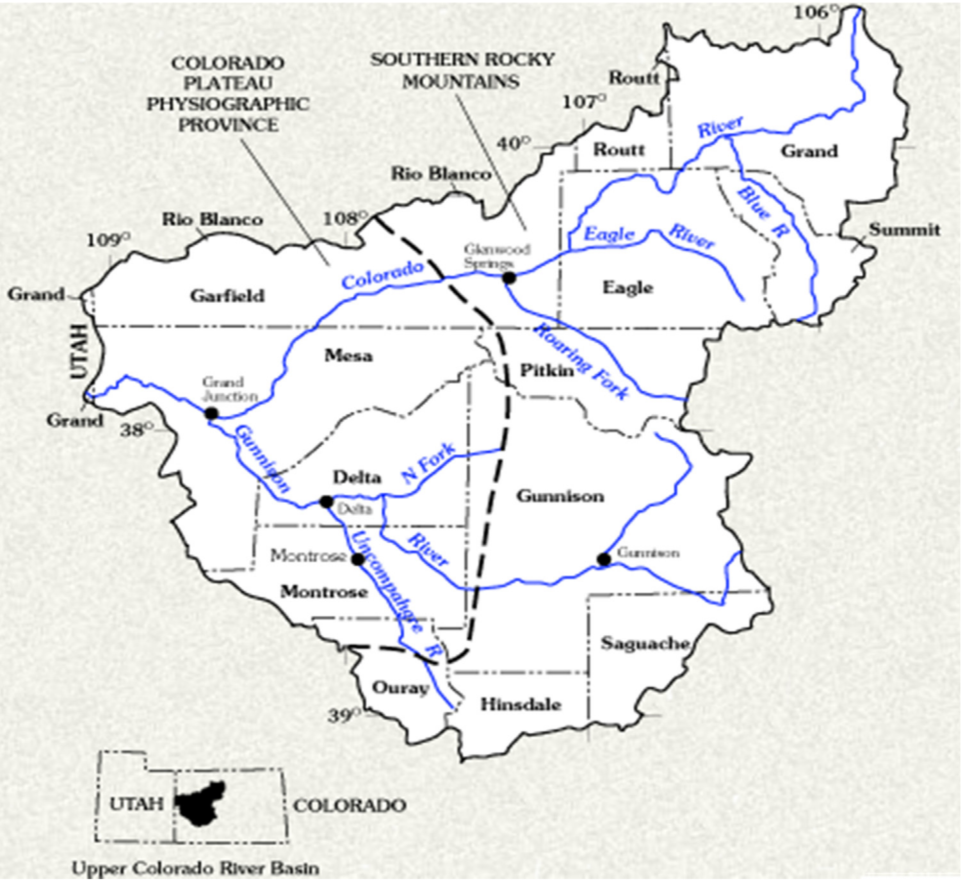


**Fig. 1.** Upper Colorado River Basin, including Colorado and Gunnison Rivers.
*Source*: USGS NAWQA.

### 1.2. Climate models

The global climate models used in this study are three of the 24 identified by the Intergovernmental Panel on Climate Change (IPCC, 2007): Japan's Meteorological Research Institute's MRI-CGCM2.3.2 (MRI), Japan's MIROC3.2 (MIROC), and the Canadian Centre for Climate Modeling and Analysis CGCM3.1 (CGCM3) under Special Report on Emission Scenarios (SRES) A2 and B1 emission scenarios. The MRI is a coupled ocean-atmosphere GCM with a horizontal resolution of about 2.8 degrees (T42) with 30 vertical layers. The major parameterizations are cloud, convection, boundary layer, long and short wave radiation, wind, and temperature with recent improvements for radiation budget distribution along the meridians and improved the cloud radiative forcings. These parameterizations have improved reproduction of extreme events caused by climate change (Yukimoto, 2005). MRI also GHGs, $CO_2$, $CH_4$, $N_2O$, sulfate aerosols, and solar activity. The MIROC3.2 GCM is comprised of 5 components: atmosphere, land, river, sea ice, and ocean (K-1 Model Developers, 2004) with two atmospheric resolutions. We used the 2.8 degrees grid resolution with 20 levels (T42 L20). The CCCMa's CGCM3.1 is a coupled ocean-atmosphere GCM with a horizontal resolution of 2.8 degrees (T42) and 31 (L31) layers in the vertical. The major parameterizations are water vapor continuum (controlling infrared cooling rate), stomatal conductance, orographic gravity wave drag, cloud and solar properties (McFarlane et al., 2005) with updated representation of the water vapor continuum.

### 1.3. Climate scenarios

In the SRES the IPCC identified six storylines for future emission pathways: (1) A1, which describes a future of rapid economic growth, a global population that peaks in mid-century and declines thereafter, and the introduction of new and more efficient technologies which include A1FI (a Fossil Intensive A1 scenario); (2) A1B (Emphasis on all energy sources); (3) A1T (Emphasis on non-fossil fuel energy sources); (4) A2, a Business-as-Usual (BAU) scenario that describes a very heterogeneous world with high population growth; (5) B1, which describes a world with the same low population growth as in A1 but with changes in economic structures toward a service and information economy; and (6) B2, which describes a world focused on local solutions to economic, social, and environmental sustainability. Of the six scenarios, A2 and B1 were selected for this study. They represent distinctly different paths of development. Each describes different demographic, social, economic, ecological, and environmental developments (Nakicenovic et al., 2000). Of the six, the A2 and B1 are most widely simulated in climate change studies (IPCC, 2007). They were chosen to represent climate change in this study because they describe a realistic range of conditions and uncertainties of the next century.

One of the primary factors that limit direct application of climate projections to hydrologic modeling for water resources assessment is the coarse spatial scale of GCM outputs. The grid resolution of GCMs used to develop future climate projections is at hundreds of kilometers, which is often difficult to relate to watershed-scale models. Thus, assessment of hydrologic impacts relies on spatial downscaling to translate the large-scale GCM projections to scales more representative of the physical implications of climate change (Christensen et al., 2004). There are two major techniques in downscaling: statistical and dynamic. Dynamic downscaling that simulates physical processes at finer scales is generally too computationally intensive for multi-decadal analysis (Maurer, 2007). Statistical downscaling is more widely used and essentially scales a GCM projection based on observed quantitative relationships between climates at the two spatial resolutions (Maurer et al., 2010). The three available methods of statistical downscaling considered for this study were as follows: bias-corrected and spatially downscaled (BCSD), constructed analogues (CA), and a hybrid method, bias-corrected constructed analogues (BCCA). Only BCCA was used in this study; however, general features of each method are described briefly below and illustrate why we implemented BCCA for this study.

There is usually a difference (bias) between observed and GCM-predicted climate outputs for almost all of the GCMs. In bias-corrected statistical downscaling, or BCSD approach, the observed climate data is evaluated against GCM output to remove bias. BCSD downscales monthly data, with a random resampling technique to generate daily values. This method inherently assumes that the climate projections simulations hold a constant bias in the GCM. The CA method, described by Hidalgo et al. (2008), uses daily large-scale output to directly downscale daily precipitation and temperature, instead of the more general monthly scale. It is based on the anomalies of daily precipitation and temperature but does not correct for bias. It ensures that daily fluctuations match the observed daily distribution, but does not guarantee monthly equivalents (Maurer et al., 2010). Furthermore, the same study found that in mountainous regions, the CA method produced better results, making it more appropriate to the UCRB.

The BCCA is a hybrid approach, following the CA approach of working with daily outputs but also recognizing the need for bias-correction. The process is almost identical to BCSD, but instead of applying it to monthly data, quantile mapping is imposed on daily values (Maurer et al., 2010). The BCCA technique explicitly corrects bias, creating datasets of actual values rather than anomalies (as in CA), but some downscaling bias remains. Capturing the variability of daily conditions is especially significant in a mountainous environment such as the CRB. Furthermore, the hydrology model used in this study (discussed below) requires daily data. Raff et al. (2009) demonstrated that while all downscaling methods produced reasonable streamflow statistics at most locations, the BCCA method consistently outperformed the other methods. BCCA captured daily large-scale skill and translated it to simulated streamflows with better reproduction of the observationally driven stream flows. Thus, the BCCA daily downscaled future data was selected to force a hydrologic model Watershed Analysis Risk Management Framework (WARMF). The BCCA daily datasets were recently made available by a joint project of the USBR, Lawrence Livermore National Laboratory (LLNL), Santa Clara University Climate Central, United States Geological Survey (USGS), and Scripps Institution of Oceanography. The hydrologic projection datasets were made possible by the efforts of the USBR, University of Washington's Climate Impacts Group (CIG) and the National Oceanic and Atmospheric Administration (NOAA) National Weather Service (NWS) Colorado Basin River Forecast Center. Their work created 1/8 degree gridded future climate hydrologic projection over the western U.S (Reclamation 2011, 2013). Time periods of historical (1961–2000), future Period 1 (2046–2065), and Future Period 2 (2081–2100) were used as these are the time scales for which the downscaled data is available for research use.

## 2. Materials and methods

### *2.1. Hydrologic modeling and model development*

Daily downscaled climate projections were used to drive the WARMF hydrologic model. WARMF was chosen for this study because it is a continuous simulation model that can provide a physical representation of the UCRB using a GIS database with inherent reservoir capabilities and stream diversions. A complete description is available in Chen et al. (2001). As a continuous model, WARMF considers soil moisture accounting and evapotranspiration. WARMF calculates daily runoff of a basin that is divided into catchments, stream segments, and lakes. Geza et al. (2009) successfully modeled the Turkey Creek Watershed of Colorado using WARMF. Their study analyzed calibration methods to improve performance of WARMF and was able to accurately simulate observed changes. WARMF uses daily time steps and requires daily records of precipitation, minimum and maximum temperature, cloud cover, dew point temperature, as well as air pressure and wind speed, which are used in the evapotranspiration, snow-formation, and snow-melt algorithms (Chen et al., 2001).

Daily precipitation is partitioned into rain and snow depending on daily temperature. Precipitation data is routed through the land layers to simulate snow and soil hydrology, producing runoff and shallow groundwater flow. A water-balance approach is used to calculate the hydrologic budget for each catchment resulting in runoff and base flow to river segments (Chen et al., 2001).

Several land use types can be defined for a sub-watershed-scale unit called a catchment (described in more detail below). The catchments may contain up to five soil layers. Each layer is assigned a thickness, initial soil moisture content, horizontal and vertical hydraulic conductivities, field capacity and porosity. The rate of percolation in the vadose zone from one soil layer to an underlying layer is limited by soil moisture content of the layer relative to its field capacity, level of saturation of the underlying layer, and vertical hydraulic conductivity. Lateral flow from a layer is based on Darcy's Law, where the head gradient is approximated as the slope of the land surface. The water balance is used to compute moisture content of each layer based on infiltration into the layer, percolation out of the layer, lateral inflow and outflow, and evapotranspiration (ET). Potential evapotranspiration is a function of total free surface water evaporation and soil transpiration based on Hargreaves equation. The model requires reservoir bathymetric data in the form of stage-area relationship.

The UCRB is delineated into 24 sub-watersheds, comprised of catchments, river segments, and 17 reservoirs (Fig. 2). The 24 sub-watersheds are further divided to over 600 catchments. All of the tributaries eventually feed into the main stem of the UCRB, prior to reaching the Colorado-Utah border. Model input parameters must be obtained for each catchment. Some input parameters are treated as catchment coefficients varied by catchment, defining the physical, chemical, and biological characteristics of each catchment, while others are defined as system coefficients with uniform coefficient applied to the entire basin.

Daily time-series of meteorological inputs such as precipitation and minimum and maximum temperatures are required for WARMF simulation. The data can be downloaded from the National Climactic Data Center (NCDC). USDA's National Resources Conservation Service (NRCS) Web Soil Survey (WSS) provides soil data and information. Soils data for the 13 counties were downloaded. The three prominent soil types in the basin were identified as sandstone (48%), limestone (15%) and 23 other soil types making the rest of the basin. Based on these soil types, soil parameters such as soil thickness, field capacity, porosity, horizontal and vertical conductivity were estimated. Land-use data were derived from the National Land Cover Dataset (NLCD) and imported to WARMF. The land surface of the basin is dominated by forest and rangeland. USGS water data web site (USGS, 2010) provides daily flow data for specific USGS gauging stations on river segments needed for model calibration. Diversions describe

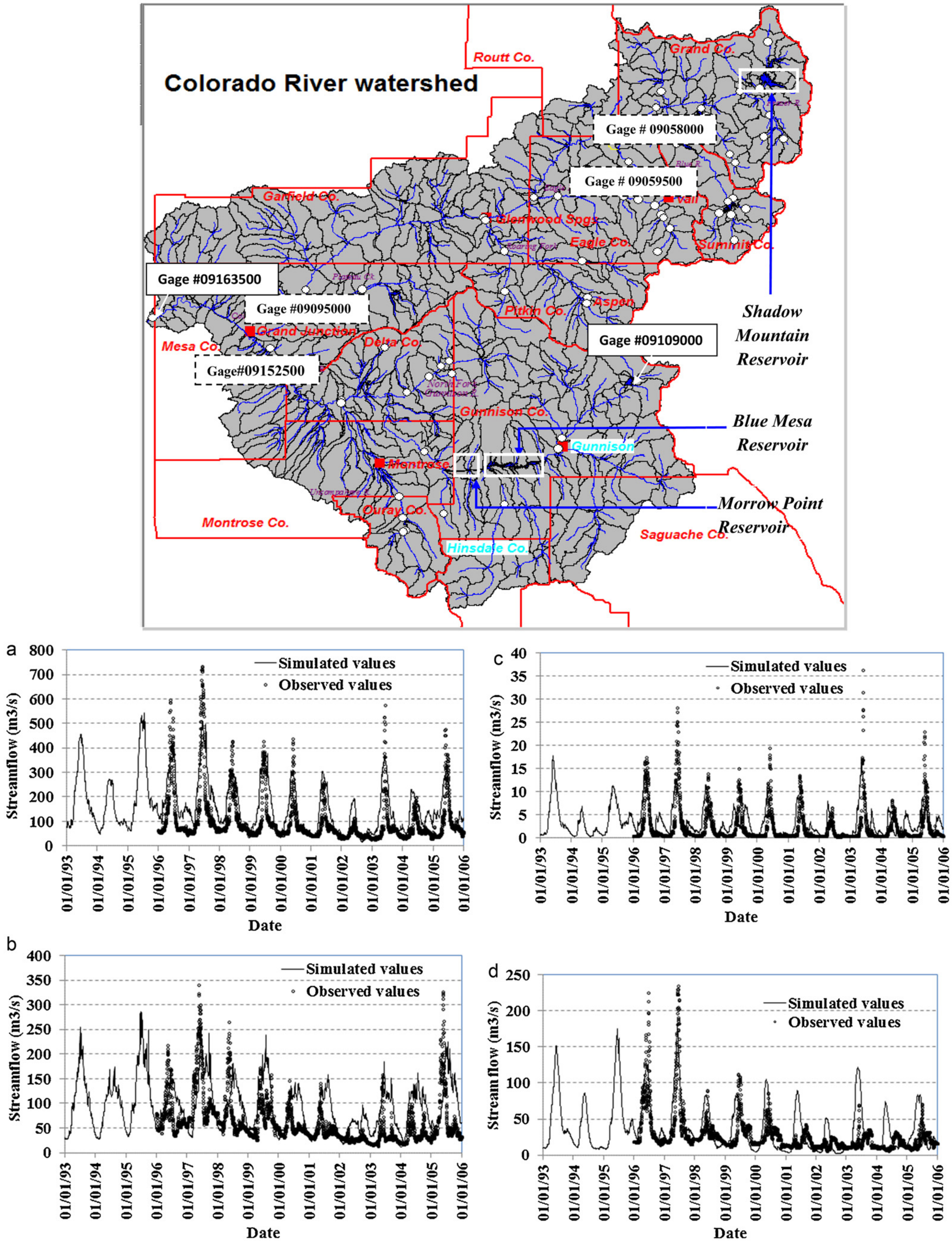


**Fig. 2.** UCRB catchments, gauge stations, and reservoir locations. (a) Simulated versus observed flow at station #09095000 Colorado River near Cameo, CO (Low elevation station). (b) Simulated versus observed flow at station #09152500, Gunnison River near Grand Junction, CO (Low elevation station). (c) Simulated versus observed flow at station #09059500, Piney River near State Bridge, CO (High elevation station) station). (d) Simulated versus observed flow at station #0905800 at Colorado River near Kremmling, CO (High elevation).

water removed from a stream predominantly for agricultural use. Diversions did not alter the water balance since most of the diverted water returns back to the streams as base or surface flow after use, over time. Our model included over 4500 diversions from Colorado Decision Support System (CDSS, 2010), which required an enormous effort to compile and post-process, but that greatly enhanced the realism of the model and improved model robustness. CDSS provides data organized by water division, river basin, and structure type. Our study area comprises of Colorado Water Divisions 4 and 5.

Seventeen reservoirs in the UCRB were incorporated into the WARMF model. The reservoirs that are used for hydropower include Blue Mesa, Morrow Point, and Green Mountain. Each reservoir is populated with observed data on reservoir geometry, existing water level, and stage-area-discharge data for the reservoir and the inflow/outflow structures. Physical data was obtained online from USBR (Reclamation, 2010) and through personal communication with each reservoir's operational personnel to develop stage-discharge tables describing spillway operation for reservoir simulation.

The impact on hydrology and reservoir storage due to climate change was analyzed under future climate projections using 3 GCMs and 2 SRES scenarios: MRI CGCM2 A2 and B1, CGCM3 A2 and B1, and MIROC A2 and B1. The output from each GCM was further categorized into two time frames: Period 1 (2046–2065) and Period 2 (2081–2100), with only Period 1 simulated in WARMF and compared with baseline scenario (1986–2000). Gauges were selected at significant locations considering watersheds, water supply impacts, climate characteristics, and hydropower influence (if leading to a producing reservoir), as well as geographic location (cross-boundary locations, elevation). Reservoirs were similarly selected, with most emphasis on hydropower production or potential at varying elevations.

### *2.2. WARMF model sensitivity analysis and calibration using UCODE*

Watershed models have more credibility when used as a decision-making tool or for assessing the impact of climate change after calibration. Geza et al. (2009), used UCODE (Poeter, 2005) for calibration of a WARMF model for Turkey Creek Watershed, Colorado. UCODE is a calibration and sensitivity analysis tool that minimizes the sum of weighted-squared-residuals with respect to the parameter values using a modified Gauss-Newton or Trust-Region method. We used UCODE linked to WARMF for sensitivity analysis and calibration. For the calibration, UCODE executes WARMF repeatedly, comparing simulated and observed data and adjusting parameter values to obtain the best fit.

Calibration of models with numerous input parameters requires identification of the most sensitive input parameters. Sensitivities reveal the significance of certain parameters on model performance. In UCODE, sensitivities are calculated and normalized to values between 0 and 1, with a value of 1 for parameters with maximum sensitivity and a value of zero for parameters that are not sensitive. Normally, parameters with a normalized value of less than about 0.01 are relatively insensitive and difficult to estimate during calibration and are associated with larger uncertainty (Hill and Tiedeman, 2007). It was determined through sensitivity analysis that the most sensitive parameters for the UCRB model are as follows: the Precipitation Weighting Factor (PF), a multiplier applied to the precipitation to account for local variations in precipitation amount from orographic effects; Evaporation Magnitude (EM), a scaling factor for evaporation used as an adjustment factor for ET calculated via the Hargreaves equation (Hargreaves, 1974); Evaporation Skewness (ES), a factor that accounts for seasonal variability of evaporation; Temperature Lapse rate (TF), a parameter that accounts for regional variations in temperature from orographic effects; Altitude Lapse rate (AF), a decrease in temperature with increasing elevation; and Soil Moisture Content (SM), Field Capacity (FC), and Horizontal Conductivity (Kh) (Table 1). Climate related parameters PF, EM, TF, AF and ES control the water balance and the remaining soil related parameters control runoff from rainfall.

Fig. 2 illustrates the gauge station locations used in calibration. In the study area, four gage stations were used to assess model fit (Figs. 2a–d). Three are located on the Colorado River. The first gage is Gauge #09095000, located at a low elevation on the Colorado River near Cameo. The other two gauges are further upstream at higher elevation on the Colorado River: Gauge #09058000, on the Colorado River near Kremmling, CO; and gauge #09059500, on the Piney River near State Bridge. The fourth gauge is located on the Gunnison River, Gauge #09152500 near Grand Junction.

**Table 1**
UCODE sensitivity analysis results of most significant parameters.

| Parameter name | Parameter symbol | Normalized value | Literature value |
|---|---|---|---|
| Evaporation magnitude | EM | 1.0 | 0.6–1.4 |
| Evaporation skewness | ES | 0.33 | 0.4–1.4 |
| Temperature lapse rate (°C) | TF | 0.31 | −5 to 5 |
| Precipitation weighting factor | PF | 0.3 | Varies by catchment (0.35–1.5) |
| Porosity or saturated moisture content | SM | 0.2 | 0.2–0.6 |
| Field capacity ($m^3/m^3$) | FC | 0.1 | 0.0–0.4 |
| Altitude lapse rate (°C/m) | AF | 0.16 | 0.001–0.009 |

Other WARMF input parameters were found to be relatively not sensitive and were thus not included in detailed analysis.

The time series of observed vs. simulated values for gauges #09095000, #09152500, #09058000, #09059500 after model calibration are illustrated in Figs. 2a–d. We limited the calibration to only few sensitive parameters in order to achieve model convergence to a unique solution. Of the 9 parameters evaluated for system sensitivity, 3 were found to exhibit the most influence on model results. Calibration of a large hydraulic model to all 9 parameters was deemed too exhaustive and would not converge the model in a reasonable length of time. Only the most sensitive parameters of EM, ES, and PF were estimated during calibration. Literature values were used for the rest of the parameters. In WARMF, EM is a system coefficient and only one value could be used for all of the catchments in the basin.

The EM factor usually has a value between 0.6 and 1.4 (Herr et al., 2000) (see Table 1). With a starting value set at 1.0, the final calibrated value for EM was 1.3. In a region with much variable topography, such as the UCRB, the magnitude of evaporation is expected to vary greatly. Thus, ES was also calibrated to a value of 1.27 (within the literature range of 0.6–1.4). PF in WARMF is responsible for the effects of elevation difference on precipitation. PF was adjusted at the catchment level, based on site-specific conditions. Parameter values over all of the catchments varied from 0.35 to 1.5 and varying the PF factor by catchment during calibration significantly improved model performance.

Snow melt rates were generally less sensitive and were not critical to model performance. Open area melt rate is even less sensitive compared to forest area melt rates mainly due to limited area extent for open area in the basin. Hence melt rates were set to a value of 0.1 cm/day. Summary of parameter values determined via literature review and through calibration are listed in Table 1.

## 3. Results

### 3.1. Precipitation projections

We analyzed precipitation projections based on BCCA datasets at two contrasting locations in the UCRB with respect of elevation that are approximately 255 miles apart: a lower elevation station near the Utah State Line (4325 feet), and a higher elevation station near the Taylor Park Reservoir (9170 feet) (Figs. 3a and 4a). Taylor Park reservoir sits along a tributary of the Gunnison River and serves as a good indicator of a possible high elevation impacts. The study demonstrated that projected hydrologic response to climate change is greatly influenced by elevation. The figures illustrate the mean daily precipitation (inches), organized by month, based on average daily accumulation for both A2 and B1 (using all 3 GCMs) climate scenarios for a specific time period.

Figs. 3a and 4a illustrate precipitation trends exclusive of all climate scenarios and models, isolating only the time period. The variability across the climate models and the two scenarios was relatively small compared to the difference between historical data and GCM predictions; thus, we compared the observed values to the average of all climate models and scenarios. The purpose being to demonstrate performance of GCMs compared to observation, the figures include the historical precipitation values (1961–2000) and precipitation predictions from downscaled GCM data using BCCA method for the same historical period. At low elevation, historical precipitation prediction from BCCA captured seasonal variation in the observed data but differed in magnitude. At higher elevation, precipitation predictions from BCCA illustrate a trend toward increased precipitation for the winter months, but a

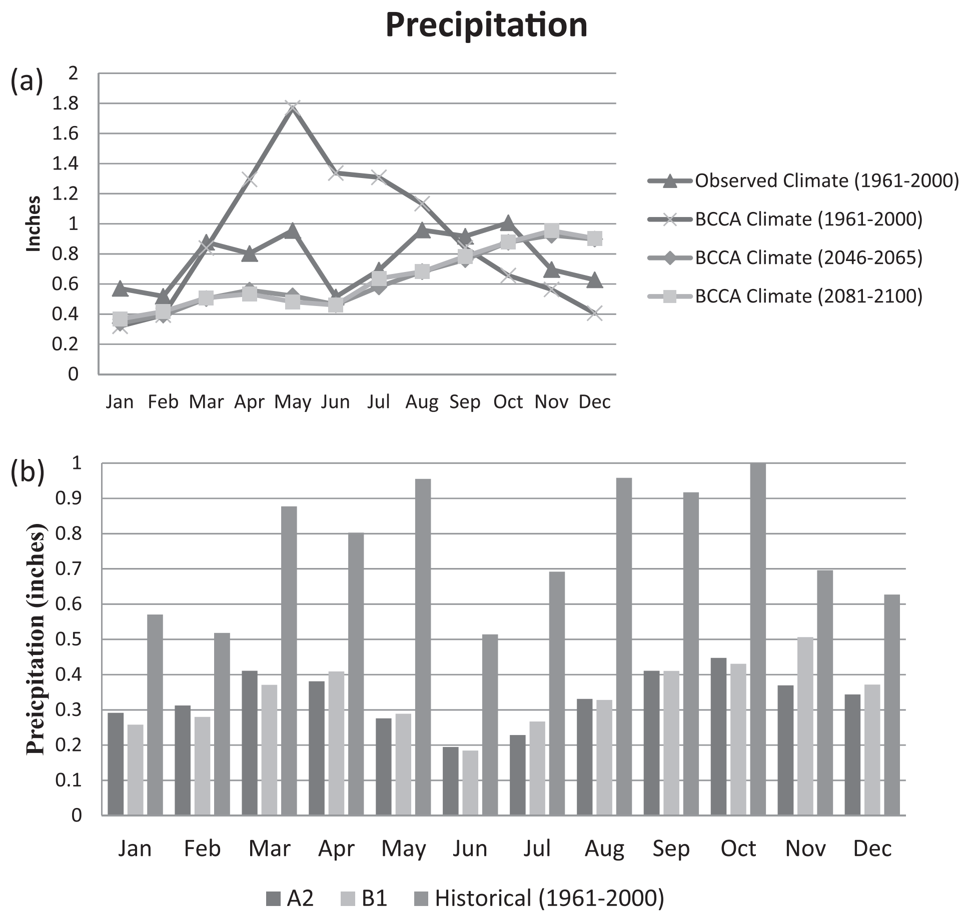


**Fig. 3.** (a) Average of daily precipitation, summarized for each month, at low elevation near Utah State Line (USGS #09163500). (b) Average of daily precipitation summarized for each month at low elevation near Utah State Line under SRES A2 & B1 of all GCMs in Period 1 (2046–2065) compared to observed climate data.

decrease in spring months. The analysis showed the model captured the general seasonal trend but the observed data and the climate model showed a considerable difference in magnitude with BCCA over-predicting precipitation during the high rainfall months in the lower elevation and consistently under-predicting precipitation in the higher elevation. Our results showed that for lower elevation, the climate projections describe a reduction in annual precipitation (compared to historical observed values) illustrated in Figs. 3a through 4a. Assuming the over-predictions at low elevation are propagated to future years, the lower elevations would have even higher shortage of precipitation and reduction in stream flows than predicted in our study. Oppositely, assuming the BCCA under-predicted future climate as was seen in the observed data, the higher elevations would experience increases in precipitation and increased runoff. This supports prior work which emphasized wetter conditions during winter months and drier in summer in the near future (2046–2065), but overall drying toward the end of the 21st Century. The GCMs predicted reductions in precipitation (10–40%) compared to observed values at lower elevations, while at higher elevation an increase in precipitation (20–35%) was observed during some months.

Figs. 3b and 4b describe impacts of the SRES scenarios A2 and B1 on predicted precipitation under each GCM at low elevation. For lower elevation, the climate projections describe a reduction in annual precipitation (compared to historical observed values) of over 54%. Similarly, at low elevation, the

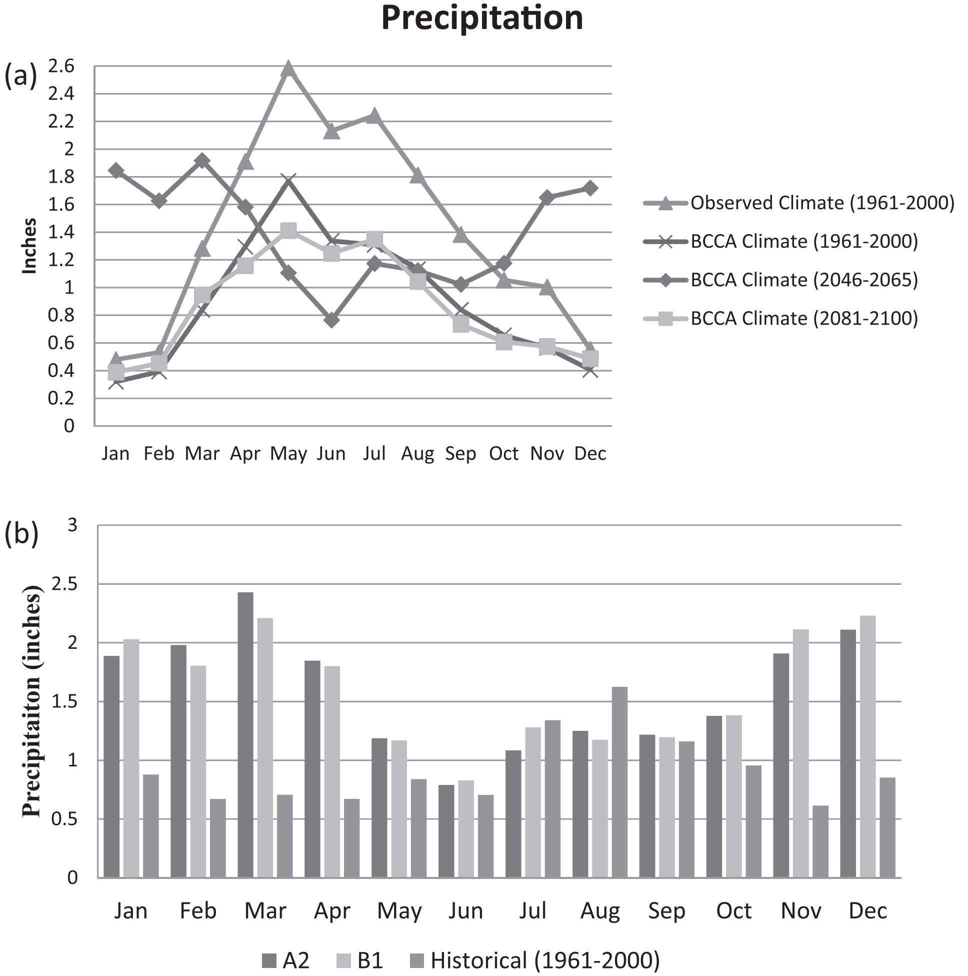


**Fig. 4.** (a) Average of daily precipitation, summarized for each month, at high elevation near Taylor Park Reservoir (USGS #09109000). (b) Average of daily precipitation at high elevation near Taylor Park Reservoir summarized for each month under SRES A2 & B1 of all GCMs in Period 1 (2046–2065) compared to observed climate data.

largest reduction in future precipitation (greater than 60%) occurs during the summer months of May to August. This reduced precipitation combined with increasing summer temperatures (discussed below) is expected to exacerbate the drying conditions and reduction in stream flow. From November to February, the reduction in precipitation is relatively lower, although specific results vary depending on climate scenario. Low elevations under B1 scenario show a reduction in November precipitation of (only 27% less than the historical), but the reduction becomes 47% under the A2 condition. January and February amounts also differ depending on climate scenario, with A2 showing more precipitation during both months. These finding echo prior climate studies that indicate wetter winters and hotter, drier summers, under extreme climate conditions.

On the contrary, the higher elevation (Fig. 4a) experiences precipitation volume increase from 57% to 71% (depending on climate scenario) compared to historical data, but distinct drying during summer (May to August), when future precipitation falls below historic values. The greatest precipitation increases under future climate scenarios occur during the months of December and March. In mountainous high elevation terrains such as the one in our study, the months of December through

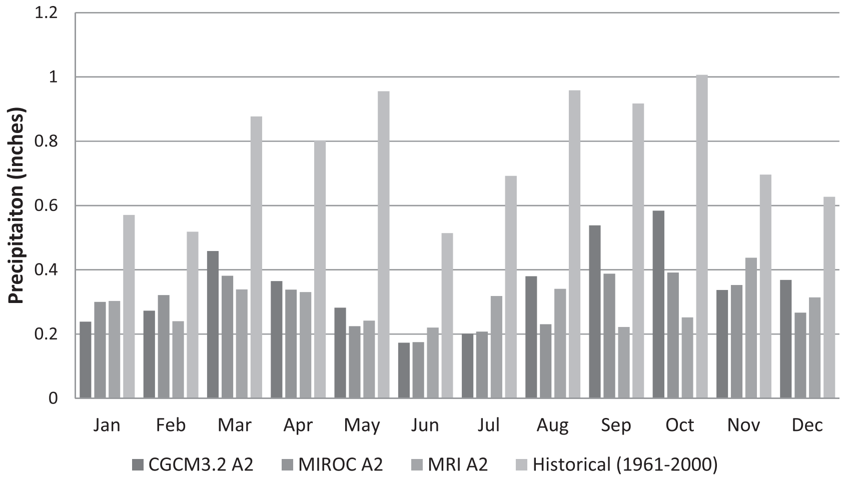


**Fig. 5.** Daily-averaged precipitation comparison of GCMs under SRES A2 condition in Period 1 (2046–2065) and observed historical climate at low elevation near Utah State Line.

March experience the most frequent and greatest snow accumulation largely due to significant orographic effect. During the summer drying period, similar to that of lower elevation, a reduction in precipitation is predicted compared to historical data (as much as 27%) (Fig. 4b). Again, these drying conditions are exacerbated by predicted temperature changes in the region (discussed in Section 3.2). This agrees with the IPCC's (2007) finding of substantial summer drying in the mid-latitudes. These trends, although averaged across the three GCMs, display a strong dependency on elevation.

We observed that climate change is closely linked to elevation in the UCRB. Thus, changes in reservoir operations and management in response to climate change should be addressed based on reservoir elevation and location. Many of the reservoirs on the UCRB, including those with the most hydropower production potential, reside at high elevations. From these results, we can see that there will be significantly more water in winter months from precipitation increase, but severe drying in summer. This is problematic because water shortages generally occur during summer months. This will require adaptive policies and action by water managers (presented in more detail in a subsequent section).

Next, we analyzed the differences between GCMs with respect to precipitation predictions in only the low elevation (Figs. 5 and 6) station to gain a better understanding of how variability in climate models might impact the results of a hydrologic model intended to analyze climate-change impacts on water resources. The B1 scenario shows 8% more precipitation annually than the A2 scenario. Winter precipitation is more pronounced under A2, as is summer drying. The A2 scenario also exhibits more extreme seasonality than B1. Under both the A2 and B1 scenarios, CGCM3 trends toward higher precipitation values, MIROC generally describes the lower values, and the MRI predictions are intermediate.

These results suggest a consistent bias exists between the different GCMs, but the difference was not more than 16%. When analyzing GCM results for climate change analysis, no single model can be regarded as an ideal one. Thus, the major purpose and benefit of analyzing several climate models, as in this study, is to produce a range of outputs from different GCMs and investigate the envelope of influence in climate projections on the water resources, such as predicted stream flow and reservoir levels, to better understand associated uncertainties. This approach should aid water managers and operators in assessing future changes and risks under uncertainty.

### 3.2. Temperature projections

Figs. 9 and 10 describe the average of daily minimum temperatures summarized for each month at the Utah State Line (low elevation) and Taylor Park (high elevation) gauges. At low elevation (Fig. 9),

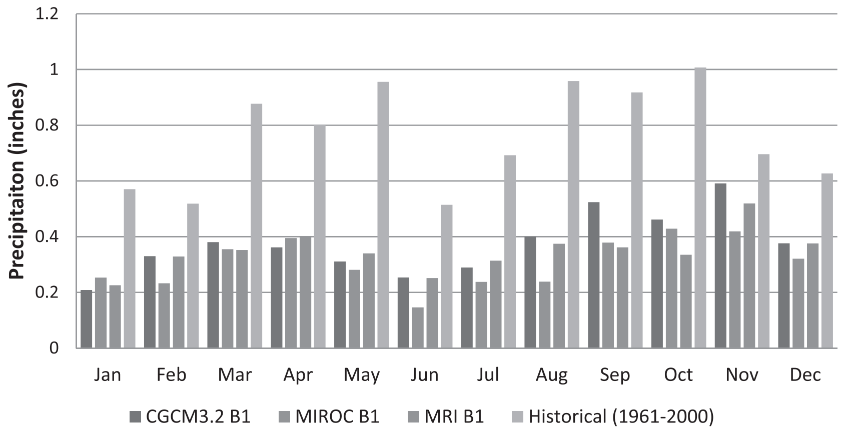


**Fig. 6.** Daily-averaged precipitation comparison of GCMs under SRES B1 condition in Period 1 (2046–2065) and observed historical climate at low elevation near Utah State Line.

GCM predictions describe an increase in minimum temperatures compared to historical observations for the historical period (1961–2000). The increase is more pronounced for the far future, Period 2 (2081–2100), compared to near future, Period 1 (2046–2065). This behavior differs from precipitation trends, where the decline was more pronounced in the near future of Period 1 (2046–2065) than the far future (2081–2100). It is widely agreed that global temperatures will increase under future climate conditions (Christensen and Lettenmaier, 2007; Barnett and Pierce, 2009; and others). There is a general trend toward warming at high and low elevations, but the increase in temperature is predicted to be greater at lower elevations, exacerbating already dry and warm conditions. Fig. 9 illustrates the months of January through March experiencing higher temperatures under observed climate, rather than predicted. With a reduction in minimum temperatures in the future, snow as snow and not as melt may propagate for longer than has been expected in the historical past at higher elevations. At low elevations, the opposite is true, where the minimum temperature has been shown to increase in winter and generate early snow melt, specifically an increase in early spring flows (1–2 weeks earlier) than in the past (IPCC, 2007). Fig. 7 illustrates a 3–5 degree Fahrenheit (°F) mean annual increase in maximum temperature at low elevation, while Fig. 8 shows an increase of 0.7–2 °F at higher elevation.

Temperature changes in response to climate scenarios A2 and B1 are illustrated in Figs. 9 and 10 for lower and higher elevation, respectively, during Period 1 (2046–2065). The maximum change in

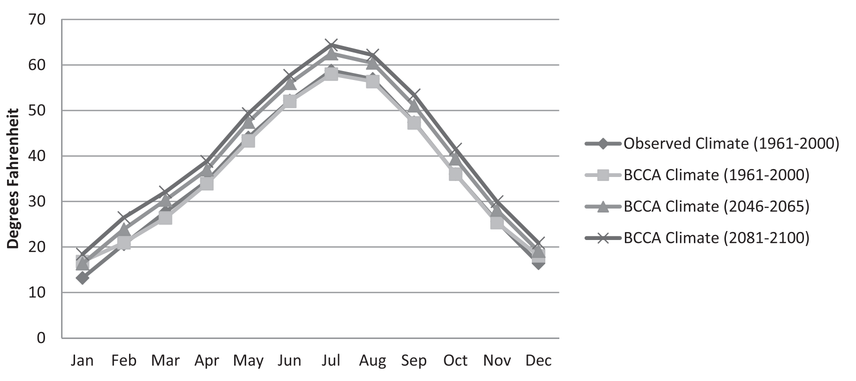


**Fig. 7.** Average of Daily Maximum Temperatures (F) for each month under Future Climate at #09163500 at low elevation near Utah State Line for future time periods.

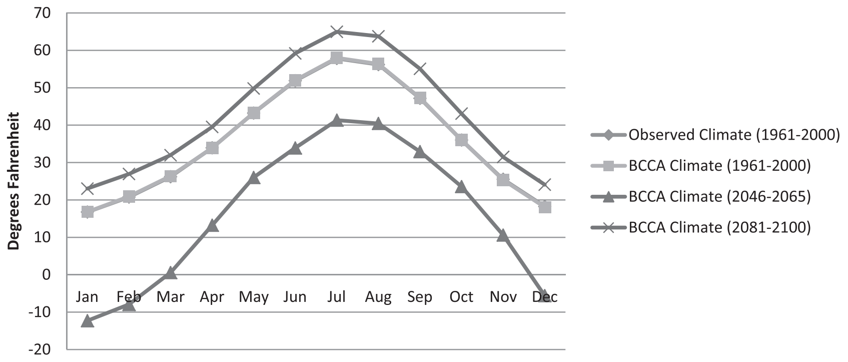


**Fig. 8.** Average of Daily Maximum Temperature (F) for each month under Future Climate at #09109000 at high elevation near Taylor Park for future time periods.

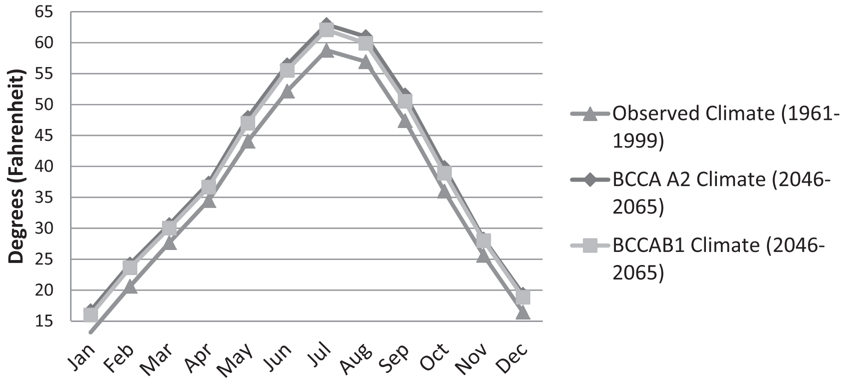


**Fig. 9.** Comparison of minimum temperature at low elevations for scenarios A2 and B1 with observed climate Period 1 (2046–2065) near Utah State.

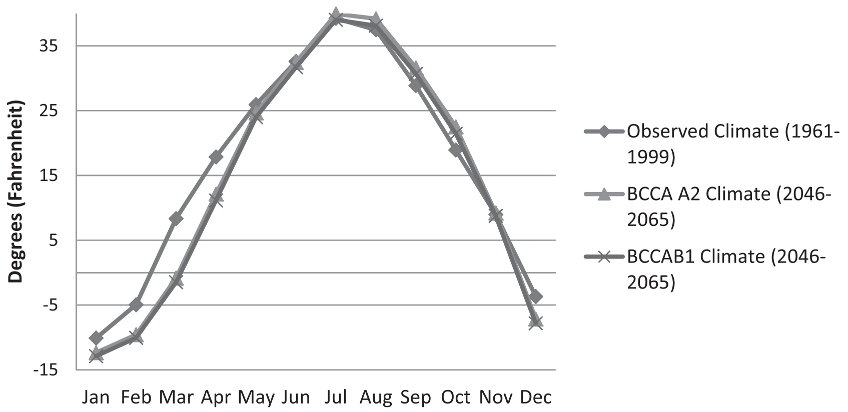


**Fig. 10.** Comparison of minimum temperature at high elevations for scenarios A2 and B1 with observed climate Period 1 (2046–2065) near Taylor Park.

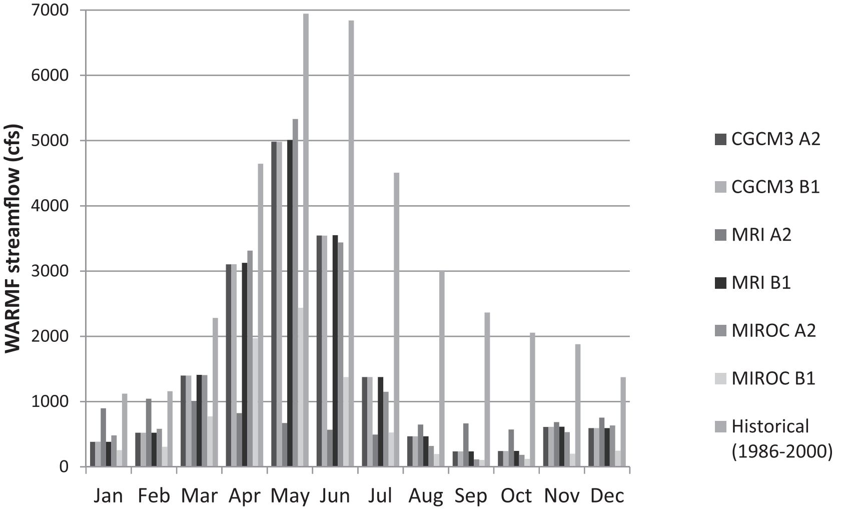


**Fig. 11.** Comparison of predicted streamflow under all GCMs and emission scenarios in Period 1 (2046–2065) at gage #09163500 at low elevation near Utah State Line.

temperature at lower elevation is 3.5 °F for A2 scenario and 2.8 °F for B1 scenario, as compared to historical data. Rise in temperature is exacerbated during the summer months of June to September, where a 4 °F difference is produced. The difference between the two climate scenarios, A2 and B1, was only 1.8% (or 0.7 °F), showing the uniformity of increasing summer temperatures. At high elevations, temperature is also predicted to increase but differs in timing and is much less pronounced in magnitude. Fig. 10 illustrates the pattern of winter months growing colder, while the summer months become hotter. A2 illustrates only a maximum increase of 2 °F and B1 demonstrates a 1.5 °F rise, as compared to historical data. With temperatures actually decreasing in winter months (as much as 9 °F decrease in March), this directly impacts snowmelt and, consequently, streamflow. Hydropower is inherently dependent on streamflow, which is highly influenced by snowmelt at high elevations. The timing of snowmelt would be altered at high elevations under future temperature conditions, due to changes in the hydrograph, with melt occurring earlier in the season than historical averages.

### 3.3. *Stream flow projections*

The WARMF hydrologic model was used to analyze the impact of the projected climate changes presented earlier on water resources in the UCRB. Figs. 11–13 illustrate stream flow changes under scenarios A2 and B1 for the 3 GCMs at flow gauge near the Utah state line, after the confluence of the Gunnison and Colorado Rivers. Historical stream flow values are significantly greater than any of the predicted scenarios, showing a pronounced reduction in future stream flow. Future stream flow is shown to decline considerably by about 62%. Most pronounced is the change in summer months (June to August), followed by September and October months. Historical peak flows generally occurred between May and July, although distinct peaks were observed during May and June as shown in Fig. 11. This moves the centroid of the hydrograph to an earlier period of April to June from the observed May to July period under historical conditions, resulting in most of the stream flow to occur a month earlier. In Fig. 12, stream flow projections are compared for the different GCMs, at low elevation near the Utah-Colorado State line. Projected stream flows are 52% greater under CGCM3 than MIROC (similar to precipitation trends) in the B1 scenario, but only 4% more in A2 conditions. MRI results illustrate 50% more streamflow under A2 conditions than in B1. MIROC behaves similarly to MRI in A2 scenario but is only half of the B1 predicted streamflow for both MRI and CGCM3. Essentially, MIROC consistently shows the least streamflow (consistent with our prior findings), but not the least precipitation accumulation; hence, streamflow response is not linearly dependent on precipitation

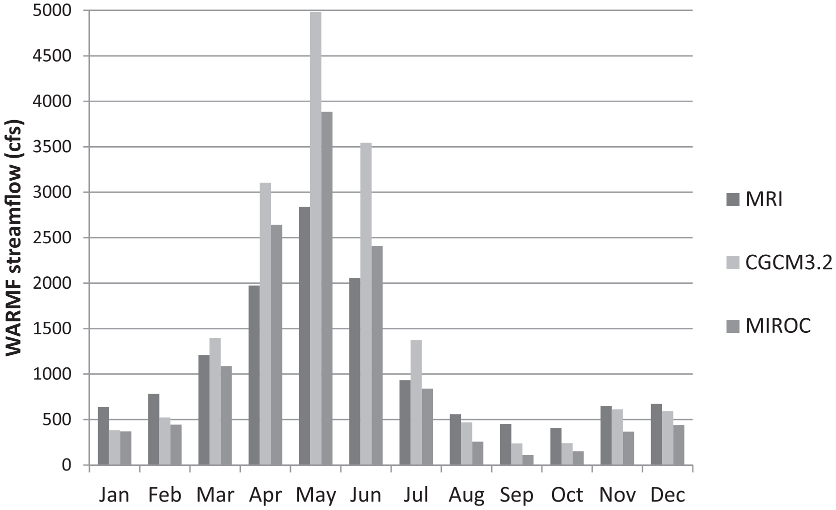


**Fig. 12.** Comparison of predicted streamflow (cfs) for each GCM, average of A2 and B1 scenarios in Period 1 (2046–2065) at low elevation near Utah State Line.

trends. Although MIROC predicts an overall decrease in streamflow, it does show higher volumes in the summer than MRI. Overall, all GCMs illustrate an average streamflow reduction of approximately 78% in A2 and 72% in B1, with the greatest decrease described in the months of May through August. From these results, we can see that hydrologic response may differ based on the GCM used to predict the changes but the impact is the same: an overwhelming reduction in future streamflows along the Colorado River.

Fig. 13 describes the impact of the emission scenarios A2 and B1 on stream flow in comparison to historical values and to each other (difference). A2 illustrates a more extreme behavior envelope, i.e., more wet winters and more dry summers. For the months of November to February, streamflow under scenario A2 is greater than that simulated by the B1 scenario. However, streamflow is dramatically

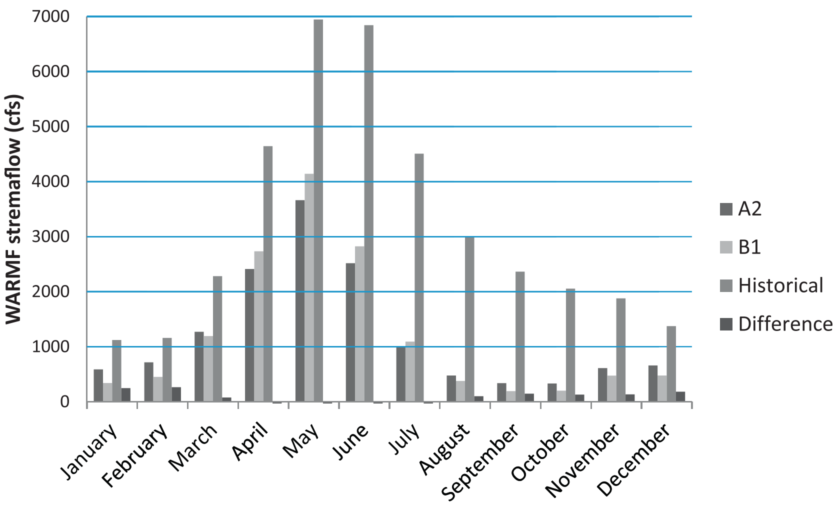


**Fig. 13.** Mean of daily streamflow values from SRES A2 and B1 compared historical values. The difference value is between A2 and B1 in Period 1 (2046–2065) at low elevation near Utah State Line.

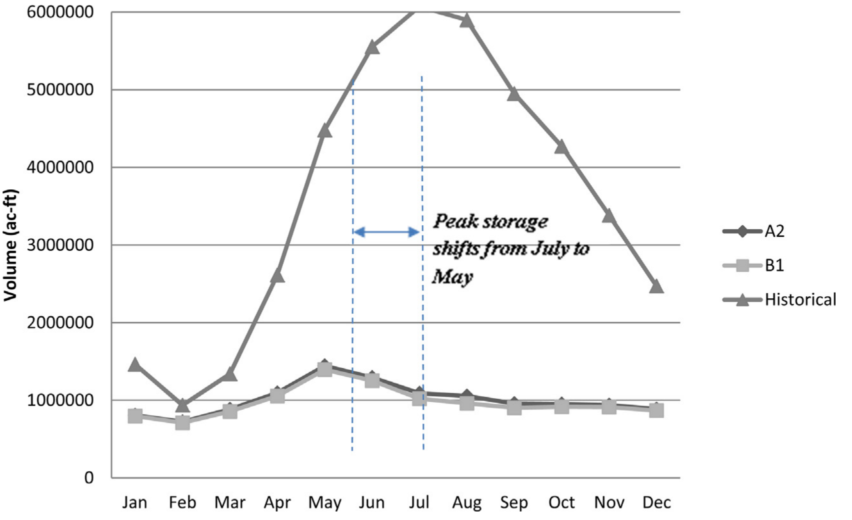


**Fig. 14.** Monthly Mean Water Storage for all GCMs for Blue Mesa Reservoir in Period 1 (2046–2065).

reduced in rainfall–runoff summer months (April to July) under A2. Temperature is also predicted to increase annually, resulting in increased evaporation rates and reduced soil moisture, and therefore reduced runoff; flow is shown to decrease during the most affected summer months under both A2 and B1 scenarios. A 62% reduction occurs in annual flow volume occurs under A2, exacerbating the already over-allocated water deliveries downstream.

### 3.4. *Reservoirs and hydropower production impact*

The hydrologic impact of climate shift on reservoir levels and hydropower production was analyzed considering an overall increase in temperature and flow reduction, with earlier snowmelt across the UCRB. Hydropower-producing reservoirs Blue Mesa, Morrow Point, and Shadow Mountain Reservoir (Fig. 2) were assessed. The forthcoming discussion focuses on comparison and evaluation of monthly averaged historical reservoir volume and spill versus the predicted volumes for scenarios A2 and B1 (averaged across the three climate models). Spill is the volume released without producing hydropower when river flows exceed the hydraulic capacity of the system to generate electricity. The Blue Mesa reservoir is the largest reservoir in the state, at an elevation of more than 7500 feet with a surface area of 9200 acres. It is located on the Gunnison River and produces over 260 MW each year. Under projected climate conditions, it experiences reduction of 76–85% in spill (depending on scenario and GCM) and 70–73% in volume (Fig. 14). Note that peak storage occurs two months earlier (in May instead of the historical July) for both emission scenarios, which is attributed to earlier snow melt causing earlier peak in volumes. Despite a projected temperature increase, a decrease in evaporation is expected (not shown), which is attributed to the large decrease in surface area. The decrease in surface area is attributed to depletion in storage volume due to increasing temperatures in summer months which is propagated to the lower water levels, thus decreasing surface area from which evaporative losses become less influential.

Morrow Point reservoir is 12 miles downstream of Blue Mesa on the Gunnison River with a surface area of 918 acres and a maximum capacity of 117,000 acre-feet. Its 173 MW capacity is used for water supply and irrigation. Under future climate projections, changes in spill and volume were not nearly as significant as for Blue Mesa (Fig. 15), although a general trend indicated slightly reduced reservoir levels in the winter months, with increased levels during the late spring and summer months. The projected climate, elevation, and location of this reservoir are not much different than that of the Blue Mesa Reservoir, but the two vary greatly in size. Blue Mesa reservoir has a maximum capacity of

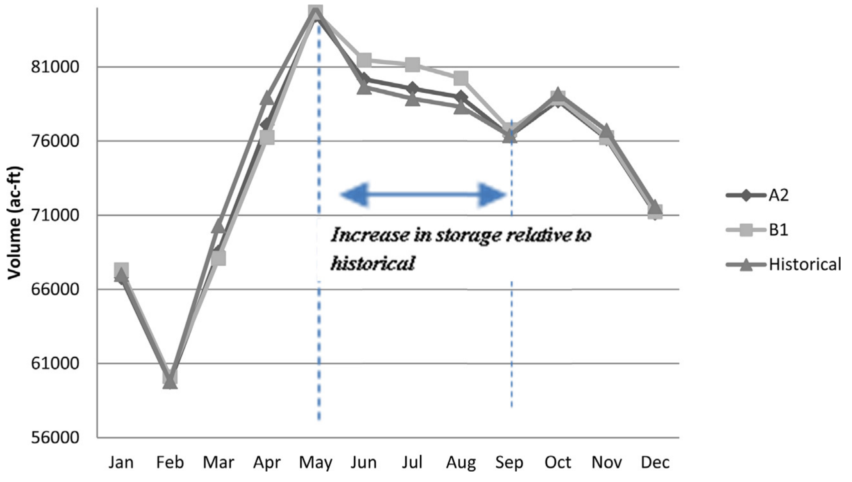


**Fig. 15.** Monthly Mean Water Storage for all GCMs for Morrow Point Reservoir in Period 1 (2046–2065).

940,700 acre-feet and is located about 350 feet higher than Morrow Point. The relatively small change in Morrow Point storage is attributed to its being managed by Blue Mesa Reservoir upstream; the larger reservoir controls the flows to Morrow Point, mitigating climate influenced impacts of increasing temperatures and decreasing precipitation. Since Blue Mesa controls the flow, its reduction in volume due to a reduction in precipitation and increase in temperature also results in less flow to Morrow Point and decrease in storage volume. This demonstrated that there is a cross basin effect between reservoirs under climate change scenarios which could be different from what is observed based on historical climate, indicating the need for updating of reservoir rule curves considering the impact of climate change.

Shadow Mountain reservoir lies upstream of the glacial limit at about 8300 feet, located in a glacial moraine. It is part of the Colorado-Big Thompson project water collection system and is critical to providing water for consumption, energy, and irrigation needs. It is approximately 1337 surface acres with maximum capacity of 17,354 acre-feet. Under future climate conditions, there is a 1–3% increase in precipitation in the proximity of the reservoir and a 5–7% reduction in overall evaporation. The hydrologic model predicts 8–10% increase in spill and a 1–5% increase in total volume (Fig. 16). A

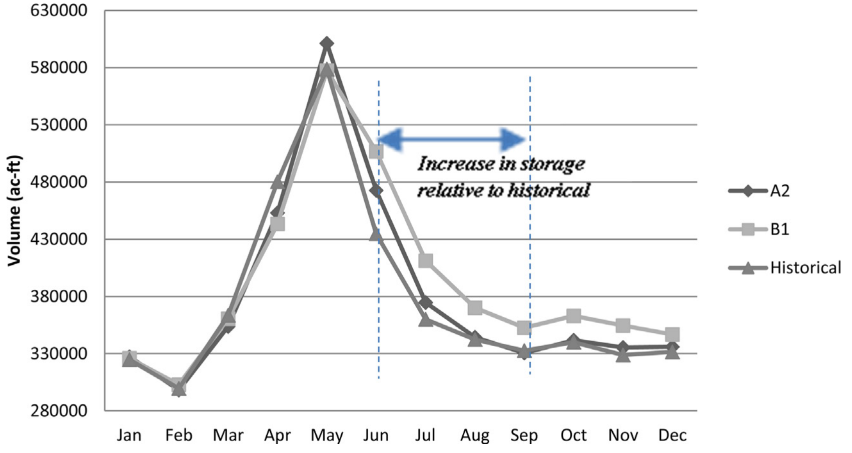


**Fig. 16.** Monthly Mean Water Storage for all GCMs for Shadow Mountain Reservoir in Period 1 (2046–2065).

slight decrease in volume is predicted during late winter and spring, with a corresponding slight increase in volume from June to September under both climate scenarios, whereas a slight increase is projected from September to December for the reduced emission (B1) scenario. The earlier onset of snowmelt and subsequent earlier intense runoff may also have a significant impact on hydropower, particularly for small reservoirs. Earlier more intense runoff leads to more dam spillage during peak storage, reducing the volume retained entering the summer months when power demand is highest. Additional storage for early spring melt in smaller reservoirs is necessary to avoid spillage in spring to enable operators to accommodate demand later in summer.

Hydropower production is inherently reliant on storage or head for energy production. In the above scenarios, power generation for the Blue Mesa Reservoir could decline significantly due to reduced volume and head. Adaptive management is necessary to address a changing environment. This involves identification of varying climate variables (precipitation, temperature) and implementing strategies to mitigate the variability. Then, perhaps most significantly, we can evaluate the effectiveness of the new strategies and adapt them further if results are unsatisfactory. A significant portion of adaptive management involves changing existing rule curves, which are used to guide reservoir operations with regard to power generation. Rule curves describe the water level, or range of acceptable levels, for each day of the year (i.e., levels needed to generate a certain hydraulic head and thus control power generation to meet historic demand on a daily basis). Reservoir rule curves specify the target elevation of the reservoir. When water level is below the level specified by the rule curve, discharge to downstream could be reduced to increase water level in the reservoir and release as much as possible to regain flood storage when storage levels exceed the rule curve. The amount that you release can be constrained by factors such as downstream flooding and the physical release capacity at the dam. Dropping the rule curve to a lower elevation will produce more flood storage; however, those decisions and established practices were set based on historic levels and approaches. Rule curves need to be accurately managed as they may optimize flood operations but negatively impact other operations such as water supply and hydropower production. Furthermore, rule curves need to be adapted to the changing climate, as levels that were historically acceptable and annual time periods for which they were created may no longer apply in future climate conditions.

## 4. Conclusions

Future projections show that precipitation changes vary by elevation. At low elevation near the Utah state line, the projections describe more than a 60% decline in precipitation. Conversely, at high elevation near Taylor Park Reservoir projected precipitation increases by as much as 74% compared to historical values. Regardless, all elevations depict a decline during summer months, which agrees with the IPCC's (2007) finding of substantial summer drying in the mid-latitudes. A basin-wide increase in temperature, especially the minimum temperature, causes precipitation to fall as rain instead of snow. At lower elevations, the projections show an increase in temperature more pronounced during the summer months of June to September. At high elevations, temperature is also predicted to increase but differs in timing and is much less pronounced. Under the higher emission A2 scenario, streamflow is greater during winter months but is dramatically reduced in runoff-dominated spring and summer months (April to July). Under A2 scenario, the hydrologic response is more pronounced when precipitation effects are strongest in winter. Temperature is projected to increase annually resulting in increased evaporation and reduced soil moisture (the latter results in greater infiltration capacity during storms), leading to decreased stream flow during the summer months under both A2 and B1 scenarios. This process exacerbates and/or creates drying conditions. With an increase in temperature of 2–4 °F basin-wide, timing and magnitude of stream flow is also impacted. We found snowmelt to occur 2–4 weeks earlier, leading to reduction in streamflow.

Our simulation results showed reduction in water storage at the high elevation for hydropower-generating Blue Mesa reservoir, while only slight changes are projected 12 miles downstream at Morrow Point reservoir. This discrepancy in water storage is attributed to the influence of surface area on evaporative demand, where the latter reservoir was less impacted by evaporation. At Shadow Mountain reservoir, volume increased by up to 5%, mainly ascribed to precipitation increases from orographic effects.

Hydropower is dependent on inflow conditions. Smaller reservoirs are most significantly impacted if early melt inflow overwhelms capacity; necessitating spill of extra water needed in later summer months. Additional spilling of reservoirs in early spring could limit water volume in reservoirs during summer and make it more difficult for power operators to meet peak demand. Larger reservoirs are less impacted but still experience a changed regime in response to climactic changes. Water managers will need to adjust rule curves and operation policies to accommodate all demands (specifically for multi-use reservoirs of water supply, irrigation, and hydropower production).

Projected warmer and drier conditions resulted in reduction of river flow and increased evaporation, which tend to reduce reservoir levels and thus hydropower capacity but also impact the ability to meet water subscriptions downstream. Most of the sub-catchments of the UCRB face a decrease in future precipitation, with potential for more frequent occurrence of intense events. The combination of less precipitation with higher temperatures indicates a potential for water stress. Adaptive policies are necessary to deal with projected changes. Without proactive action, current practices will lead to annual loss in hydropower potential and reliability in future climate. Rule curves, on which operations are based, must be changed to optimize production while saving water when necessary and minimizing flood risk.

## Conflict of interest statement

None declared.

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