A STUDY OF CLIMATE CHANGE IMPACTS OF THE UPPER COLORADO RIVER BASIN ON WATER RESOURCES AND HYDROPOWER PRODUCTION

By

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ABSTRACT

The Upper Colorado River Basin (UCRB), comprised of the Colorado and Gunnison River basins, is regulated by 17 major reservoirs to provide water supply, flood control, and hydropower. It is the prime water source for much of the western United States, as well as key wildlife and fish habitat. Climate change is an issue of concern on the basin due to the sensitivity of snow accumulation processes that dominate runoff generation within the region. Climate models project an average warming of up to 4^{o} F, coupled with a decline in precipitation falling as snow. There is no numerical consensus of the magnitude of change in precipitation, but there is general agreement that precipitation changes will be exacerbated by increased evapotranspiration rates, reducing overall runoff. This is expected to cause a decline in runoff and hydropower generation capacity.

Potential impacts of climate change on the hydrology and water resources of the UCRB were assessed through a comparison of simulated stream flow, temperatures, and reservoir volumes and storage levels. Future climate conditions derived from climate centers: Meteorological Research Institute (MRI-CGCM2.3.2), Canadian Centre for Climate Modeling and Analysis (CGCM3.2 T47), and the Center for Climate System Research at the University of Tokyo with the National Institute for Environmental Studies and Frontier Research Center for Global Change (MIROC 3.2) under A2 and B1 emission scenarios were compared to historical conditions. From the joint venture of the United States Bureau of Reclamation (USBR) and other research and university facilities, bias-corrected constructed dialogues (BCCA) daily downscaled precipitation and climate data was processed and used to drive the Watershed Analysis Risk Management Framework (WARMF) hydrologic model to simulate future changes in the UCRB. WARMF performs daily simulations of snow and soil hydrology to calculate surface runoff and groundwater accretion to river segments, lakes, and reservoirs. All model scenarios project a reduction in 21st century flows, though the magnitude varies with location and elevation. Results illustrate basin-wide temperature increases at low elevations, with extreme seasonality increasing at high elevation stations in future climate. Reservoir levels in Blue Mesa declined more than 70%, but other reservoirs showed varying results dependent on location and climactic conditions. The resultant climate change scenarios will motivate adaptive watershed planning and management decisions and policies in response a changing climate and mitigate future concerns.

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LIST OF ABBREVIATIONS

ASCE	American Society of Civil Engineers
BASINS Better	Assessment Science Integrating Point and Nonpoint Sources
BAU	Business-as-Usual
BCSD	Bias Corrected and Spatially Downscaled
BCCA	Bias Corrected Constructed Analogues
CA	Constructed Analogues
CFS	Cubic Feet per Second
CRB	Colorado River Basin
CRBM	Colorado River Budget Model
CRRM	Colorado River Reservoir Model
CSTR	Continuously Stirred Tank Reactor
DEM	Digital Elevation Model
DO	Dissolved Oxygen
ET	Evapotranspiration
GCM	General Circulation Model
GHG	Greenhouse Gas
GIS	Geographic Information System
GSOD	Global Summary of Day
HadCM3	Hadley Centre Coupled Model, version 3
HEC	Hydrologic Engineering Center
HSPF	Hydrological Simulation Program - Fortran
HUC	Hydrologic Unit Codes
IPCC	Intergovernmental Panel on Climate Change
LAI	Leaf Area Index
NCDC	National Climatic Data Center
NHD	National Hydrography Dataset
NLCD	National Land Cover Dataset

NOAA	National Oceanic and Atmospheric Administration
NRCS	National Resources Conservation Service
PRMS	Precipitation Runoff Modeling System
PGW	Pseudo Global Warming
RCM	Regional Climate Models
SDSM	Statistical Downscaling Model
SRES	Special Report on Emission Scenarios
SSURGO	Soil Survey Geographic Database
SWAT	Soil and Water Assessment Tool
SWE	Snow Water Equivalent
SWMM	Storm Water Management Model
TMDL	Total Maximum Daily Load
UCRB	Upper Colorado River Basin
USBR	United States Bureau of Reclamation
USDA	United States Department of Agriculture
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
VIC	Variable Infiltration Capacity
WARMF	Watershed Analysis Risk Management Framework
WRF	Weather Research Forecasting

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CHAPTER 1: INTRODUCTION

The Upper Colorado River and Gunnison River basins included in our study of the Upper Colorado River Basin (UCRB) contribute to a drainage area greater than 17,800 square miles with a mean flow of over 3000 cfs. Approximately 50% of the mean flow originates in the Gunnison River Basin, with the rest coming from the upper Colorado River. From its headwaters in Grand County to Mesa County, Colorado, the Colorado River is the life source for much of the Southwest United States, impacting seven states, two nations, and irrigating more than 3 million acres of farmland (Barnett et al., 2009). With rapid regional population growth and development, water resources are becoming critical. Historical trends are no longer reliable for predicting future behavior for water planners under a changing climate. Future climate conditions may alter surface and groundwater hydrology, projecting less overall precipitation and more drying in the UCRB (Christensen et al., 2004). Most global climate models predict regional runoff to decrease from 10-30% (Barnett et al., 2009), stressing water supply. The International Panel on Climate Change (IPCC) lists the region as "water stressed," based on population, runoff, and withdrawals (2007). Many studies have shown that at least some of the climatic changes can be attributed to anthropogenic influence (Bonfils et al., 2008; Barnett et al., 2008; Pierce et al., 2008; Hidalgo et al., 2009; among others). To mitigate and monitor climate change impacts, more sustainable and climate conscious strategies have to be implemented. Hydropower is a source of sustainable and renewable energy in the region. This impact study explores the regional hydrologic response to climate change and impact on hydropower potential under a range of climate projections. It includes historical time series of over 4,500 diversions which contribute to water management considerations of water rights, allocations, irrigation concerns, and operations. Additionally, the inclusion of the Gunnison River basin considers impact of future climate on significant hydropower producing infrastructure. Addressing climate change response in reservoir operations analyzes specific impact and creates potential conditionals to directly aid water managers and decision makers in mitigating concerns of the immediate future. The results from this study can be utilized in watershed management and planning strategies.

1.1 Purpose

The purpose of this work is to: 1) provide water resource planners (e.g. utility designers, reservoir operation and managers) with a better understanding of impact of anticipated climate change on the UCRB to aid in their long term decision making process, 2) predict changes in stream flow (magnitude and timing) due to climate change, 3) predict changes in reservoir storage and hydropower production, 4) assess impact of climate change on ensuring delivery of the required flow to the lower basin according to the agreements on allocation of water rights. Previous work has begun to address these UCRB concerns, but not under a single modeling approach with the capability to incorporate an inherent decision-making framework in conjunction with a hydrologic assessment of future climate.

1.2 Scope

Climate models and scenarios are selected to obtain projections of future climate change. Appropriate climate models and scenarios are identified through literature review. The climate models have been used to generate future climate ensembles for emission scenarios from the Special Report on Emission Scenarios (SRES) by the Intergovernmental Panel on Climate Change (IPCC). Future climate projections need to be spatially downscaled from low-resolution General Circulation Models (GCMs) to a scale usable for the watershed level analysis. Thus, selection and utilization of statistically downscaled data is an integral part of this study. The results from climate simulations were transferred into the hydrologic and reservoir Watershed Analysis Risk Management Framework model (WARMF). WARMF was selected to simulate the hydrologic response to climate change because it includes an integrated 2D reservoir processes, in addition to watershed analysis on the Upper Colorado River basin. Few continuous, physical models simulate both reservoir and watershed hydrology. WARMF calculates daily stream flow of a basin that is divided into catchments, stream segments, and lakes or reservoirs. WARMF simulates a river basin with multiple reservoirs and calculates the reservoir elevations based on inflow and outflow including diversion from the reservoirs. For the evaluation of the effect of climate change on hydropower production, we focused on reservoirs that are currently used to produce power.

1.3 Climate Models and Scenarios

Studies have examined reservoir performance in other basins (few in the UCRB) globally based on several climate scenarios, due to the uncertainty in climate models, scenarios, and downscaling methods. We explore the impacts of climate change using three global climate models (GCMs) under two climate scenarios (A1 and B2). GCMs are complex simulations describing physical laws of atmosphere and ocean behavior using mathematical equations (Skoulikaris and Ganoulis, 2011), which are highly dependent on initial boundary conditions. This necessitates coupled atmosphere-ocean GCMs with individual components pertaining to sea-ice, land-surface, and chemical transport (IPCC, 2000). It has also been shown that feedback effects are best represented in coupled models (Fowler et al., 2007). The most widely used GCMs (Hadley Centre and the Canadian Centre for Climate and Analysis) agree that global surface temperatures will increase by 2100 along with evapotranspiration rate and, therefore, global precipitation. IPCC also lists an increased frequency of extreme events and decreases in summer soil moisture (droughts).

The International Panel on Climate Change (IPCC) in the SRES identified six storylines for future emission pathways and are described in detail in Chapter 3. Of the six available scenarios, two (A2 and B1) were selected for this study. They represent distinctly different paths of development. Each storyline describes different demographic, social, economic, ecological, and environmental developments (Nakicenovic et al., 2000). It is also useful to note that GCMs are used to provide future climate projections using a very coarse spatial resolution, which is unsuitable for watershed studies. To minimize uncertainties resulting from GCMs, the data outputs are downscaled to finer spatial resolution (Christensen et al., 2004), described in the following section.

1.4 Downscaling

Future climate projections need to be spatially downscaled from low-resolution GCMs to the watershed scale. Downscaling takes raw GCM response to changing global conditions and post-processes those by dynamical or statistical models to produce more relevant datasets of regional impacts. More specifically, downscaling transforms data from coarse to fine spatial resolution. There are two major techniques in downscaling: statistical and dynamical. Dynamical downscaling simulates physical processes at finer scales, a process generally too computationally intensive for multi-decadal analysis (Maurer and Hidalgo, 2008). It is also significantly impacted by bias from the original GCM and by regional characteristics (e.g., orography) and has in most cases performed equal to statistical methods (Fowler et al, 2007). Statistical downscaling is more widely used and essentially scales a GCM projection. It does the conversion based on observed quantitative relationships between climates at the two spatial resolutions. The relationships developed are based on two statistical factors, the "predictors", or large-scale atmospheric variables, and "predictands", or local climate variables, and are assumed to be stationary in time. Stationarity assumes that past relationships will hold in future time periods. Statistical methods build associations between the factors and apply those to future projections (Maurer et al., 2010). Both methods have shown greatest skill at the mid-latitudes for cool/dry seasons and least skill in wet seasons (Fowler et al., 2007). No general consensus exists on whether dynamical or statistical methods are best. Statistical downscaling methods have been more recommended as more effective in heterogeneous regions with complex terrain, such as the western United States (Wood et al., 2004). Most of the effort has been to reproduce monthly data, but extreme events are best characterized at the daily time scale, and daily data has recently become available. Traditionally, these techniques underestimated variance and illustrated poor skill for extreme events. With new daily data those limitations can now be addressed. Uncertainty is a critical issue in downscaling; Wilby and Harris (2006) illustrated that uncertainty is predominantly associated with choice of driving GCM, rather than technique. Although there are strengths and weaknesses to all downscaling techniques, Fowler (2007) emphasized the lack of direct application of these methods to impact studies. The three available methods of statistical downscaling considered for this study were: bias-corrected and spatially downscaled (BCSD), constructed analogues (CA), and bias-corrected and spatially downscaled (BCCA). The methods are discussed in more detail in Chapter 3.

1.5 Watershed Modeling

To analyze a hydrologic response of hydropower to climate change, watershed-based analysis is necessary. The application of watershed hydrologic models is recommended to appropriately characterize projected climate change impacts on specific regions. Physically-based watershed models describe complex systems and hydrologic processes controlling the response. The Watershed Analysis Risk Management Framework (WARMF) model was used in this study. WARMF was selected because it is a physical model capable of continuous reservoir simulation, hydrologic analysis, and performs at daily time scales. As a continuous-simulation model, WARMF could be operated over a longer period, which includes time series of rainfall events under future climate scenarios. Furthermore, existing research collaborations and subsequent familiarity with the model contribute to its selection.

1.6 Motivation for Research

Global climate change has been widely researched worldwide. Recently there has been noticed a need for more impact assessment studies of the changes. Fowler, et al. (2007) explicitly details the need for applied research. They call for studies which consider hydrological impacts and how those can then be utilized by planners and stakeholders to make informed decisions. In this study, we explore climate change impacts on the water resources and hydropower potential of the UCRB. Although these watersheds have been examined in previous studies (expounded in Chapter 2), our watershed analysis approach, combined with several future climatic conditions and an innate reservoir simulation model, robustly explores the hydrologic response and influence on reservoir based water resources. The results of this study can be incorporated into watershed or management strategies regionally. Furthermore, WARMF watershed model developed in this study can be used by stakeholders to analyze potential adaptation and mitigation strategies. The model can be implemented to analyze impacts of other conditions on the water resources. The changes in land use, water quality and quantity analysis, and ecological impacts are just some of potential future scenarios for this model.

CHAPTER 2: LITERATURE REVIEW

The Colorado River is a critical system to water deliveries in the southwestern U.S. and Mexico (Barnett and Pierce, 2009). It currently allocates 17.5 billion cubic feet of freshwater to more than 27 million people. More than 90% of the high elevation snowpack runoff water originates in the Upper Colorado River Basin (Christensen et al., 2004). In recent history, the Southwest has experienced unprecedented growth at the same time as the hydrologic cycle has begun to change. Global GCMs project a substantial increase in global mean surface air temperatures between 1.8°C and 5.4°C from 1990-2100 (IPCC, 2001). Multiple studies have been conducted to analyze the impact of climate change in the CRB. An overview of climate and hydrology of the CRB is presented in section 2.1 and 2.2 and a review of previous studies is presented in section 2.3 below.

2.1 Description of Study Area

The Colorado River is an integral part of water supply for the Western United States. The river has been utilized for mining, lumber, cattle ranching, and farming prior to the twentieth century. In the early 1900s, a need for legal water rights in the basin arose with population growth. States wanted to guarantee water supply to increasing populations and agricultural demand. An agreement between the seven basin states of Colorado, Utah, Wyoming, New Mexico, Nevada, Arizona, and California was signed in 1922 called the Colorado River Compact (NAS, 2007). According to a report from Colorado Decision Support (CDSS, 2010), the agreement guaranteed 7.5 million acre-feet (AF) of consumptive water use to the Upper Colorado River Basin (parts of Arizona, Colorado, New Mexico, Utah, and Wyoming above Lee Ferry, Arizona), and the Lower Colorado River Basin (those parts of Arizona, California and Nevada below Lee Ferry, Arizona). The new UCRB Compact of 1948 described apportionments (CDSS, 2010) from the 7.5 million AF to the following states; Arizona (50,000 AF/year), Colorado (51.75%), Utah (23%), Wyoming (14%) and New Mexico (11.25%).

The UCRB has an arid to semi-arid climate, with more pronounced periods of drought in the last half of the twentieth century. Under future climate projections, snow accumulation and precipitation volume are projected to decline, while temperatures are set to increase, increasing regional aridity. It is widely agreed that the UCRB will experience a 2-4 degree Celsius increase in upcoming years (Christensen et al., 2004), but precipitation projections are not as certain. Many studies note the variability in precipitation trends in the area, 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)]. Water resources of the UCRB are highly dependent upon and sensitive to snowfall and may be severely impacted by a changing climate. Warming of the basin has exceeded all other regions of the U.S (NAS, 2007) and is projected to increase even more. Over 75% of the streamflow is generated in the high elevation mountains from snow melt (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 is determined by low-flows, which have already shown to be unsustainably low in summer, with the extreme flow conditions (both low and high) projected increase under future climate. According to the IPCC (2007), there is a much greater drought risk in lower altitudes, where irrigation demands are more significant. Furthermore, surface and groundwater quality has generally decreased in recent decades due to population growth and agricultural practices (IPCC, 2007).

The UCRB's natural flow regime has long been affected by management practices. Series of diversion and reservoirs to provide for hydropower and irrigation systems significantly affect the natural flow. Reservoirs are operated in accordance with downstream water rights based on water demand for a variety of uses (domestic, industrial, hydropower, etc.) and to maintain ecological integrity (Majone et al., 2012). Hydropower production is reliant on runoff, timing and reservoir storage elevations (IPCC, 2007). Reservoir levels will be significantly impacted, requiring new mitigation and adaptation strategies in the 21st Century. Hydropower, inherently dependent on water levels to dictate production, will be affected. A decline in hydropower potential, combined with potential water spillage from altered runoff timing regimes, intensifies the response. Temporal runoff variability necessitates additional storage behind dams in energy-producing dams. Environmental flow requirements will also become a more significant issue, potentially impeding anthropogenic use to ensure ecological vitality. It is impossible to ignore the demand for a changing perspective of water use, along with climate change. More efficient, water conscious practices will become crucial. Water supply is projected by many to become stressed in much of the global community. Water-efficient practices and technologies will become essential for human use to meet agricultural demand and to slow the effects of climate change itself.

2.2 Climate and Hydrology of the Colorado River Basin

Urban development in the Western United States has greatly affected the land-energy budget affecting the hydrologic cycles, among other processes. Regional Climate Models (RCMs) being used globally are not able to capture the variability of many Western mountain ranges (Kueppers et al., 2008). These systems are very sensitive to snow accumulation and melt, soil moisture, evaporation rates, and surface runoff and baseflow routing (Christensen and Lettenmaier, 2007). Because over 70% of the total flow of the Colorado River derives from snow melt, variability in accumulation and timing results in critical consequences downstream. Specifically critical to the CRB as it is almost wholly allocated, making it highly sensitive to reductions in runoff. The impact from climate change is expected to vary in different regions of the West. Large-scale climate warming will induce springtime streamflow to arrive progressively earlier, mainly due to more precipitation arriving early as rain rather than snow (Knowles et al., 2006). This is specifically significant for lower elevation systems, such as those of the Sierra Nevadas and the Pacific Northwest. Similarly, in the Rocky Mountain region most of the warming characteristics will impact snowmelt generation, moving spring melt flows as much as a month earlier than the historical record.

Hydrological feedbacks are especially significant to the mountainous regions of the western U.S (Bales et al., 2006). In addition to the knowledge gap regarding the spatial variability of snow and soil moisture, the carbon turnover of forest and mountain resources is also not understood. The latter greatly contributes to the carbon budget (and, in turn, climate change), while the former contributes to the subject of snowmelt, critical to runoff generation.

It is very important to consider scale when evaluating snow accumulation and melt in the West. At different scales, varying factors become important. For high elevation systems, albedo is the dominant driving force for snow melt. Dust cover and vegetation greatly impact albedo rates and it is therefore important to evaluate each region specifically, considering unique tree cover and solar radiation rates (Bales et al., 2006). Better hydrologic models can help elucidate elevation interactions with seasonal evaporative demand (Christensen and Lettenmaier, 2007). A negative feedback exists between increased temperature rates predicted for future climate scenarios and evaporative demands (reduced due to shift in seasonal variability of soil moisture content). The timing shift of snowmelt, (altering soil moisture characteristics) to earlier than in previous centuries reduces runoff and evaporation sensitivity to increased temperatures. This indicates that evaporation effects are minimized, but more research is necessary to truly understand the intricacies of this relationship at high elevations.

Most of the southwest United States, including the CRB, is covered by water-limited herbaceous systems. These plant-water savings help to alleviate some of the demand for water vapor and actually serve to delay the onset of drought. The response of plant canopies to CO_2 is "critical for land surface hydrology in a CO_2 rich world" (Kergoat et al., 2002). As soil moisture is a critical component of Western hydrology, this behavior greatly delays soil moisture depletion (mitigating runoff depletion). When CO_2 levels are increased herbaceous canopies also reduce evapotranspiration demands, enhancing soil moisture. Vegetative climate feedbacks indicate energy budget and precipitation cycling, helping to better understand the sensitive behavior of these hydrology and ecosystems. Kergoat et al., (2002) show that the doubling of CO_2 nets a globally insignificant response, but a moderately important local hydrology impact. CO_2 stimulated plant growth appears to negate the water savings expected by some in an elevated CO_2 environment.

2.3 Previous Studies of the Colorado River Basin

The Colorado River is crucial to the water resources of southwestern United States. As current GCMs predict that climatic changes will critically impact the water resources of the world in general, the Colorado River Basin is also becoming a pressing region. Already almost wholly allocated (Christensen et al., 2004), water management and supply issues of the basin will be exacerbated by any climate change (Nash and Gleick, 1991).

Most of the previous studies on climate change effects on hydrologic responses generally followed an impact approach, focusing on analysis of what happens if climate changes in a defined way. Examples include studies on the CRB (Rosenberg et al., 2003; Christensen et al., 2004; Barnett et al., 2004); Upper Mississippi River Basin using SWAT (Jha et al., 2006); and the Monocacy River, Maryland using EPA's BASINS CAT (Imhoff et al., 2007). Multiple studies have shown that the CRB will respond to the temperature increases with an increase in the rain-to-snow ratio, increased winter runoff, and earlier snow melt in the spring. Although precipitation predictions vary, most climate models agree in the overall reduction of runoff in the basin (Barnett and Pierce, 2009). This will greatly impact management of flow and reservoir regimes as the Colorado River is very sensitive to runoff changes (Christensen et al., 2004), and is predicted to reduce in flow by 10-30%. The changes have already been noted from storage levels of two significant reservoirs downstream, Lake Mead and Lake Powell. Many have investigated these reservoirs (Christensen and Lettenmaier, 2007; Barnett and Pierce, 2009; and others), concluding the dependency of water supply on the Colorado River.

Barnett and Pierce (2009) explored the impact of anthropogenic changes on hydrology of Western U.S., finding that human-induced change has contributed significantly to the climate of the 20th century. The managed water resources of the CRB are heavily reliant upon mean annual river flow (Christensen and Lettenmaier, 2007). Storage reductions indicate a reduction of hydropower generation, which is dependent on head and discharge flowing through a turbine. These impacts of climate change not only alter the hydrology of the region, they also threaten populations dependent upon the freshwater resources downstream. While effects of evaporation/infiltration are significant to water availability, when Barnett and Pierce (2009) held those parameters constant, human-induced changes were shown to overwhelm all other parameters. They found that with a conservative approach of deterministic analysis, the reservoir system becomes more sensitive to climactic changes when it is fully subscribed and net inflow nears zero.

Nash and Gleick (1991) originally explored the impact of changes in surface runoff on water supply and management. Using GCMs and a hydrology model which combined soil-moisture with snow contribution, they performed an early assessment of climate change on water resources. They found that streamflow was most impacted in low-flow years, and that a general temperature increase of 4°C caused peak runoff to take place earlier than normal. Most significantly, Nash and Gleick concluded that previous works overstate the significance of evaporation in the region and that the effects of temperature increases have less significance at higher elevation. It is generally understood that an increase in winter maximum and minimum temperatures will promote earlier snowmelt than in past years. At higher elevations, they contend that the rise of several degrees (at the worst case) will not cause significant hydrologic changes.

Maurer (2007) echoes these findings. Using 11 GCMs and 2 emission scenarios (A2 and B1) using BCSD downscaled data to force the VIC hydrologic model. He concludes that higher elevation locations are less sensitive to emission scenarios, although still influenced.

Christensen et al. (2004) studied the impact of climate change on the CRB extensively, using three 105-year future climate scenarios based on a "business-as-usual" (BAU) greenhouse gas (GHG) emission scenario in comparison to a static 1995 GHG simulation. They implemented a coupled atmospheric system to create a continuous analysis against the historic baseline. The BAU was bias-corrected and used to force the VIC hydrology model. The VIC streamflow outputs were then implemented in the Colorado River Reservoir Model (CRRM). The CRRM represents the major physical water management systems and operating policies of the CRB. Reservoir levels, releases, hydropower production, and diversions are all included. Hydropower is a function of the reservoir's surface area and monthly temperature variability. Major dams such as Glen Canyon and Imperial, as well as reservoirs such as Lake Powell, Lake Mead, Navajo, etc. were all described. The study concluded that there will be a 0-10% increase in precipitation at the headwaters of the Colorado River but a 10-15% decrease in precipitation in the northwest portion of the river in Arizona. Snowpack was shown to decrease, reducing mean annual flow and streamflow timing. The small changes in streamflow behavior result in massive reservoir fluxes. Mean streamflow reduction of 10-20% indicates a reservoir storage decrease of 30-60% or a failure to provide the necessary resources in future simulations under the BAU scenario. Reliability of downstream deliveries is reduced along with hydropower capacity. The total system demand overwhelms reservoir inflows, producing repeated failures; this indicates a necessity to change the BAU behavior.

In 2007, Christensen and Lettenmaier used an ensemble approach to characterize the hydrologic response to climate change in the CRB. Using 11 GCMs and an A2 and B1 climate scenario, the VIC model was again used to drive the CRRM with varying conditions and methods. The A2 (BAU) scenario evaluates untamed CO_2 levels (850 ppm) until the year 2100. B1 considers a reduction of CO_2 levels to 550 ppm, a more moderate assessment. This study downscales the GCMs using bias-corrected downscaling techniques for temperature and precipitation at the monthly scale. Using only 11 diversion points for the most critical junctures, all scenarios illustrate more warming from mid-summer to early fall. Winter precipitation was found to increase while the snow water equivalent (SWE) decreased. All scenarios illustrated a reduction in hydropower production. ET was shown to have minimal impact because the increase in winter precipitation contributes more runoff than the reduction in annual runoff from ET effects in summer. Overall, Christensen and Lettenmaier showed that regardless of emission scenario, water shortages occurred in 20% more by 2070 and require drastic changes to present demand to avoid catastrophic future consequences.

Several of the studies have applied the statistical downscaling approach. The approach began to be an issue of serious study as early as 1991 when Wilby et al. explored the topic. Comparing different downscaling techniques effects on GCM outputs, which were then routed through a physical process watershed model, the group concluded that downscaled results could be used for future basin studies. Three variables (minimum and maximum temperatures and precipitation time series) were downscaled at daily time-steps to force the UK Meteorological Office coupled ocean-atmosphere GCM (HadCM2) for the Animas River in the San Juan River Basin, Colorado. These time series were then used for the watershed model Precipitation-Runoff Modelling System (PRMS). The PRMS used in this study is a distributed parameter watershed model which incorporates GIS-based watershed delineations to calculate the water and energy balance and snow accumulation and depletion with daily simulations (Wilby et al., 1999). Model results predicted a reduction in snow accumulation, with most precipitation falling as rain (echoed by many studies previous and since) and a general decline in snow-covered areas and snowpack water equivalents. Winter and summer results were worse than those for spring and fall due to seasonal variation. They found that statistical downscaling valid for impact studies of climate change due to its accurate reproduction of meteorological data, but dependent upon stationarity. Statistical downscaling assumes that the empirical relationships (predictors and predictands) on which it is based remain the same in future time periods. The uncertainty in this assumption is a current topic for study (Dibike and Coulibaly, 2005; Hay and Clark, 2003; and more). Most analysis has found that although accepting stationarity for some basins is questionable (Miller et al, 2011), but defendable especially when considering the computational demand of dynamic downscaling techniques and ultimately dependent on the GCM forcing (Wilby et al., 1998).

More recently, climate change effects have begun to be analyzed for specific impacts. Barnett et al., (2008) analyzed climate change impacts on water supply in the western U.S and its regional hydrology. Using a high resolution model forced by future climate data, they observed increasing runoff in Spring, with a significant reduction in Summer months. McCabe and Wolock (2007) used a water balance model to describe streamflow changes in the CRB and their impacts on long term water sustainability of the southwest. Only considering warming effects, the basin will experience water supply shortages and other sustainability concerns under future climate conditions. The United States Bureau of Reclamation (USBR) recently analyzed the basin under varying future scenarios, emphasizing the impact of ET. Using BCSD data they modified ET rates and noted a 6-13% runoff decrease in the Gunnison River basin (Miller et al., 2011). Raff et al., (2009) used statistically downscaled precipitation and temperature sub-daily time series, at 1/8° spatial resolutions to study flood potential under future climate conditions. Examining four study basins (the Boise River, the San Joaquin River, James River, and the Gunnison River) under nine Coupled Model Intercomparison Project Phase 3 (CMIP3) projections, flood frequencies were analyzed. Using the statistically downscaled, they simulated annual maximum flood potential and concluded a 4-17% variance, by basin, but a cumulative increase for future predictions of annual flood. Raff also noted a need for recent more studies of climate research, as recent advances in GCM data to identify local climate effects and land-surface feedbacks will further past research efforts.

Rasmussen and coauthors (2011) also analyzed runoff and snowfall trends over Colorado using higher-resolution models to better simulate “orographic precipitation, snowpack accumulation, ablation, evaporation and runoff processes,” to more accurately analyze regional climate influence. They 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 observational data. Results indicate snowfall at higher elevations, with a 10-15% increase in precipitation at the Colorado River headwaters due to the rain shadow effect. The precipitation increase they posed is due to higher cloud-water mixing ratio and increased conversion of snow to rain (Rasmussen and coauthors, 2011). They also note less runoff in summer months, similar to studies prior (mentioned above).

Our study compliments previous work and contributes to the available body of current knowledge. It analyzes streamflow, precipitation, temperature and reservoir impacts like the studies mentioned above but adds in using different GCMs and watershed and reservoir analysis models. Our work considers the CRB, but also the Gunnison River basin which is also critical in assessing climate change impacts under varying climactic conditions and regional topography.

Table 2.1: Summary of some prior research on the Colorado River

Area of Focus	Authors	Significant Findings
Water Supply	Nash & Gleick, 1991; Barnett & Pierce, 2009	Infiltration & evaporation rates less impactful than anthropogenic influence on future climate; used two GCMs.
Western United States hydrology & climate (current & future)	Bales et al., 2006; Fowler et al., 2007; Kergoat et al., 2002; Knowles et al., 2006; Maurer et al., 2007; 2008; Kueppers et al., 2008; Miller et al., 2011; Raff et al., 2009	Signal analysis, feedbacks better represented in coupled GCMs, statistical downscaling techniques used, VIC hydrologic analysis.
Upper Colorado River Basin	Wilby et al., 1991; 1999; Rosenberg et al., 2003; Christensen et al., 2004; Christensen & Lettenmaier, 2007; McCabe & Wolock, 2007; Raff et al.,	Streamflow reduction of 10-20%, reservoir storage reduction 30-60%, up to 10% increase in precipitation at Colorado River headwaters; VIC hydrologic analysis, Colorado River Reservoir Model analysis; 11 diversions included in models; flood risk management.
Hydropower Production	Brekke et al., 2009; Fowler et al., 2012; Raje & Mujumdar, 2009; Vicuna et al., 2010; Majone et al., 2012	Risk assessment framework, VIC hydrological analysis; analyzes reservoir and adaptive policies.

Furthermore, the inclusion of over 4,500 diversion points enables a thorough water rights assessment (although not explored in our study). Climate change impacts water allocations, which are explicitly detailed in our study and will be useful for future decision making processes. Table 2.1 illustrates a brief summary of research on the Colorado River. Our study shares some of the methods of previous work, but addresses most of the areas of focus in a single work. We use multiple GCMs and climate scenarios with a physical watershed model that includes an integrated 2D reservoir model. This adds to previous work in assessing future climate conditions with some of the same techniques, but also some different methods to facilitate a more complete envelope of future climate change conditions. Also, since most of the assessments on the CRB have used the VIC model, implementing WARMF adds to existing results (and agrees with them).

2.4 Hydropower Implication of Future Climate Change

Much research has been dedicated to illustrate the impacts of climate change on “various sectors of the economy” (Vicuna et al., 2010). This section will specifically explore review of literature on the impact of this behavior on the UCRB and hydropower. The primary focus of the review is high elevation hydropower-producing reservoirs, as well as other significant implications on water management and generation.

Hydropower generation is a function of head (elevation) and flow (discharge) through a turbine. Hydrologic timing is an important factor in dictating the ability of a plant to generate specific power requirements, along with reliability and spill potential. With ongoing climate change, increase in temperate has led to more precipitation falling as rain and earlier spring melt (Vicuna et al., 2010). This facilitates a timing mismatch between energy generation and demand, especially for periods of low storage. Early melt provides hydropower potential in early spring, when the highest demand is during the summer months. Changes in instream conditions drive hydrological changes which impact power production. Timing changes provide a variety of challenges, both economical and hydrological. In smaller systems, timing affects storage capacity by forcing the reservoirs to release if becoming full earlier in Spring when generation is less needed. If ample storage is not present, these releases become costly for smaller power generating utilities. Furthermore, if releases are forced earlier, reliability of providing water in later summer months become vulnerable to availability of leftover supply. Therefore at the most financially lucrative (since demand drives cost) and human needed summer months, the required water resources may not be obtainable (Majone et al., 2012). Also, spillage (water lost without generating electricity, power) will increase with increased winter inflows and earlier melt. This reduces overall energy generation, creating a mismatch between timing and energy prices. Systems with larger storage capacity are better buffered against this consequence but still always vulnerable to streamflow changes.

Raje and Mujumdar (2009) evaluated climate change impacts on reservoirs performance and adaptive strategies for the future. They used three climate scenarios of A2, A1B, and B1, and three GCMs: CGCM2, MIROC3.2 medium resolution, and GISS model with conditional random fields (CRF) to downscale the GCMs. which is different than the BCCA method in our study. CRFs is a stochastic model, it uses streamflow sequence data with observed atmospheric data to produce the conditional distribution of streamflow at a particular site (Raje, 2010). The major difference is that BCCA uses deterministic methods, while CRF is stochastic. With deterministic models, the inputs are fixed and a single result is produced every time the model is run. In stochastic simulation, there is randomness, which can alter the results with each iteration. Both are valid downscaling techniques, but it is significant to note that stochastic methods are much more resource intensive (often prohibitively so).

They found that hydropower generation and reliability (of both power and irrigation) will decrease in the future. Reservoir operations were analyzed using rule curves, which describe frequency and severity of flood events as well as demand satisfaction. Mean monthly storage and, therefore, power generation is predicted to decline in future years. To provide better assessments, sub-daily simulations are suggested. Nonetheless, with annual demand increasing, optimal operative policies indicate a balance between increased power reliability, and reduced irrigation reliability. All adaptive policies can offset performance decrease but are ultimately limited by overall water balance deficits of the future.

Studies have been conducted to assess impacts of climate change on hydropower production in UCRB and other watersheds that provided recommendations on possible mitigation measures. Brekke et al. (2009) explore an evaluation metric for assessing climate impact on reservoir operations based on risk assessments. Understanding a specific level of tolerable risk, critical decision are made using a probabilistic distribution of impact which includes a selection of climate projections, scenario-specific hydrologic impacts, and specific future periods. This method was not used to evaluate the UCRB reservoirs because it is a specific case-by-case issue requiring input from decision-makers and constituent for which there was not enough time to execute. Vicuna et al., (2007) also explored impacts of climate change on hydropower in the Upper American River Basin of the Sierra Nevada Mountain Range in California. Similar to Maurer's study (Maurer et al., 2007), the VIC model was used with outputs of 2 GCMs under 2 emission scenarios. Their study analyzed stream flows to evaluate hydrologic timing. As in our study presented above, increase in temperature leads to more precipitation falling as rain and an earlier spring snowmelt, both significant to hydropower production. This leads to a timing mismatch between available energy generation and demand. Early melt creates early production available in spring, causing water to be lost via spillage. Furthermore, early spill reduces reservoir levels for summer demand and decreases available head for hydropower production when it is most needed. A change in timing also affects hydropower systems, but smaller plants are much more impacted. Overall, an increase in storage capacity, increases generating capabilities, improving production and revenue generation. Systems of large spring and summer flows will be affected by inflow timing, unless adequate capacity is available to store early melt water.

2.5 Other Water Resources Implications

As reservoir management becomes increasingly significant, so does flood management, hydropower, and irrigation control. An increase in precipitation events, combined with an increase in frequency of more high precipitation events, creates a fertile environment for floods (Raff et al., 2009). Past water resource planning and infrastructure has utilized historical precipitation events to guide future decisions, but that is no longer acceptable. The 100-year flood is shown to increase in frequency by 2040, exacerbating water management concerns worldwide. Changes in future climate may necessitate changes in water resources infrastructure and adaptation operations to attain maximum efficiency and flood control (Vicuna et al., 2010). Flood management strategies have historically been based on the concept of stationarity, an assumption shown to be invalid under projected conditions. A modified climate includes changes to flood-related parameters, such as precipitation, runoff magnitude and timing, and seasonality. Milly et al., (2005) described increased flood risk in the 20th century, and that the trends may continue further into the future. Using statistically downscaled monthly data from 11 GCMs, Raff et al. (2009) found that flood potential increased through time, and requires new decision making procedures. Christensen and Lettenmaier (2007) analyzed hydrologic impacts of future conditions, finding that changes in operational reservoir policies may not mitigate the increasing stress of the UCRB.

Water resources sustainability becomes questionable in projected climate. Critical downstream water deliveries experience greater stress than in previous time periods (Barnett and Pierce, 2009). As net inflow is reduced, the Colorado River system becomes more unstable and sensitive to climate variability. Tree ring data indicates that the past 100 years have experienced less variability than any historical 100 year record prior, yet the worst droughts have been seen only recently. Increased water stress also impacts crop production. Water availability dictates crop selection and can affect growing choices and irrigation practices (Majone et al., 2012). Barnett and Pierce (2008) analyzed the sustainability of existing water allocations under future climate conditions. Using the Colorado River Budget Model (CRBM) they describe that without any climate variation, deliveries fall short about 40% of the time in the next 50 years; with moderate climate impacts (10% reduction in runoff) allocations can no longer be met more than 60% of the time, and with a 20% runoff decrease deliveries are mostly not met by 2050. They suggest that current flow allocations are unsustainable and require either careful delivery schedule adjustment or reduction in demand to meet needs. Dawadi and Ahmad (2012) also explore the impact of climate change on regional hydrology and water resources. Using 16 GCMs and 3 emission scenarios (from 1970-2035) they assessed the variability of future streamflow and its influence. With a system dynamics (SD) hydrologic, reservoir operations, and water allocating model, they explored streamflow and water resources of the CRB. SD is based on a hydrologic water balance, regulatory releases of releases of reservoirs, and allocation requirements. Findings illustrated increasing temperatures with little consensus of precipitation trends (especially when analyzed per GCM instead of per emission scenario A1b, A2, or B1) but an overall reduction in flow of the Basin. The flow reduction leads to a decrease in reservoir storage and, henceforth, hydropower potential. Downstream water supply requirements are not met either. To mitigate these results, Dawadi and Ahmad suggest improving reservoir operation efficiency, emphasizing water conservation and modifying allocation requirement.

Climate change impacts on irrigation were analyzed by Majone et al., (2012). Describing irrigation districts in Spain, they analyzed reservoir inflows as indicators of climate change. They found uniform increases in dry years and the inability to meet agricultural demands under future conditions. This requires farmers to alter crop selection and irrigation practices. Furthermore, advanced seasonality (most severe during the irrigation period of April to September) reduces irrigation system efficiency and alters crop timing. Reservoir analysis showed a reduction in irrigation storage volume, limiting water availability for farming. Management rules for reservoirs must be adjusted on an individual basis, along with adaptation and mitigation strategies for agricultural practices.

Hydrologic changes also impact dependent ecosystems. Minimum flows are critical to river and stream ecosystems (Wang et al., 2011). A reduction or increase in minimum and maximum stream flows can have extremely detrimental environmental effects, where wet and dry cycles dictate aquatic life. Changes in population, land use, and vegetation also influence ecosystem health (Ficklin et al., 2012). Stream temperature is impacted under a changing climate, affecting aquatic life. Dependent on inflow source, streamflow temperature varies regionally, especially in mountainous areas (Ficklin et al., 2012). Reservoir management must adapt to address these concerns.

2.6 Uncertainty in Climate Change Impacts

Uncertainties associated with climate change impact studies are innate. Climate projections from global modeling centers still struggle to characterize future climate despite accurately describing historical behavior. Uncertainty exists in GCMs, emissions scenarios, downscaling techniques, and hydrologic models used to evaluate impacts. It arises from inter-model and intra-model variability of GCMs, when different GCMs produce different results and when the same GCM has different outcomes based on initial conditions. Emissions scenarios also contain uncertainty, as do downscaling techniques (Dawadi and Ahmad, 2012). To address these concerns, several GCMs were used in their study to allow for variability in individual model characteristics. To address intra-model GCM variability, several runs of each were simulated, the average of which was then used in the hydrologic analysis by WARMF. Downscaling techniques also contain their own uncertainty, as statistical downscaling is dependent on stationarity, but those are frequently found to be less than the uncertainties in GCM selection and therefore mitigated in the multiple run simulations. The use of multiple GCMs and emission scenarios also adds to the robustness of the results, as using only a single GCM is not reliable (Chen et al., 2012).

Assuming stationarity is not entirely true (though it is not the same as using past hydrologic events to predict future regimes). Additional uncertainty is present in GCMs and downscaling techniques, but the unpredictability of the naturally variable future climate may be greater than either (Brekke et al., 2009; Fowler et al., 2007). GCMs provide a rough assessment of future variability, even at the most state-of-the-art facilities (Skoulikaris and Ganoulis, 2012). Many significant assumptions include their own uncertainties. Climate forcings, projection downscaling, and long-term groundwater response are a few among many possibilities, described by Brekke et al. (2009). Uncertainty could also result from land cover changes caused by population demands and/or changes and future climate

For adaptation, specifically of reservoirs, it is critical to incorporate uncertainty in decision making. It is necessary to provide for a range of future climactic variations, rather than for a specific condition. Adaptation and mitigation strategies must be made to account for trends (such as increasing or decreasing precipitation), rather than exact future projections. For example, Maurer (2007) used 11 GCMs under the same emission scenarios, BSCD downscaled, with the VIC Model. Exploring uncertainty of the results, he identified several possibilities for uncertainty in climate change impacts. Precipitation is not generally impacted by emission scenarios (A2 or B1), but has shown to be elevation dependent in some regions. Winter flows increase, with a reduction in SWE, as temperatures rise. Maurer identified uncertainty in future land cover changes caused by climate change as a potential cause for uncertainty in impacts. Majone et al., (2012) pose that it is possible for climate modeling uncertainties to be greater than the results from the effort. When a drainage area is greater than 50,000 km^2, deviations may be 100 percent. This is based on a conceptual model with daily time steps, which considers factors such as: snow accumulation/melt, evapotranspiration, infiltration and subsurface flow. Using the A2 scenario, which could partially account for their extreme conclusions, reproduced flows do not capture peak flows well. Majone et al., (2012) justify their calibration stating their motivation is on availability of total water resources, not individual events, as in our work. They conclude that a multi-model ensemble reduces climate uncertainty, which our GCMs are, and therefore produce valid and valuable results

It should be noted that groundwater feedbacks were not explicitly analyzed in our study, other than the flux treatment provided in the GCMs. Studies have shown a response to climate change responsive to groundwater feedbacks, but the hydrologic model used in this impact study is not able to robustly address these cycles as suggested in Ferguson and Maxwell (2010). They propose that the hydrologic response to climate is interdependent on feedbacks of "groundwater, overland flow, and the surface water and energy balance." Though valid, our resources did not allow for in-depth study into these impacts on the UCRB. Land use changes were also not addressed in our study. It is understood that future conditions will include land use management implication, impacted by either direct climate concerns (such as pine beetle infestation in Colorado, increase in wild fires, etc.) and/or a human response to these changes by moving or adapting with alternate land management practices. Wang et al., (2011) explore climate impacts on streamflow using GCM dataset data with Soil and Water Assessment Tool (SWAT). SWAT is a watershed model which considers meteorological and hydrological conditions. With the A2 and B2 scenarios, they observe similar results in that land use and soils greatly impact reservoir performance. Though these conditions are not explicitly considered, our efforts have made it possible to address these issues with relative ease by just changing some input data (such as landuse imports, temperature changes, etc.). Using our model, decision makers are able to either use existing results or supplement the model with data to address specific concerns. Our research is a valuable tool in mitigating and adapting to future climate changes.

CHAPTER 3: METHODOLOGY

For this study, the UCRB is comprised of the Upper Colorado River and Gunnison River watersheds (Figure 3.1). Their confluence near Grand Junction, CO impacts water resources downstream and so both regions are significant to the study of climate change impacts of the Colorado. Much of the hydropower producing reservoirs are located on the Gunnison, so it is critical to include this part of the watershed, which has not been studied extensively. The UCRB has a drainage area of over 17,800 sq miles and includes reservoirs with over 493,000 MWH generating capacity, concentrated on the Gunnison river at Blue Mesa and Morrow Point reservoirs.

3.1 Description of Study Area

The UCRB includes 13 counties and 17 reservoirs, delineated into 24 sub-watersheds in this study. The region is a mountainous plateau of 4,850 to 13,000 feet in elevation, comprised of valleys, canyons and mountain ranges (Nealon, 2008). The headwaters originate in an area of granite, schists, gneisses, lava, and sedimentary rock but the entire UCRB is predominantly limestone, sandstone, and shale (USGS, 2012). The basin has one of the highest sediment loads in the nation, contributing to the numerous water quality issues in the region; however, water quality issues are not addressed in this study. The dissolved salts carried from surface and groundwaters have been estimated at 8 tons of salt per year per irrigated acre (Maughan, 1978).

The average annual flow of the Colorado river measured at 15 million AF at Lees Ferry, AZ from 1906-2006 (NAS, 2007), where the Upper Basin is separated from the Lower Basin (in the Compact). Most of the supply originates as snowmelt in the headwaters. The river is now directly managed with over 4,500 diversions and 17 reservoirs to provide reliable water supply for farming and cities. To accurately model the basin, all of these components were addressed and physically represented in WARMF. Groundwater flow contributes to discharge in the UCRB. Dependent on rock permeability and fracturing, most of the regional groundwater resources contribute to effluent at all times. WARMF, and this study, does not explicitly deal with groundwater resources but it is an important hydrological response to consider in future studies.

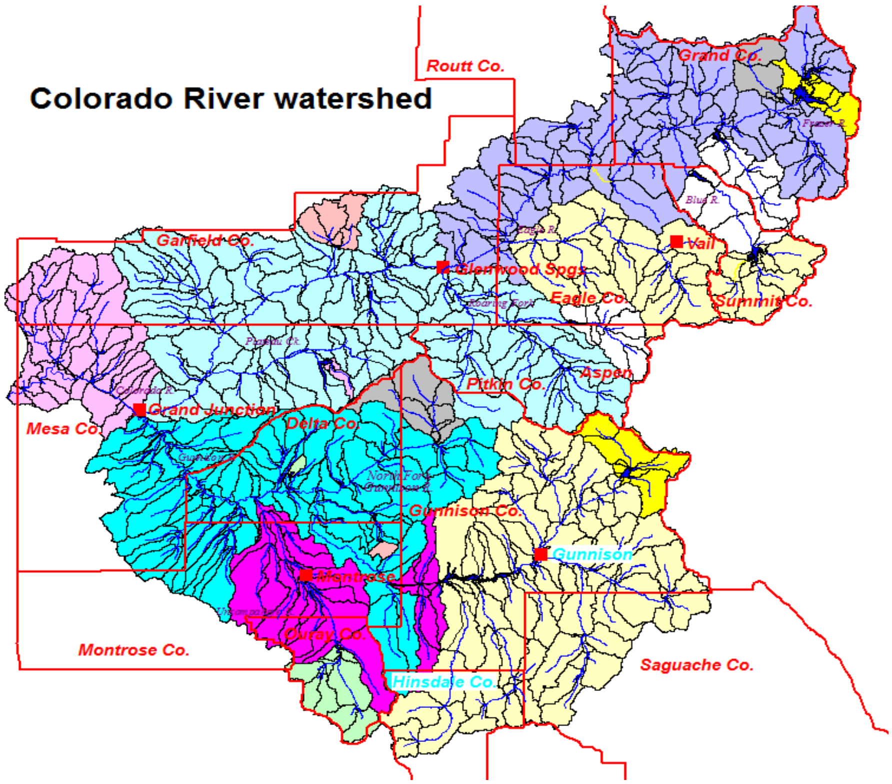


Figure 3.1: Upper Colorado River Basin

3.2 Review and Selection of Climate Models

The global climate models used in this study are three of the 24 identified by the IPCC (2007) and are described in detail by Tables 3.1 and 3.2 below (IPCC, AR4 WGI Chapter 8: Climate Models and their Evaluation, 2007). These climate models are developed by the Canadian Centre for Climate Modelling and Analysis CGCM3.1 (CGCM3) Japan's MIROC3.2 (MIROC) and Japan's Meteorological Research Institute's MRI-CGCM2.3.2 (MRI) under Special Report on Emission Scenarios (SRES) A2 and B1. To analyze the impact of climate change on the water resources of the UCRB, future climate data, precipitation, and temperature was incorporated into the calibrated WARMF model. WARMF was calibrated by comparing historical data to simulated values. Once model performance was assessed suitable, future climate inputs of temperature and precipitation were imported to analyze changes. Climate data from three climate models under two scenarios and two time periods were evaluated. Each of these GCMs has undergone significant improvements since the Third Assessment Report (TAR) of 2001 to the Fourth Assessment Report (AR4) of 2007. In the AR4 Working Group I identified the physical science basis advances in the GCM models. All were characterized by three major advances: 1) modeling of dynamical cores (such as advection, etc.), 2) more robust processes included such as aerosols, sea ice, and land surface processes, and 3) the parameterizations of the physical process were enhanced (IPCC, 2007). A2 assumes an essentially "business-as-usual scenario" in which emission levels are not moderated beyond the current efforts, at about 990 ppb. B1 assumes a considerable effort to minimize human induced warming by reducing emissions to about 550 ppb. WARMF only simulated data for Period 1, years 2046-2065. Period 2 (2081-2100) was only analyzed based on predicted data but not simulated in WARMF. The second period was not simulated in WARMF due to the intensive computational effort necessary to run the scenarios. A thorough analysis of both datasets, including a comparison of each period to past conditions is provided in this study.

Table 3.1: Boundary conditions of GCMs used in study (adapted from AR4 WGI, 2007)

Model ID, Vintage	Atmosphere Top Resolution	Ocean Resolution	Sea Ice Dynamics	Coupling Flux	Land, Soil, Plants Routing
CGCM3.1 (T47), 2005[1]	Top=1 hPa T47(~2.8°x2.8°)	1.9° x 1.9° Depth, rigid lid	Rheology, leads	Heat, Freshwater	Layers, Canopy, Routing
MIROC 3.2, 2004[2]	Top= 30 km T42(~2.8°x2.8°)	0.5°-1.4°x 1.4° Sigma/depth, free surface	Rheology, leads	No adjustments	Layers, Canopy, Routing
CGCM2.3.2, 2003[3]	Top=0.4 hPa T42(~2.8°x2.8°)	0.5°-2°x 2.5° Depth, free surface	Free drift, leads	Heat, freshwater, momentum	Layers, Canopy, Routing

In Table 3.1, degrees (°) refer to latitude and longitude; top is the pressure at the top of the atmospheric model; rheology refers to sea ice flow (material) characteristics; free drift is the modeling of ice movement so that ice drifts freely with the ocean currents or leads, the ice free portions within the pack ice; routing indicates where there is river routing in the land surface

[1] Canadian Centre for Climate Modelling and Analysis (CCCMa)
[2] Japan's Center for Climate System Research (CCSR), National Institute for Environmental Studies (NIES), and the Frontier Research Center for Global Change (FRCGC), and Japan's Agency for Marine-Earth Science and Technology (JAMSTEC)
[3] Japan's Meteorological Research Institute (MRI)

model; layers or bucket indicates how the soil layers are modeled; canopy indicates that a full vegetation canopy is simulated in the land surface model (IPCC, 2007).

Table 3.2: Comparison of Modeled Forcings (adapted from AR4 WGI, 2007)

Entries mean Y: forcing agent included, C: forcing agent varies with time during the 20th Century Climate in Coupled Models (20C3M) simulations, NA: forcing agent not specified. More information on the specific SO_4 forcings can be found at CGCM3.1: Boucher and Pham(2002), and MRI-CGCM2.3.2: Ukimoto et al. (2006).

Model	Greenhouse Gas (Forcing Agents)					Aerosols (Forcing Agents)				
	CO_2	CH_4	N_2O	Ozone	CFCs	SO_4	Carbon	Indirect	Volcanic	Dust
CGCM3.1	Y	Y	Y	C	Y	Y	NA	NA	C	C
MIROC3.2	Y	Y	Y	Y	Y	Y	Y	Y	C	Y
MRI	Y	Y	Y	C	Y	Y	NA	NA	C	Y

3.2.1 Meteorological Research Institute (MRI-CGCM2.3) GCM

The MRI is a coupled ocean-atmosphere GCM with a horizontal resolution of about 2.8 degrees (T42). It is based on the spectral transform numerical scheme of 30 layers in the vertical. The major parameterizations included in the model are as follows: cloud, convection, boundary layer, long and short wave radiation, wind, and temperature (IPCC, 2007). Since contributing to the Third Assessment Report (IPCC, 2001), the group has updated their representation of radiation budget distribution along the meridians and improved the cloud radiative forcings, which improved reproduction of extreme events caused by climate change (Yukimoto et al., 2005). Adjusting cloud representation improved the energy budget significantly. Cloud feedback is critical to shortwave forcing, important to middle and low-level clouds of the tropics and has been shown to effect climate model sensitivity (Yukimoto et al., 2003). Climate model sensitivity is very responsive to the mean climate response, which is predicted on the behavior of low and middle level clouds in the convective region.

The coupled scheme is comprised of the following model components and their characteristics: Atmosphere-Ocean (heat flux, solar radiative flux, freshwater mass flux, eastward and northward wind stress); Atmosphere-Land (sensible and latent heat flux, long wave and solar radiation, precipitation, evaporation/sublimation, eastward and northward wind stress); Land-Ocean (river discharge [freshwater mass flux], iceberg discharge [ice mass flux]); Sea Ice-Ocean (heat and salt flux, frazil ice mass, eastward and northward ocean surface velocities); Sea Ice-Atmosphere (sensible and latent heat flux, long wave and solar radiation, precipitation, evaporation/sublimation, eastward and northward wind stress). MRI is a coupled GCM which considers long wave and solar radiation and a cloud scheme based on relative humidity. Used in the IPCC 3rd Assessment Report (IPCC, 2001), the enhanced vertical profile of critical relative humidity is responsible for their improved cloud representation (Yukimoto et al., 2005) with specific model components listed in Table 3.3. The sea-ice model is based on thermodynamics, advection, and diffusion. An oceanic component is represented by realistic vertical topography of 23 vertical levels unevenly spaced from the bottom at 5000m to the surface. The surface albedo scheme models soil based on vegetation type and snow on snow temperature. MRI considers greenhouse gases (GHG) forcing agents of CO_2, CH_4, N_2O, sulfate aerosols, and solar activity. There is a pre-industrial control condition run (PIcntrl) used to reference the historical climate condition (20C3M). A 428-year spin-up run was simulated first, the results of which are used to initialize the control. The 20C3M is a 20th Century climate experiment (starting in mid-19th century) (Yukimoto et al., 2005). The SRES scenarios and other experiments are explicitly detailed in Table 3.4. Additional experiments include: a 720 ppm stabilization (SRESA1B) experiment, slab ocean model (Slabcntl), an instantaneous CO_2 doubling run (2xCO_2), a future climate change run based on the year 2000 conditions (Commit), and an Atmospheric Model Intercomparison Project (AMIP) model type simulation.

The MRI model demonstrated different levels of climate change under different scenarios A2 and B1 discussed in section 3.3. Yukimoto et al., (2005) found that globally averaged Surface Air Temperature (SAT) experienced the largest warming under the A2 scenario (3°) at the end of the 20th Century, with largest increases over Middle-Eastern Eurasia and northern North America. Central America and the tropical Pacific also experienced warming, especially in the Sahara through the Middle East, South Africa, and Australia. B1 scenario resulted in a minor climate change trend, with large internal variability. The high latitudes warmed the most during

Table 3.3: MRI Model Run Components adapted from Yukimoto et al. (2005)

Model Component	Boundary Condition (BC)	Routing	Characteristics	Function
Atmosphere	LW and SW radiation, cloud scheme, convection and boundary layer	--	Cloud and aerosols, temperature, specific humidity	--
Land Surface (includes River component)	Land cover and vegetation type, soil type, Leaf area index (LAI), albedo, snow temperature, soil moisture.	• Surface runoff from land to ocean at river mouth • Lake drainage omitted	• Thermodynamic processes of snow	Illustrates energy and water exchange between the land surface and atmosphere and river runoff in to sea-ice component
Ocean	Bottom layer to represent dense water	• Ocean floor depths interpolated on models grids and spatially smoothed	•Explicit sea surface elevation	Simulate deep overturning circulation, applied at high altitudes.
Sea Ice	Ocean current advection and diffusion; fixed salinity	•Ice flow impact on sea ice concentration and thickness • Forward difference of advection	•Thermodynamic treatment of sea ice processes	• Atm-ocean fluxes calculated for the air-sea interface.

winter, but experienced only slight warming in the summer months. Globally averaged precipitation rate increased in the high latitudes in winter, while decreasing in the Mediterranean and Central Asia. Overall, precipitation contained larger uncertainty from a greater internal variability. Sea level pressure indicated a negative trend in the Arctic, showing a positive correlation with climate changes over time. Atmospheric warming in the troposphere and cooling in the stratosphere were also noticed, specifically significant in the northern high latitudes and tropical upper troposphere. Ocean temperatures experienced even warming worldwide and sea levels rise globally. The latter was only evaluated in relationship to thermal expansion of sea water, causing freshwater inflow from glacier and ice sheet melt and ocean circulation changes. The North Pacific described a rise of as much as 20cm, with lowest impact around Antarctica.

Table 3.4: MRI Model Run Characteristics adapted from Yukimoto et al. (2005)

Model Experiment	Time Period (yrs)	Sulfates	GHGs	Solar Constant
Control (PIcntrl)	450 year pre-industrial spinup	No volcanics or aerosols	CO_2=290 ppmv CH_4=792 ppbv N_2O=285 ppbv CFCs=0	1366 Wm^{-2}
20C3M	Mid-19th to 2000	Sulfate aerosols direct effect, volcanoes, and solar forcings	All considered as in PIcntrl	1366 Wm^{-2}
SRESA2	1990-2100	Aerosol direct effects	CO_2, CH_4, N_2O, CFCs	1366 Wm^{-2}
SRESB1 (550ppm)	1990-2100 (1 run to 2300)	Aerosol direct effects	CO_2, CH_4, N_2O, CFCs	1366 Wm^{-2}
1%to2x	1% per yr increase of CO_2 concentration to doubling	Aerosol direct effects	CO_2 from 348ppmv, to 696 ppmv and then fixed CH_4 = 1650 ppmv N_2O = 306 ppbv	1367 Wm^{-2}
1%to4x	1% per yr increase of CO_2 concentration to quadrupling	Aerosol direct effects	CO_2 from 348ppmv, to 1392 ppmv and then fixed CH_4 = 1650 ppmv N_2O = 306 ppbv	1367 Wm^{-2}

Sea ice was observed to reduce in ice thickness and coverage, especially in summer when ice albedo is highest and there is a larger temperature difference between the ice and ocean temperatures. Some locations showed a summer reduction of greater than 45%, an alarming result.

Originally the model underestimated global warming due to emissions because there were too many low level clouds. This estimated less incoming solar radiation with more solar radiation exiting the atmosphere and therefore less overall warming. The improved scheme conditions relative humidity and pressure levels with surface albedo to account for seasonality differences in solar radiation.

3.2.2 Model of Interdisciplinary Research on Climate (MIROC3.2 medres) GCM

Japan's Center for Climate System Research (CCSR), National Institute for Environmental Studies (NIES), and the Frontier Research Center for Global Change (FRCGC), and Japan's Agency for Marine-Earth Science and Technology (JAMSTEC) have collaborated to produce the coupled MIROC3.2 model, among others, (K-1 model developers, 2004). First published in 2004, the MIROC model is comprised of 5 components: atmosphere, land, river, sea ice, and ocean (K-1 model developers, 2004). Each component individually interacts with some of the others in a large synergistic relationship, accounting for all hydrologic regimes. There are two atmospheric resolutions available: a high-resolution, T106 L56; and medium-resolution, T42 L20, version of MIROC3.2 (where "L" indicates the number of layers in the vertical). The high-resolution is at about 1.125 horizontal degrees with 56 levels in the vertical. The less intensive medium-resolution model is at 2.8 degrees grid resolution with 20 levels represented.

The coupled grid system divides each atmospheric grid by meridian and latitude circles, set up under the following structure: Atmosphere-Land (coupler considers land-surface fluxes); Atmosphere-Sea Ice (fluxes and variables converted between the coupler grid system and sea-ice model grid using tabulated relationships and aerial weights); Land-River-Sea Ice (ground runoff from Atmosphere-Land is routed to Atmosphere-Sea ice coupler, water is conserved) and Coastal Boundary (sea-ice grid system). Parallel computing on different processors allows the simultaneous simulations of atm-land-river and sea-ice-ocean parts, divided at the atm-sea ice coupler. Each model component has a unique set of boundary conditions, characteristics, and functions expounded in Tables 3.5 and 3.6. The individual model experiment conditions are similar to those described for MRI's CGCM3.2 model, with some differences, listed in Table 3.3.

Table 3.5: MIROC Model Component Details

Model Component	Boundary Condition (BC)	Routing	Characteristics	Function
Atmosphere	Surface Height, 3D distribution of Ozone concentration.	--	Cloud and aerosols radiative forcings	--
Land Surface	Land cover, soil type, Leaf area index (LAI), albedo.	Provides runoff to the river model	• Flux: invoked by atmospheric model Integration: Updates canopy water content, snow, and soil variables	Illustrates energy and water exchange between the land surface and atmosphere.
River	Velocity constant at 0.3 m/s worldwide	• Runoff from land surface to ocean model at river mouths	•Runoff and glacier flow considered' •Dense water analyzed	Receives ground runoff and drains river runoff into sea-ice component.
Ocean	Bottom layer to represent dense water	• Ocean floor depths interpolated on models grids and spatially smoothed	•Explicit sea surface elevation	Simulate deep overturning circulation, applied at high altitudes.
Sea Ice	Sea ice when top layer = freezing point	•Ice flow impact on sea ice concentration and thickness	•Treats newly formed ice differently than thick ice (different mechanisms) • Salinity considered	• Atm-ocean fluxes calculated for the air-sea interface.

Table 3.6: MIROC 3.2 (medres) Model Run Characteristics adapted from K-1 model developers (2004)

Model Experiment	Time Period (years)	Emissions	GHGs	Solar
Pre-Industrial Control (PIcntrl)		Sulfate aerosols, black and organic carbon, volcanics	CO_2,CH_4, N_2O, 13 halo-carbons	1366 Wm^{-2}
20C3M	1850-2000 (151 years)	Sulfate aerosols, black and organic carbon, volcanics	CO_2,CH_4, N_2O, 13 halo-carbons	1366 Wm^{-2}
SRESA2	1990-2100	Sulfate aerosols, black and organic carbon, volcanics	CO_2,CH_4, N_2O, 13 halo-carbons	1366 Wm^{-2}
SRESB1 (*CO_2 at 550ppm)*	2001-2100	Sulfate aerosols, black and organic carbon, volcanics fixed at 2000 levels	CO_2,CH_4, N_2O, 13 halo-carbons	1366 Wm^{-2}
%to2x	1% per yr increase of CO_2 concentration to doubling (70 years)	Sulfate aerosols, black and organic carbon, volcanics	CO_2,CH_4, N_2O, 13 halo-carbons	1367 Wm^{-2}
1%to4x	1% per yr increase of CO_2 concentration to quadrupling (140 years)	Sulfate aerosols, black and organic carbon, volcanics	CO_2,CH_4, N_2O, 13 halo-carbons	1367 Wm^{-2}

Additional experiments include: a CO_2 at 720 ppm stabilization (SRESA1B) experiment, slab ocean model (Slabcntl) with emissions fixed at 1900 levels (CO_2=295.9 ppm), an instantaneous CO_2 doubling run (2xCO_2=591.8 ppm), and an Atmospheric Model Intercomparison Project (AMIP) model type simulation (K-1 model developers, 2004). The medium-resolution model also includes a Commit run, as described above.

3.2.3 Canadian Centre for Climate Modeling and Analysis (CCCMa) CGCM3.1

CCCMa's CGCM3.1 climate model illustrates a symmetric warming between the northern and southern latitudes. It 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 included in the model are the water vapor continuum (controlling infrared cooling rate), stomatal conductance, orographic gravity wave drag, cloud and solar properties (including cloud emissivity) (McFarlane et al., 2005). Since contributing to the Third Assessment Report (IPCC, 2001), the group has updated their representation of the water vapor continuum, which contributed to a lower tropospheric cooling rate.

Various run conditions of the CGCM3 model are presented in Table 3.7 below. Multiple runs, at different starting conditions are necessary to model natural climate variability. As with the other climate models, there is a pre-industrial control run.

Table 3.7: CGCM3.1 Model Run Components adapted from Boer et al. (2000)

Model Experiment	Time Period (yrs)	Emissions	GHGs	Solar
Pre-Industrial Control (PIcntrl)				1366 Wm^{-2}
20C3M	1900-2000 (101 years)			1366 Wm^{-2}
SRESA2	2001-2100	Sulfate aerosols	CO_2,CH_4, N_2O	1366 Wm^{-2}
SRESB1	2001-2100 (1 run to 2300)	Sulfate aerosols	CO_2,CH_4, N_2O	1366 Wm^{-2}
1%to2x	1% per yr increase of CO_2 concentration to doubling	Sulfate aerosols	CO_2,CH_4, N_2O	1367 Wm^{-2}
1%to4x	1% per yr increase of CO_2 concentration to quadrupling	Sulfate aerosols	CO_2,CH_4, N_2O	1367 Wm^{-2}

Coupled global models generally illustrated hemispheric bias, with more warming in the northern latitudes than in the southern. This has been attributed to greater heat uptake at high southern latitudes, leading to a reduction in heat penetration in the south. Deep mixing in the southern hemisphere around Antarctica has been thought to sequester heat, but sea-ice extent indicates do not support this hypothesis (Boer et al., 2001). Improvements to the CGCM3 model describe more advanced mixing parameterization scheme affecting the location of ocean uptake, though globally averaged ocean temperatures do not appear to change. This model considers symmetric warming between the two hemispheres along with surface air temperature, snow cover, sea-ice, precipitation, evaporation, sea level pressure, and soil moisture. It utilizes short and long-wave radiation, air temperature, humidity, wind speed, precipitation rate to calculate the energy and moisture budgets. With a more active hydrologic cycle predicted, increased precipitation and evaporation are both expected and observed. An update land surface scheme considers 3 soil layers, snow layer, and vegetated canopy. There is also a large increase in inter-annual variability and reduction in seasonal soil moisture, indicative of drying. Snow and sea ice changes are indicative of albedo effect, while sea level pressure describes large-scale wind flow alterations in both direction and magnitude (Boer et al., 2000).

3.3 Review and Selection of Climate Scenarios

Of the six greenhouse emission scenarios (A1FI, A1B, A1T, A2, B1, B2) developed by the IPCC (IPCC, 2004), the A2 and B1 are most widely simulated in climate change studies. They were chosen to represent climate change in this study because they describe a realistic range of conditions in the next century. The Special Report on Emission Scenarios (SRES) explores the uncertainties of future trends in global development and GHG emissions (Nakicenovic et al., 2000). The SRES storylines are described in detail below:

• <u>A1</u>: The A1 storyline and scenario family describes a future of rapid economic growth, global population that peaks in mid-century and declines thereafter, and the introduction of new and more efficient technologies. There is an increase in capacity building and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income.
A1FI : A1 scenario with an emphasis on fossil fuel emission (Fossil Intensive)
A1B: Emphasis on all energy sources
A1T: Emphasis on non-fossil fuel energy sources

• A2: The A2 storyline and scenario family describes a very heterogeneous world with high population growth and is most representative of a Business-as-Usual (BAU) scenario. It is marked by self-reliance and preservation of local identities. Regional economic growth and development, per capita economic growth, and technological change are more uneven and slower than in other storylines. There is added emphasis on global climate initiatives.

B1: The B1 storyline and scenario family describes a world with the same low population growth as in the A1 storyline, but with changes in economic structures toward a service and information economy. The emphasis is on reductions in material intensity and introduction of clean and resource-efficient and sustainable technologies. There is a strong focus on global solutions to economic, social, and environmental sustainability, without additional climate initiatives.

B2: The B2 storyline and scenario family describes a world focused on local solutions to economic, social, and environmental sustainability. There is moderate population growth and levels of economic development with more diverse technological change than in the B1 and A1 storylines, though less rapid. There is local and regional focus on environmental protection and social equity.

3.4 Review of and Selection of Downscaling Methods

GCMs are coupled numerical models to describe a plethora of systems such as land surface, ocean, and atmosphere and are used to study climate change impacts globally (Fowler et al, 2007). Their resolution is fairly coarse and cannot therefore accurately represent specific topographic features, among others. Therefore, downscaling techniques are used to resolve this considerable issue. There are two approaches for downscaling: dynamical and statistical downscaling methods. These are discussed in detail in the following sections and summarized below in Table 3.8.

Dynamical downscaling is the implementation of Regional Climate Models (RCMs). Usually resolved to a 0.5 deg scale, the modeling quality is significantly affected by GCM bias and regional characteristics (orography, etc.) (Fowler et al., 2007). The greatest source of uncertainty is introduced by boundary forcings (of the original GCM), especially by temperature, a significant driver of climate change impacts. Yet this technique more accurately simulates extreme climate events and regional anomalies, significant in the study of water resource dependencies due to climate change.

Table 3.8: Summary of the individual downscaling techniques characteristics (adapted from Fowler et al., 2007)

	Statistical Downscaling	Dynamical Downscaling
Benefits	Computationally efficient Provides point-scale climatic variable from GCMs Regionally transferable Includes observational data Standardized statistical methods	Physically based response Finer resolution output from GCMs
Shortcomings	Observed historical datasets required Predictor choice critical Non-stationary of predictor-predictand relationship Climate system feedback not included Affected by GCM biases Dependent on initial boundary conditions Domain size, climatic region and season affects downscaling skill	Computationally intensive Only some scenarios available Reliant on initial boundary conditions

Statistical downscaling is used to scale a GCM projection to a particular finer region of interest. The method assumes a constant bias through time (a change) while also keeping the spatial pattern constant. It ignores changes in variability to apply the bias statically to GCMs. In order to apply this fairly simple method, several caveats exist. "Predictor" values need to have physical significance, and the "predictor/predictand" relationship is assumed stationary in time.

Predictors are the large-scale atmospheric variables, while predictands are the regional climate variables. Statistical downscaling is critically dependent on the selected predictor/predictand variables selected and on the region used (Fowler et al., 2007). In this impact study, we have chosen to implement statistical downscaling approach because it is widely accepted by the literature, has been used in other studies extensively, and has been shown to produce comparable results to dynamic method (Wood et al., 2004).

Dynamical downscaling using RCMs has been used in the Western U.S to produce physically realistic projections of changes in hydrologic extremes (Kim et al., 2002; Snyder and Sloan, 2005). Although these models account for atmospheric and physical changes in the environment, they have not been shown to lead to large improvement over statistically downscaled data, particularly in hydrological simulation after bias correction and spatial disaggregation (Wood et al. 2004). Their value is strongest where orographic effects and other localized surface conditions are significant climate influences. The fact that RCMs are computationally demanding is also a drawback; typical prediction/analysis periods are restricted (often to 10 years) due to processing limitations, and are still not meeting needs of spatially explicit models (Kunstmann and Jung 2005; Wilby and Wigley 1997). Thus, more computationally efficient statistical downscaling approaches continue to serve for downscaling ensembles of long climate simulations. Statistical downscaling approaches are favorable because they are based on standard and accepted principles, computationally inexpensive, flexible, and they use explicit observed records; however, they also assume no future change in statistical relationships, require long calibration records, and demonstrate skill depenent on climatic region and season (Wetterhall et al, 2005). Statistical downscaling approaches are discussed in more detail in the sections below.

A. Bias-Corrected and Spatially Downscaled (BCSD) Method

Statistical downscaling methods have been widely used for local and regional-scale hydrologic impact analysis: constructed analogues (CA) (Hidalgo et al., 2009) and bias-corrected and spatially downscaled (BCSD) (Wood et al., 2004). The BCSD data archive includes downscaled projections of 16 climate models and 112 emissions scenarios simulated monthly. Statistically downscaled climate projections using both the CA and BCSD methods are available online for the entire US for the period 1950-2099 at 1/8th degree (approximately 12km) resolution via the statistically Downscaled World Climate Research Program (WCRP) CMIP3 Climate Projections Archive (Maurer et al. 2007*).* These datasets have been used for several studies on projected hydrologic impacts (Maurer, 2007; Christensen and Lettenmaier, 2007; Brekke et al., 2009). Maurer et al., (2010) concluded that for extreme peak flows all methods performed well and that the ability to produce downscaled daily data skillfully mostly depends on the climate model's daily skill.

The BCSD method is most commonly used because it is able to produce time series at a fine resolution of 1/8 degree over a large region and is comparable to other statistical/dynamic methods in evaluating hydrologic impacts (Maurer and Hidalgo, 2008). Wood et al., (2004) described the satisfactory results of using BCSD data in comparison to other techniques when evaluating hydrologic impacts. It is an empirical statistical technique using monthly precipitation and temperature output from the GCM. The bias correction step uses a quantile mapping approach. It arranges the GCM precipitation and temperature data into a probability density function and then maps it onto observed historical data from 1950-99 (Maurer et al., 2009). The same mapping is forced on the projected future GCM simulations. This technique creates quantile maps of simulated and observed conditions during the bias-associated period. It conserves monthly data, but randomly resamples daily data to match the projected monthly values (Maurer et al., 2010). These randomly generated daily sequences have negligible impacts on less sensitive watersheds, but are critical to the UCRB where daily variations have impactful consequences.

The methodology assumes some key principles. Initially, it is assumed that the 20th and 21st (projected) simulations hold a constant bias in the GCM. This bias is a uniform trend, independent of time, identified in the past and projected onto the future. It also assumes stationarity, or an unvarying pattern constant across time and space, and ignores potential variability from those trends in the future.

Downscaling skill has been shown to be markedly better for temperature, rather than precipitation (Maurer and Hidalgo, 2008). Overall skill is related to the GCM predictors, which capture spatial complexities. It has also been shown that downscaling dry areas is more difficult than wet, with even more bias along complex terrain such as mountain ranges. For our study, it is critical to understand both dry and wet regimes along with complex terrain, as that is the nature of the UCRB. Hydropower is reliant upon rule curves in assessing production, which are dependent on available resources. With better predictor values, a more accurate assessment of available power and possible interruption can be made. This would greatly assist stakeholders in making appropriate choices in future conditions.

B. Constructed Analogues (CA)

The Constructed Analogues method, described by Hidalgo et al. (2008), uses daily large-scale output to downscale daily precipitation and temperature directly. It conserves daily data, performing very well in reproducing extreme peak flows, with daily skill dependent upon the predictor values in the GCM (precipitation and temperature). It is based on the anomalies of daily precipitation and temperature, but does not correct for bias. To construct an analogue, a relationship is built between large-scale and fine-scale anomalies, capturing mean bias but may not match monthly distributions (Maurer et al., 2010). It ensures that daily fluctuations match the observed daily distribution, creating more accurate spatial gradients of precipitation and temperature changes, but does not guarantee monthly equivalents (Maurer et al., 2010). In mountainous regions the CA method has produced better results, making it appropriate to the UCRW.

Daily skill is modest at best in describing winter predictands, but wet extremes are captured relatively well (Maurer and Hidalgo, 2008). CA skill is extremely dependent upon the statistics being represented, region, and season. Analogue method captures extreme events better than other statistical downscaling options, a significant benefit in our area of study. Unlike the BCSD technique, CA does not have bias-correction, so it transfers bias to the downscaled data and must be dealt with at the finer scale.

With hydropower generation, rule curves are responsible for assessing production. These predict the frequency and severity of flood events dictating power availability and predict interruption. Raje and Mujumdar (2009) suggest that hourly projections would be even more indicative of reservoir reliability, so our daily approach is much more robust than the traditional monthly scale used. They indicate that mean monthly power generation will decrease under future climate scenarios. The daily analysis approach will enable decision makers to understand reservoir variations daily, enabling the prevention of power interruption or other critical events.

C. Bias Corrected Constructed Analogues (BCCA)

The BCCA technique shares many similarities with the BCSD, but was specifically developed to analyze sub-monthly climate changes. It follows the CA approach of working with anomalies but recognizes the need for bias-correction at finer scale. Therefore, the BCSD trend removal is applied to the CA technique. The trend is a tendency for a GCM to be too dry/warm/wet/cool when simulating relative to past conditions. This process is almost identical to that in BCSD, but instead of applying it to monthly P and T data, quantile mapping is imposed on daily values (Maurer et al., 2010). Quantile mapping addresses mean and variability on a daily scale, which appears to produce the most significant bias, and is therefore the most robust approach. In the daily BCCA datasets, better evaluation of daily intricacies is simulated. The BCCA technique explicitly corrects all 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 that of the UCRB. This difference greatly impacts precipitation and temperature values, specifically the hydrologically significant extremes. Furthermore, the hydrology model WARMF is based on daily data, so daily datasets are needed to run the model.

Maurer et al., (2010) compared the CA and BCSD methods to the new BCCA technique. While all downscaling methods produced reasonable stream flow statistics at most locations, the hybrid BCCA method consistently outperformed the BCSD and CA, capturing daily large-scale skill and translating it to simulated stream flows. Selection of downscaling technique and data depends on the variables, seasons, regions of interest, availability, and whether the day to day correspondence needs to be reproduced (Maurer and Hidalgo, 2008). Future climate data is often required at a finer temporal scale (daily or sub-daily) than that previously available, particularly for watershed modeling. Numerous current efforts aim to make high resolution data available for planners, researchers, and modelers worldwide.

Both the BCSD and BCCA methods have some limitations. They cannot capture regional phenomena well, such as monsoons, but that is not an explicit concern in our area of interest. The BCCA technique, reflecting sub-monthly projections, possesses the inherent uncertainties of the GCM it uses. Many publications have validated the use of the technique nonetheless (Maurer et al., 2010). When comparing temperature driven statistics, BCCA performs similar to CA. The more the climate changes from the historical record, the greater are differences between BCSD and the CA/BCCA results. BCSD performs better when precipitation dominates, but BCCA has also shown to capture the wet year daily signal. This illustrates the BCCA as a more robust method, capturing wet conditions relatively well, but also recovering dry year daily signals and annual flow volume. BCSD is slightly worse in dry conditions because it becomes too difficult to match peak events when many low flows are present (Maurer et al., 2010). For the reasons mentioned above, BCCA daily downscaled future data was selected to force the WARMF hydrologic model.

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 (http://gdo-dcp.ucllnl.org). This effort aims to facilitate more uniform modeling, research, and planning studies in the region.

3.5 Review and Selection of Watershed Model

There are numerous hydrologic models that can be and have been applied to the CRB for climate change impact analysis. CRB is a complex watershed where both snowmelt and rainfall events occur. Consequently, differing hydrological processes dominate watershed behavior which can cause a unique response to the predicted changing climate. Only a slight increase in air temperatures could cause dramatic change in mountainous hydrology and regional water resources (Kienzle et al., 2012). Understanding of future climate change on the hydrological cycle within a watershed scale is crucial for water resources planning. This makes the selection of hydrologic modeling technique crucial to the validity and accuracy of results.

Impacts of climate change on the hydrological behavior of a particular watershed are only meaningful if the physical, spatial, and hydrological cycles are accurately represented (Kienzle, 2012). The hydrological response to predicted change has been extensively studied (as described prior) through a variety of hydrological models. Watershed-scale models have been used to assess the hydrologic response to climate change forced by GCM future conditions (Kienzle, 2012). Hydrologic behavior is best described by a physically-based complex watershed model, which can accurately simulate potential future climate scenarios and water resources impacts. Both, continuous simulation or extreme event-based models, have been applied to assess the impact of climate change on water resources. Some of them are described below. Continuous simulation models are beneficial in analyzing flows (high and low) because they account for the influence of preceding climate events on current and future hydrologic conditions. Current and future flows can be assessed through the inclusion of preceding events such as soil moisture accounting. These are critical to reservoir inflows and storage, indicating periods of drought and/or flood. On the contrary, extreme event models simulate occurrences, such as floods, as discrete events; simulating only from one event occurrence to the next. The direct passage of time does not explicitly influence the model, only the occurrence of events, which can increase in frequency under changing climate conditions. Simulating only discrete events would simulate only event instances, rather than the continuous passage of time. In predicting future climate, a continuous model is better suited to analyze impacts based on direct and exact changes in time.

3.5.1 Continuous Simulation Models

A. Variable Infiltration Capacity (VIC)

The Variable Infiltration Capacity is a macro scale hydrology model which uses GCM outputs to produce hydrology and water resources results (Christensen et al., 2004). VIC is a gridded model driven by precipitation, temperature and wind time series from the 1/8 to 2 degrees spatial scale. It models soil moisture processes and evapotranspiration, surface runoff and baseflow, and snow accumulation and melt. VIC uses a cell-based routing technique to simulate streamflow at specified junctures in the system (Liang et al., 1994). It can run at daily and sub-daily time steps for an energy or water balance analysis.

B. Watershed Assessment Resources Management Framework (WARMF)

The Watershed Assessment Resources Management Framework is a decision support system for water management. It is a GIS-based physical watershed model integrating models, databases, and graphical software using data from meteorological, air quality, point source, diversion, and reservoir data propel the model engine. WARMF is a seamless river basin model comprised of catchment, river, lake and reservoir segments for soil and surface hydrology evaluation based on physical principles. The river basin serves as an interconnected reactor of vegetation, land surface, soil layers, river segments and lakes, routing movement to evaluate infiltration, evapotranspiration, stream flow, daily runoff and shallow ground water flow. The hydrology budget is calculated by the water balance which analyzes precipitation and irrigation water infiltration to the land layer, percolation out of the layer, lateral in/outflow and evapotranspiration (Geza et al., 2009). Individual catchments can be divided into five soil layers. WARMF is a dynamic simulation model and can run at daily time steps to analyze the water balance for watersheds to produce runoff, soil hydrology, ground water lateral flows, stream flows, and point source loads, if necessary. Physically based, spatially distributed hydrological models are an effective means to assess the impacts of climate change on hydrological response, as they are able to capture the spatial variability of hydrological processes throughout complex watersheds (Kienzle, 2012).

C. Soil and Water Assessment Tool (SWAT)

SWAT is a river, basin, or watershed scale model that analyzes the impact of land management practices on water, sediment and agricultural chemical yields (http://swat.tamu.edu). It is frequently used with differing soils, land use patterns, and management conditions in large and complex watersheds for long term impact analysis. It is physically-based, using weather, soils, topography, and vegetation properties to drive a continuous time model for long-term yield. SWAT models watershed even when monitoring data is unavailable, and is capable of quantifying change in input data for impact analysis. It is computationally and fiscally efficient.

D. Hydrological Simulation Program- Fortran (HSPF)

HSPF is a widely used program simulating watershed hydrology and water quality for conventional and toxic organic pollutants. It is a physical, continuous, distributed parameter watershed model. HSPF simulates runoff, sediment, and water quality. The watershed is divided into catchments based on climate stations and soils types. Each catchment includes landuse data and soil classification. It analyzes the fate and transport of contaminants while calculating water quantity and quality at any point in the watershed. . The total load from HSPF includes the contribution from groundwater and overland flow (Geza and McCray, 2007)*:* HSPF is more robust for in-stream processes than upland (overland) processes. It has some groundwater transport routine but is not sufficient in its analysis.

E. Water Evaluation And Planning system (WEAP)

WEAP is a Windows-based decision support system for water resource managers and policy decision-makers to analyze long-term decision planning (www.weap21.org). It contains a GIS-based, graphical interface. WEAP simulates water supply and demand, runoff, evapotranspiration, infiltration, irrigation needs, instream flow requirements, groundwater and storage analysis. Pollution creation, treatment, discharge and stream quality, and reservoir operations under possible varying scenarios of policy, hydrology, climate, land use, technology and socio-economic factors. It can link to the USGS MODFLOW for dynamic groundwater analysis and the US EPA QUAL2K surface water quality model.

3.5.2 Extreme Event Models

A. Storm Water Management Model (SWMM)

SWMM is a dynamic rainfall-runoff model for runoff simulation. It routes runoff quantity and quality through pipes, channels, storage/ treatment facilities, pumps, and other hydraulic structures. Mostly used for urban hydrology applications of sizing and flood control, it uses rainfall interception and infiltration for hydraulic modeling. SWMM is also capable of examining pollutant loads, producing management strategies.

B. Hydrologic Engineering Center (United State Army Corps of Engineers) Models

Hydrologic Engineering Center (HEC) offers a suite of modeling systems to individually address a variety of needs. HEC-RAS (River Analysis System) is a 1D steady and unsteady flow and transport analysis model. HEC-HMS (Hydrologic Modeling System) is a precipitation runoff model of water systems. It can model water supply, flood hydrology, and watershed runoff to produce hydrographs for future analysis. ResPRM (Prescriptive Reservoir Model) is a reservoir system operations optimization software which can be used in conjunction with other HEC suites, but is not explicitly joined. It is a network schematic of reservoir and stream reaches, simulated at monthly time steps only when used in conjunction with simulation software ResSim (which is capable of modeling several reservoirs).

C.TR 55 (HydroCAD Stormwater Modeling)

TR 55 is a simplified model to calculate storm runoff, peak discharge rate, hydrographs, and storage volumes for flood reservoirs. Designed for urbanized, small watersheds it uses runoff curve numbers to analyze single event simulations. Rainfall is estimated using Tc (time of concentration) or the time it takes for a single droplet to travel from the fartherst hydraulically significant point, to the point of interest. Runoff estimation uses the curve number method, which depends on soil and cover conditions (). Peak discharge, hydrographs and detention storage are also calculated. TR-55 is specifically used for sizing flood detention facilities.

3.6 Selection of a Watershed Model

Hydrologic impacts of climate change can be analyzed using the various modeling methods mentioned prior. WARMF was selected for a variety of reasons. The integration of stream segment and reservoir models in a continuous simulation is most beneficial for a water resources impact study. WARMF is also capable of analyzing varying meteorological scenarios, under differing conditions. Several peer reviews have analyzed WARMF and compared it to other watershed models, finding it to perform as well or better. Chen C. H., (2005), implemented WARMF to simulate hydrological processes and perform very well in forested watersheds. Previous work by the Colorado School of Mines (CSM) group has also used WARMF to model parts of the UCRB. WARMF was chosen for this study because it is a dynamic continuous simulation model with inherent reservoir capabilities, based on a realistic GIS-based physical representation of the UCRB (such as the numerous diversions). As a continuous model, WARMF considers the influence of preceding events and evapotranspiration. To characterize potential climate change impacts on water resources, it is crucial to model continuous flows rather than a single event.

3.7 Description of WARMF Model

Watershed Analysis Risk Management Framework (WARMF) is a GIS-based integrated model and decision support network for watershed resource management (Ecosystems). WARMF is comprised of five modules: engineering, data, knowledge, TMDL, and consensus (Herr et al., 2001).WARMF stores data on meteorology, air quality, point source pollutants, reservoir curves and releases, and flow diversion data. WARMF performs mass balance, heat balance, reaction kinetics, chemical equilibrium and other calculations and returns model outputs (Herr et al. 2001). WARMF simulates daily runoff, water quality, hydrology and shallow groundwater flow (Ecosystems). Each watershed is partitioned into catchments of land data, river segments, and reservoir layers. Land use and land cover describe the surface. Precipitation data is routed through the land layers to simulate snow and soil hydrology, producing runoff and shallow groundwater flow. Precipitation falls as either rain or snow, depending on temperature. The hydrologic budget is calculated at the catchment level using a water-balance approach (Chen et al., 2001). From each catchment, runoff and groundwater flow are routed to the river segments.

Routing originates from precipitation, continues to stream segments, from where it reaches the reservoirs and then to downstream river segments until the extent of the watershed is reached. Runoff on pervious surfaces may either infiltrate in the five soil layers, or run off. Hydrologic processes of canopy interception, snow pack and snow melt, soil layer infiltration and evapotranspiration, along with groundwater ex-filtration to stream segments are all modeled. The physically-based model relies on mass and heat balance, reaction kinetics and chemical equilibrium approach to calculate for an output. Atmospheric and land application data is used as the boundary conditions. Specific treatment of the various WARMF model components are described in more detail below:

Potential and actual evapotranspiration: potential evapotranspiration is a function of total free surface water evaporation and soil transpiration. Initially, water on the canopy surface evaporates after which water collected on land evaporates. Leaf area index (LAI) is used to determine canopy interception, along with maximum canopy interception and precipitation. When precipitation exceeds canopy interception, the surplus becomes throughfall.

Snow Hydrology: Snow hydrology simulates accumulation and snowmelt by air and/or rain under open conditions and those under canopy cover. Throughfall and snowmelt descend on ground surface.

Runoff: An impervious surface will produce immediate runoff. On impervious surfaces the water may infiltrate flow as surface runoff or remain as storage on surface. Each catchment may contain up to 5 soil layers. The layer processes are dependent upon soil moisture content, horizontal and vertical hydraulic conductivities, field capacity and saturated soil moisture content. Infiltration to each layer is dependent upon water available for infiltration, vertical infiltration rate, and void spaced in the layers below. Lateral flow is derived from Darcy's Law.

Soil moisture content : Resultant water balance is performed from the bottom layer to the top layer, one layer at a time. The surface water which does not infiltrate into the soil may collect on the surface as detention storage or it will runoff as sheet flow. The sheet flow is calculated by Manning's equation. The water from the upstream stream segment is fully mixed with the water in the stream segment from previous time step and the point and nonpoint loads entering the stream segment during the time step. For each CSTR (canopy layer, soil layer, stream segment, reservoir layer, etc.), the flow continuity equation can be written based on conservation of mass. Inflows to a stream segment can include flows from upstream stream segments, reservoirs, surrounding land catchment, soil layers, and point sources. Heat budget and mass balance calculation are performed to calculate the water temperature and concentrations of various water quality constituents in each soil layer, stream segment, and reservoir layer (Chen et al. 2001).

Reservoir simulation: A reservoir is further divided into about 30 horizontal layers along depth to simulate water quality in a stratified reservoir. Each layer is assumed to be horizontally mixed. When reservoir elevation rise and fall due to variations of inflow(s) and outflow(s), the model correspondingly add or delete layers. The model requires reservoir bathymetric data in the form of stage-area relationship for simulation. The reservoir flow balance is predicated on conservation of mass.

3.8. Model Development

In WARMF, a watershed is divided into several catchments, and each catchment is drained via a stream segment, reservoirs can also be added. The UCRB (including some of the

Gunnison River basin) is delineated into 24 sub-watersheds, comprised of catchments, river segments and 17 reservoirs. The delineation is completed in ARCGIS and imported into the WARMF interface as shown in Figure 3.1.There are over 600 subcatchments in the study area. All of the tributaries eventually feed into the main stem of the Colorado River, prior to reaching the Colorado-Utah border. Nealon (2008) explicitly details the Upper Colorado River Watershed (UCRW) delineation. This study builds on that model and expands to the Gunnison River basin to provide a more complete picture of the UCRB water resources. Input data is required to run the simulations and is described in detail below.

3.8.1 WARMF Model Input

Prior to WARMF simulation of watershed hydrology, input data must be appropriately prepared. Model inputs include climate, soils, land use, observed flow, diversion, and reservoir data. Some of the model inputs are treated as model coefficients, defining the physical, chemical, and biological characteristics of each watershed. While others are considered time-series data, which are time dependent and provides daily accounting for input data like meteorology and pollutant loads (not discussed here). The specific model inputs are described below:

A. Climate data:

Time-series meteorological inputs such as precipitation (cm), minimum and maximum temperatures (C°), wind speed (m/s), atmospheric pressure (mbar), dew point temperature, and cloud cover are necessary for WARMF to run a hydrologic simulation. Air chemistry is not considered because water quality is not assessed in this project. Most of the meteorological data can be downloaded from the National Climactic Data Center (NCDC) website, with specific data needed to model the study region described in Table 3.9 below. Many of the stations in the project area did not have complete datasets. Therefore only stations with data were considered. WARMF requires fraction of cloud cover, when cloud cover data is available, it could directly be input to the model as time series. When cloud cover data is not available, it can be calculated from Tmin, Tmax, Tdew, Precipitation data.

Table 3.9: Data Types and Source for Model Development

Data Source	Data Type	Purpose
CDSS, USGS USDA,	Physical Data (cities, townships, contours soil, data, land use, vegetation, polygon shape files and GIS data points)	Physical description of basin: land and soils information
NHD PLUS	Elevation data (GIS elevation contours and GIS data points)	Physical topographic description of basin
CDSS	Diversion Data (GIS based time series of all diversion points in the basin)	Water allocation that describes water to and from streams
CDSS, NCDC Global Summary of the Day (GSOD),	Climate Data (meteorological data of Tmin, Tmax, Precipitation, Wind speed, Atmospheric Pressure and Dew temperature)	Historical climate characterization of basin
USGS	Stream Flow (Observed flow gage stations)	Calibration

B. Soils Data:

USDA's National Resources Conservation Service (NRCS) Web Soil Survey (WSS) provides soil data and information. Soils data for the 13 counties were downloaded and the three prominent soil types were sandstone (48%) and limestone (15%), with the rest of the heterogeneous basin comprised of 23 other soils. Based on these soil types, soil parameters such as soil thickness, field capacity, saturation moisture, horizontal conductivity and vertical conductivity were estimated. The soil parameters were slightly adjusted during model calibration to generate good match between modeled and observed data. These soil parameters along with other adjusted parameters for calibration are listed in Table 3.14.

C. Land Use:

The land use characterizes the land surface of the UCRB was gathered from several Geographic Information System (GIS) sources. The basin was cropped using GIS tools and

USGS seamless GIS coverage data (Nealon, 2008). The land surface of the basin is dominated by forest and rangeland, as identified by the United States Geological Survey Land Use and Land Cover Classification System illustrated in Table 3.10 below.

Using the CDSS, a joint project by the Colorado Water Conservation Board (CWDB) and the Division of Water Resources (DWR) for water management (CDSS, 2010), the appropriate shape files can be selected and directly imported into WARMF after the projection has been altered from unprojected to the appropriate decimal degree projection. Although WARMF can automatically calculate landuse for each catchment on import, if any of the boundaries overlap, land use is not accurately presented. Therefore, incorrect land use allotment was identified and populated with the correct data.

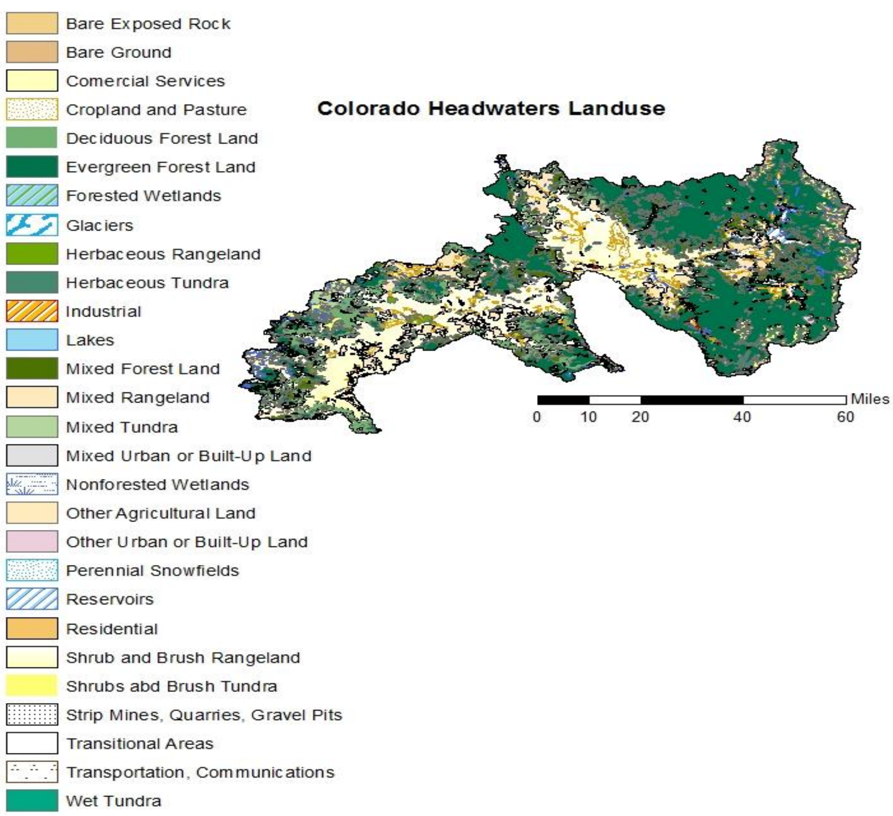


Figure 3.2: Land use in the Upper Colorado River Watershed

Table 3.10: U.S Geological Survey Land Use and Land Cover Classification System for Use with Remote Sensor Data (USGS, 2010)

Level I	Level II
1 Urban or Built-Up Land	11 Residential
	12 Commercial and Services
	13 Industrial
	14 Transportation, Communications and Utilities
	15 Industrial and Commercial Complexes
	16 Mixed Urban or Built-up Land
	17 Other Urban or Built-up Land
2 Agricultural Land	21 Cropland and Pasture
	22 Orchards, Groves, Vineyards, Nurseries, and Ornamental Horticultural Areas
	23 Confined Feeding Operations
	24 Other Agricultural Land
3 Rangeland	31 Herbaceous Rangeland
	32 Shrub and Brush Rangeland
	33 Mixed Rangeland
4 Forest Land	41 Deciduous Forest Land
	42 Evergreen Forest Land
	43 Streams and Canals
5 Water	51 Lakes
	53 Reservoirs
	54 Bays and Estuaries
6 Wetland	61 Forested Wetland
	62 Nonforested Wetland
7 Barren Land	71 Dry Salt Flats
	72 Beaches
	73 Sandy Areas Other than Beaches
	74 Bare Exposed Rock
	75 Strip Mines, Quarries, and Gravel Pits
	76 Transitional Areas
	77 Mixed Barren Land
8 Tundra	81 Shrub and Brush Tundra
	82 Herbaceous Tundra
	83 Bare Ground
	84 Wet Tundra
	85 Mixed Tundra
9 Perennial Snow or Ice	91 Perennial Snowfields
	92 laciers

D. Observed Flow:

USGS water data web site (USGS, 2010) provides daily flow data for specific USGS gaging stations on river segments. The stations in the UCRB WARMF model were used for model calibration and validation. Water quality is not considered in this study, so no observed water quality files were attributed anywhere.

E. Diversion Data:

Diversions, or managed flow, describe water added and removed from a stream for predominantly agricultural use. Diversions do not alter the water balance, and cannot take more what than available in stream, more characterizing the physical system at any one point. Our model includes over 4,500 individual diversion points, which is a considerable effort to compile and post-process and contributes to the value of the existing model and resultant conclusion. CDSS provides data organized by water division, river basin, and structure type which was used to accumulate the data. Our study area comprises of Colorado Water Divisions 4 and 5, each with their respective river basins as shown in Table 3.11. From each basin, each structure type was indentified to evaluate all diversions. Of the 9 structure types shown in Table 3.12, all were considered except for wells, springs, seeps, and mines for the period of analysis.

Table 3.11: Water Divisions for Diversion Records

Water Division 4	Gunnison
District 28	Tomichi Creek
District 40	North Fork/Tributaries
District 41	Lower Uncompahgre River
District 42	Lower Gunnison River
District 59	East River Basin
District 60	San Miguel River Basin
District 61	Paradox Creek
District 62	Upper Gunnison River
District 63	Dolores River Basin
District 68	Upper Uncompahgre River
District 73	Little Dolores River
Water Division 5	Colorado
District 36	Blue River Basin
District 37	Eagle River Basin
District 38	Roaring Fork River Basin
District 39	Rifle/Elk/Parachute Creeks
District 45	Divide Creek
District 50	Muddy/Troublesome Creeks
District 51	Upper Colorado/ Fraser Rivers
District 52	Piney/Cottonwood Creeks
District 53	Tributaries of Northern Colorado River
District 70	Roan Creek Basin
District 72	Lower Colorado River

From structure selection, each diversion was then evaluated for the content of the data. Those without data were discounted; incomplete data was considered for time of relevance (if valid for the period of study 1986-2006). Some diversions may have water rights, but water may not be diverted so these are considered inactive structures.

Table 3.12: Diversion Structures

Structure
Ditch
Well
Reservoir
Spring
Seep
Mine
Pipeline
Pump
Powerplant

F. Reservoir Data:

Reservoirs for study in the UCRB are listed in Table 3.13, focusing on hydropower producing Blue Mesa, Morrow Point, and Green Mountain Reservoirs. Each reservoir is populated with the following: physical data, stage-area-discharge table, observed data, inflow/outflow structures, point sources, and meteorological data (water quality data and coefficients were not considered). Physical data was resourced from United States Bureau of Reclamation Water Operations web site (Reclamation, 2010), in addition to personal communication with each reservoir's operations personnel, where USBR data was incomplete.

Physical data includes reservoir name and initial water surface elevation (m). Minimum and maximum water surface elevations are taken from the data entered for stage-area curve. Stage-area curve data is taken from USBR and/or specific reservoir communication. Intermediate inputs were then adjusted during simulations if necessary, with initial and final point assumed from data and held constant. Stage-discharge table describes spillway operation. Stage discharge data for reservoir simulation was gathered from personal communication with the individual operating facilities. Data points create a curve dictating reservoir flow. As before, if issues arose during simulation, intermediate curve values were adjusted for improved performance.

Table 3.13: Power Generation in the UCRB

Reservoir Name	Watershed	Power Generation
Williams Fork	1	--
Shadow Mountain	3	--
Willow Creek	4	--
Dillon	5	--
Green Mountain	6	21,214 mWh
Vega	7	--
Reudi	8	--
Lake Granby	10	--
Rifle Gap	11	--
Ridgway	14	--
Gould	16	--
Crawford	17	--
Fruit Growers	18	--
Paonia	19	--
Taylor Park	21	--
Blue Mesa	22	203,411.938 mWh
Morrow Point	23	269,193.371 mWh

G. Future Climate Data:

Future climate data from the three GCM models under A2 and B1 scenarios were used to simulate future climate conditions. We acknowledge the modeling groups, the Program for Climate Model Diagnosis and Intercomparison (PCMDI) and the WCRP's Working Group on coupled Modelling (WGCM) for their roles in making available the WCRP CMIPS mutli-model dataset. Support of this dataset is provided by the Office of Science, U.S Department of Energy. Data was gathered from the database of the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model datasets of daily BCCA downscaled data. The impact on flow due to future climate was analyzed under future climate projections from the following GCMs and scenarios: MRI CGCM2 A2 and B1, CGCM3 A2 and B1, and MIROC A2 and B1 (described in detail in Chapter 3). 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. The simulated temperature and precipitation results for Period 1 were then compared with baseline scenario (1986-2006) in WARMF. Tmin, Tmax, and precipitation data of the 6 runs was used to drive the WARMF model, with all other parameters held constant.

3.9 WARMF Model Sensitivity Analysis and Calibration

Watershed models require calibration before they are utilized as a decision-making tool or for assessing the impact of change in hydrologic conditions. Calibration requires identification of sensitive parameters. WARMF is a complex watershed model with several parameters. There are hydrologic parameters pertaining to individual catchments and to the entire UCRB as a whole. Individual parameters are catchment coefficients, river coefficients, and reservoir coefficients. System coefficients pertain to the entire watershed. To evaluate performance of the WARMF model, two auto calibration techniques were evaluated; an external auto calibration inverse code UCODE_2005 (Poeter, 2005) and WARMF autocalibration tool with in WARMF. Geza et al. (2009) have implemented UCODE for parameter sensitivity and calibration of Turkey Creek Watershed, Colorado. These model evaluation techniques involve an initial sensitivity analysis, followed by parameter estimation (Geza et al., 2009) described in detail below.

3.9.1Sensitivity Analysis

Sensitivities reveal the significance of certain parameters on model performance. The autocalibration tool, UCODE was used to perform a sensitivity analysis to identifying the most responsive parameters based on site-specific conditions. WARMF model was linked to UCODE to modify various input parameters. To identify the most sensitive parameters, Dimensionless-Scaled Sensitivities (DSS) and Composite Scaled Sensitivity (CSS) values are implemented given by (Hill and Tiedeman, 2007):

$$DSS_{ij} = (\frac{\partial \hat{y}}{\partial \beta})\beta_j w_i^{1/2} \tag{3.1}$$

$$CSS_j = (\frac{1}{N}\sum_{i=1}^{N} DSS_{\overline{ij}}^{\,2})^{1/2} \tag{3.2}$$

These parameters measure the change in simulated value with respect to change in parameter value and eventually help to rank the parameters according to their importance. CSS is the average of DSS values for a particular parameter and describes the importance of a simulated value to the parameter (Poeter, 2005). CSS values indicate the likelihood that a parameter has enough information to be estimated. The larger the ratio of each CSS to maximum CSS value, the more likely that parameter can be estimated through calibration. During the sensitivities perturbation, UCODE utilizes the Gauss-Newton method to determine best fit parameters using DSS and CSS values. Table 3.14 illustrates the parameters included in UCODE analysis. Precipitation Factor (PF), Soil Moisture (SM), Evaporation Magnitude (EM), Evaporation Skewness (ES), Field Capacity (FC), Horizontal Conductivity (Kh) are most significant to streamflow calibration, since PF, EM, ES, and SM control the water balance and available water to the stream and the remaining parameters control runoff. From the UCODE sensitivity analysis results (Table 3.15), EM is determined as most sensitive parameter for calibration. Parameters within two orders of magnitude (listed in Table 3.15) are also prioritized for further analysis, such as ES, FC, and SM. TF and AF, while critical, are also highly correlated (>0.95) and have a unique solution. To address this, additional data is necessary to break the correlation or reparameterization. We held one of the two factors constant, while the other was analyzed for uniqueness.

Table 3.14: Model Parameters evaluated in UCODE Analysis

Parameter Name	Paramater Symbol	Literature Value[4]	Calibrated Value	Units
System Coefficients				
Evaporation Magnitude	EM	0.6-1.4	1.31	--
Evaporation Skewness	ES	0.6-1.4	1.273	--
Catchment Coefficients				
Precipitation weighting Factor	PF	0.5-1.5	Varies by catchment (0.35-1.5)	--
Temperature Lapse Rate	TF	-5 to 5	0.0	°C
Altitude Lapse Rate	AF	0.001-0.009	0.005	°C/m
Field Capacity	FC	0.0-0.4	0.25	m^3/m^3
Saturation Moisture Layer I, II, III	SM	0.2-0.6	0.5, 0.45, 0.35	m^3/m^3
Horizontal Conductivity	Kh	>0	8,000-10,000	cm/day
Vertical Conductivity	kV	>0	50-100	cm/day

[4] Geza et al., 2009

When individually assessed, AF and TF were found to be insignificant based on UCODE statistics. This simplifies the model by estimating only the most critical parameters, while also limiting predictive uncertainty by eliminating groups of highly correlated parameters. PF is also significant which was confirmed during the manual calibration of the WARMF model. SM, FC, AF were not assessed significant to the entire model, but were considered during WARMF calibration on a catchment by catchment basis.

Table 3.15: UCODE Sensitivity Analysis Results of most significant parameters

Parameter	Composite Scaled Sensitivity (CSS)	Ratio to Maximum	Explanation
EM	331	1.0	Baseline
ES	10.7	0.33	Significant w/in 2 orders of magnitude and calibrated
TF	112	0.31	Significant and correlated (insignificant when un-correlated)
PF	101	0.3	Significant
SM	66	0.2	Significant w/in 2 orders of magnitude
FC	45	0.1	Significant w/in 2 orders of magnitude
AF	59.7	0.16	Significant and correlated (insignificant when un-correlated)

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

The sensitivity analysis identifies the parameters of most significance, but each catchment may reassess the contribution of each to that particular subcatchments depending climate, topography, etc.

3.9.2 Model Calibration

When calibrating¸ model simulated flow is compared to observed flow to compare accuracy, therefore the presence of a gaging station allows calibration at that point. Figure 3.3 illustrates the stations present in the watershed with white circles. UCODE runs the WARMF model repeatedly by adjusting selected parameter values until the simulated streamflow values match to actual gage values. UCODE is used to calibrate the WARMF model by carrying out linear regressions. Using a modified Gauss-Newton method, UCODE minimizes the sum of weighted-squared-residuals in relationship to the parameter values (Geza et al., 2009).

Adjusted parameters are selected through sensitivity analysis discussed earlier. Best fit is achieved by decreasing of weighted squared differences between simulated and observed values. When the parameter values change less than the user-specified % change between iterations, calibration is said to converge and the values producing convergence are considered optimal parameters. After sensitivities have been determined, only the most sensitive parameters are selected for adjustment during calibration.

Using UCODE sensitivity analysis results, we have selected the most significant parameters of EM, ES, and PF to estimate during calibration. Convergence became an issue in using UCODE for the full calibration process, so preliminary results were used to guide the process. The best UCODE run results were used to guide manual calibration for the most significant parameters. Thus, we made use of the sensitcity results along with preliminary calibration runs as guidance to improve model fit. For all soil and climated related parmaters illustrated in Table 3.13, we have used literature values for the calibration procedure. The EM and ES are scaling factors for evaporation to account for seasonal differences and PF is a precipitation multiplier. In WARMF, EM is a system coefficient, so only one value could be used for all of the catchments in the basin , although this paramater is expected to vary over differing topology and geography especially for a large watershed like the UCRB. In WARMF, evapotranspiration (ET) is calculated based on vegetation based on the Hargreaves method (Hargreaves, 1974), using precipitation data. The EM factor is used to counter errors in calculating potential evaporation via the Hargreaves equation (which are usually a factor of 0.6-1.2, Herr et al., 2000). Originally set at 1.0, we increased EM to an acceptable value of 1.31 (within the recommended range: 0.6-1.4). In a region with much variation in topography, such as the UCRB, the magnitude of evaporation is expected to vary greatly. Increasing the EM value allowed a better approximation of evaporation by the Hargreaves equation and improved model fit. We also increased the ES parameter value from 1.0 to 1.273. ES accounts for seasonal variability of evaporation, which is susceptible to fluctuation in the study area. Snow melt rates were also adjusted. Open area melt rate was shown as less sensitive, partially due to less open area in the watershed, than the forested melt rate. Melt rate is dominated by temperature, which exceeds the open area melt rate of 0.15 cm/C/day. Hence, melt rates were slightly adjusted from default values, but are not critical to model performance. PF is responsible for the orographic effects between precipitation stations, which greatly vary over the project area and requires adjustment on a catchment scale when insufficient meteorology stations are present. PF was adjusted at the catchment level, based on site-specific conditions. Parameter values varied from 0.35-1.5 (depending on catchment) and significantly improved model performance.

In the study area, two gage stations were used to assess model fit. Figure 3.3 illustrates the gage locations. Immediately downstream of power generating Blue Mesa Reservoir is USGS gauge #09128000 (1) and gauge #09152500 (2) upstream at the confluence of the Gunnison River, with emphasis on the former. Other than differences in location, the gauges were simulated under different EM conditions for each scenario. Scenario 7B was executed at the literature limit of 1.41, while 8B held a value of 1.31.

It should be noted that smaller values of EM were previously utilized, but best performance for the entire basin resulted from higher EM and ES values. The immediate impact of EM on streamflow is shown in Figures 3.4 and 3.5. In both scenarios, the timing of simulated flow correlates to observed hydrograph, but the magnitude greatly differs. In scenario 7B, flow exceeds that of the gage and cumulative volume also exceeds the observed (shown in blue in Figure 3.6). Lowering the EM value produces a more accurate simulation, sometimes underpredicting flow (shown in green). Although the R^2 values are ostensibly low, 0.26, they are suitable for the complexity of the watershed. In addition to modifying EM and ES values, a combination of other factors were adjusted on catchment levels to better match observed.

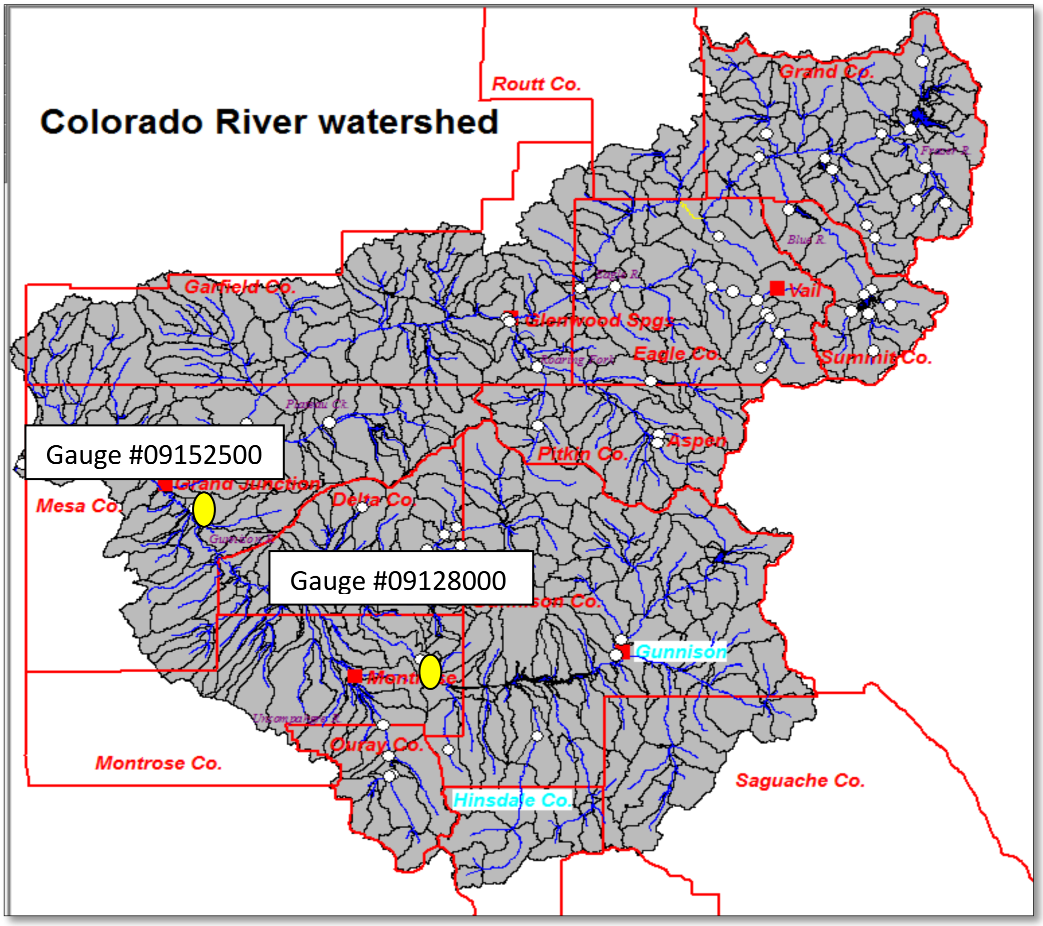


Figure 3.3: UCRB USGS Gauge Stations

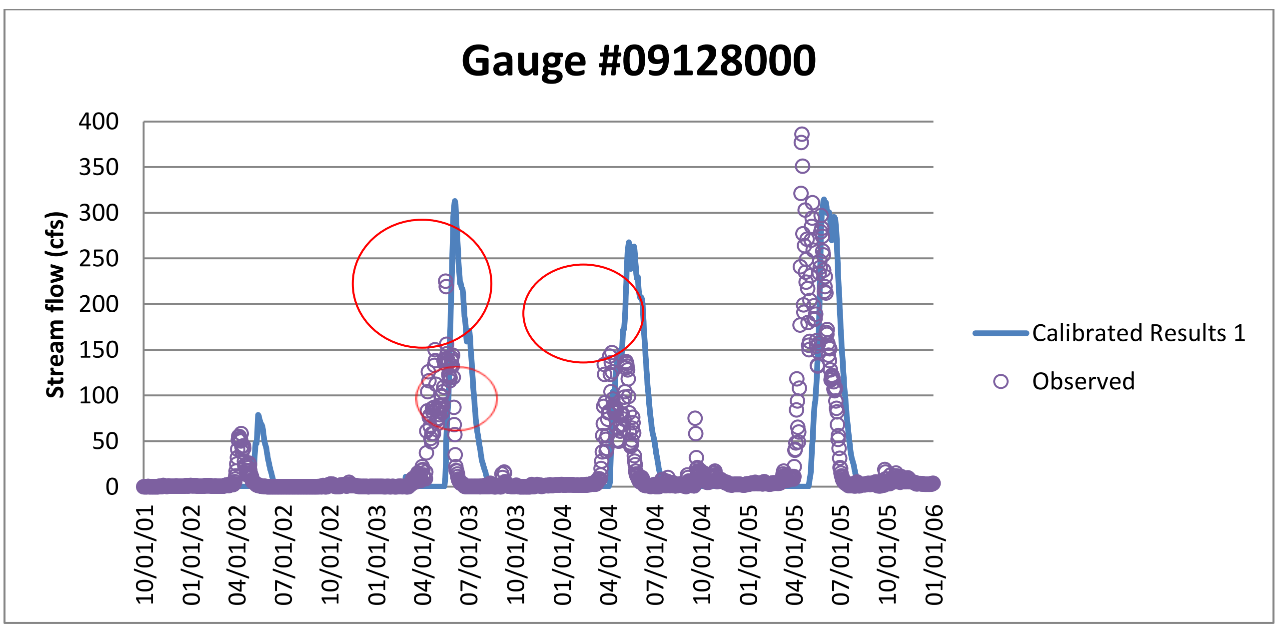


Figure 3.4: Simulated vs. Observed Flow

To increase peaks and decrease baseflow soil depth was reduced with soil moisture content. Hydraulic honrizontal conductiviy was also reduced, with field capacity adjusted to better fit the observed data. This minimizes the difference between soil moisture and fielc capacity, producing more peaks while reducing baseflow as seen in the change from Figure 3.4 to Figure 3.5 and identified in red. The timing lag is also more pronounced in Figure 3.4. Since this gauge is downstream of reservoir releases, which are predefined, timing is going to be altered from natural flow behavior. Nonetheless, the calibrated effort visibly improved this mis-match although still some is present.

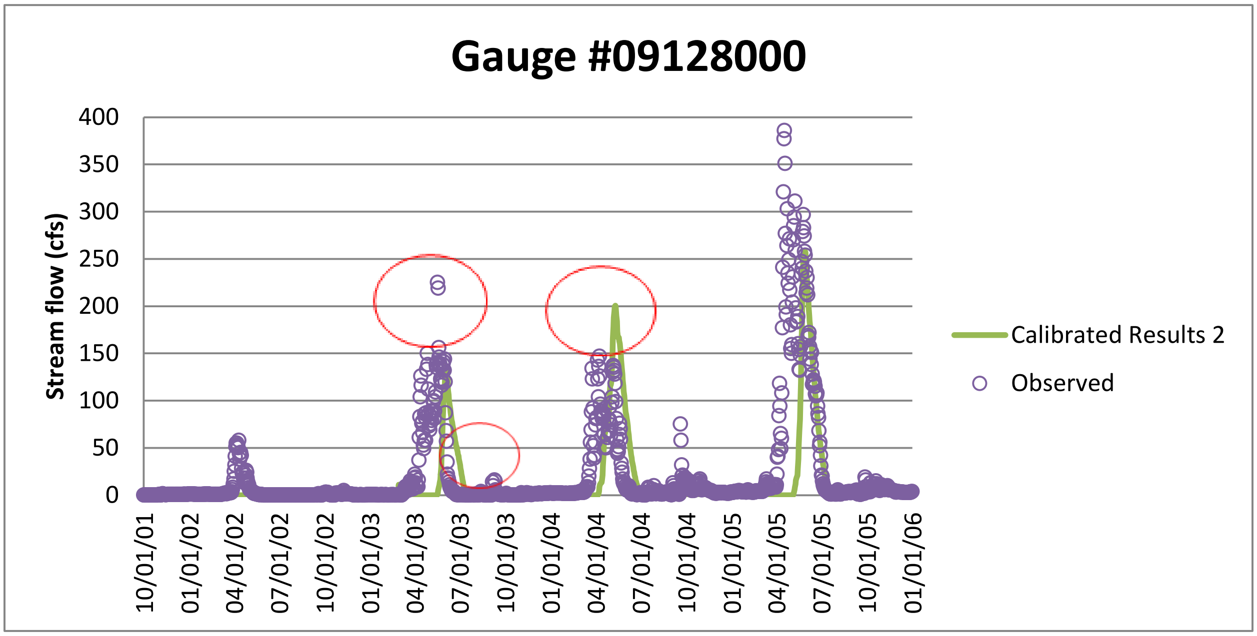
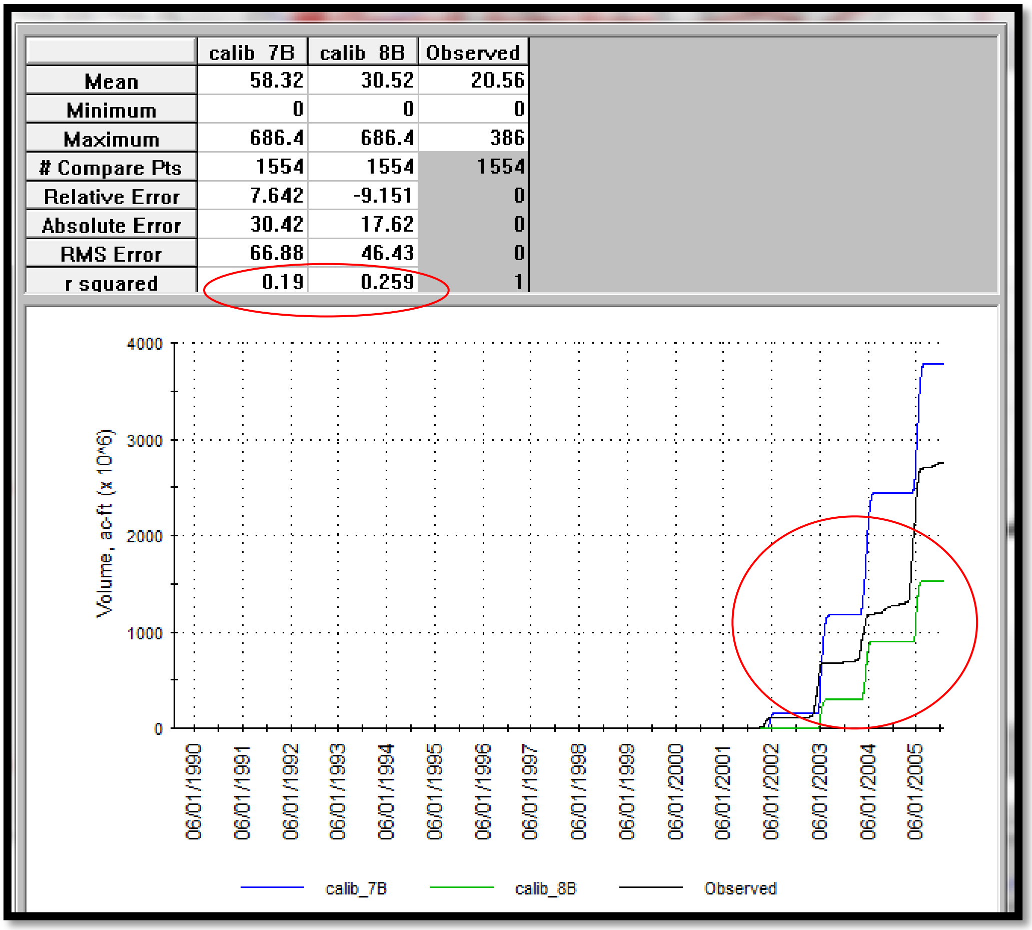


Figure 3.5: Simulated vs. Observed Flow after adjustments

At gauge #09152500 near the cofluence of the Colorado and Gunnison Rivers, calibration results are shown in Figures 3.7-3.9. Streamflow has similar timing, but baseflow is underpredicted by our model and is shown in cumulative volume results of Figure 3.9. With an R^2 value of 0.48 the site was assumed acceptable due to the complexity of watershed hydrology and topography. Also, due to the location of the station in the waershed, it is upstream of most of the Gunnison River basin. It reflects a large portion of the downstream flow conditions in its results. With that in mind and because total flow volume does not exceed observed, the calibration was suitable for our study.



	calib_7B	calib_8B	Observed
Mean	58.32	30.52	20.56
Minimum	0	0	0
Maximum	686.4	686.4	386
# Compare Pts	1554	1554	1554
Relative Error	7.642	-9.151	0
Absolute Error	30.42	17.62	0
RMS Error	66.88	46.43	0
r squared	0.19	0.259	1

Figure 3.6: Flow Volume at gauge #0912800

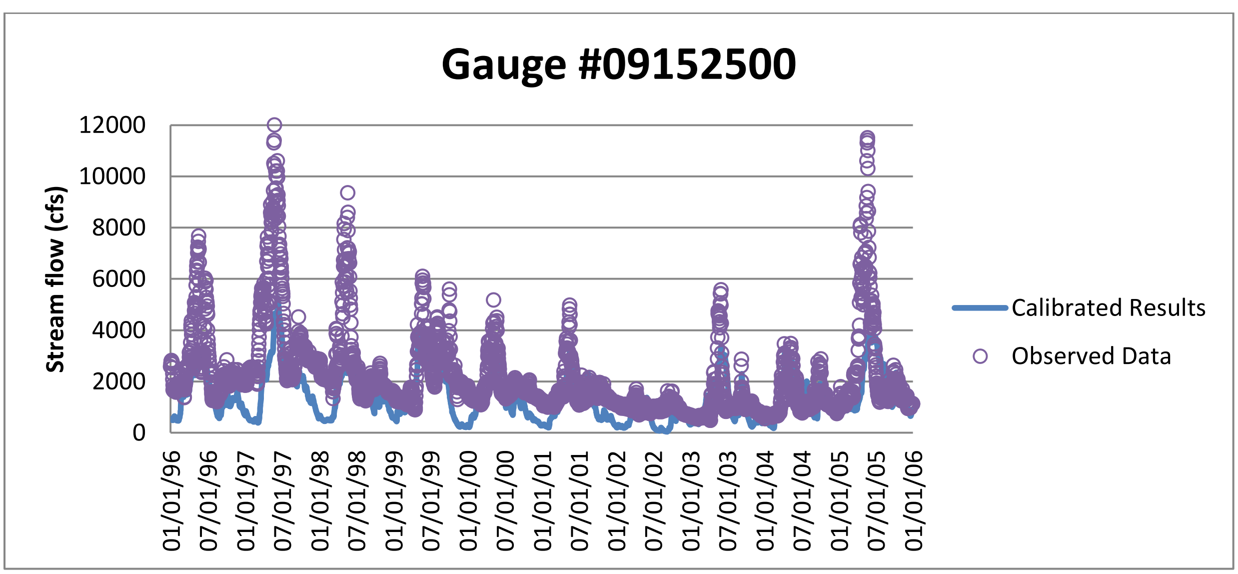


Figure 3.7: Calibration results at gauge #09152500

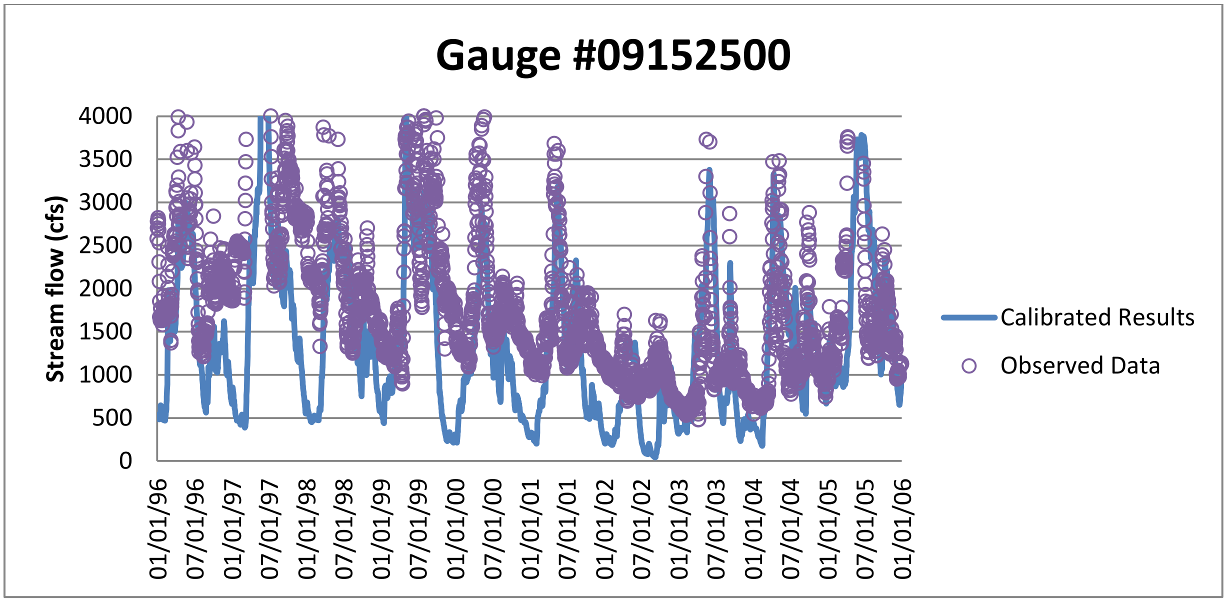
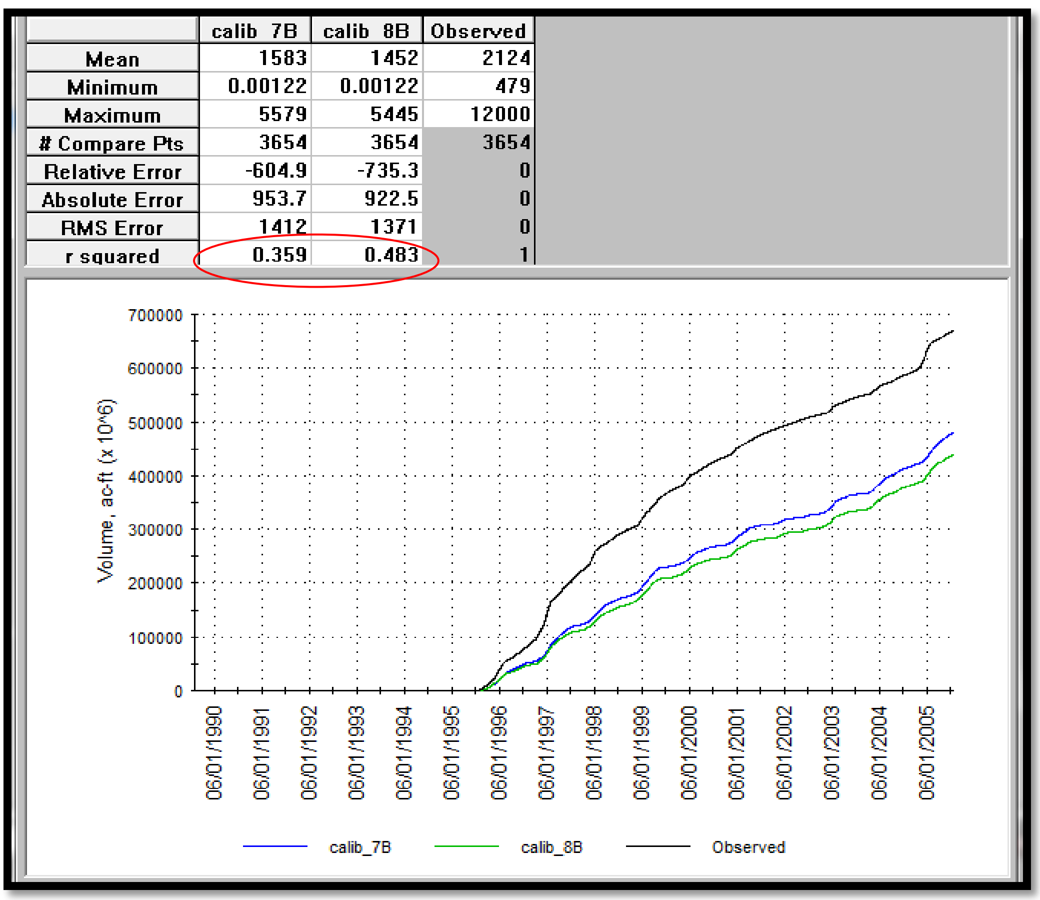


Figure 3.8: In depth look at gauge #09152500



	calib_7B	calib_8B	Observed
Mean	1583	1452	2124
Minimum	0.00122	0.00122	479
Maximum	5579	5445	12000
# Compare Pts	3654	3654	3654
Relative Error	-604.9	-735.3	0
Absolute Error	953.7	922.5	0
RMS Error	1412	1371	0
r squared	0.359	0.483	1

Figure 3.9: Flow Volume at gauge #09152500

CHAPTER 4: RESULTS AND DISCUSSION

Many studies have mentioned the potential for more extreme precipitation events under future climate scenarios. This study was not able to confirm such findings basin wide, but it does show a distinct change in future trends from the historical. Mean precipitation is dependent on latent heat (soil moisture) and is inhibited by GHG increases (Solomon et al., 2007). Extreme events, such as those simulated at higher elevations in the UCRB, are projected to become more frequent, raising flood potential. In such arid and semi-arid regions, intense precipitation events can infiltrate before evaporating and serve to recharge groundwater resources, but such behavior is dependent on antecedent conditions. These heavy instances cause high runoff, contributing to flash flood potential in the region.

4.1 Precipitation Impacts

Specific station hydrologic behavior is described later in this study, with the initial comparison motivated by an interest to analyze spatial trends in the UCRB. The two points of interest are at the location of USGS gauge #09163500 near the Utah State Line and gauge #09109000 near Taylor Park Reservoir. The stations are approximately 255 miles apart and have a difference of 5,000 ft in elevation, with similar land use. Using BCCA downscaled USBR datasets, we were able to extract precipitation and temperature data at these locations to analyze changing conditions. Figure 4.1 illustrates predicted precipitation at the location of gauge #09163500 at an elevation of 4,325 ft. Figure 4.2 describes predicted precipitation at the location of gauge #09109000 at 9,170 ft in elevation. They illustrate mean daily values of precipitation (in) for each month averaged for both A2 and B1 climate scenarios and all three GCMs, to analyze the impact of climate change on time periods. Observed climate illustrates historical conditions at the location of interest, while the BCCA Climate (1986-2000) describes the reproduction of the same historical period when downscaling via the BCCA method from GCMs. At low elevation, historical precipitation prediction from BCCA captured seasonal variation when compared to observed data but differed in magnitude. At higher elevation, historical precipitation predictions from BCCA matched with observed precipitation data within 5%, and thus this was not assumed to be GCM bias but indeed a climate signal especially at the high elevation stations. Furthermore, there was no significant difference in precipitation predictions between Period 1 (2046-2065), the near future, and Period 2 (2081-2100). This implies that the efforts to curb the climate response will have some impact at the end of the 21st Century.

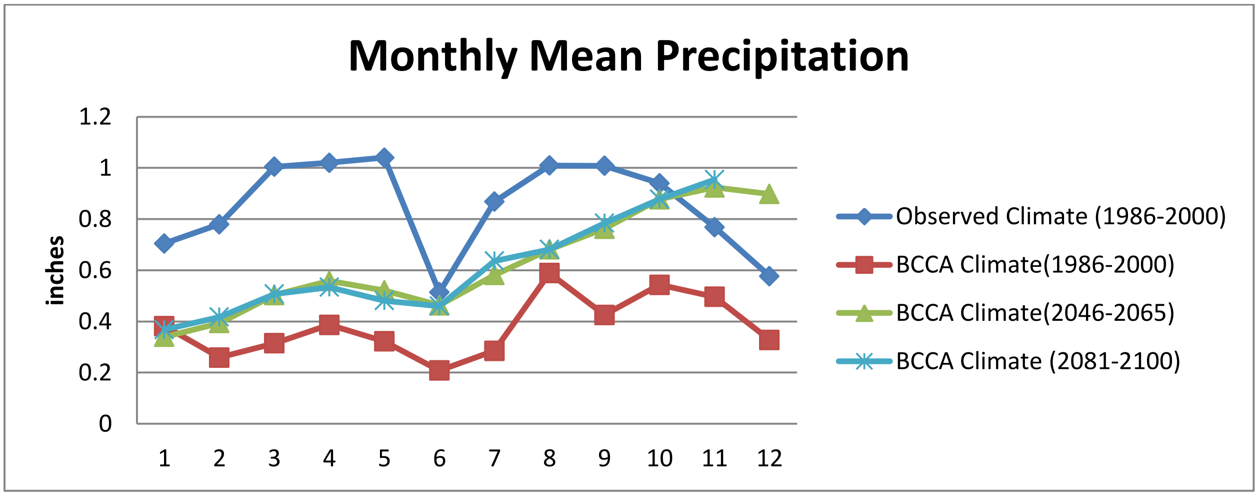


Figure 4.1: Daily average precipitation at low elevation near Utah State Line (USGS #09163500)

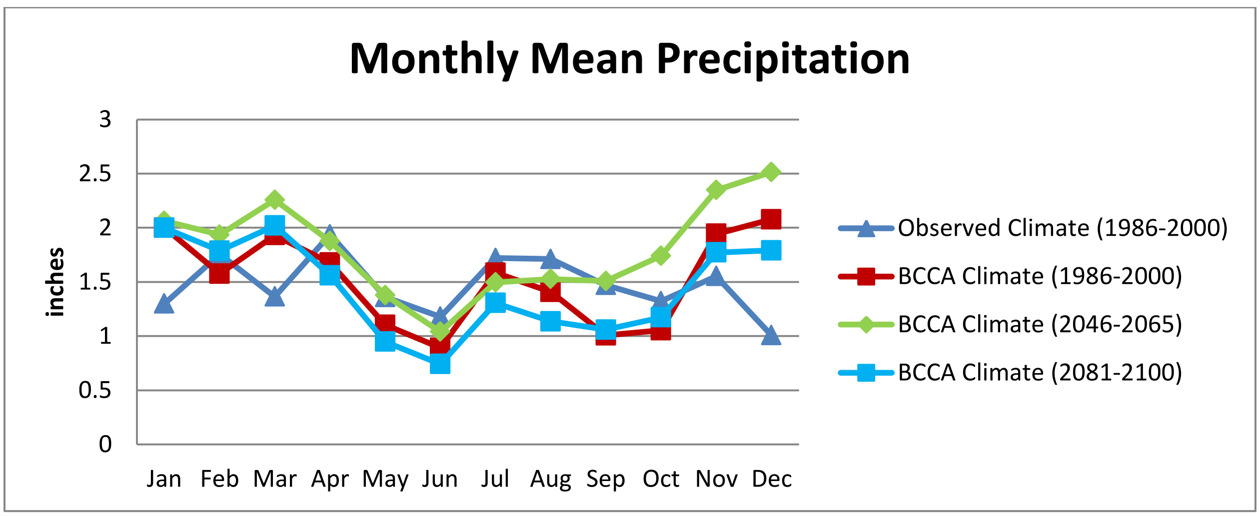


Figure 4.2: Daily average precipitation at high elevation near Taylor Park Reservoir (USGS #09109000)

The figures also indicate increasing divergence of future precipitation from historic conditions. The monthly averaged daily precipitation value is predominantly projected to decrease under all GCM models and climate scenarios by a range of 10-40 percent, varying greatly on a catchment scale. Figures 4.3 and 4.4 describe precipitation changes when analyzing the SRES scenarios A2 and B1, of all of the GCMs. The data describes different trends at different locations, greatly varying with elevation. The lower elevation gauge describes a reduction in annual precipitation (when compared to observed values) of over 54%. On the contrary, the higher elevation experiences precipitation volume increase from 57-71% (depending on future climate scenario) compared to the historical, but distinct drying during summer when future precipitation falls below historic values. At low elevation, the largest reduction in future precipitation (greater than 60%) occurs during the summer months (May to August) . This combined with increasing summer temperatures is expected to exacerbate the drying conditions. From November to February, the reduction in precipitation is less, although the results vary depending on climate scenario. Under B1, November precipitation is 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. This echoes previous climate studies which indicate more wet winters under extreme climate conditions. At high elevations, future precipitation exceeds historical by 74% annually. November to March describe the greatest precipitation increases under future climate, with most change during the months of November and March. In the mountainous high elevation terrains such as the one in our study, the months of November and March are months of most frequent and greatest snow accumulation largely due to significant orographic effect. During the summer drying period, the reduction in precipitation is more pronounced that the historical data actually shows as much as 27% more precipitation than the future. It is predicted that there will be extreme drying in the summer due to reduction in precipitation at high elevations as shown in Figure 4.4. These drying conditions will also be exacerbated by temperature changes in the region. 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 UCRB. Thus, changes in reservoir operations and management in response to climate change have to vary depending on reservoir elevation and location. Many of the reservoirs on the UCRB, including those with 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 increases, but severe drying in summer. This will require adaptive policies and action by water managers and will be discussed in more detail in section 4.4. Furthermore, this study emphasizes the need for high resolution models (1/8°) to capture such significant topographical changes which are essential to regional hydrology in mountainous regions.

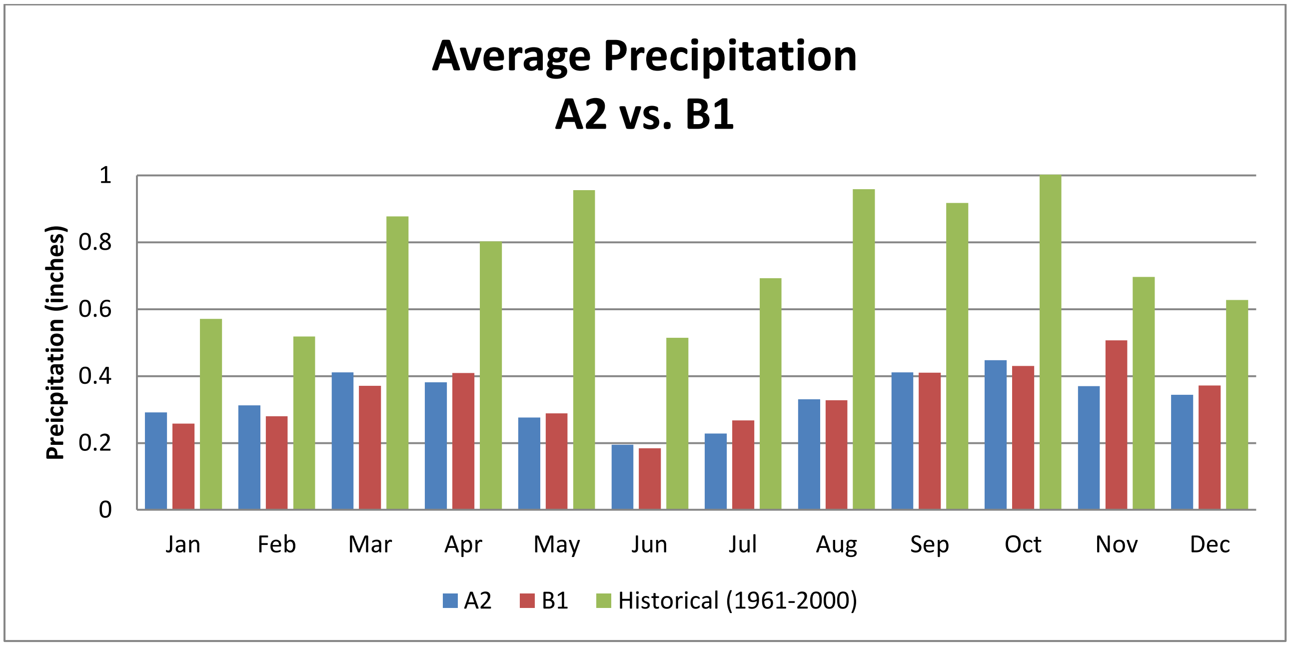


Figure 4.3: Average precipitation at low elevation near Utah State Line under SRES A2 & B1 of all GCMs in Period 1 (2046-2065) compared to observed climate data

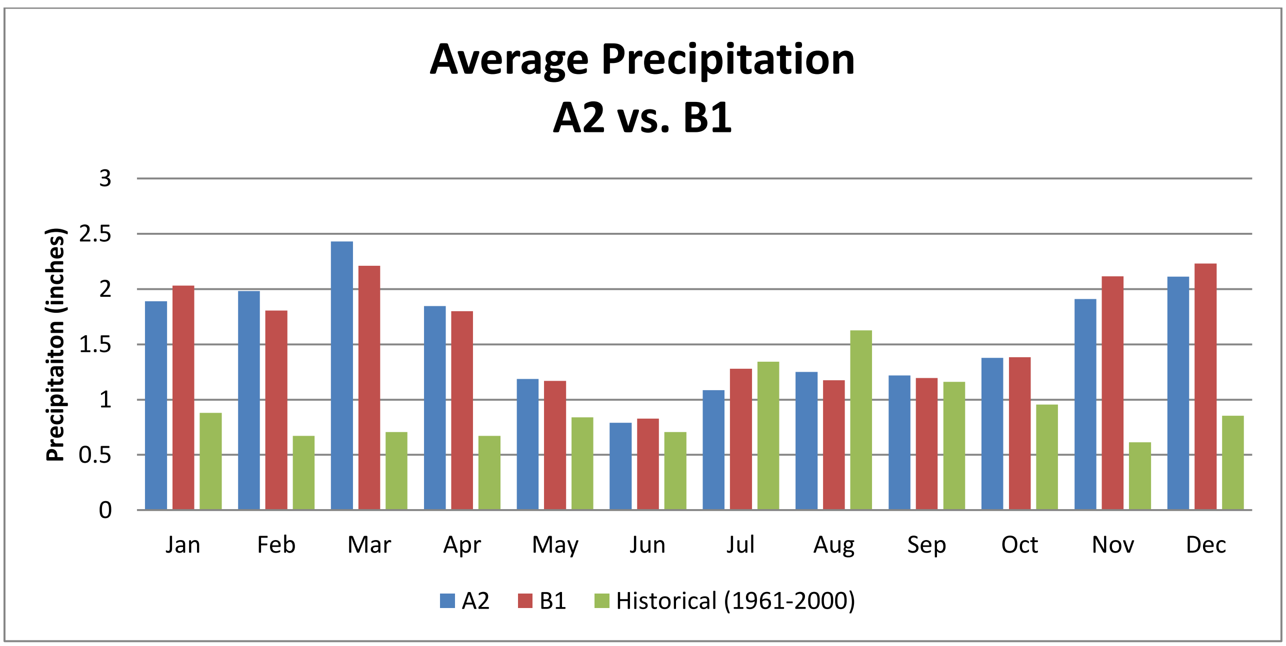


Figure 4.4: Average precipitation at high elevation near Taylor Park Reservoir under SRES A2 & B1 of all GCMs in Period 1 (2046-2065) compared to observed climate data

Projected hydrologic response to climate change is greatly influenced by elevation. It has also been shown that regional precipitation events, and consequently flow regimes, are significantly impacted by large-scale climate patterns such as the El Nino-Southern Oscillation (ENSO), North Atlantic Oscillation (NAO), among others. This natural variability can affect the precipitation and temperature in the region, altering predicted behavior (Solomon, et al., 2007).

After analyzing future precipitation with respect to elevation, we will now address the issue of GCMs. Figures 4.5 to 4.7 illustrates GCM results near the Utah State Line to analyze impact of each climate model separately. This location was chosen because the entire CRB in draining to this river segment and is at low elevation, which allows to exclusively analyze the impact from GCM only. Figure 4.5 includes all three GCMs, averaged across both the B1 and A2 scenario, compared to historical. The A2 condition generally presents a more extreme result, so this is only to evaluate GCM behavior versus the historical data. It shows that while all the three models predicted a decrease in future precipitation compared to historic precipitation, the results differed by climate model. CGCM3 trends toward predicting higher values, MIROC predicts the lowest precipitation, while MRI predictions are in between.

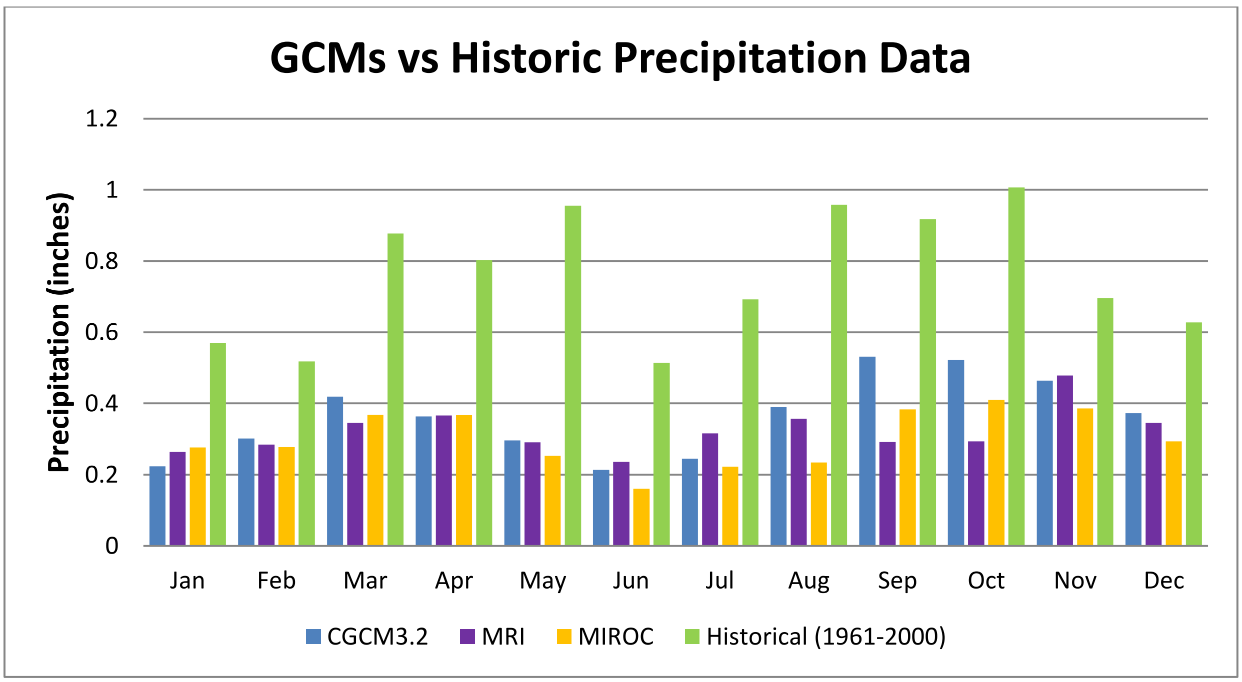


Figure 4.5: Averaged daily precipitation at low elevation near Utah State Line under all GCMs in Period 1 (2046-2065) compared to observed climate data, for SRES A2 and B1 conditions

Figures 4.6 to 4.7 illustrate each GCM under each of the A2 and B1 conditions. All future GCM precipitation projections are less than the historical values. B1 scenario shows 8% more precipitation annually than the A2 scenario. Winter precipitation is more pronounced under A2 as is summer drying. It is observed that there is more extreme seasonality in A2 scenarios than B1. Under both A2 and B1 scenarios, CGCM3 trends toward higher precipitation values. MIROC generally describes the lower values, while MRI predicted intermediate between the two.

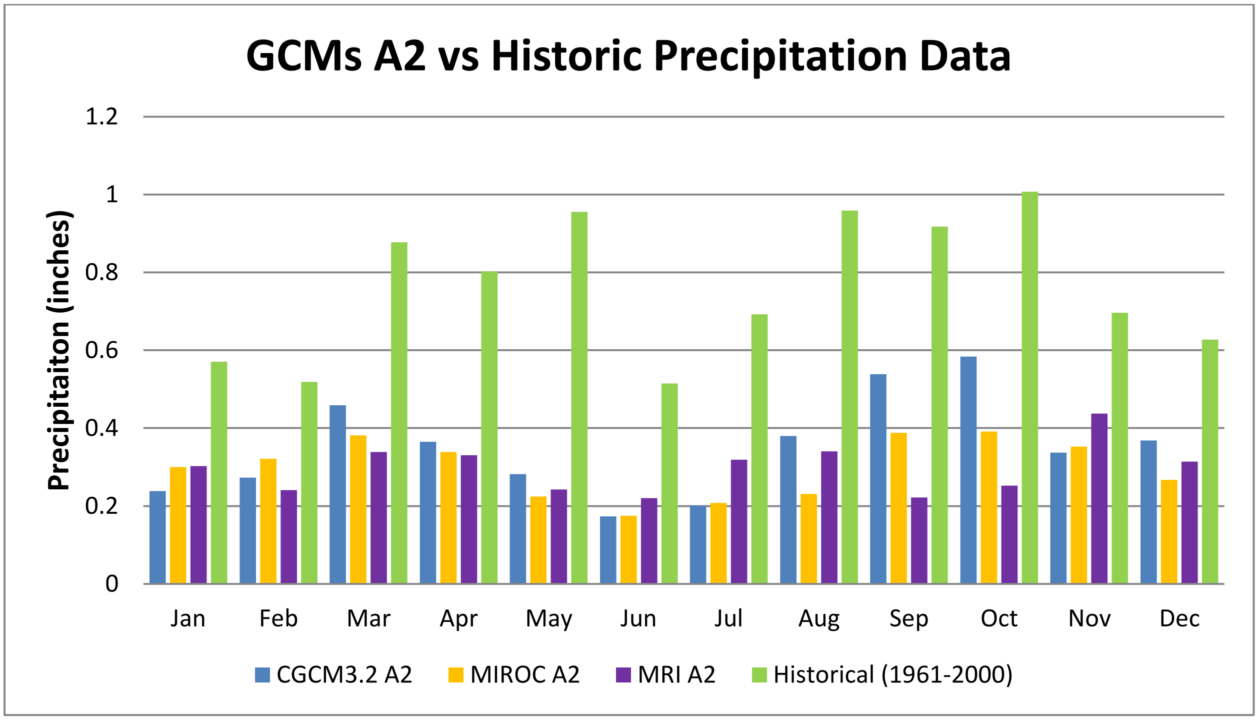


Figure 4.6: Daily-averaged precipitation comparison of GCMs under SRES A2condition in Period 1 (2046-2065) and observed historical climate Utah State Line

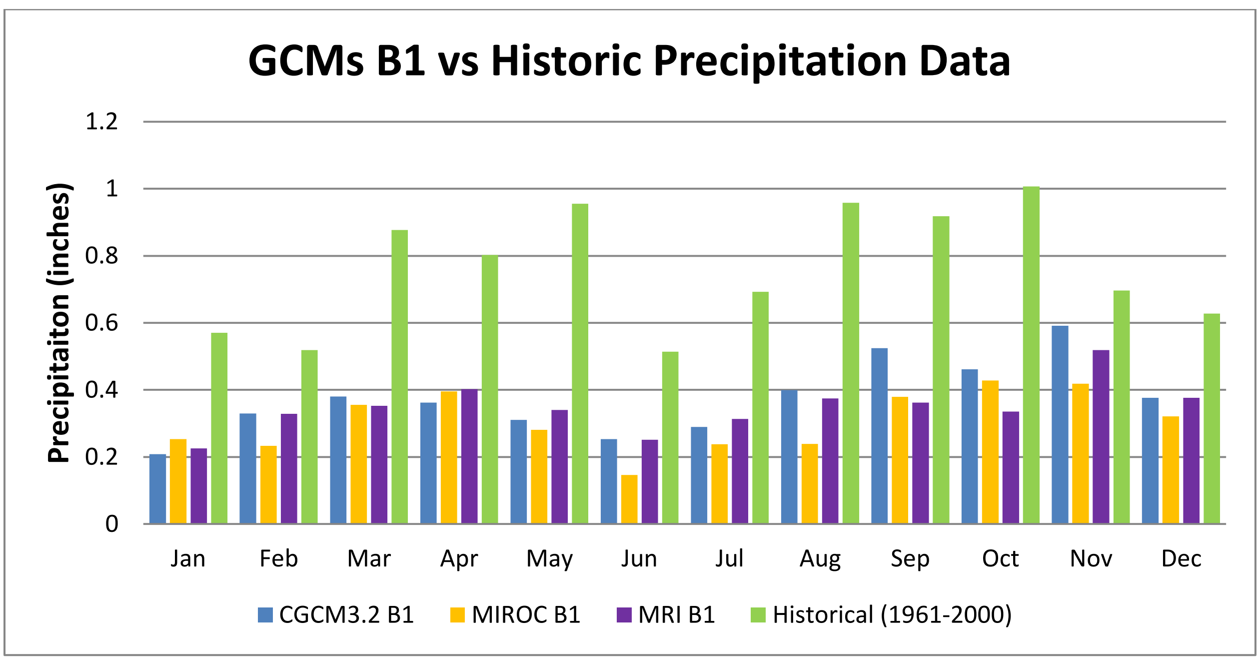


Figure 4.7: Daily-averaged precipitation comparison of GCMs under SRES B1 condition in Period 1 (2046-2065) and observed historical climate Utah State Line

It is important to note that although the different GCMs resulted in different predictions, the difference between each was not more than 16%. When analyzing GCM results for climate change analysis, a single model will not have the ideal or most correct future climate condition. 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 create an envelope or range of influence in climate projection and other consequences from climate projections such as stream flow and reservoir levels. This will allow insight into the uncertainties of climate projections. This study is successful in creating potential variability in predictions and to aid water managers and operators in assessing future changes and risks under uncertainty.

4.2 Temperature Impacts

Figure 4.8 and 4.9 describe the mean minimum temperatures at the Utah State Line and Taylor Park gauges. It is widely agreed that global temperatures will increase under future climate conditions. At low elevation, as shown in Figure 4.8, future climate describes an increase in minimum temperatures when compared to historical values. Climate of the later 21st century is shown to become more heated than in recent conditions. This behavior differs from precipitation trends, where most of the decline was shown in the near future of Period 1 (2046-2065). As temperatures rise, global atmospheric and climate regimes become more extreme, causing more severe droughts in regions where drying was already present and more wet conditions in those regions that were already (for the most part). Assuming the trends in temperature continue to increase as predicted by GCMS, this could push the UCRB into its severe dry conditions later in the century. Exacerbating already occurring droughts in the basin, some of the region could experience more drying while other areas becoming more wet causing a deviation from current climate norm in the basin requiring more water management and adaptation strategies. At high elevations the trend is similar as shown in Figure 4.8. There is a general warming trend, but the magnitude is greatly different compared to the low elevation. Significant to water resources is the minimum temperature which has been shown to increase in winter and generate early snow melt, initiating spring flows from 1to2 weeks earlier than in past (IPCC, 2007). Figure 4.5

illustrates a 3-5 degree Fahrenheit (F) mean annual increase in temperature, while 4.6 shows an increase of 0.7-2 degree F.

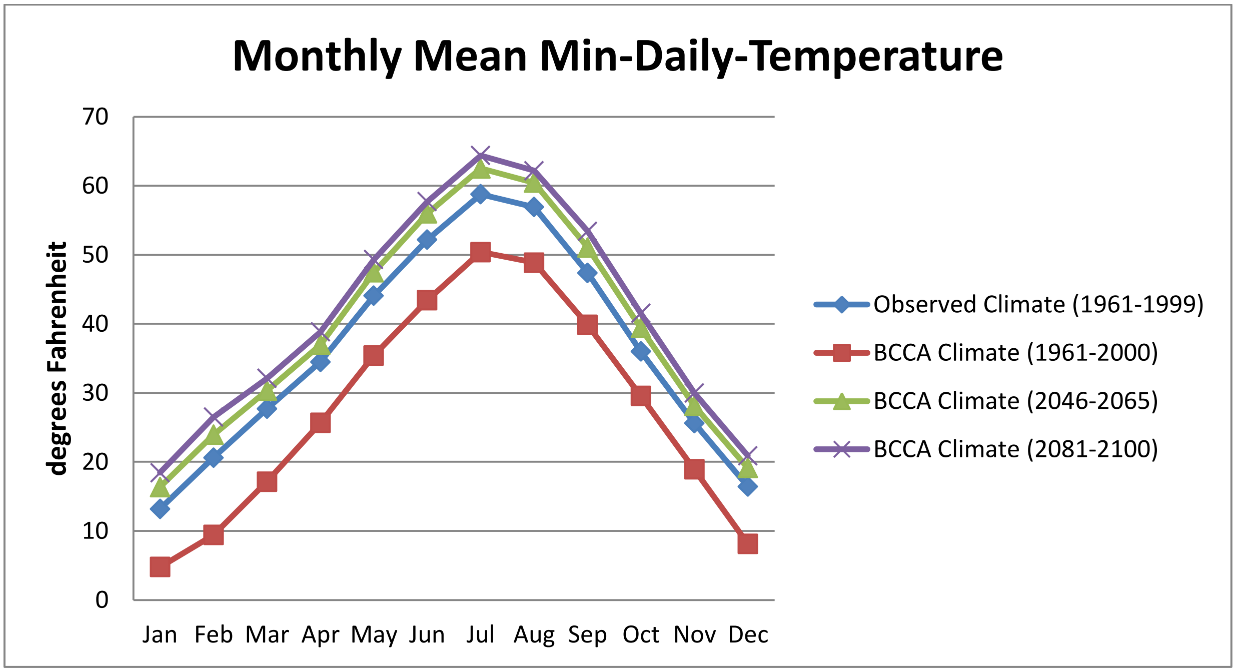


Figure 4.8: Daily Minimum Temperature (F) under Future Climate at #09163500 near Utah State Line for future time periods

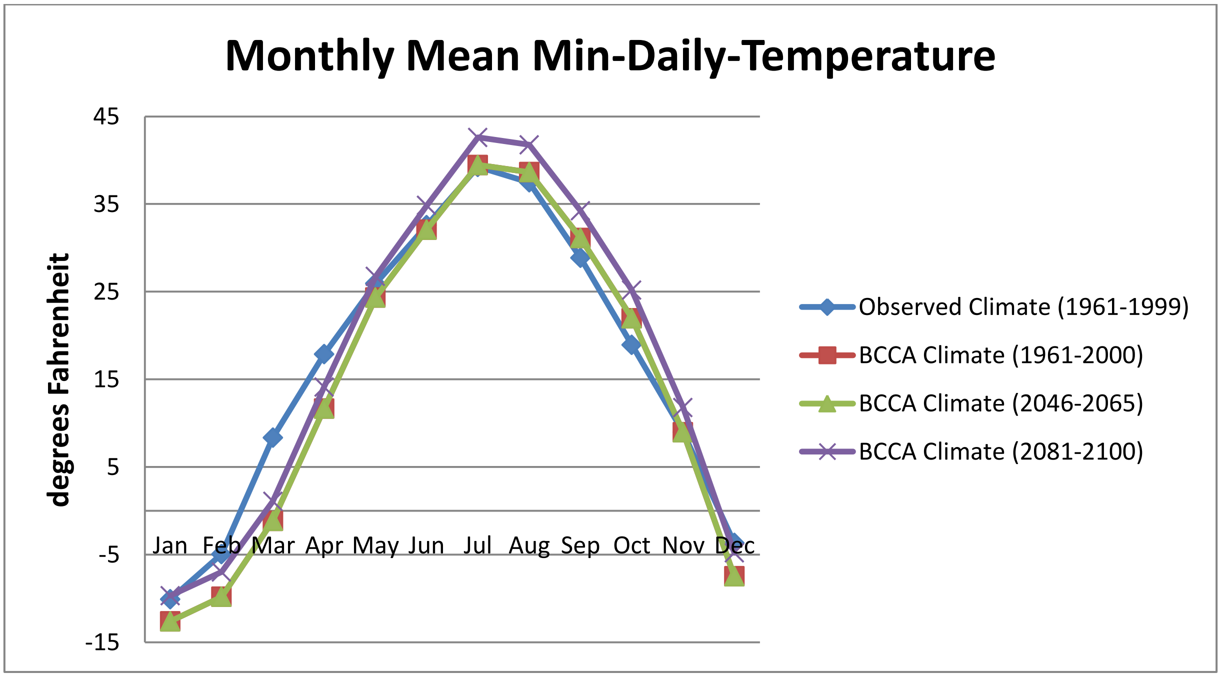


Figure 4.9: Daily Minimum Temperature (F) under Future Climate at #09109000 near Taylor Park for future time periods

To analyze the influence of each climate scenario on temperature, Figures 4.10 and 4.11 describe the two stations under future and historical conditions for Period 1 2046-2065. At lower elevations, future temperature is more than historical, with the difference between A2 (3.45°F) and B1(2.7°F) only 1.8% (or 0.7°F). When evaluating historical to future, the change is much more significant at 3.5°F and 2.8°F for A2 and B1 scenarios, respectively. Rise in temperature is exacerbated during the summer months of June-September, where a 4°F difference exists.

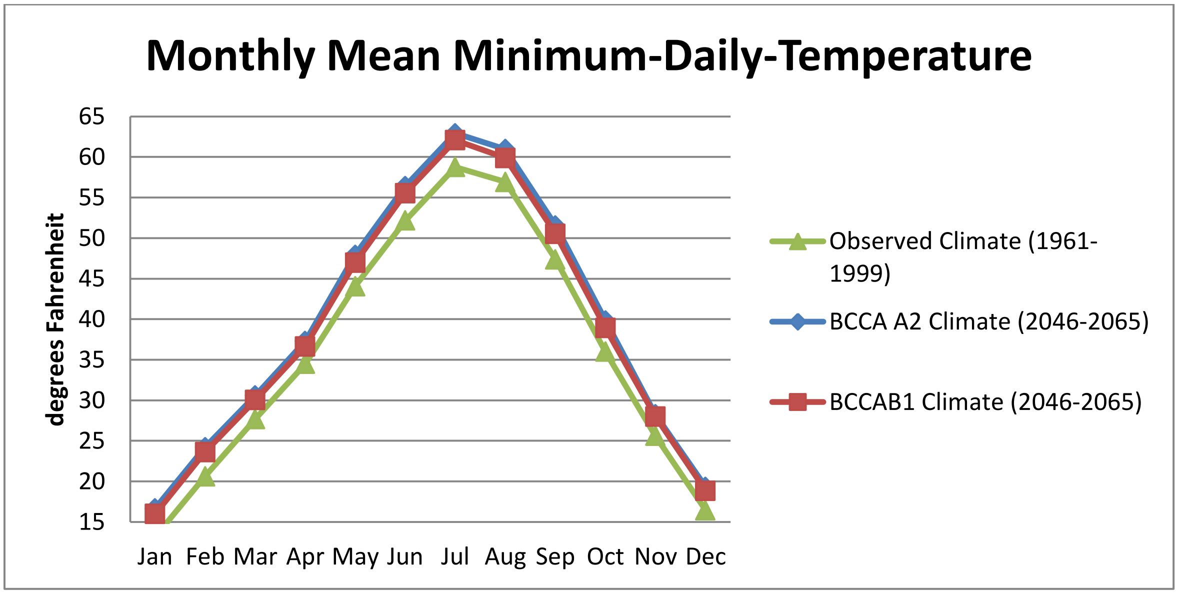


Figure 4.10: Comparison of minimum temperature at low elevations for scenarios A2 and B1 with observed climate Period 1 (2046-2065)

At high elevations, temperature is also predicted to increase but differs in timing and much less pronounced. Figure 4.10 captures behavior when colder months get colder with more warming during summer. A2 illustrates only a 2°F increase and B1 experiences a 1.5°F rise. These temperature impacts are especially significant for high elevation reservoirs, since runoff depends on temperature and dictates hydropower potential. With temperatures actually decreasing in winter months (as much as 9°F decrease in March under future climate), this directly impacts snowmelt and, consequently, streamflow. Hydropower is inherently dependent on streamflow, which can be delayed at high elevations under future temperature conditions. Section 4.4 will further analyze climate change impacts on hydropower potential and production under conditional climate, illustrating the varying impact of temperature, precipitation, evaporation, and streamflow on the resource.

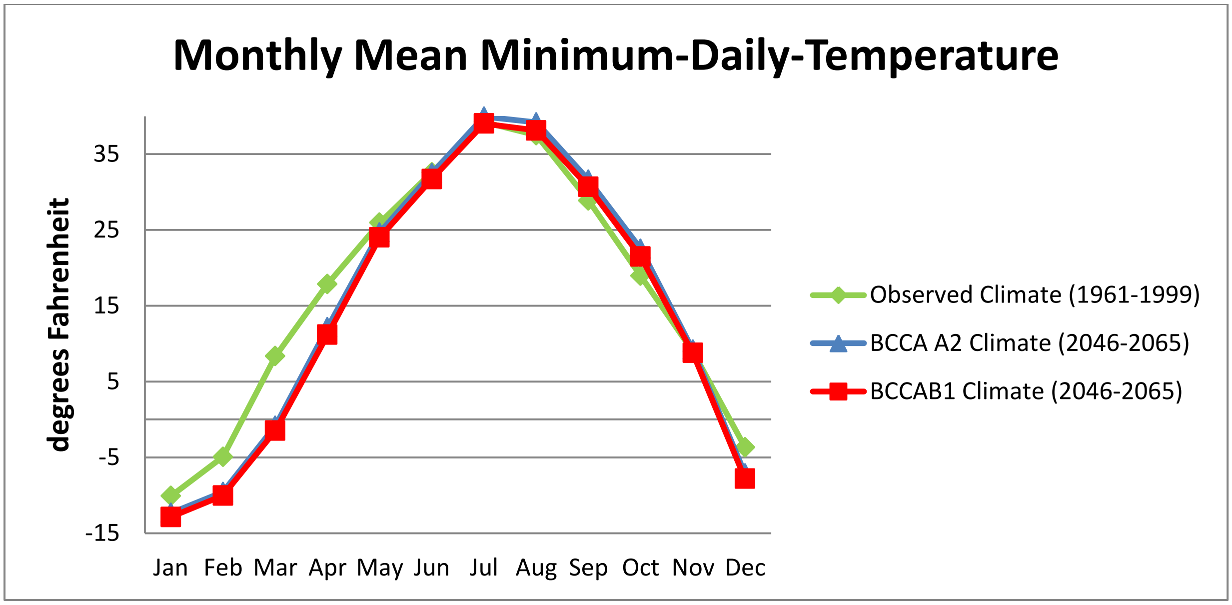


Figure 4.11: Comparison of minimum temperature at high elevations for scenarios A2 and B1 with observed climate Period 1 (2046-2065)

4.3 Stream flow impact

Several studies have analyzed climate impacts on river flows, finding runoff to increase in the high latitudes and decrease in the mid-latitudes (IPCC, 2007). Figures 4.12 to 4.14 illustrate the impact of scenarios A2 and B1 under the 3 GCMs on flow rate (cfs) at a low elevation gauge (#09163500) on the Colorado River near the Utah state line, after the confluence of the Gunnison and Colorado Rivers. The data shows the mean of daily values for each month under the aforementioned scenarios. Figure 4.12 describes the 6 climate scenarios analyzed in this study. Historical stream flow values are significantly greater than any of the predicted scenarios, showing a pronounced reduction in future streamflow. Future streamflow is shown to decline about 62%, with a difference between A2 and B1 scenarios less than 1%. Most pronounced is this change in summer months of June to August, with September and October also with a significant reduction. Historical peak flows generally occurred between May and July, although distinct peaks were observed during May and June as shown in 12. This moves the centroid of the hydrograph from May to July to April to-June in future climate, a month earlier and a month shorter than the historical May to-July peak flow.

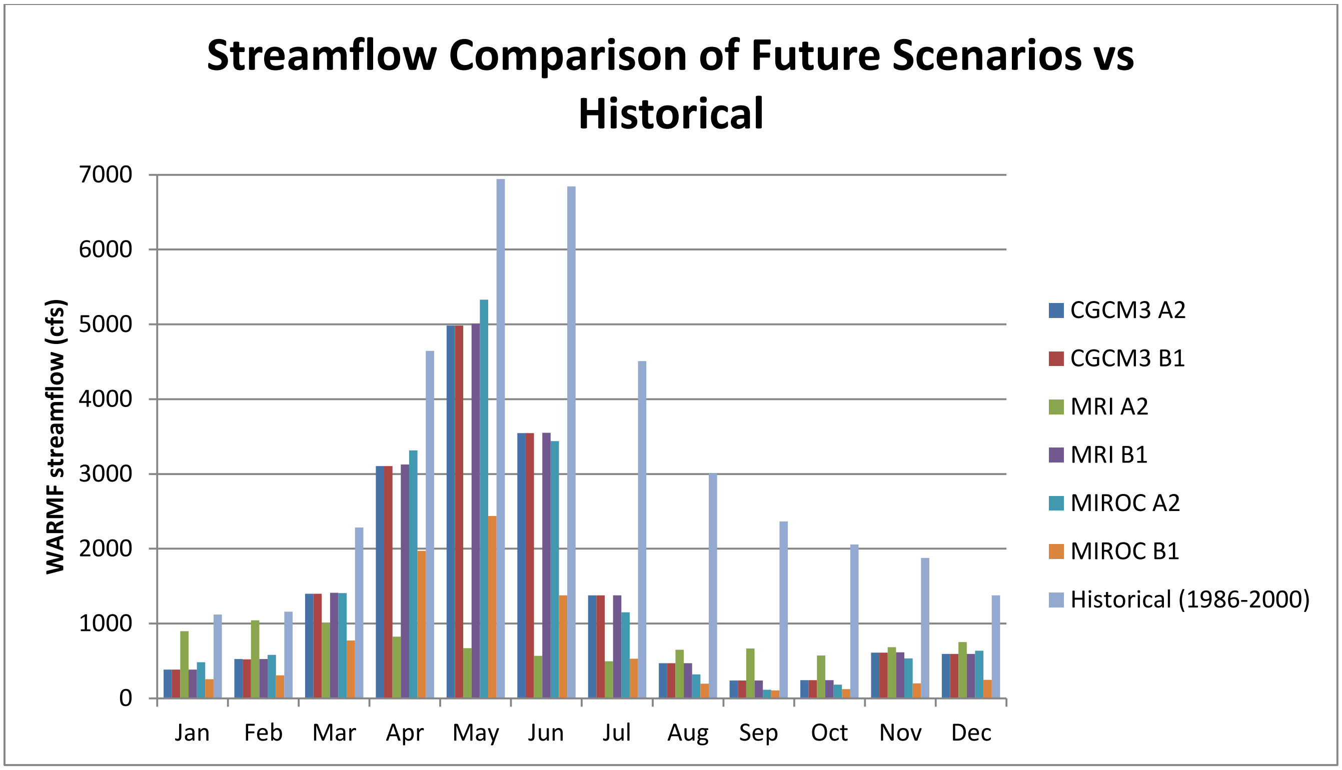


Figure 4.12: Comparison of predicted streamflow under all GCMs and emission scenarios in Period 1 (2046-2065) at gage #09163500 at Utah State Line

Figure 4.13 illustrates climate change impacts from each GCM. CGCM3 tends to predict significantly greater runoff than the other two models (as for precipitation trends). MRI predicts the least snowmelt runoff, but not the least precipitation accumulation; hence streamflow response is not linearly dependent on precipitation trends. MIROC predicts more streamflow than MRI in summer, but less in winter, this indicates specific parameters within the model responsible for this particular response. UCRB flow is highly managed, with flows altered by diversion and reservoirs along with other hydrologic and atmospheric processes. From the results, we can see that in order to analyze the impact of climate change on a particular watershed each region needs to be modeled since the hydrologic response to precipitation changes are not uniform in a basin (increase in some regions, while decreasing in others).

, Figure 4.14 describes the impact of the emission scenarios oA2 and B1 on stream flow in comparison to historical values and to each other. Figure 14 also illustrates the difference between A2 and B1 for each month labeled as “difference”. For the months of November to February, A2 streamflow under scenario A2 is greater than that simulated by the B1 scenario.

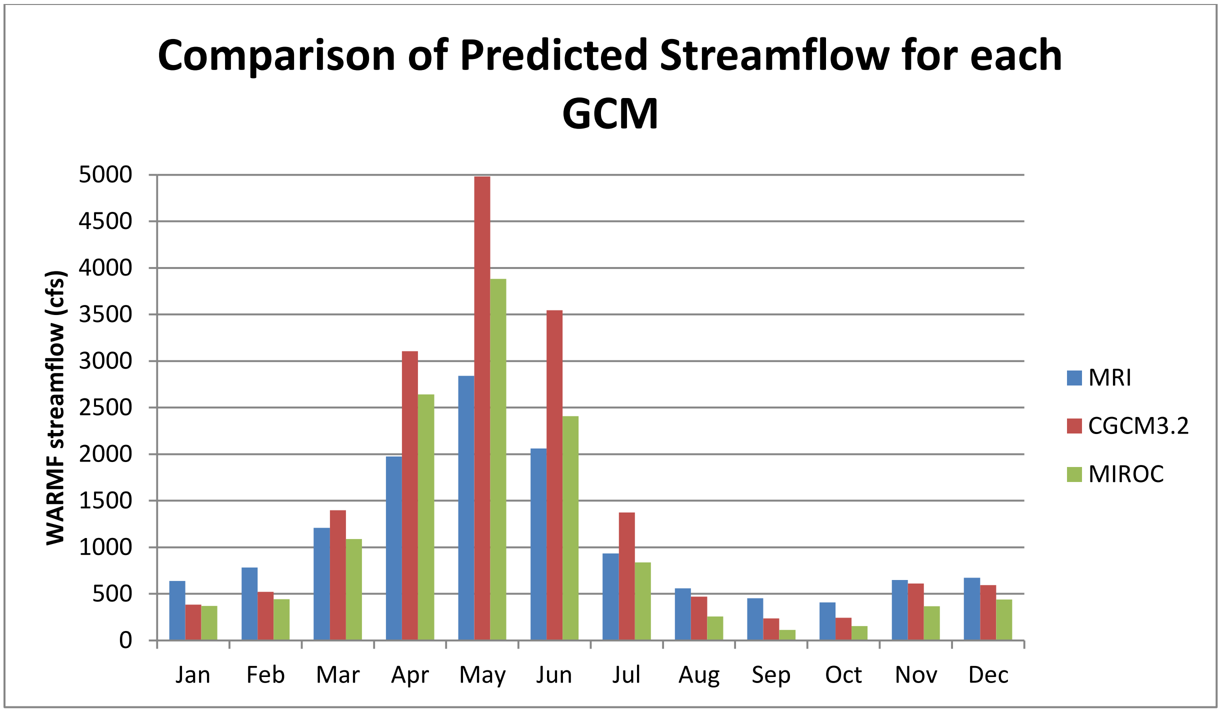


Figure 4.13: Comparison of predicted streamflow for each GCM, average of A2 and B1 scenarios in Period 1 (2046-2065)

Since A2 illustrates more extreme behavior, more wet winters and more dry summers are expected as shown in our results. 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 the more dramatic A2 scenario, the hydrologic response is more pronounced when precipitation effects are strongest in winter. As temperature is also predicted to increase annually, resulting in increasing evaporation rates and reducing soil moisture, flow is also shown to decrease during the most affected summer months under both A2 and B1 scenarios. There is a 62% reduction in annual flow volume, impacting the over allocated water deliveries downstream. Prolonged and seasonal drought events have already impacted the southwestern United States, with water demand only expected to increase due to the rapid growth in the region. Increased temperatures raise evaporation rates and reduce available soil moisture, reducing onset of runoff in summer. Reduction in summer flows in the arid Southwest further exacerbates water shortages. For the stations of interest, our simulations did not identify explicit early melt, but data on regional projected temperatures supported that result.

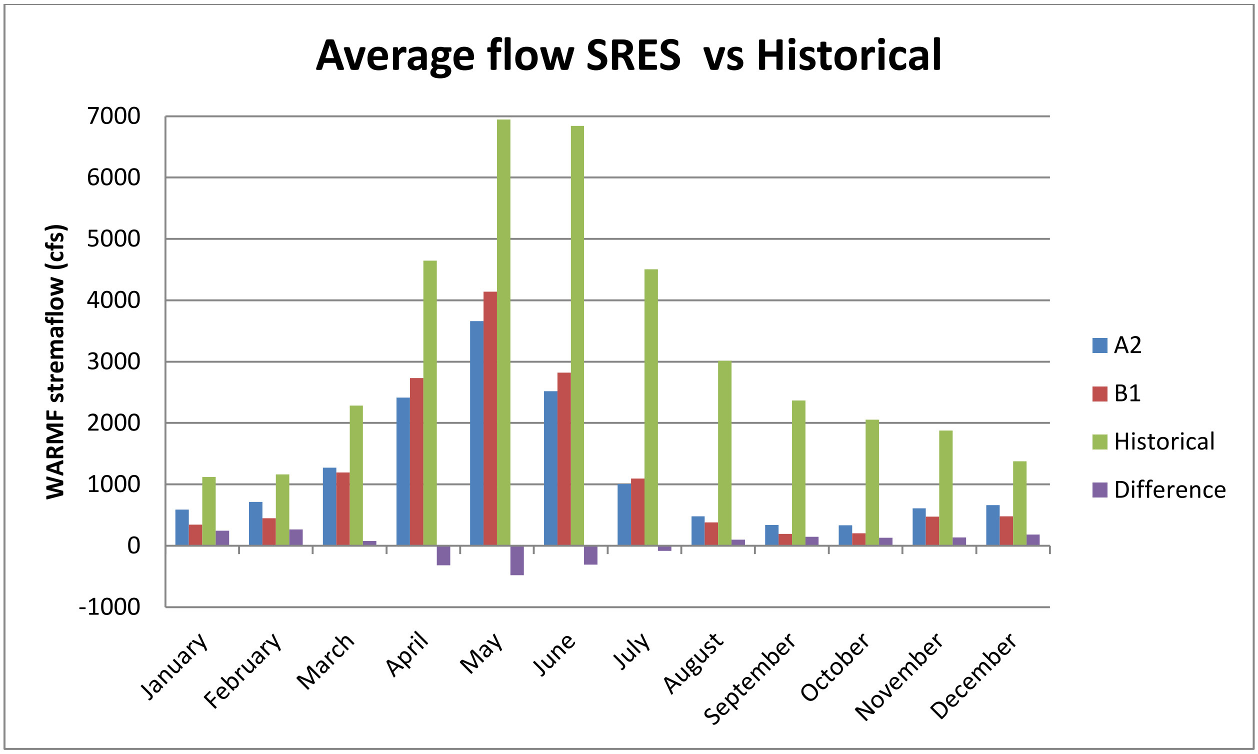


Figure 4.14: Mean of daily streamflow values from SRES A2 and B1 compared historical values. The difference value is between A2 and B1 in Period 1 (2046-2065)

An increase in temperature, especially minimum temperature, may cause precipitation to fall as rain instead of snow. On average, across the entire UCRB maximum and minimum temperatures increase 4°F for Period 1 and 2°F for period 2. Such large temperature rises should affect the timing of regional hydrology as seen in streamflow response and will later be presented in reservoir volume.

4.4 Reservoirs and Hydropower Production Impact

Hydropower is especially susceptible to climate change-induced hydrologic conditions. Hydropower production is inherently dependent, and consequently sensitive, to runoff. It is also greatly dependent on reservoir levels, timing, and volume of flows (IPCC, 2007). It has been shown in this study and others that hydropower yields will likely experience significant reductions under future climate conditions (Christensen et al., 2004). The UCRB has already experienced regional droughts. Droughts are predominantly impacted by water demand, land use, and land cover. A reduction in the snow pack of Western United States, compounded by less overall precipitation, higher temperatures, and a soil moisture response, exacerbate the drying conditions. Reservoir operations will become even more vulnerable to long term droughts, unless demand recedes (Christensen and Lettenmaier, 2007). To address impacts of predicted water stress on hydropower production, increase in reservoir capacity and/or changes in reservoir operations are needed. These measures could be implemented to alleviate the impacts to some extent though it may not generally be possible to totally mitigate the problem given the uncertainty both in climate and flow predictions.

Our study analyzes the hydrologic impact of climate shift on hydropower production considering an overall increase in temperature and flow reduction, with earlier snowmelt across the UCRB. Reservoirs for analysis are the hydropower producing Blue Mesa and Morrow Point, and Shadow Mountain Reservoir near Grand Lake and illustrated in Figure 4.15 below. Our simulation results, depicted in Figures 4.16, illustrate a variety of climate change impacts on reservoirs and hydropower production.

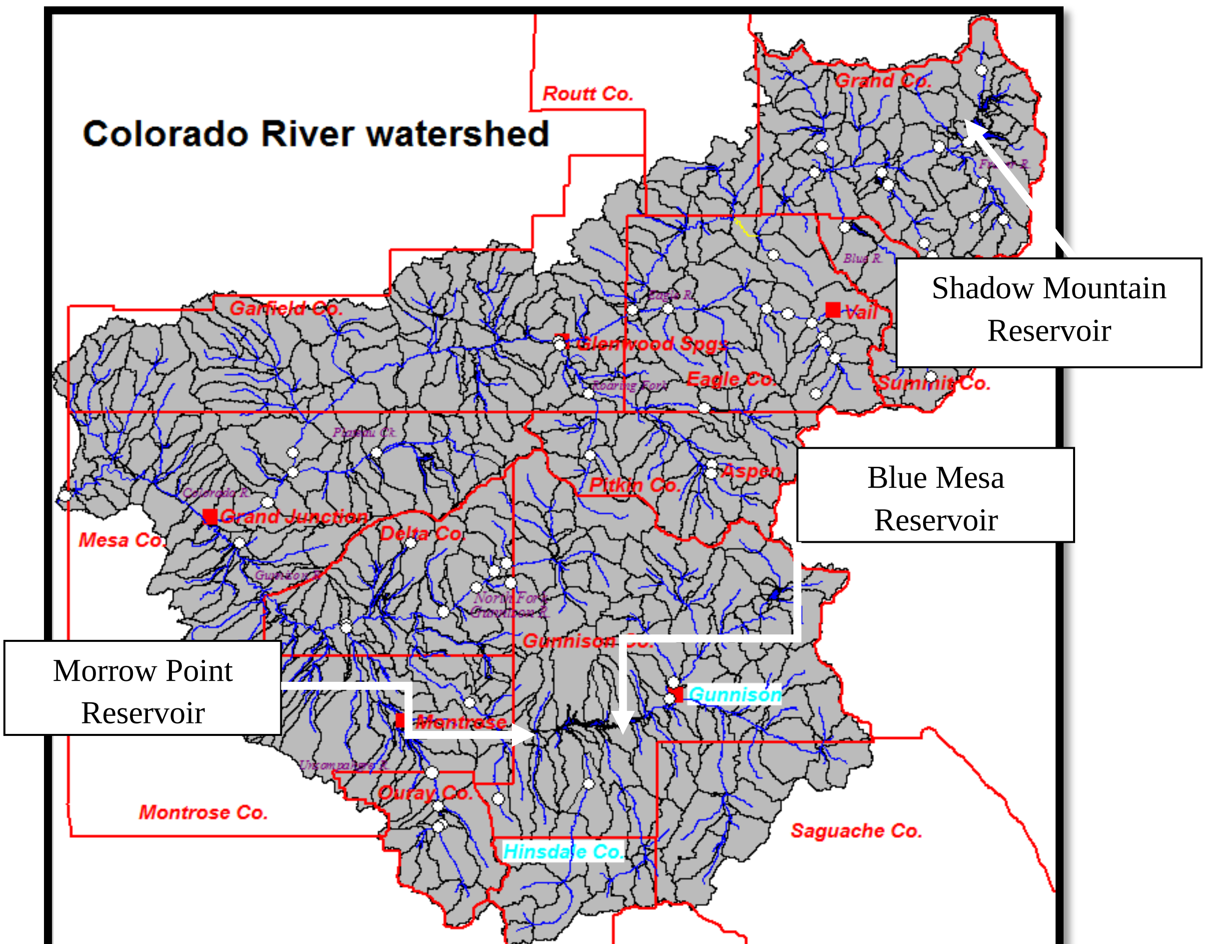


Figure 4.15: Map of reservoirs under analysis in the UCRB

Blue Mesa reservoir is the largest body of water inside the state of Colorado and is located at more than 7,5000ft in elevation with a surface area of 9,180 acres. It is located on the Gunnison River and produces over 260 MW each year, so it is a structure of critical interest for study. Under future climate conditions, it experiences reduction of 12% in precipitation, 83% in evaporation, 76-85% in spill (depending on scenario and GCM), and 70-73% in volume. Figure 4.16 describes Blue Mesa water storage under future conditions. There is a clear lag in peak storage from May to July in future climate conditions, for both climate scenarios. This is attributed to earlier melt causing earlier peak volumes, due to early runoff. The reduction in

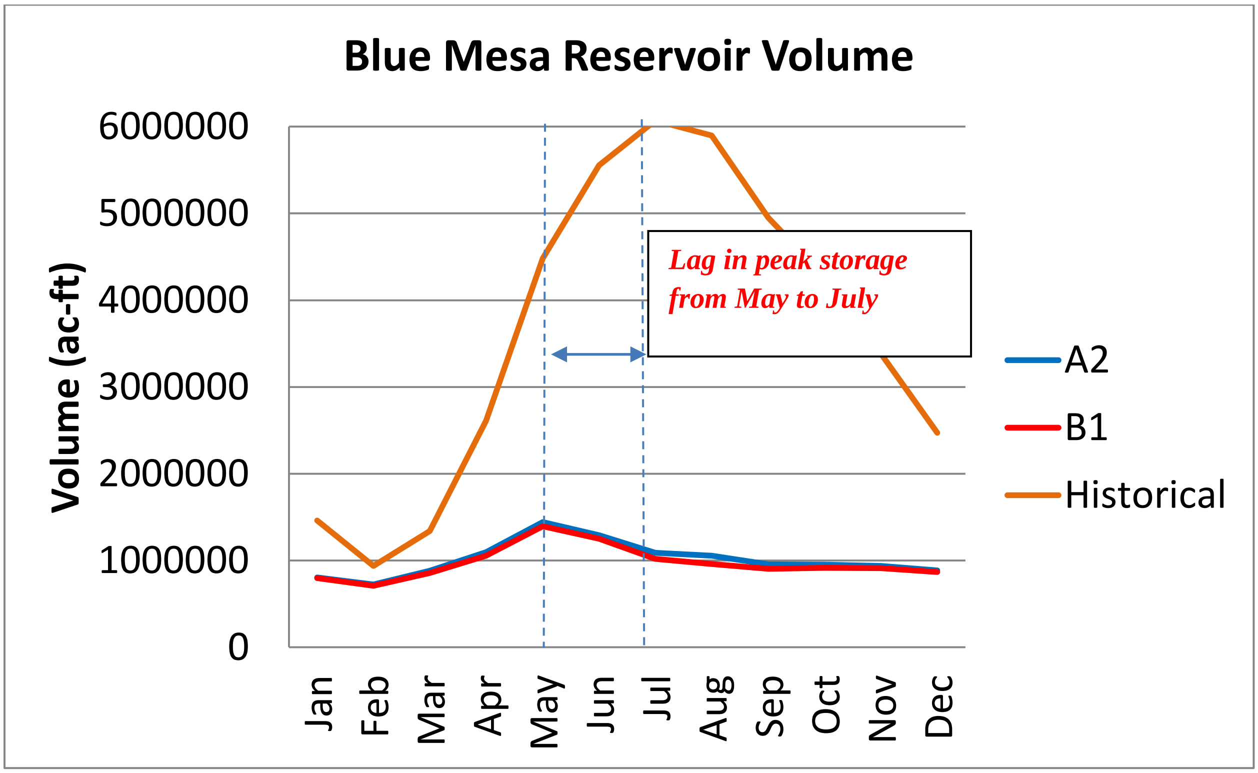


Figure 4.16: Monthly Mean Water Storage for all GCMs for Blue Mesa Reservoir in Period 1 (2046-2065)

precipitation at Blue Mesa and decrease in evaporation is dominated by the large decrease in reservoir surface area. This indicates an increase in temperature, though not as pronounced as at low elevation reservoirs. Despite this temperature increase, there is an 83% evaporation decrease, which is attributed to the large decrease in surface area.

Morrow Point reservoir is 12 miles downstream of Blue Mesa on the Gunnison River, with a surface area of 918 acres. It has 173 MW capacity and is critical to water supply and irrigation in the region, as well as for the rest of the UCRB. Under future climate, Morrow Point experienced a 5-10% increase in precipitation, with 9-15% reduction in evaporation, while spill and volume remained relatively unchanged (Figure 4.17). Although total volume remains relatively unchanged, there is a period from May to September where future conditions increase available storage during months of greatest demand. With increase in precipitation and a decrease in evaporation under projected climate, it is predicted that more volume and head will be available for hydropower production in this reservoir. Shadow Mountain reservoir lies between Lake Granby and Grand Lake near the Colorado River headwaters and above the glacial line at over 8,000 ft in elevation. Since it serves as a conduit of water between Lake Granby and Grand Lake, its behavior under future climactic conditions is indicative of Lake characteristics as well. Under future climate conditions, there is a 1-3% increase in precipitation, 5-7% reduction in evaporation, 8-10% spill increase, and a 1-5% increase in total volume (illustrated in Figure 4.18).

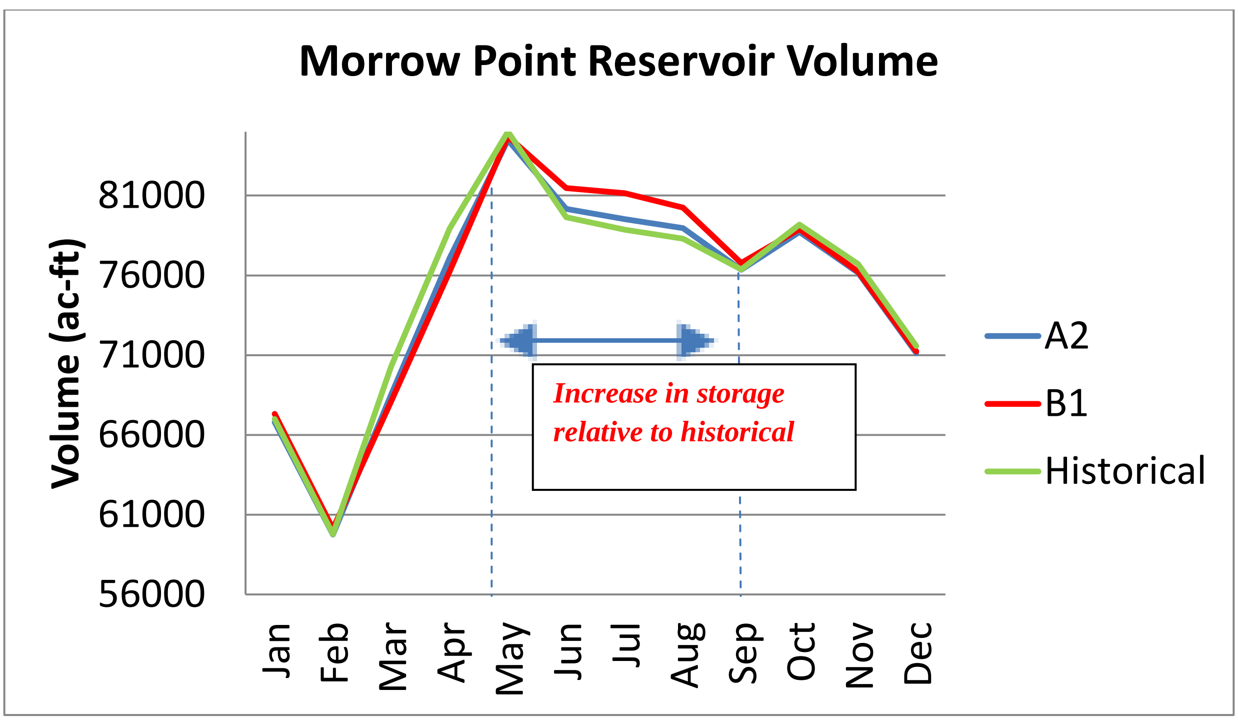


Figure 4.17: Monthly Mean Water Storage for all GCMs for Morrow Point Reservoir in Period 1 (2046-2065)

Thus, unlike the other low elevation reservoirs (Blue Mesa and morrow point reservoir), an increase in volume was predicted from June to September under both climate scenarios is due to the combined increase in precipitation and evaporation decrease.

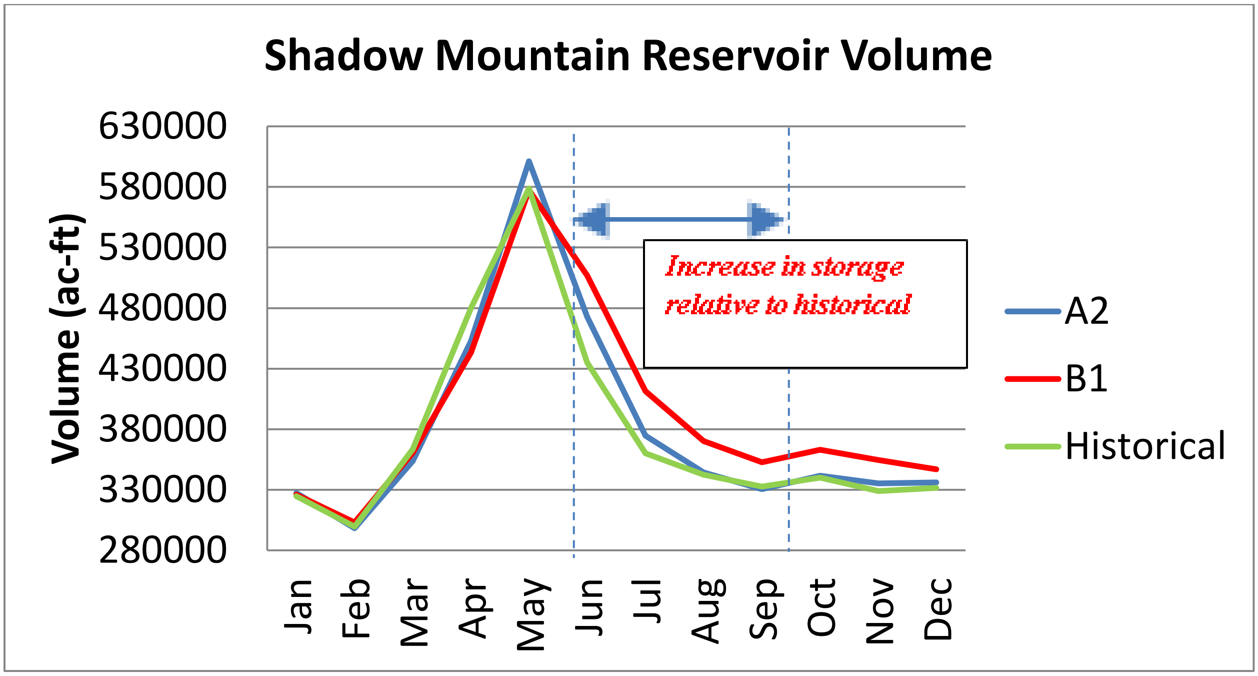


Figure 4.18: Monthly Mean Water Storage for all GCMs for Shadow Mountain Reservoir in Period 1 (2046-2065)

Shadow Mountain depicts peak storage volume in May, consistent with the previous two reservoirs, suggesting earlier melt and with other studies (IPCC, 2007). Additional storage of yield from early spring melt (especially in smaller reservoirs) is necessary to avoid spillage (in spring) and accommodate demand later in summer. Early season spills that may occur if sufficient storage isn’t present, can instead be stored to supply water to increasing population and agricultural demand.

Projected climate conditions describe significant volume reductions and can exacerbate current water stress. Critical regional and seasonal demands may not be fulfilled if trends follow the A2 and B1 climate scenarios, and must be considered by water planners and hydropower operators regionally. Hydropower production is also affected as it is inherently reliant on head for energy production. The energy relies upon height of water surface elevation and discharge, passing through a turbine, which experience some reductions in our study (based on specific conditions). From our results, a reduction in water surface elevation (and therefore less available head) and discharge, contributes to the cumulative decrease in hydropower potential. Rule curves, which are guidelines for reservoir levels depending on time of year, will need to be altered in order to address the changing climate. It describes the water level, or range of acceptable levels, for each day of the year. Water levels are regulated depending on demand and climate conditions, governing runoff patterns. Generally, large-sized reservoirs are less sensitive to climate change but smaller reservoirs are deeply impacted (Eum and Simonovic, 2010). Flood control emphasis is reflected in Figure 4.19 in the Oroville rule curve there is an early drawdown by managers to allow for available volume within the reservoir to accommodate incoming flows (Willis et al., 2011). The table is difficult to read which is significant, it is a pen and ink drawing and the most current curve available. Many operational reservoirs still operate under antiquated

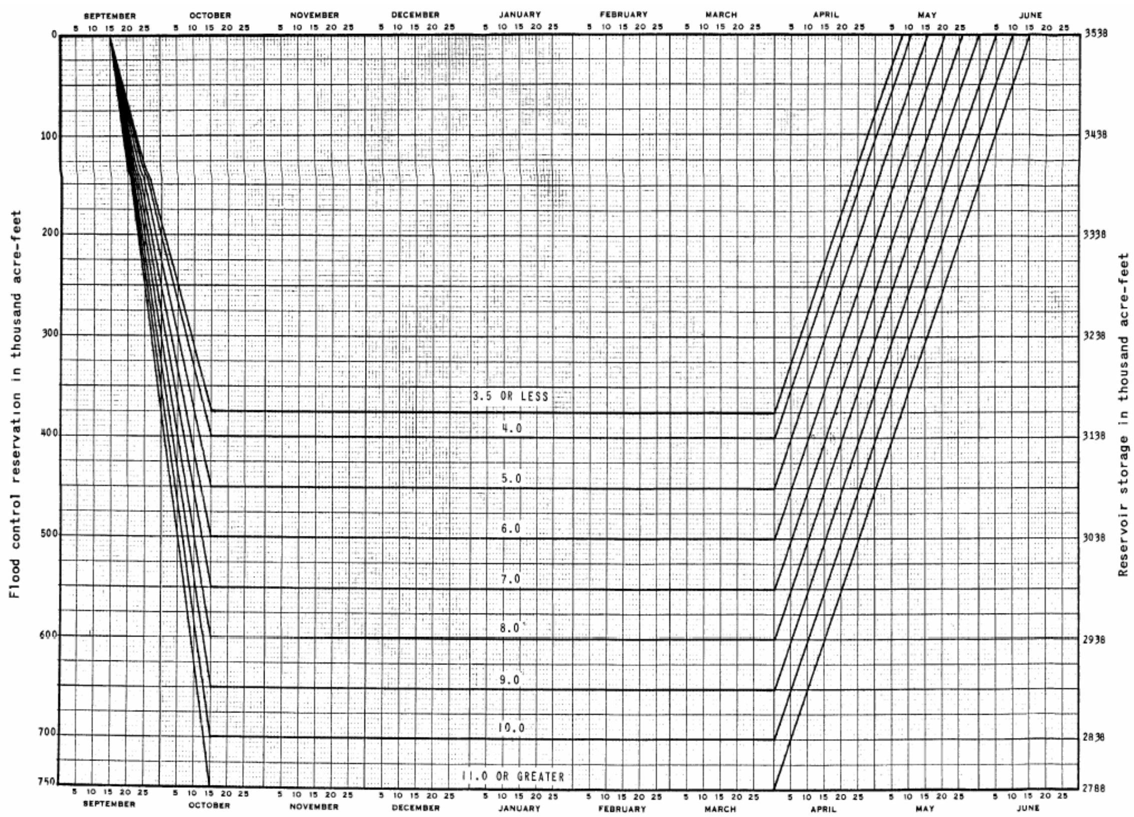


Figure 4.19: Operational rule curve for Oroville Dam in the Sacramento Valley (Willis et al., 2011)

guidelines and are unprepared for a changing climate. This specific curve illustrates the drawdown, stabilization period, and refill (which begins in late March in the 1950s). Figure 4.20 illustrates a more updated reservoir curve and includes volume limits for storage requirements.

Adaptive policies, even with altered rule curves, are still necessary to mitigate climate change influence. Reservoirs utilized for irrigation, hydropower production, and/or flood control need to be considered individually for each purpose. Thus multi-use reservoirs pose the greatest challenge. Raje and Mujumdar (2009) address all of the reservoir constraints under future climate change using a variety of modeling techniques to create adaptive rule curves for

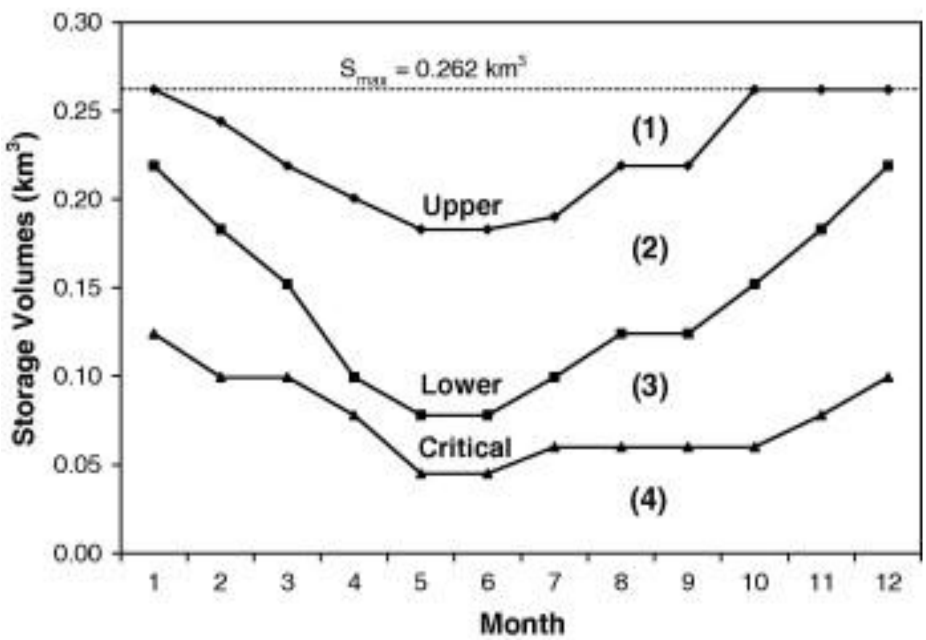


Figure 4.20: Operational rule curve for Delaware River Basin (Chaves and Chang, 2008)

future conditions in Figure 4.21. It describes adaptive strategies under future climate conditions in comparison to current operation. Reservoir operations under MIROC B1 scenario (same scenario, different location, to the one in our study) visibly increase reservoir levels during traditionally low summer months of July to September. These adaptive policies were attained through complex, regional analysis and such is needed to accommodate changing conditions in high risk reservoirs along with water resources adaptive policies of sustainable irrigation practices. Raje and Mujumdar (2009) conclude that after curve optimization that with an increase in power reliability annual demand increases, but irrigation reliability decreases. By increasing hydropower reliability, other aspects of the system experienced additional stress, such as irrigation. Irrigation reliability suffered as a tradeoff for energy. Adaptive policies would serve to offset performance increases, but are still limited by overall water balance deficits in future climate scenarios.

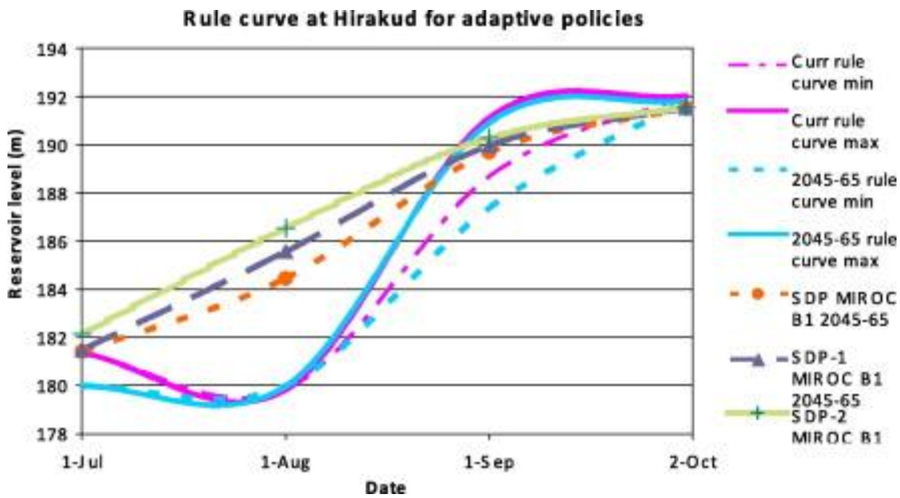


Figure 4.21: Reservoir operations under MIROC B1 scenario for historic and future conditions with adaptive strategies

4.5 Comparison of Results to Similar Studies

Results of our study compliment the other work done in the region, while adding key information regarding hydropower production and expanding on the basins of previous study. Nash and Gleick (1991) analyzed streamflow sensitivity of the Colorado River Basin (CRB) to climatic variability. Using similar deterministic modeling, they identified streamflow changes most pronounced in low flow years, while overall impact is markedly greater during high flow conditions, and an increase in temperature causes earlier peak runoff. They also noted, as discussed later in this study, that evaporation did not have a great impact under future climate scenarios. Furthermore, they mention (later echoed by Maurer in 2007) that at higher elevations, temperature increases have smaller significance. This is because at higher elevations a temperature increase will most likely not raise temperatures above freezing, mitigating that impact (Maurer et al., 2007). Christensen and Lettenmaier (2004; 2007) also evaluated climate change impacts on the entire CRB. They used 11 GCMs with A2 and B1 scenarios, to force the VIC and the CRRM models for a comprehensive reduction in reservoir storage of 30-60% (to our 70% decline). At the headwaters of the Colorado River they found precipitation to increase up to 10%, which is also consistent with our findings. The group also calls for more research in the basin, since few studies are specific to the CRB and inclusive of reservoir considerations, as we have included. Our study adds to theirs by analyzing watershed hydrology with integrated reservoir processes within in a single watershed model. We compliment their work and expound on it by including the Gunnison River basin. It is critical to hydropower production in Colorado and must be considered when analyzing future changes on the entire CRB. The UCRB is a high priority region since it is almost entirely allocated and therefore highly sensitive to snowmelt runoff fluctuations, where most of the Colorado River's flow originates. Furthermore, Christensen and Lettenmaier (2007) stated that there is a constant discrepancy in streamflow behavior and specific temperatures under future climate conditions and more studies are necessary to examine the possibilities. Their study differs from ours in downscaling technique and hydrology model selection, but results are comparable and add to the current body of knowledge. Also, their reservoir model was not a part of the hydrologic VIC analysis. The VIC model simulated at daily time steps but their reservoir model only utilized monthly aggregates, where we perform our reservoir analysis daily. Raje and Mujumdar (2009) also evaluated reservoir performance under climate change and emphasized the importance of daily and sub-daily analysis for management. They specifically analyzed rule curves of reservoirs emphasizing the significance of analysis at daily or sub-daily scale. Our study creates an envelope of potential future climate conditions from which decision makers can begin to create mitigation and adaptation strategies.

Our study describes daily fluctuations of reservoir behavior under future climate conditions. Unlike the CRRM, which identifies only 11 diversion points for the entire CRB, our UCRB WARMF model includes over 4,500 diversions (a feature unique to this analysis, to our knowledge). Although this does not significantly alter the water balance on which both hydrology models are based, a more accurate representation of the system provides greater insight into future behavior. Diversion flows act to increase soil moisture content and may percolate to groundwater. Exfiltration from groundwater will join to streamflow as baseflow, feeding back into the system. Losses to processes such as ET are probably, but will not likely be dominant processes. Like other studies (Christensen and Lettenmaier, 2007; Raje and Mujumdar, 2009; Barnett and Pierce, 2008, 2009; Vicuna et al., 2007; etc.) we illustrate summer to early fall warming compared to the historical record, with some increasing winter precipitation at high elevation, and a reduction in hydropower production. Christensen and Lettenmaier (2007) found, that there is a negative feedback between increasing temperatures and evaporative demand. This means that runoff and ET sensitivity to increasing temperatures is reduced, one of the many studies (including ours) which describe a reduction in ET in response to higher temperatures, mostly due to other factors reducing its sensitivity such as soil moisture. Raje and Mujumdar (2009) also found that mean monthly storage would likely decrease under future scenarios. A reduction in storage, such as the 70% decline discussed in this study, would also reduce hydropower generating potential and reliability.

Other basin impacts under climate change have been evaluated worldwide. Maurer et al. (2008) evaluated temperature and precipitation data from 16 GCMs under A2 and B1 emission scenarios to drive a land surface model. Analyzing the Rio Lempa Basin, the largest river basin in Central America (18,000 km^2 to the Colorado's 44,000 km^2), which similarly provides water and hydropower services to its region. The data used came from the World Climate Research Program's (WCRP) Coupled Model Intercomparison Project Phase 3 (CMIP3) GCM datasets. The dataset were downscaled with a bias-corrected density function for monthly precipitation and temperature data, to force VIC. It considers topography, infiltration, and land cover impacts similar and generates surface runoff and baseflow to route through the grid network. Unlike WARMF which routes based on the actual GIS-based network, VIC routes at user specified point in the basin (Christensen and Lettenmaier, 2007). VIC models "natural" flows, where a lot of the UCRB is managed flow and would not illustrate the most accurate representation. The results illustrate a general drying and warming trend of 1-4°C, similar to other studies mentioned previously. Implications to future hydrology indicate earlier onset of snow melt and an escalation of mid-Summer drought. Our study of the UCRB also showed temperature increases for both the maximum and minimum daily temperatures.

The study also notes the effect of plants on CO_2 concentrations. In the Rio Lempa Basin, CO_2-induced stomatal closure reduced ET (Kergoat et al., 2002), but was offset by the photosynthesis stimulation which increases ET. Overall, Maurer et al., (2008) found that CO_2 impacts from plants contribute little in comparison to that of climate change. It has been shown that water vapor fluxes over the continents are largely controlled by plant canopies (Kergoat et al., 2002), which are greatly impacted by CO_2 levels. In high latitude systems nutrient-limited soils could actually benefit from an increase in CO_2 levels causing more photosynthesis in cold climates, stimulating plant growth. They found that vegetation- climate feedbacks although critical to regional ET levels, globally are second to plant response. Therefore, the doubling run identifies behavior in extremely elevated CO_2 environments by identifying a small response on global ET, due to the plant's compensatory response (Kergoat et al., 2002). Furthermore, like Barnett and Pierce the study identified a reduction in power production of 33-53%, from low flow frequency, in drier years. Ultimately, Maurer et al., (2008) found that the A2 scenario was nearly twice the negative impacts as the B1, which is unlike the results we demonstrate in the UCRB. With the more mountainous topography of our basin, A2 and B1 scenario results were not as dramatically different from each other.

CHAPTER 5: SUMMARY AND CONCLUSIONS

Climate change will impact reservoir operations and hydropower potential in the 21st Century. Projected warmer and drier conditions will reduce river flow, on which hydropower is dependent (Barnett and Pierce, 2008). Reductions in runoff and flow will not only decrease available potential for hydropower generation, but also impact the ability to meet water subscriptions downstream. Water delivery shortages and shortfalls are expected if circumstances are such as depicted by future climate predictions (Barnett and Pierce, 2008).

Barnett and Pierce (2008) quantified the projected delivery shortfalls under various climate scenarios. Using 20th-century flows with a 10% runoff decline, shortfalls appear in 2040, but a 20% reduction causes shortages in as early as 2025. This also assumes an effort to allocate Colorado River water as it is prescribed, not what is sustainable. If deliveries are reduced to more sustainable levels (Barnett and Pierce, 2008) they can continue for longer than 2060 without shortfalls, however, this is not realistic considering increasing demand for increasing population and development.

In this study, WARMF model was applied to assess the impact of projected climate change on hydrology and hydropower production of the UCRB. WARMF simulated precipitation and temperature data for several time periods under a variety of climate scenarios. It was found that both maximum and minimum temperatures will generally increase in summer and winter months, impacting regional hydrology and hydropower response. Simulations for most of the subcatchments of the UCRB described 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. With an increase in temperature on the order of 2-4°F basin-wide, timing and magnitude of streamflow is impacted.

Instead of snow melt in late spring, the centroid of the hydrograph moves earlier, influencing reservoir curves in the region. With snowmelt occurring earlier, storage is critical. Since demand is greatest in summer months, reservoirs must now be equipped or retrofitted to capture the valuable resource or waste it to spillage. In large systems this issue is mitigated by reservoir size, but with smaller systems spillage becomes critical. Not only is water lost without consumption, or any other beneficial use, it is also not financially utilized. Pricing is based on demand and releasing water without adequate compensation is never positive for hydropower operations. Better management and mitigation strategies are needed to account for future climate impacts.

Adaptive policies are necessary to deal with projected changes. Efficient practices could mitigate climate influence on hydropower and diminish some of the economic effect. Without proactive action, current practices will lead to annual loss in hydropower potential and reliability in future climate. Irrigation is inherently dependent on these sources for water supply, and it is imperative to minimize loss. Mitigating irrigation demand in practice, such as by growing crops that are less water intensive and/or which do not have both water and power demand, can help alleviate extreme conditions of future climate. Reservoir operations must also accommodate increased risk for future droughts and floods through management practices. Rule curves, on which operations are based, must be changed to optimize production while saving water when necessary and minimizing flood risk. Under careful selection of adaptive operation strategies projected flood damage could be limited, while also retaining necessary water resources to meet demand. Specific conclusions of this study follow:

1. Future projections show that precipitation changes vary by elevation. At low elevation near the Utah State line, future climate describes more than a 60% decline in precipitation. Conversely, at high elevation near Taylor Park Reservoir precipitation increase up to 74 % compared to historical. Regardless, all elevations depict a decline in accumulation during summer months which agrees with the IPCC's (2007) finding of substantial summer drying in the mid-latitudes.
2. An increase in temperature, especially minimum, causes precipitation to fall as rain instead of snow. At lower elevations, future temperature is more than historical, with the difference between A2 (3.45°F) and B1(2.7°F) only 1.8% (or 0.7°F). When evaluating historical to future, the change is much more significant at 3.5°F and 2.8°F for A2 and B1 scenarios, respectively. Rise in temperature is exacerbated during the summer months of June-September, where a 4°F difference exists. At high elevations, temperature is also predicted to increase but differs in timing and is much less pronounced. A2scenario illustrates only a 2°F increase and B1 experiences a 1.5°F rise.
3. 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 the more dramatic A2 scenario, the hydrologic response is more pronounced when precipitation effects are strongest in winter. As temperature is also predicted to increase annually, resulting in increasing evaporation rates and reducing soil moisture, flow is also shown to decrease during the most affected summer months under both A2 and B1 scenarios. There is a 62% reduction in annual flow volume, impacting the over allocated water deliveries downstream.

4. Our study analyzed the hydrologic impact of climate shift on hydropower production considering an increase in temperature with reduced stream flows and earlier snowmelt across the UCRB. Our simulation results show a 70% reduction in water storage at the high elevation hydropower generating Blue Mesa Reservoir, while no changes is seen 12 miles downstream at Morrow Point Reservoir. This is attributed to the influence of surface area on evaporative demand, where the latter reservoir was less impacted due to a decrease in evaporation rates. At Shadow Mountain Reservoir volume increased by up to 5% predominantly due to precipitation increases from orographic effects.
5. Climate change induced temperature rise impacts snowmelt and streamflow conditions. We found snowmelt to occur earlier from 2-4 weeks, with a general reduction in streamflow. 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. Increased temperatures raise evaporation rates and reduce available soil moisture, reducing onset of runoff in summer exacerbating and/or creating drying conditions. The spilling of resources in early spring could limit a water supply reservoir from being able to meet peak demand. Larger reservoirs are less impacted, but still experience a changed regime in response to climactic changes. While spilling water may not be necessary, 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).

5.1 Recommendations for Future Research

The following recommendations for future research address the research limitations discussed previously, as well as consider different extensions of this study. By addressing these limitations and applying this framework methodology, a decision making framework may be further developed to be more versatile in direct application to hydropower and water resource adaptation strategies.

1. Extend the analysis presented in this impact study with the decision making framework, optimizing sizing of reservoirs and hydropower generation for performance and economic benefits. Expand those results to an envelope of potential options for future conditions using other research results as well.
2. Analyze existing BCCA datasets using other hydrologic watershed models (such as VIC) to evaluate variability of results between hydrologic models.
3. Analyze existing datasets using models which better consider reservoir evapotranspiration rate and the land-atmosphere energy flux component.
4. Utilize and/or create a hydrologic model which also considers groundwater movement to evaluate its response to climatic change.
5. Use a watershed based hydrologic model to analyze dynamically downscaled climate and precipitation results for hydropower and water resources impacts in the region.

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APPENDIX A

SUPPLEMENTAL ELECTRONIC FILES

The supplemental files are a collection of data used in this study for analysis and to post-process and analyze the results. They include input datasets of specific significance and novelty, such as the diversion files, as well as datasets used to examine future climate conditions. Future climate data includes raw output from climate models and post-processed workbooks complete with data analysis and conclusions. There are also summary sheets for trend analysis.

File Name	**Description**
WARMF DATA.zip	Includes WARMF model input data of over 4,500 diversion (.flo), meteorological data (.met), and reservoir stage-storage-discharge (SSD) table EXCEL worksheets which were used to populate model input.
Future Climate Data.zip	Includes future datasets (with descriptions) under different climate scenarios and historical datasets, BCCA worksheets where the future climate scenarios were summarized per each stations of interest within the model and identify specific trends analyzed in the study. Additional analysis worksheets for Blue Mesa, Morrow Point, and Shadow Mountain reservoirs.