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Assessment of impacts to hydroclimatology and river operations due to climate change over the Colorado River Basin

William Paul Miller
University of Nevada, Las Vegas

ASSESSMENT OF IMPACTS TO HYDROCLIMATOLOGY AND RIVER OPERATIONS DUE TO CLIMATE CHANGE OVER THE COLORADO RIVER BASIN

by

William Paul Miller

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University of Arizona
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Master of Science
University of Notre Dame
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Howard R. Hughes College of Engineering

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William Paul Miller

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Thomas C. Piechota, Committee Chair

Jacimaria R. Batista, Committee Member

Sajjad Ahmad, Committee Member

Terrance J. Fulp, Committee Member

William J. Smith, Graduate Faculty Representative

Ronald Smith, Ph. D., Vice President for Research and Graduate Studies
and Dean of the Graduate College

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ABSTRACT

Assessment of Impacts to Hydroclimatology and River Operations Due to Climate Change Over the Colorado River Basin

by

William Paul Miller

Dr. Thomas C. Piechota, Examination Committee Chair
Director of Sustainability and Multidisciplinary Research
Associate Professor, Civil and Environmental Engineering
University of Nevada, Las Vegas

This dissertation investigated the impacts of climate change to the hydroclimatology and river and reservoir management operations within the Colorado River Basin. Preliminary research indicated observed warming trends throughout the Colorado River Basin and corresponding seasonal trends to the magnitude and timing of runoff in the Colorado River Basin. Subsequent research investigated the changing character of precipitation and corresponding impacts to streamflow over the Colorado River Basin. Analysis of snowpack telemetry (SNOTEL) stations over the American West and Colorado River Basin indicated decreasing trends in annual snowpack, often at least at the 95% confidence interval. A shorter snowpack season was observed within the gage record at most SNOTEL locations throughout the western United States; the length of the snowpack season decreased approximately 1 day per year throughout much of the Colorado River Basin. Decreasing snowpack trends correspond with decreased runoff over the Colorado River Basin.

Research then focused on the derivation of streamflow projections under changing climate conditions. Using temporally disaggregated, bias corrected and spatially downscaled climate projections of temperature and precipitation to force the National

Weather Service River Forecasting System developed over the Colorado River Basin by the Colorado Basin River Forecast Center, projections of unregulated streamflow under climate change conditions were derived over three Colorado River headwater basins. Projections of unregulated streamflow over the Gunnison and San Juan River Basin decreased approximately 15% to 20% over the 90 year projection period. Over the Green River Basin, an increase of approximately 3% was projected over the same 90 year period. Information from these streamflow projections were then used to force a river management planning model utilized by the United States Bureau of Reclamation (Reclamation) over the San Juan River Basin.

This research contributed to the understanding of hydroclimatology within the Colorado River Basin and impacts to river hydrology and management under changing climate conditions. This was done primarily in three sections. First, trends in snowpack characteristics were compared to annual and seasonal trends in streamflow to improve understanding of how hydroclimatic indices impact streamflow within the Colorado River Basin. Secondly, temporally disaggregated bias-corrected spatially downscaled projections of climate were used to derive streamflow projections over the Green, Gunnison, and San Juan River Basin. Changes to evapotranspiration with temperature were taken into consideration, and projections were subjected to analysis for evidence of nonstationary behavior. Finally, this dissertation represents Reclamation's first effort in the Colorado River Basin to incorporate climate change information into a planning model.

This research improves the understanding of the relationship between climatic variables and hydrology within the Colorado River Basin, and successfully derives

projections of streamflow using projections of temperature and precipitation over Colorado River headwater basins. These streamflow projections may be used by water resource managers to evaluate potential ranges of resource management as impacts from climate change are realized. Information from these streamflow projections are incorporated into a Reclamation planning model. This research provides a proof of concept that may be followed to incorporate climate change information into environmental water resource planning and operations. With changing climate conditions, Reclamation must maintain proactive conservation efforts and efficient water management practices to meet water delivery requirements and flow recommendations.

DEDICATION AND ACKNOWLEDGEMENTS

I would like to dedicate this dissertation to his wonderful family. My parents, Bill and Leticia Miller, have given me more than I could ever hope for and have made so many opportunities possible for me. I could never thank them enough and can only hope to pay forward their never ending love and support. My brothers, Eric and Bobby Miller have always meant more to me than I could ever describe. They are the best brothers in every sense of the word, and my best friends. I love them all so much; I am too fortunate.

I would like to acknowledge my advisor Dr. Tom Piechota whose considerable guidance and support not only made this work possible, but beneficial and engaging. I sincerely appreciate all of his help and feel that I have learned so much from him, not only about hydrology and engineering, but about being a professional and a teacher. I can not thank him enough for the opportunity he gave me; I don't know where I would be without it.

This work would not have been possible without the support from the United States Bureau of Reclamation, Lower Colorado Region in Boulder City, Nevada. In particular, I sincerely appreciate and am impressed by my colleagues that I work with, and have worked with, within the River Operations Group in the Boulder Canyon Operations Office. I am a better person for everything I have learned from Bruce Williams, Janie Jo Smith, Joe Donnelly, Shana Tighi, Julie Merchen, Dan Bunk, Kyle Cavalier, Rich Hedrich, and Doug Blatchford. I can not imagine working with a better group of people or a better career.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

1.1 Research Problem

In January of 1999, the Colorado River System was at approximately 91% capacity; collectively, Lakes Powell and Mead were at approximately 95% capacity. Since then, the Colorado River Basin has experienced the driest 10-year period (2000 – 2009) over the historical gaged record (in excess of 100 years), decreasing system capacity to approximately 52%. Recent studies have indicated this current drought to be one of the most severe in history (e.g, T. Piechota et al., 2004; Timilsena et al., 2007). Since 1950, the contiguous United States has experienced warming trends, and, with the exception of the American southwest, increased precipitation. Without this increase in precipitation, most of the United States may have experienced periods of extreme drought (Easterling et al., 2007), much like the Colorado River Basin.

The United States Department of the Interior, Bureau of Reclamation (Reclamation) manages a complex water storage and delivery system on the Colorado River Basin. As the impact of increasing temperature and decreasing precipitation trends become more prevalent to streamflow and resultant reservoir operations, Reclamation must examine risks and uncertainty associated with operating this complex river system under changing climate conditions. Reclamation has often relied on past observations of climate and hydrology to plan and model reservoir operations within the Colorado River Basin; in light of climate change, the assumption that past hydroclimatology is representative of future hydroclimatology may no longer be accurate. In this dissertation the understanding of climate change impacts to water resources in the Colorado River Basin

is expanded. Furthermore, projections of climate data are investigated to exhibit how projections of future climate may be incorporated into Reclamation planning and operations.

1.1.1 Trends in Western U.S. Snowpack and Corresponding Impacts to Streamflow in the Colorado River Basin

The timing and magnitude of streamflow in the Western U.S. and Colorado River Basin is related to the character of precipitation events (i.e. snowfall as opposed to rainfall) and timing and magnitude of snowmelt. Research has indentified changes to the timing and distribution of streamflow in the Colorado River Basin (Cayan et al., 2001; Fassnacht, 2006; Groisman et al., 2001; Hamlet et al., 2007; e.g, Lins & Slack, 1999; Mauget, 2003; McCabe & Dettinger, 2002; Pagano & Garen, 2005; Regonda et al., 2005; Rood et al., 2005; Stewart et al., 2004; Stewart et al., 2005) under changing climatic conditions, most notably increased warming trends. Research has also begun to identify changes in the character of precipitation; that is, changes to the frequency and duration of rainfall and snowfall events in the Western U.S. and Colorado River Basin (Feng & Hu, 2007; Gutzler, 2000; Knowles et al., 2006; Trenberth et al., 2003). However, most studies have focused on declining snowpack trends and changes to streamflow as a result (e.g., Clark et al., 2001; Hamlet et al., 2005; Kalra et al., 2008; McCabe & Dettinger, 2002; McCabe & Clark, 2005; Mote, 2003; Mote et al., 2005; Mote, 2006; Serreze et al., 1999; Serreze et al., 2001; Stewart et al., 2004). While many of these studies offer some insight as to the impact of changing precipitation characteristics on streamflow, the comparisons of precipitation character (i.e., snow or rain) and the corresponding streamflow are lacking. Currently, no studies have been performed that evaluate the

impacts of changing precipitation characteristics (the frequency and volume of rainfall and snowfall events) with changes in the timing and magnitude of streamflow in the Colorado River Basin. In this dissertation, the correspondance of precipitation characteristics to streamflow over the Colorado River Basin will be addressed. This will be explained through the use of Kendall's tau (τ) nonparametric test for monotonic trend with a correction for ties. Kendall's τ is well-suited for applications to water resources, as it is a rank-based procedure that is resistant to outliers in time series (e.g. Helsel & Hirsch, 1992). Kendall's τ test has successfully been used in previous research investigating the trends in precipitation and streamflow observations (e.g. Huntington et al., 2004; Knowles et al., 2006; Rood et al., 2005).

1.1.2 Derivation of Streamflow Projections from Statistically Downscaled, Bias-Corrected Climate Data at Colorado River Basin Headwaters

As climate change impacts affect the hydroclimatology of the Colorado River Basin, temperature and precipitation changes directly impact the magnitude and timing of streamflow (e.g. Cooley, 1990; Easterling et al., 2007; Gleick & Chalecki, 1999; Groisman et al., 2001; Hamlet et al., 2005; Lins & Slack, 1999; Mauget, 2003; Maurer & Duffy, 2005; Milly et al., 2005; Nash & Gleick, 1991; Regonda et al., 2005; Stewart et al., 2004). In light of altering climatic conditions and projections that climate conditions will continue to change under anthropogenic forcing (Metz & Intergovernmental Panel on Climate Change, Working Group III, 2007; Parry & Intergovernmental Panel on Climate Change, Working Group II, 2007; Solomon & Intergovernmental Panel on Climate Change, Working Group I, 2007), historical observations of streamflow may no

longer accurately project future streamflow; projections of streamflow must now incorporate hydroclimatic trends under changing climate conditions.

Recently, Reclamation used multiple methods to address future hydrology in the development of the Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lakes Powell and Mead (Interim Guidelines) (U.S. Department of the Interior, Bureau of Reclamation, Upper and Lower Colorado Regions, 2007). Among those methods used to address future hydrologic conditions over the Colorado River Basin are the Index Sequential Method (ISM), Direct Paleo (DP), and Nonparametric Paleo Conditioning (NPC) methods (each of these methods are discussed in Appendix N of the Interim Guidelines). Through the use of these methods, Reclamation is able to address hydrologic variability within the Colorado River Basin as a result of possible changes to climate for long-term (approximately 20 years) planning.

Streamflow traces such as those developed through an ISM are relatively limited. Streamflow projections derived through the use of the traditional ISM are constrained by reconstructions or historical observations of flow and assume that past land and atmospheric conditions are representative of future conditions. Reclamation's short and long term operations are dependent on streamflow projections and now face the challenge of incorporating climate change into the development of improved streamflow projections.

Studies have consistently incorporated hydroclimatic variables into the development of streamflow projections. Most commonly, these studies have examined the link between naturally recurring teleconnection patterns and their correlation with hydroclimatic variables such as temperature, precipitation, and streamflow. Research has

shown varying degrees of correlation between teleconnection patterns with hydroclimatic variables under various spatial and temporal conditions. Hydroclimatic and drought response to teleconnection patterns in the Colorado River Basin is most often associated with the El Niño Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), Atlantic Multidecadal Oscillation (AMO), and Southern Oscillation Index (SOI) teleconnection patterns, among others (e.g., Clark et al., 2001; Hamlet & Lettenmaier, 1999; Hamlet & Lettenmaier, 2007; Hamlet et al., 2007; McCabe & Dettinger, 2002; McCabe et al., 2007; T. C. Piechota & Dracup, 1996; T. C. Piechota et al., 1997; Thomas, 2007; G. Tootle et al., 2009; G. A. Tootle & Piechota, 2006). While teleconnection and sea surface temperature data have been used to forecast or model streamflow directly or based upon expected temperature and precipitation response to atmospheric circulation patterns (e.g. Chiew et al., 1998; T. C. Piechota et al., 1998; T. C. Piechota et al., 2001; G. A. Tootle & Piechota, 2004), only a spatially broad and generally qualitative approach has been explored examining the response of streamflow projections to changes in hydroclimatic variables over the Colorado River Basin.

The World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset has recently been made available through a joint effort between Reclamation, Santa Clara University (SCU), and the Lawrence Livermore National Laboratory (LLNL) and provides statistically downscaled, bias corrected climate projection data from a myriad of climate models over the continental United States. Currently, there are no studies that have incorporated this advanced downscaled dataset into projections of streamflow data in the Colorado River Basin.

The Colorado Basin River Forecast Center (CBRFC) provides Reclamation with unregulated inflow forecasts which are used as input into Reclamation's operational forecasting and policy models. The term "unregulated" as it pertains to streamflow is that streamflow modeled or calculated if the absence of reservoir regulation and anthropogenic diversions is assumed. Unregulated streamflow forecasts are developed from an ensemble of streamflow models incorporating a wide breadth of hydrologic and climatic data. While these models are statistically robust and utilize the most accurate historical and current data available, no studies have determined the effect to unregulated inflow forecasts derived from CBRFC models forced with projected, downscaled climate conditions (e.g. temperature and precipitation characteristics) from a multi-model dataset such as that from WCRP's CMIP3. Currently, no study has developed unregulated streamflow projections from the ensemble of CBRFC models from downscaled climate projection data from WCRP's CMIP3 multi-model dataset. In this dissertation, streamflow projections developed through the use of projected climate data (i.e., temperature and precipitation projections) will be discussed.

1.1.3 Incorporation of Streamflow Projections Under Changing Climate Conditions into Reclamation's Planning Model for the San Juan River Basin

Reclamation has traditionally relied on historical data to project future hydroclimatic and reservoir conditions within the Colorado River Basin. To date, climate change information directly from Global Climate Models (GCMs) has not been incorporated into hydrologic models used by Reclamation to make operational and policy decisions over the Colorado River Basin. In this dissertation, streamflow projections derived from projections of future climate conditions will be used to force a Reclamation planning

model over the San Juan River basin. Model results will be used to assess the ability of Reclamation to meet current environmental flow recommendations in the San Juan river basin in light of changing climate conditions.

1.2 Research Questions and Hypothesis

The goals of the research presented in this dissertation are to address the potential impacts of climate change to the hydroclimatology of the Colorado River Basin and potential impacts to the Reclamation reservoir operations under projections of changing climate. This will be accomplished by investigating the relationship between precipitation characteristics and basin snowpack, utilizing climate projections to derive projections of future streamflow, and evaluating the impacts of those projected streamflow conditions on reservoir operations on the San Juan River Basin. Prior research focused on the analysis of hydroclimatic trends over the Colorado River Basin region (Miller & Piechota, 2008).

An improved understanding of how climate change will impact water resources and the management of resources within the Colorado River Basin will be accomplished by first investigating the current linkages between hydroclimatic trends (i.e. trends in precipitation characteristics and trends in streamflow). River management impacts will be assessed first through the derivation of projected streamflow using the CBRFC model forced with projections of future climate data from the WCRP CMIP3 dataset. These projections of streamflow will be used in a Reclamation planning model to assess potential impacts of climate change to reservoir operations and Reclamation's ability to meet recommended environmental flows in the San Juan River Basin. The research questions and hypothesis addressed in this dissertation are as follows:

Research Question #1 – How have changes in precipitation characteristics impacted streamflow conditions in the Colorado River Basin as climate change is occurring? Has the timing and magnitude of streamflow within the Colorado River Basin changed?

Hypothesis #1 – As the impacts of climate change is realized over the Colorado River Basin, temperatures in the region have increased while precipitation has decreased. Recent study has indicated a shift in the timing and magnitude of streamflow throughout the basin (Miller & Piechota, 2008). With increasing temperatures, the character of precipitation (i.e. snowfall as compared to rainfall) events has changed, resulting in less snowpack and earlier runoff throughout the basin.

Research Question #2 – Reclamation has traditionally used historic data to project streamflow conditions within the Colorado River Basin. However, due to climate change, past hydrologic conditions may no longer be representative of future hydrologic conditions. Can projections of future climate conditions over the Colorado River Basin be used to project future streamflow conditions over the region? How might those projections of streamflow be incorporated into Reclamation operations and planning?

Hypothesis #2 – Recently available downscaled and bias-corrected data from the WCRP CMIP3 dataset may be used to force the CBRFC River Forecasting System (RFS) currently used to provide Reclamation with forecasts of unregulated streamflow within the Colorado River Basin. These streamflow projections may then be used to force Reclamation river and reservoir management models.

Research Question #3 – What are the impacts to reservoir operations and the ability of Reclamation to meet environmental and water delivery requirements under changing climate conditions?

Hypothesis #3 – Under changing climate conditions, the timing of magnitude of streamflow into Reclamation reservoirs will change. Reclamation may need to adjust reservoir operations to be more responsive to changes in streamflow characteristics as climate change impacts are realized.

1.3 Presentation of this Research

This dissertation is presented in seven chapters. Chapter 2 presents an overview of the current state of knowledge with regards to the overall study of climate change, the Colorado River Basin, and climate change studies previously done over the Colorado River Basin. Chapter 3 presents preliminary research examining temperature, precipitation, and streamflow trends over the Colorado River Basin region and published in the Journal of Hydrometeorology. Chapter 4 examines trends in snowpack over the Western U.S. using the Kendall's tau (τ) nonparametric test for monotonic trend with a correction for ties. The correlation between changes in the character of precipitation and changes streamflow are considered within the Colorado River Basin. Chapter 5 investigates how statistically downscaled, bias corrected climate data from the WCRP CMIP3 dataset can be used to derive projections of future streamflow in Colorado River Basin headwaters using the CBRFC RFS. Projected streamflow conditions are examined for decadal changes and potential for nonstationarity with changes in climate. Chapter 6 examines the impacts to Reclamation operations within the San Juan river basin under changing climate conditions by using streamflow projections derived through the use of the WCRP CMIP3 dataset to force a Reclamation planning model. Chapter 7 will summarize the results and conclusions of this study as well as provide some guidance for future research.

CHAPTER 2

STATE OF KNOWLEDGE

2.1 Colorado River Basin

Water resources, policy, and management have become the Gordian knot of the American West (Bates & University of Colorado, 1993). This is no truer than in the Colorado River Basin (Figure 1), which spans much of the American West, providing water to seven basin states and Mexico. The Colorado River provides water to over 27 million people and irrigates over 3.5 million acres of farmland. The Colorado River Basin is divided between the supply-driven Upper Colorado River Basin and the demand-driven Lower Colorado River Basin; that is, water allocation in the Upper Colorado River Basin is dependent on available resources, whereas water is allocated based on demand in the Lower Colorado River Basin. Of the approximately 15 million acre-feet (MAF) of inflow into the Colorado River Basin, approximately 14.5 MAF is currently allocated annually. The Colorado River Basin is unique from other water management systems in that it has the capability to store approximately four times, 60 MAF, the average annual inflow; most of the storage is concentrated within the Lake Powell and Lake Mead reservoirs. Historically, inflow into the Colorado River Basin is highly variable and typically driven by snowpack in the Upper Colorado River Basin.

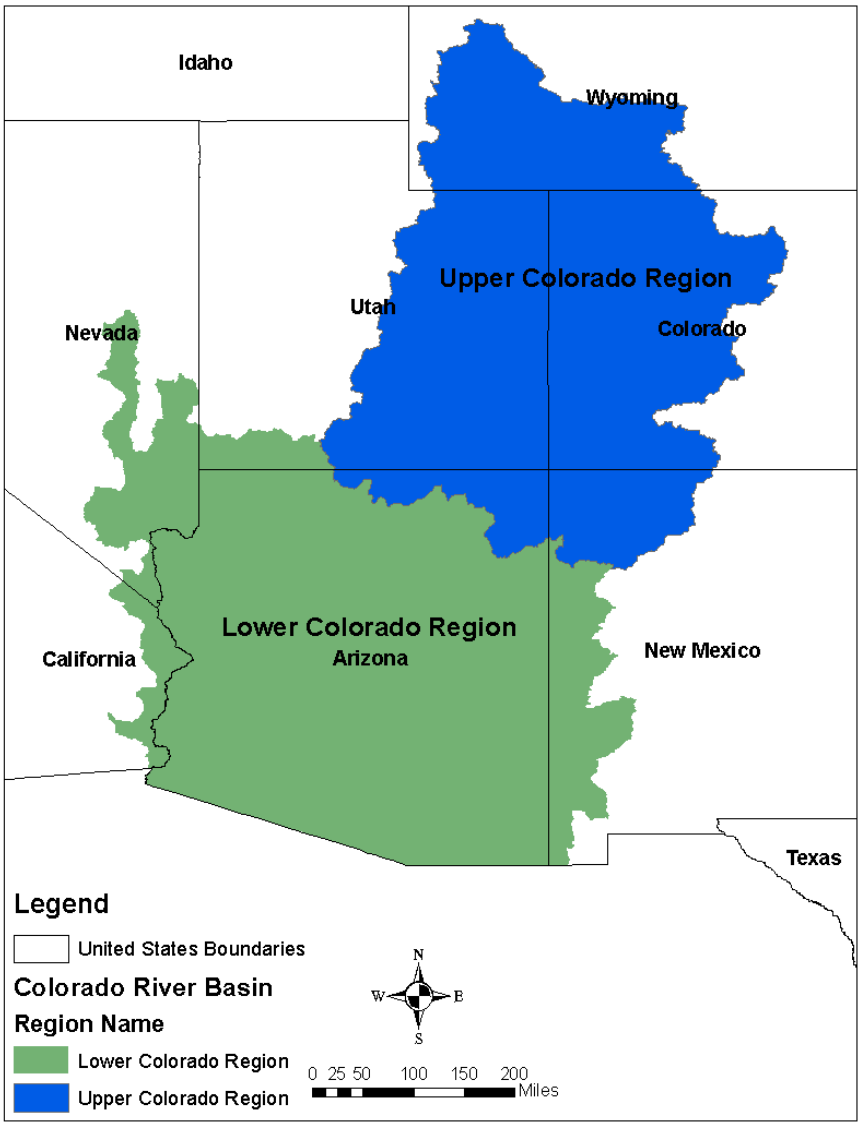

Figure 1: The Colorado River Basin is divided into the Upper and Lower Colorado Regions.

The Colorado River Basin is a tremendously legislated river and has been called the great epic in American water law and politics (Sax, 2000). Since 1922, Reclamation has managed the Colorado River based on a myriad of federal laws, compacts, court decisions, agreements, and international treaties collectively known as the "Law of River." In essence, the Law of the River defines the allocation of Colorado River Water to each of the seven basin states and Mexico, defines reservoir operations within the

basin, and, since 2007, begun to define water management operations in times of shortage. To date, there has never been a water allocation shortage declared by Reclamation for the Colorado River Basin.

2.1.1 Current Colorado River Basin Drought

Long-term paleologic streamflow records have been reconstructed using data from tree-rings within the Colorado River Basin (Meko et al., 2007; Woodhouse et al., 2006). These streamflow reconstructions may be used as indicators of drought within the Colorado River Basin and have been utilized by Reclamation in the development of reservoir management strategies. Tree-ring reconstructions have shown severe droughts in the region over the past 1200 years (e.g., Meko et al., 2007; Woodhouse et al., 2006), implying the potential for the current severe drought to continue and for future severe drought events. Tree-ring reconstructions by Meko et al. (2007) show that the Colorado River Basin has experienced long-term, severe droughts in the past; most notably, the lowest 25-year average flow was experienced between 1130 – 1154, when the basin experienced only 87% of average over the historical, observed record (1906-2004). Taking into account tree-ring reconstructions, the current drought in the Colorado River Basin is the worst since 1923. Based on research by Timilsena et al. (2007), the current drought is between the 7th and 14th worst drought in terms of magnitude and 1st to 12th worst in terms of severity (Timilsena et al., 2007).

In light of the current drought, Reclamation developed the Interim Guidelines (U.S. Department of the Interior, Bureau of Reclamation, Upper and Lower Colorado Regions, 2007), further structuring the Law of the River.

2.1.2 Colorado River Interim Guidelines

In May of 2005, the United States Secretary of the Interior initiated a public process to address declining reservoir levels in the Colorado River Basin and assuage tension between states and the Upper and Lower Colorado River Basins over the management of water resources during the drought. At this time, neither Reclamation nor the overarching Department of the Interior had defined the operation of Lake Powell and Lake Mead throughout the full range of reservoir conditions because low reservoir conditions as the result of drought and increased consumptive use in the Colorado River Basin had not occurred in the past. The goal of the Secretary of the Interior was to define a strategy for addressing shortage in the Colorado River Basin should reservoir levels continue to decrease, and also fully develop the range of operating criteria for Lakes Powell and Mead. The culmination of this work was the 2007 Interim Guidelines.

As stated previously, there has never been a water allocation shortage imposed upon the Lower Colorado River Basin; a testament to the immense amount of storage and management practices in the basin. In addition to defining a strategy regarding shortages and defining the full range of operation for Lakes Powell and Mead, the Interim Guidelines introduced new water management mechanisms to allow states and water users the opportunity to use and manage water more efficiently and with more flexibility. For example, the Interim Guidelines defined Intentionally Created Surplus (ICS). ICS water may be created by Colorado River stakeholders through projects which conserve or import water into the Colorado River system. This ICS water may then be saved in Lake Mead for future use and benefit to the basin. The Interim Guidelines also facilitate the exchange of water between states, which was very difficult and subject to political

sensitivity prior to the implementation of the guidelines. The Interim Guidelines are in place through 2026, allowing for the collection of operational data and experience. The Interim Guidelines declare a shortage in the Lower Colorado River Basin when Lake Mead's surface water elevation falls below 1075 feet; currently, Lake Mead's surface water elevation is approximately 1100 feet, and projected to be approximately 1077 feet at the end of 2010. At this first level of shortage, the Lower Colorado River Basin reduces the total water allocation by 333,000 acre-feet. This initial shortage is divided between junior priority users in Arizona and Nevada, with Arizona taking approximately 97% of the shortage.

2.1.3 Colorado River System Modeling

Reclamation's Interim Guidelines were developed using the Colorado River Simulation System (CRSS) model (U.S. Department of the Interior, Bureau of Reclamation, Lower Colorado Region, 1985; U.S. Department of the Interior, Bureau of Reclamation, Lower Colorado Region, 1992). Reclamation's CRSS model is a long-term policy model within the RiverWare framework. RiverWare is an object-oriented, rule-based simulation modeling software developed by the Center for Advanced Decision Support for Water and Environmental Systems (CADSWES) at the University of Colorado (Zagona et al., 2001). Most operational and planning models utilized by Reclamation in the Colorado River Basin are based within the RiverWare framework.

The CRSS model is rule based and operates under the legal guidelines imposed by Reclamation on the operation of reservoirs within the Colorado River System in response to current and projected water availability. Although the CRSS model was used extensively in the development of the Interim Guidelines, traditional assumptions of

water availability and streamflow were used to drive the model. These assumptions do not take into account long-term impacts of climate change or trends in hydroclimatology.

Reclamation also utilizes a mid-term deterministic model which projects monthly reservoir operations over a 2-year period commonly referred to as the "24-Month Study." The results of the 24-Month Study define the operational tier under which the Lake Powell and Lake Mead reservoirs operate. Operational tiers at Lakes Powell and Mead are set by the 24-Month Study, which takes into account current reservoir levels, current water demand, and forecasts of streamflow provided by the Colorado Basin River Forecast Center (CBRFC). Although climate change impacts are typically realized over the time period of decades, the 24-Month Study model utilizes static variables related to evapotranspiration, intervening flow, and forecasted streamflow outside of the CBRFC forecast which may be influenced by climate change.

Traditionally, Reclamation has used an index sequential method (ISM) to project future streamflow events in modeling efforts. However, methods such as ISM do not explicitly take into account changes to climate dynamics and are limited by the observed period of record. Methods such as ISM assume the past to be representative of future conditions; however, as climate change impacts are realized, past hydroclimatic conditions may not be representative of future conditions. Reclamation is actively engaged in developing and utilizing streamflow datasets conditioned on advanced statistical methods and current and projected climate conditions (J. Prairie & Callejo, 2005; J. Prairie et al., 2007).

2.1.4 Climate Change Streamflow Scenarios

The development of streamflow conditions under projections of Colorado River Basin hydroclimatology impacted by climate change may allow for the long-term evaluation of Colorado River Basin operations when input into the CRSS or another Reclamation operational model. Christensen et al. (2004) investigated the impacts to Colorado River operations under three business-as-usual (BAU) emissions scenarios and static 1995 greenhouse gas concentrations using a simplified version of CRSS, the Colorado River Reservoir Model (CRRM). Christensen et al. (2004) utilized climate signal results from the Parallel Climate Model (PCM) to force the Variable Infiltration Capacity (VIC) hydrologic model. Streamflow results from the VIC model were used to force the CRRM, and results were divided up into three time periods: 2010-2039, 2040-2069, and 2070-2098. Among other findings indicating consistently increasing average annual temperatures and decreasing precipitation and snowpack trends over the Colorado River Basin, runoff over the Colorado River Basin decreased by 10% in the control run, and decreased by 14%, 18%, and 17% over the aforementioned time periods, respectively; storage decreased by 7% in the control run, and decreased by 36%, 32%, and 40% over each respective time period (Christensen et al., 2004). Most interestingly, Christensen et al. (2004) was able to examine impacts to Colorado River operational policy through the CRRM, and found that mandated releases from the Upper Colorado River Basin to the Lower Colorado River Basin were met only 80% of the time during the control simulation, and between 59% and 75% of the time under the BAU scenarios; however, it is important to note that this study occurred before the implementation of Reclamation's most recent guidelines.

Similar results over the Sacramento-San Joaquin River Basin (L. D. Brekke et al., 2004; VanRheenen et al., 2004), Sierra Nevada region (Dettinger et al., 2004), and the Columbia River Basin (Payne et al., 2004) have been reported. Other significant efforts incorporating climate change into the management of water resources and projections in the California region have been made (J. Anderson et al., 2007; Cayan et al., 2007; Vicuna & Dracup, 2007). However, most climate change impact studies in the Colorado River Basin have focused on incorporating extensive streamflow observations from tree-ring reconstructions rather than projections of future climate.

2.2 State of the Science of Global Climate Change

Despite public perception and popular media reports to the contrary, scientific consensus regarding climate change does exist (Oreskes, 2004). While scientists and researchers may disagree with the extent of current or potential impact climate change may have on the environment and water resources and the level of uncertainty (Stainforth et al., 2005), there is unequivocal agreement that climate change exists and resultant impacts are forthcoming. The issue of climate change is a far-reaching one, and one whose scope breaches purely scientific boundaries and reaches into a realm of ethics and morals. The World Health Organization (WHO) estimates that since 2000, the annual death toll due to climate change is in excess of 150,000 people (Broome, 2008). Ultimately, addressing the issue of climate change will involve more than just the scientific community; it will involve the global community and a commitment to an unprecedented investment in humanity. In this dissertation, the focus will be on climate change impacts to the Colorado River Basin from a research-driven, scientific and

operational perspective, though it is acknowledged that sociopolitical and economic factors exist.

With the recent release of the Fourth Assessment Report by the World Meteorological Organization's Intergovernmental Panel on Climate Change (IPCC), interest in climate change and the impacts to natural resources has never been higher. The findings published by the IPCC report with very high confidence (i.e., at least a 90% chance of being correct) that regional climate change, particularly increasing temperatures, have been observed on every continent and ocean in the world; furthermore, it is likely (i.e., 66% to 90% probability) this global warming is driven by anthropogenic factors (Metz & Intergovernmental Panel on Climate Change, Working Group III, 2007; Parry & Intergovernmental Panel on Climate Change, Working Group II, 2007; Solomon & Intergovernmental Panel on Climate Change, Working Group I, 2007). A 2008 report by the United States Climate Change Science Program concurs that anthropogenically driven global warming will impact nearly every facet of America (Climate Change Science Program (U.S.) et al., 2008).

Stainforth et al. (2005) utilized the Met Office Unified Model, a global circulation model (GCM) consisting of the HadAM3 atmospheric model coupled with a mixed-layer ocean to produce 2017 unique simulations, each contributing to an ensemble of climate change scenarios. In climate change studies, ensembles are essential to capture the large degree of variability in weather characteristics and physical representation of Earth's processes (Karl & Trenberth, 2003). Each simulation is a unique set of six parameter perturbations considered plausible by climate change experts; model simulations consist of a 15-year calibration phase, a 15-year control phase, and a 15-year phase subjected to

doubled levels of atmospheric CO_2. Global mean temperatures of the simulations ranged between 49°C and 72°C, with most simulations approximately equal to 61°C (Stainforth et al., 2005). These results suggest that while the atmosphere is warming, the degree to which it is warming is uncertain. As such, the range of impacts of climate change is of primary interest to resource managers.

While uncertainty exists as to the extent of natural climate variability and human-induced climatic change (Stainforth et al., 2005), there is no doubt that the current pattern of climate disruption is due to the influence and effects of anthropogenically driven greenhouse gas emissions. The recent IPCC Fourth Assessment Report finds that the observed increase in global average temperatures is very likely (i.e. 90% to 99% probability) and is due to an increase in anthropogenic greenhouse gas concentrations (Metz & Intergovernmental Panel on Climate Change, Working Group III, 2007; Parry & Intergovernmental Panel on Climate Change, Working Group II, 2007; Solomon & Intergovernmental Panel on Climate Change, Working Group I, 2007). The IPCC forecasts a 0.2 °C average global warming over the next two decades, which agrees with most climate projection models forecasts of a 1 °C to 2 °C average global warming over the next 20 – 60 years (L. D. Brekke et al., 2008).Climate change studies illustrate how human activities have changed the composition of the Earth's atmosphere, and have been the most dominant and detectable factor over the past 50 years (Karl & Trenberth, 2003).

2.2.1 Climate Change Impacts to Global Water Resources

Climate change will have an impact on global hydrology as well as the availability and distribution of water resources. Milly et al. (2005) analyzed the output from 12 GCMs and 165 basins with at least 28 years of well defined hydroclimatic data

worldwide. Of the ensembles in the Milly et al. (2005) study, there is consistent agreement of a 10% to 40% increase in runoff by 2050 in the high latitudes of North America, Europe, and Asia, as well as the La Plata Basin in South America and the eastern portions of Africa and Pacific Ocean islands. Decreases in runoff (10% to 30% by 2050) are observed in model output in the Middle East, southern Europe and Africa, and in the western United States. Regional and global changes in runoff and other hydroclimatic factors is echoed by Huntington (2006), whose study describes changes in the distribution and character of streamflow and precipitation as "hydrologic intensification." This intensification is reflected in higher global precipitation intensity and earlier seasonal peak streamflow magnitude. This is apparent in mountainous regions, where temperature changes have altered the timing of snowmelt runoff events and associated flooding events (Zierl & Bugmann, 2005). The frequency and intensity of rainfall events are a result of rising temperatures decreasing snowfall propensity and altering precipitation dynamics (e.g., Chiew et al., 1998; Chiew, 2006). These changes in streamflow timing and magnitude are of particular interest to water resource managers.

2.2.2 Climate Change Impacts and Drought in the United States

Chiew and McMahon (2002) investigated the correlation of teleconnection data with streamflow in 581 hydrologic catchments worldwide. Although the degree of correlation between streamflow and the ENSO climate indices varied spatially, results from the study suggest that the ability to project streamflow worldwide based on hydroclimatic variables exists. With changes in global and regional hydrology, anomalous extreme climate events, such as drought, are of concern to those affected by climate change.

The frequency and severity of climatic extremes (i.e., dry and wet conditions such as droughts and floods) have been impacted by global climate change, particularly in the southwestern United States, which is currently experiencing one of the worst droughts in history. The United States has experienced increasing temperature trends since at least 1950, particularly in the western region (e.g., Andreadis & Lettenmaier, 2006; Easterling et al., 2007; Hamlet et al., 2005; Mauget, 2003; McCabe & Wolock, 2002; Mote, 2003; Nash & Gleick, 1991; Rood et al., 2005; Stewart et al., 2005). As a result of rising temperature trends associated with climate disruption, changes in dry periods correlate with changes in streamflow and precipitation distributions, affecting the availability and management of water resources.

Easterling et al. (2007) examined the effects of temperature and precipitation trends on water availability in the United States through analysis of 4000 Cooperative Observer Network (COOP) gages made available through the National Climatic Data Center (NCDC). Through use of the COOP, Easterling et al. (2007)was able to generate monthly precipitation, temperature, and Palmer Drought Severity Index (PDSI) values for each of the 344 climate divisions in the United States. Annual total precipitation over the United States increased 0.48 in/decade between 1950 and 2006 which is consistent with other studies (Groisman et al., 2001; Huntington, 2006); temperature increased linearly 32 ^{o}F/decade over the same time frame. Although Easterling et al. (2007) saw a slight decrease in dry areas over the contiguous United States, regional results varied. The Northwest and West North Central areas of the United States indicated a higher drought frequency, while the West and Southwest showed a tendency to remain in a perpetual drought, interrupted only periodically by short wet periods. It is only due to increasing

trends in precipitation that drought circumstances in the contiguous United States has been somewhat mitigated.

Andreadis and Lettenmaier (2006) used NCDC data to force the VIC model to simulate soil moisture and runoff conditions over the contiguous United States. Modeled results from VIC simulations presented by Andreadis and Lettenmaier (2006) agree with observed trends presented in Easterling et al. (2007). Using the Mann-Kendall statistical test for time series of soil moisture and streamflow, Andreadis and Lettenmaier (2006) showed increasing soil moisture trends over 43.6% (2.9% decreasing) of the United States at the 95% confidence interval; similarly, streamflow increased over 28.1% (2.3% decreased) of the domain. Despite overall increasing trends in soil moisture and streamflow, severely dry, persistent conditions increased over the West and Southwest portion of the United States.

2.2.3 Regional Climate Change Impacts to Drought in the Western U.S. and Colorado River Basin

Anthropogenic forcing due to increased greenhouse gas emissions and changes in land cover characteristics have contributed to hydroclimatic variability (Karl & Trenberth, 2003; Meehl et al., 2004; Metz & Intergovernmental Panel on Climate Change, Working Group III, 2007; Parry & Intergovernmental Panel on Climate Change, Working Group II, 2007). As a result, the effects of climate change on hydroclimatic variability have become of particular interest to water resource managers as changes to temperature, precipitation, and streamflow characteristics can have far-reaching environmental and socioeconomic consequences. Studies have begun to indicate changes on a global and regional scale to the distribution and magnitude of precipitation and

streamflow characteristics under increasing global air temperature (e.g., Hamlet et al., 2005; Huntington, 2006; Milly et al., 2005; Pagano & Garen, 2005; Stewart et al., 2005). The western United States and the Colorado River Basin are an area of interest due to the availability and distribution of water resources which are dependent on the hydroclimatic characteristics of the region, combined with the rapid growth of population and commerce in the west.

The American southwest and Colorado River Basin has experienced, and is projected to experience, continued drought and arid climate conditions (e.g., Balling Jr. & Goodrich, 2007; Seager et al., 2007). Piechota et al. (2004) examined 81 years (1923 – 2004) of streamflow data located in the Upper Colorado River Basin from the United States Geological Survey (USGS) and Palmer Hydrological Drought Index (PHDI) values from the NCDC. Over this time frame, eleven droughts were observed at the Colorado River near Cisco, Utah and Green River, near Green River, Utah gages. When compared with tree-ring reconstructions of streamflow, the drought spanning 1999 – 2004 ranked the seventh worse in the last 500 years.

As previously mentioned, Timilsena et al. (2007) describes the current drought in the Colorado River Basin as the worst on the observed record and among the most severe over the past 500 years. As a result of this dramatic drought, increased emphasis on the study of drought and water availability in the Western United States and the Colorado River Basin has been the subject of current and recent study (e.g., Andreadis & Lettenmaier, 2006; Barnett & Pierce, 2008; Christensen et al., 2004; Christensen & Lettenmaier, 2007; Clark et al., 2001; Easterling et al., 2007; Gleick & Chalecki, 1999; Meko et al., 2007; Milly et al., 2005; Mote, 2006; Timilsena et al., 2007; Timilsena &

Piechota, 2008; U.S. Department of the Interior, Bureau of Reclamation, Upper and Lower Colorado Regions, 2007).

Droughts have been linked with changes in global teleconnection patterns (i.e., sea surface temperature profiles and correlations to hydroclimatic variables), which have proved useful in climate and streamflow prediction studies (e.g., Chiew et al., 1998; Hamlet & Lettenmaier, 1999; McCabe & Dettinger, 2002; T. C. Piechota et al., 1998; Thomas, 2007; G. A. Tootle & Piechota, 2004; Wood et al., 2002). Of the climate teleconnections, the ENSO is perhaps the most well known and most associated with climate events in the American west. Piechota and Dracup (1996) analyzed 41 years of Palmer Drought Severity Index (PDSI) values over all 344 NCDC climate divisions in the continental United States. Four regions were identified as areas where a high coherence (greater than 0.80) between the PDSI and ENSO anomalies, the largest occurring in the Pacific Northwest. The study indicated a strong relationship between drought and the ENSO, noting that the three largest droughts experienced by the Pacific Northwest between 1900 and 1993 occurred the year following an ENSO event. The study enforced research noting correlation between then ENSO and temperature and precipitation observations (T. C. Piechota et al., 1997) and streamflow data (Kahya & Dracup, 1993). Piechota and Dracup (1996) also show a correlation between the Southern Oscillation Index (SOI) and streamflow in the areas of Washington and Texas.

Piechota et al. (1997) later investigated spatial and temporal variability of western U.S. streamflow using Principal Component Analysis (PCA). Through PCA, regionalization of streamflow stations was accomplished and linked to ENSO anomalies; it was determined that the character of the ENSO anomaly with regards to pressure and

circulation pattern impacted regional streamflow observations. Thus, with adequate information regarding the nature of the ENSO anomaly, streamflow projections based on teleconnection information is possible.

As with most forecasting methodologies, increased understanding and information regarding the correlation and relationship between variables is advantageous. Additional incorporation of other teleconnection indices and hydroclimatic variables has been addressed in recent research. Chiew et al. (Chiew et al., 1998) found a statistically significant correlation between rainfall and streamflow observations against SOI and equatorial Pacific sea surface temperatures (SSTs) in Australia. Correlations between teleconnection and hydroclimatic variables and indices was found to be spatially and temporally variable; for instance, the lag correlation between average monthly rainfall and average monthly SOI between August and November was 0.45, whereas the lag correlation improved to 0.55 over June and July. ENSO events were associated with dry conditions throughout Australia, though the impacts of an El Niño event were more immediately felt in the western portion of Australia; impacts to the east were more delayed until the middle of the year.

2.2.4 Regional Climate Change Impacts to Hydroclimatology in the Western U.S. and Colorado River Basin

Piechota et al. (1998) developed a probabilistic streamflow forecast model utilizing ENSO indicators to forecast streamflow at 10 eastern Australian gaging stations. Using this model, streamflow forecasts by Piechota et al. (1998)were regularly more accurate than traditional forecasts based solely on climate data and indicated a link between ENSO anomalies and streamflow. Hamlet and Lettenmaier (1999) performed a similar analysis

over the Columbia River Basin, forecasting streamflow using different phases of ENSO and PDO and were able to increase the lead time on forecasts by about 6 months over traditional forecasts. Statistically significant oscillations in streamflow data have been seen worldwide (Chiew et al., 2005).

Recent studies have utilized teleconnection information in conjunction with hydroclimatic variables to project streamflow. Clark et al. (2001) utilized snow water equivalent (SWE) data from snow course data provided by the National Resource Conservation Service (NRCS) and streamflow from the USGS Hydro-Climatic Data Network (HCDN) and found correlation between SWE observations and ENSO events. Results of the study show a seasonal dependence of SWE observations and ENSO anomalies in both the Columbia and Colorado River Basins. SWE and streamflow mean values are typically indicative of drier (wetter) conditions in the northern portion of the Colorado River Basin and typically indicative of wetter (drier) conditions in the southwest during El Niño (La Niña) conditions. If accurate forecasts of ENSO conditions are available by autumn, Clark et al. (2001) notes that an accurate forecast of SWE and streamflow conditions in the Colorado River Basin may be attained. However, McCabe and Dettinger (2002) studied the correlation between April 1 snowpack data and ENSO and PDO indices. Using PCA, McCabe and Dettinger (2002)noted that the first two principal components explained 61% of the variability in April 1 snowpack observations; the first component explained 45% of the variability and was highly correlated with the PDO. Correlation coefficients between April 1 snowpack and winter PDO in the Pacific Northwest were as high as -0.67 and as high as -0.55 in the summer and fall. As such, PDO attributes are a better tool for projecting snowpack conditions than ENSO attributes.

Long-range projections of streamflow based on teleconnection data have been studied over the entire United States. Wood et al. (2002) disaggregated monthly climate projections provided by the National Centers for Environmental Prediction/Climate Prediction Center Global Spectral Model into daily data to force the VIC hydrologic model implemented over the eastern United States in an effort to project streamflow conditions. Wood et al. (2002) found that while model performance varied spatially and temporally, results were qualitatively reasonable. Hindcast analysis indicated that model results were highly dependent on input data, and during El Niño events, VIC output reflected higher streamflow and soil moisture values over eastern basins. Although Wood et al. (2002) did not quantify the skill associated with model results, the study did provide a framework over which projected climate data could be used to force a hydrologic model to determine impacts over a region.

Tootle and Piechota (2004) were able to develop a streamflow forecasting methodology over the Suwannee River in the southeastern United States and quantify model performance using the Linear Error in Probability Space (LEPS) measure (T. C. Piechota et al., 2001). Streamflow was modeled using the best (i.e. highest linear correlation with streamflow) three climate predictors from a dataset that included the Multivariate ENSO Index (MEI), PDO, and twelve sea surface temperature datasets. Summer streamflow forecasts LEPS measures ranged between 15.0% and 31.8%, indicative of good skill. Additional studies have shown PDO and SOI characteristics (Stewart et al., 2005), and coupled teleconnection effects (G. A. Tootle et al., 2005; G. A. Tootle & Piechota, 2006) to have a significant impact on streamflow projections. Recent studies (e.g., Hamlet et al., 2007; McCabe et al., 2007; Thomas, 2007) have investigated

correlations between streamflow and teleconnection data under changing precipitation and temperature parameters to assess the impacts of climate change on streamflow.

Research efforts have examined teleconnection information in an effort to forecast snowpack characteristics which may impact streamflow. Hunter et al. (2006) found significant (90% confidence level) correlation between coupled teleconnection signals and April 1 SWE measurements from NRCS snowpack telemetry (SNOTEL) sites in the Western United States. Despite a relatively short period of record, Hunter et al. (2006) was able to identify predictive SWE information from variability in teleconnection events. McCabe et al. (2007) identified a correlation between the spatial variability of rain-on-snow events and ENSO events that could improve risk assessments and forecasts associated with floods.

2.2.5 Regional Climate Modeling in the Western U.S. and Colorado River Basin

The IPCC Fourth Assessment Report based projections of future global and regional climate on the results of an ensemble of results obtained from GCMs. The WCRP organized the assimilation and analysis of results from 23 GCMs from 17 modeling groups. Of these 23 GCMs, 16 were subjected to statistical downscaling as part of the CMIP3.

Table 1 is adapted from Maurer et al. (2007) and presents the 16 GCMs from which results driven by statistically downscaled climate data are available.

Table 1: GCMs utilized in the IPCC Fourth Assessment Report.

Modeling Group, Country	WCRP CMIP3 I.D.	Primary Reference
Bjerknes Centre for Climate Research	BCCR-BCM2.0	(Furevik et al., 2003)
Canadian Centre for Climate Modeling and Analysis	CGCM3.1(T47)	(Flato & Boer, 2001)
Meteo-France / Centre National de Recherches Meteorologiques, France	CNRM-CM3	(Salas-Melia et al., 2005)
CSIRO Atmospheric Research, Australia	CSIRO-Mk3.0	(H. B. Gordon et al., 2002)
US Dept. of Commerce / NOAA / Geophysical Fluid Dynamics Laboratory, USA	GFDL-CM2.0	(Delworth et al., 2006)
US Dept. of Commerce / NOAA / Geophysical Fluid Dynamics Laboratory, USA	GFDL-CM2.1	(Delworth et al., 2006)
NASA / Goddard Institute for Space Studies, USA	GISS-ER	(Russell et al., 2000)
Institute for Numerical Mathematics, Russia	INM-CM3.0	(Diansky & Volodin, 2002)
Institut Pierre Simon Laplace, France	IPSL-CM4	(O et al., 2005)
Center for Climate System Research (The University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change (JAMSTEC), Japan	MIROC3.2 (medres)	(K-1 Model Developers, 2004)
Meteorological Institute of the University of Bonn, Meteorological Research Institute of KMA	ECHO-G	(Voss & Legutke, 1999)
Max Planck Institute for Meteorology, Germany	ECHAM5 / MPI-OM	(Jungclaus et al., 2006)
Meteorological Research Institute, Japan	MRI-CGCM2.3.2	(Yukimoto et al., 2001)
National Center for Atmospheric Research, USA	CCSM3	(Collins et al., 2006)
National Center for Atmospheric Research, USA	PCM	(Washington et al., 2000)
Hadley Centre for Climate Prediction and Research / Met Office, UK	UKMO-HadCM3	(C. Gordon et al., 2000)

2.2.6 Statistical Downscaling and Bias-Correction of Climate Projections from GCMs

GCMs examine the interaction between the Earth land surface and atmosphere using physically based equations that are complex and computationally intensive. As a result of limited computer processing power, GCMs are typically run at spatial scales that are large to examine climate impacts at the global scale over long periods of time. For example, the distributed GCMs utilized in the IPCC Fourth Assessment Report were run at a grid scale of approximately 15000 square miles to the year 2099. Hydrologic studies are typically developed over regional, basin scales, so there exists a disconnect between the spatial scale of the output from GCMs and their usability in hydrologic studies. Furthermore, GCMs do not capture details important to regional hydrologic studies such as local climate circulation or the orographic character of the basin (e.g., Metz & Intergovernmental Panel on Climate Change, Working Group III, 2007; Wigley, 2004). Downscaling is the process of producing regional scale information from larger-scaled output from GCMs so that information from global GCMs can be applied to regional hydrologic studies (e.g., Wigley, 2004).

Downscaling is typically accomplished through two methods; dynamical and statistical. Dynamical downscaling utilizes boundary conditions from larger scale GCMs and a high-resolution regional climate model to derive climate information at the regional scale. Regional climate models utilize comparable physical equations to describe the Earth's processes as in the larger scale GCMs, though over a much smaller spatial and temporal range that a GCM. This allows for a regional climate model to capture local or regional impacts to climate variables; however, like GCMs, regional climate models incur a high computational cost. When projecting future climates, regional climate

models may operate outside of the range for which they were designed (Solomon & Intergovernmental Panel on Climate Change, Working Group I, 2007).

Statistical downscaling utilized observed data at the desired level of resolution to derive relationships between high resolution output from GCMs and the regional climate scale of interest. Although computationally inexpensive, statistical downscaling does require a sufficiently long record of observational data to develop satisfactory cross scale relationships; most statistical downscaling methods also assume some measure of stationarity over the climate record. Under changing climate conditions, the assumption of stationarity may not be valid (e.g., Koutsoyiannis et al., 2007; Matter et al., 2010; Milly et al., 2008; Thomas, 2007). However, in addition to being computational inexpensive, statistical downscaling methods are able to develop higher scales of resolution of climate data over a longer period of time than most regional climate models. When properly applied, the level of uncertainty and the quality of downscaled data derived using dynamical and statistical methods is comparable (e.g., Parry & Intergovernmental Panel on Climate Change, Working Group II, 2007; Solomon & Intergovernmental Panel on Climate Change, Working Group I, 2007; Wigley, 2004; Wood et al., 2004). In this research, statistically downscaled data derived using the bias-corrected and spatial disaggregation (BCSD) method developed by Wood et al. (2004) is used. The method is documented in numerous peer-reviewed academic studies (Cayan et al., 2007; Christensen et al., 2004; Hayhoe et al., 2004; Hayhoe et al., 2007; Maurer & Duffy, 2005; Maurer, 2007; Payne et al., 2004; VanRheenen et al., 2004; Wood et al., 2004) and produces downscaled temperature and precipitation data that statistically matches the historical period.

The BCSD technique developed by Wood et al. (2004) is unique from other statistical downscaling methods in that the method is able to simultaneously produce gridded time series of precipitation and temperature data; most statistical downscaling methods are limited to a single variable, with some exceptions (Harpham & Wilby, 2005; e.g., Wilks, 1999). For regional hydroclimatic studies, it is important that the variables of interest (precipitation and temperature) are developed simultaneously to develop realistic spatial and temporal climate relationships. It is important to note that any biases over the historical period within the climate data that are a result of the GCM itself will be projected into the future, but the BCSD method compares very well with other statistical downscaling methods (Wood et al., 2004).

2.2.7 Reclamation Streamflow Projections under Changing Climate Conditions

Current Reclamation modeling efforts assume that hydrologic conditions over the Colorado River Basin have remained static; that is, historical streamflow is representative of future streamflow conditions and adequately capture the mean and variability of inflow to the system (L. D. Brekke et al., 2008). Streamflow projections have been based on reconstructions of annual flow events from tree-rings over increasingly longer time scales and have revealed a more variable streamflow record and an area susceptible to prolonged drought events (Meko et al., 2007; Woodhouse et al., 2006). Furthermore, studies have applied stochastic methods to annual streamflow reconstructions to spatially and temporally disaggregate flows such that they are suitable for input into Reclamation models (J. R. Prairie & Rajagopalan, 2007). Currently, little research has investigated the development of streamflow projections under changing climate conditions; this is perhaps due to uncertainty regarding future greenhouse gas emissions and their associated impact

to climate change in the region, as well as uncertainty involved in the solution of physics within various GCMs.

CHAPTER 3

PRELIMINARY RESEARCH: MILLER AND PIECHOTA, 2009

3.1 Introduction to Preliminary Research

GCMs are used for assessment of climate change and climatic variability over the Colorado River Basin. The IPCC recently reported mean global air temperature raising an average 0.2 ^{o}C per decade; historically, increasing trends in mean global air temperature are associated with decreasing trends in mean annual snowpack in the Northern Hemisphere (Metz & Intergovernmental Panel on Climate Change, Working Group III, 2007; Parry & Intergovernmental Panel on Climate Change, Working Group II, 2007; Solomon & Intergovernmental Panel on Climate Change, Working Group I, 2007). Although not addressed explicitly in this study, snowpack is the considered to be the dominant hydrologic determinant within the Colorado River Basin, making up 63% of the annual precipitation in the Upper Colorado River Basin and 39% of the annual precipitation in the Lower Colorado River Basin (Serreze et al., 1999). The distinction between precipitation as rainfall or snowfall events is important, as the frequency of these events relative to each other often corresponds to changes seen in temperature and streamflow trends.

The impact of snowpack to streamflow have been previously studied (Fassnacht, 2006; e.g Groisman et al., 2001) and researchers have used GCMs and the VIC model to quantify trends related to snowpack and dependent streamflow in the Colorado River Basin (e.g Hamlet et al., 2005). Trends in precipitation as snowfall and rainfall, temperature, and streamflow studied at the basin scale are useful for water managers and those studying inflow forecasts; however, trends at more local and regional scales are

desired to better manage and allocate water resources, particularly in the Colorado River Basin.

In this study, published in the Journal of Hydrometeorology (Miller & Piechota, 2008), statistical analysis over the 29 climate divisions covering the entire Colorado River Basin is performed in an effort to quantify the likelihood of trends in precipitation, temperature, and streamflow. An effort to distinguish between linear and step trends in monthly data is also made using a variety of parametric and non-parametric statistics. The main contribution of this preliminary research is the identification of spatial and temporal nature of trends observed over each climatic parameter and a comprehensive analysis that looks at interdependency between each variable.

3.2 Data Utilized in Preliminary Research

Data in this study were obtained from several different government agencies and included monthly data spanning from 1951 through 2005. Climate divisions incorporated in this study are defined by the NCDC based on geographical and political boundaries (Figure 2). For the purposes of this study, climate divisions use a four digit identification, where the first two numbers are associated with a particular state, and the second two numbers identify a particular climate division within the state. For instance, the climate division identification number 0502 corresponds to the state of Colorado (05) and the second climate division (02).

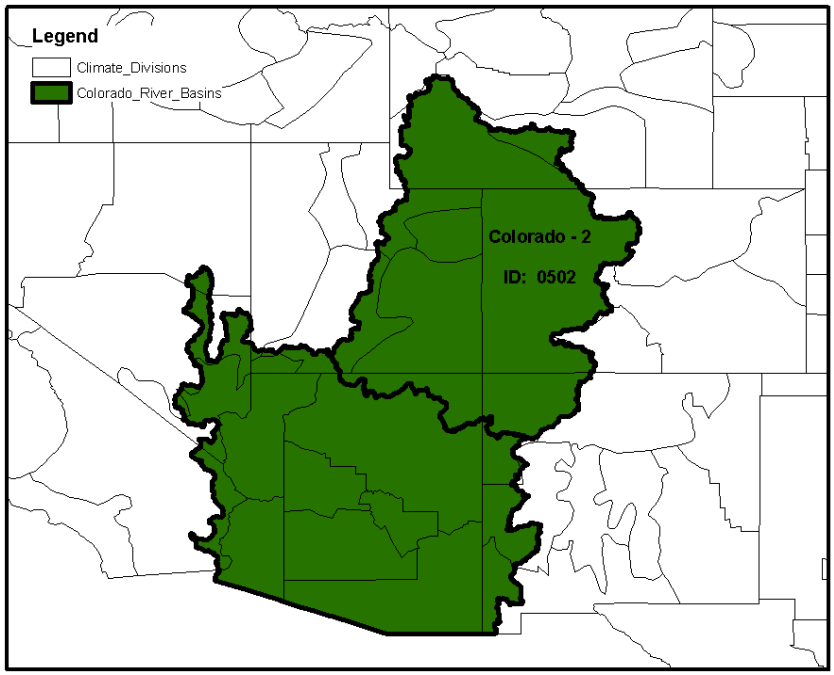

Figure 2: The Colorado River Basin, represented by the shaded area, is intersected by 29 climate divisions. In this figure, climate divisions are defined by thin lines which are both geographic and political in character; thus, state boundaries are also climate division boundaries. Climate Divisions are referenced by their state, a sequential numerical value assigned to states alphabetically (e.g. Alabama = 01), and an identifying value. In this figure Colorado-2 is identified as 0502.

Monthly average precipitation data used in this study were obtained from the NCDC and represents all reporting stations within a climate division recording temperature and precipitation data (National Climate Data Center, 1994). When NCDC developed the climate division data, equal weights were given to each recording station and reported in inches. Similarly, monthly average temperature data over each climate division were collected from the NCDC. Temperature data were bias-corrected by the NCDC for differences in spatial and temporal characteristics between each gage using a method described by Karl et al. (1986). The NCDC reports that temperature bias errors at each station were small and less than 0.3 ^{o}F (National Climate Data Center, 1994).

Climate division data are available over the 48 contiguous states since 1895, though the divisional boundaries and data derivation have been subjected to change and revision

since inception. The latest significant changes occurred in the late 1960's. The average precipitation and temperature data over each division is derived by taking an average of reporting NCDC Cooperative (COOP) Stations within the division. The number and distribution of COOP Stations has changed over time and may not be representative of topographical impacts to climate within a division. While this may be considered a limitation in the dataset, the data corresponds well to large-scale historical climate anomalies such as droughts both spatially and temporally (Guttman & Quayle, 1996).

Streamflow data used in this study consist of natural flow data calculated and distributed by Reclamation using information from USGS stream gaging locations, reservoir operations, and depletion histories of Colorado River water users (J. Prairie & Callejo, 2005). The Colorado River from the Green River below the Fontenelle Reservoir in Wyoming to Imperial Dam at the southern international boundary between Arizona and Mexico is divided into distinct reaches bounded by USGS stream gage locations. Natural flow in the Upper and Lower Colorado River Basins has been derived using historical data where natural flow is defined as the sum of historical flow observed at a particular USGS gage station included in this study and total flow depletion over the reach above the gaging station. This flow is then adjusted to subtract or add additional flow subjected to reservoir regulation. As detailed by (2005), natural flow is defined as:

$$Natural\ Flow = Historic\ Flow + Total\ Depletion \pm Reservoir\ Regulation \quad (1)$$

The period of natural flow records provided by Reclamation spans water years between 1906 and 2005 and was recently used in the development of shortage criteria governing reservoir operations in the Lower Colorado River Basin during times of low

storage (U.S. Department of the Interior, Bureau of Reclamation, Upper and Lower Colorado Regions, 2007).

Prior to 1971, consistent and complete records for many of the 29 USGS flow stations used in this study did not exist. In summary, the historical monthly record was extended by first using robust statistical methods (e.g., K-Nearest Neighbor Bootstrapping) to derive cumulative annual streamflow values in the Colorado River Basin. Through multiple linear regression and statistical analysis of the error term, these annual flows were temporally disaggregated to the monthly timescale. The extended streamflow record and historical record have similar statistical properties (Lee & Salas, 2006, In review; Salas et al., 2005).

A Microsoft Excel application customized through the Visual Basic programming language based on the functionality of TREND software originally developed by (2005) was used in the analysis.

3.2 Methodology

Monthly time series for each dataset over each climate division were subjected to statistical analysis using a variety of methods in an effort to detect trends in temperature and precipitation between 1951 and 2005 and trends in streamflow between 1906 and 2005. Each climate division was evaluated independently for trends in temperature and precipitation data. Trends in streamflow data were based on locations along the Colorado River. Kalra et al. (2008), utilized three statistical tests to evaluate linear trends and two statistical tests to evaluate step changes at USGS streamflow gage stations over the conterminous United States and SNOTEL stations in the western United States. In this study, those same statistical tests were used to evaluate linear trends and step changes in

monthly time series observed over climate divisions and gage locations in the Colorado River Basin. These tests are explained thoroughly in Chiew and Siriwardena (2005).

The Mann-Kendall test is a non-parametric test in which the rank of data values within a time series are compared. A test statistic, *S*, is derived through:

$$S = \sum_{i=1}^{n-1}\left[\sum_{j=i+1}^{n}\mathrm{sgn}\left(R_j - R_i\right)\right] \tag{2}$$

where *R* is the rank of value *x* within a time series *X*, *n* is the number of values within the time series, and sgn(*x*) = 1 for $x > 0$, sgn(*x*) = 0 for $x = 0$, and sgn(*x*) = -1 for $x < 0$. The z-statistic, *z*, from which significance levels can be derived from a normal probability table is:

$$z = |S| / \sigma^{0.5} \tag{3}$$

where

$$\sigma = n(n-1)(2n+5)/18 \tag{4}$$

Spearman's ρ Test is similar to the Mann-Kendall test in that it is a non-parametric, rank-based test for trends within a time series. However, unlike the Mann-Kendall test, the Spearman's ρ Test describes correlation of the data with time, as opposed to other values within the time series. The z-statistic, ρ_s, is described by:

$$\rho_s = S_{xy} / \left(S_x S_y\right)^{0.5} \tag{5}$$

where

$$S_x = \sum_{i=1}^{n}\left(x_i - \overline{X}\right)^2 \tag{6}$$

$$S_y = \sum_{i=1}^{n}\left(y_i - \overline{Y}\right)^2 \tag{7}$$

$$S_{xy} = \sum_{i=1}^{n} \left(x_i - \overline{X}\right)\left(y_i - \overline{Y}\right) \tag{8}$$

Like the Mann-Kendall test, ρ_s can be compared to a normal probability table to derive levels of significance.

A parametric, linear regression statistical test is also used in this study. A test statistic, *S*, is derived through:

$$S = b/\sigma \tag{9}$$

where *b* is defined as:

$$b = \frac{\sum_{i=1}^{n} \left(x_i - \overline{X}\right)\left(y_i - \overline{Y}\right)}{\sum_{i=1}^{n} \left(x_i - \overline{X}\right)^2} \tag{10}$$

and σ is defined as:

$$\sigma = \sqrt{\frac{12\sum_{i=1}^{n} \left(y_i - a - bx_i\right)^2}{n(n-2)\left(n^2 - 1\right)}} \tag{11}$$

where *a* is estimated to be:

$$a = \overline{Y} - b\overline{X} \tag{12}$$

The *S* statistic can then be compared to critical table of *t*-values, using *n*-2 degrees of freedom to derive significance levels for each dataset.

Two statistical tests were used to assess step changes within the time series data at each climate division. In step change analysis, a time series is often split and one section of data values are compared to another. In this study, 55 years of data were considered for temperature and precipitation data, while 100 years of data were considered for naturalized streamflow data. Regonda et al. (2005) present evidence that streamflow

changes are influenced by stronger trends in observational data recorded after 1974. Other studies support a step change in streamflow and snowpack observations reported after 1970 (McCabe & Wolock, 2002; Mote et al., 2005; Mote, 2006). Thus, for the purposes of step change analysis, time series data were divided into the first 24 years of data (1951-1974) and the latter 31 years of data (1975-2005) for temperature and precipitation data sets. Similarly, streamflow time series were divided into the first 69 years of data (1906 – 1974) and the latter 31 years of data (1975-2005). While this distinction is important for step change statistical analysis, it is not utilized in trend analysis.

The Rank-Sum Test is a non-parametric test comparing the medians in two different data sets; in this study, the median of earlier dataset to the median of the later dataset. Values over the entire time series are converted to ranks relative to the entire time series. S is the sum of the ranks in the smaller dataset, in this case, the first 24 years of observations for the temperature and precipitation data sets. A theoretical mean, μ, and standard deviation, σ, are defined as such:

$$\mu = n(N+1)/2 \tag{13}$$

$$\sigma = [nm(N+1)/12]^{0.5} \tag{14}$$

where *n* is the number of values in the small dataset, *m* is the number of values in the large dataset, and *N* is the total number of values in the time series. The z-statistic, Z_{rs}, is computed as:

$$Z_{rs} = (S - 0.5 - \mu) \text{ if } S > \mu \tag{15}$$

$$Z_{rs} = 0 \text{ if } S = \mu \tag{16}$$

$$Z_{rs} = (S + 0.5 - \mu) \text{ if } S < \mu \tag{17}$$

Z_{rs} can then be compared to a normal probability table to derive a level of significance.

The Student's *t* Test is a parametric statistical test comparing the means of two datasets. A test statistic, *t*, is defined as:

$$t = \left| \frac{\left(\overline{X} - \overline{Y}\right)}{S\sqrt{\frac{1}{n} + \frac{1}{m}}} \right| \tag{18}$$

where $\overline{x}$ is the mean of the first dataset and $\overline{y}$ is the mean of the second dataset. *n* and *m* are the number of observations in the first and second dataset, respectively. S is the standard deviation of all collected observations.

In this study, trends and step changes in time series were investigated at the 90%, 95%, and 99% confidence levels. Specifically, test statistics derived from the previously described statistical methods were compared to critical values expressed on standard probability tables. In an effort to prevent bias introduced by any single statistical test, a time series must show an increasing or decreasing trend at least at the 90% confidence level for all 3 linear trend tests to be recognized as exhibiting linear change. Analogously, a time series must indicate an increasing or decreasing step change at least at the 90% confidence level for both step change analytical tests to be recognized as displaying a step change.

It is important to note that the overall confidence level reported in this study is based on the all tests. The confidence levels between tests do not have to agree; rather, the lowest confidence level value is reported for each month over each climate division. For instance, in trend analysis, statistical analysis using the Mann-Kendall and Linear

Regression statistical tests may indicate an increasing trend with 95% confidence level. However, analysis performed using the Spearman's ρ statistical test may indicate an increasing trend with only a 90% confidence level for the same month over the same climate division or gage location. In this case, the parameter in question would be reported as exhibiting an increasing trend with 90% confidence level over a particular climate division.

3.4 Results and Discussion

Trend or step change results are assessed based on the confidence level calculated through use of the previously described statistical tests. While the magnitude of the change observed in the historical record is not explicitly calculated in this study, the confidence level is a quantitative measure of the confidence that there is really a trend in a particular variable. The test statistic typically increases, along with the confidence level, with greater changes in magnitude seen in trend or step change analysis.

3.4.1 Temperature Results

Increase in temperature observations have consistently been shown to be increasing worldwide, and forecasts indicate this trend to continue (e.g., Christensen et al., 2004; Hamlet et al., 2005; Solomon & Intergovernmental Panel on Climate Change, Working Group I, 2007). Figure 3 illustrates monthly trends observed in climate divisions encompassing the Colorado River Basin. Increasing temperature trends were observed consistently throughout the year, often times at greater than a 95% confidence level. Notably, increasing temperature trends were observed throughout the year below Hoover Dam and in Southern Arizona and California, areas dependent on Colorado River water

to meet irrigation demands (Sax, 2000; U.S. Department of the Interior, Bureau of Reclamation, Upper and Lower Colorado Regions, 2007; D. Wang & Cai, 2007).

The Colorado River system is highly dependent on streamflow that is a result of snowmelt in the Upper Colorado Region, especially in the months of April through July (e.g., Fassnacht, 2006; Hamlet et al., 2005). Temperature trends in the Upper Colorado Basin were consistently increasing over the April through July time frame; however, it is notable that temperature trends in the months prior, January through March, were also increasing. Increasing temperatures may affect the timing of snowmelt in the region and, in turn, affect the timing of streamflow in the region (Regonda et al., 2005).

Step changes in temperature over the same region generally agreed with profiles observed with linear trend analysis (Figure 4). However, more instances of decreasing change in temperature characteristics were seen in the step change profiles, particularly in May, July, and October. All instances were at the 90% confidence level, and with the exception of July, tend to occur on the outer boundaries of the Colorado River Basin. Increasing temperature trends in March and April may correspond to earlier peak streamflow rates observed in Regonda et al. (2005).

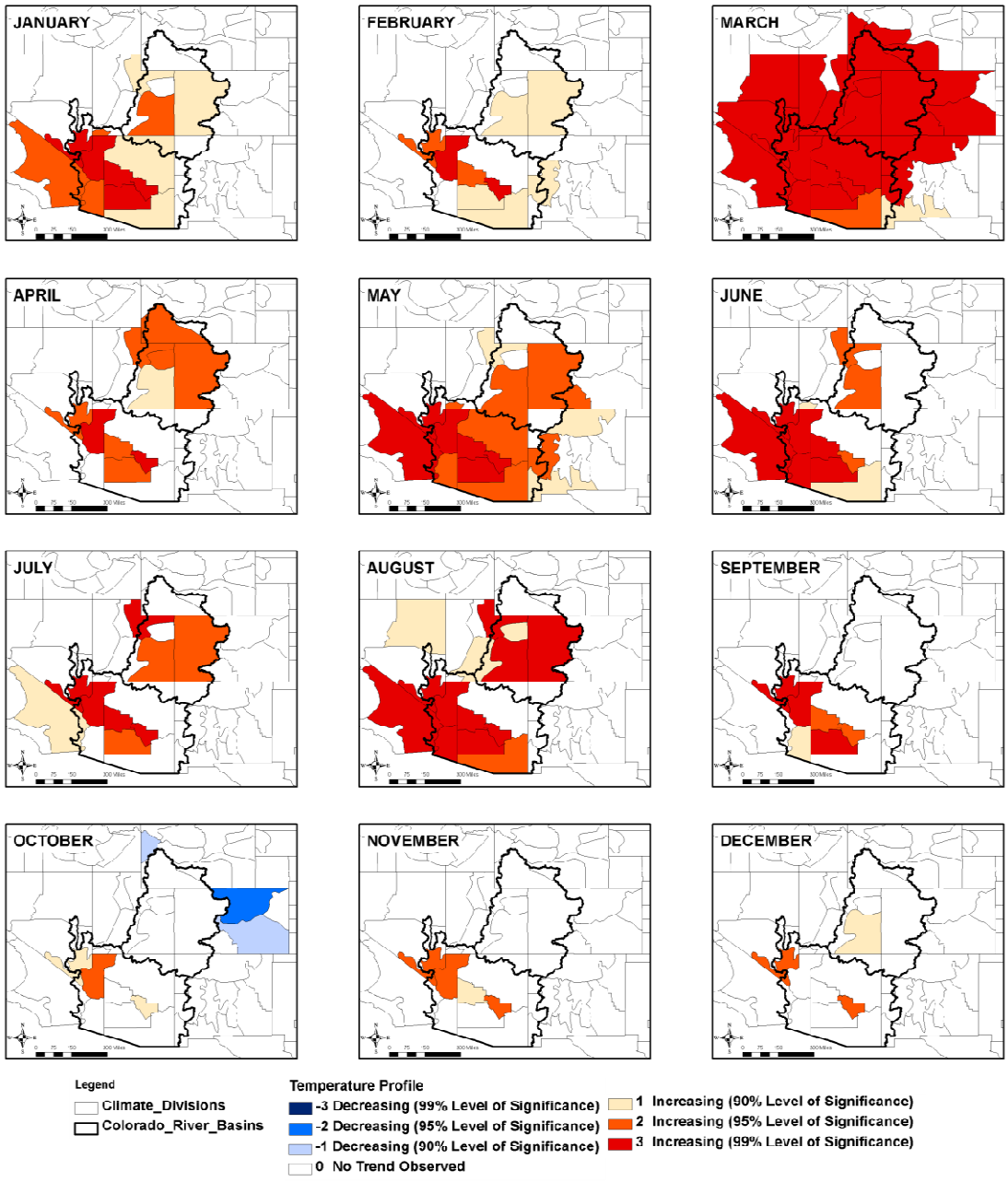

Figure 3: Trends in temperature data over each climate division intersecting the Colorado River Basin.

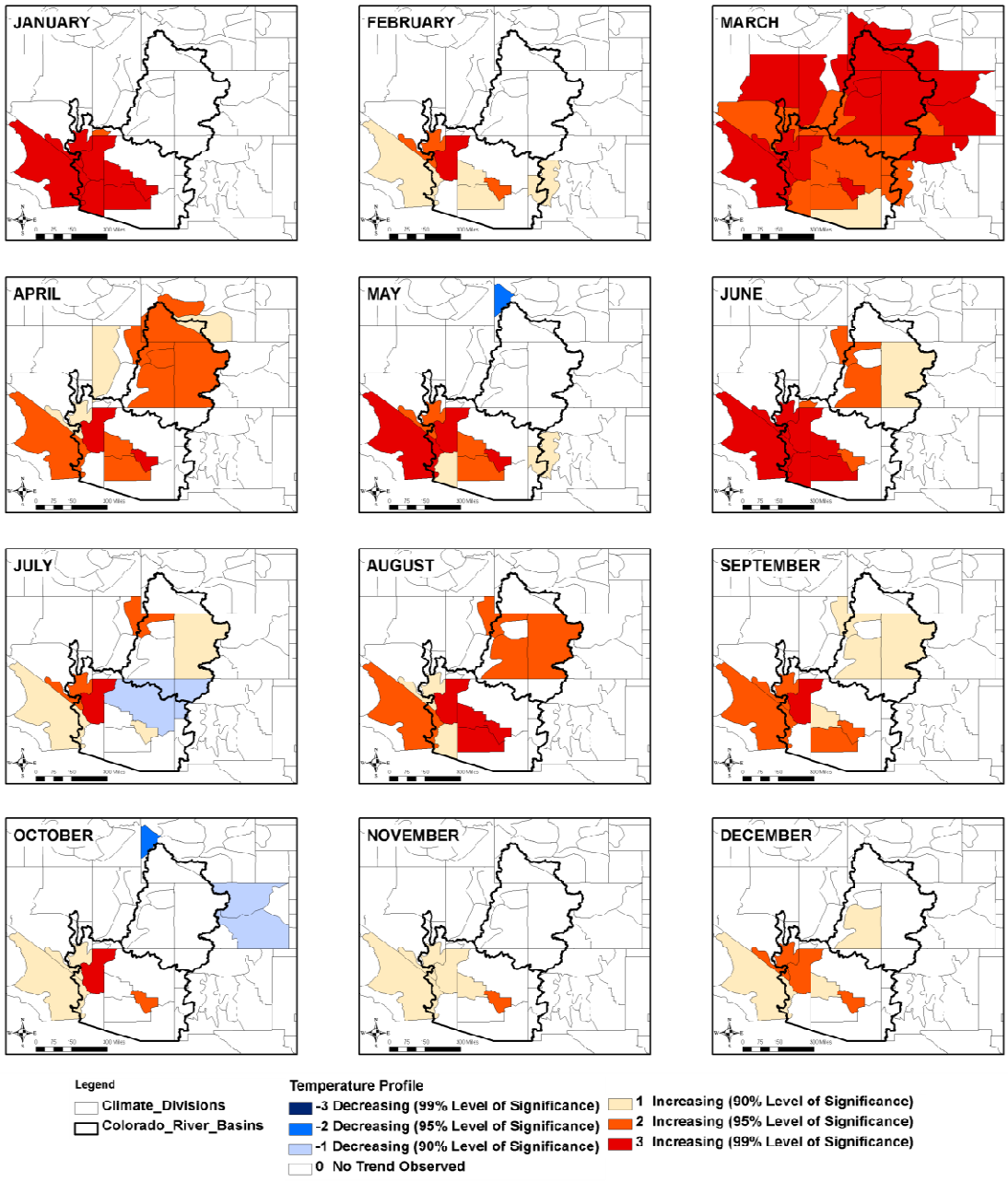

Figure 4: Step Change in temperature data over each climate division intersecting the Colorado River Basin.

3.4.2 Precipitation Results

Precipitation, and the state in which it occurs, is important in the Colorado River Basin. Precipitation in the form of snow is a benefit, particularly in the Upper Colorado River Basin, as snowfall replenishes mountain storage and is the source of snowmelt in the critical spring runoff season. Winter rainfall events in the Colorado River Basin cause concern since they do not replenish mountainous snowpack storage and can come at the expense of snowfall events (Groisman et al., 2001). Increased rainfall events naturally increase streamflow through surface runoff; when rainfall events begin to occur in place of historically observed snowfall events, streamflow rates increase and tend to peak earlier in the year. Huntington (2006) cites this global phenomenon as evidence of water cycle intensification which impedes the ability of water managers to assess water resource availability.

Figure 5 and Figure 6 depict the spatial profile of trend and step changes in precipitation in the Colorado River Basin, respectively. There were some increases in precipitation in the late fall and winter months or the beginning of the water year. Interestingly, the month of December indicates decreasing trends in the northwest, mountainous portion of the Upper Colorado River Basin. Precipitation generally remained relatively unchanged during the April through July peak runoff season.

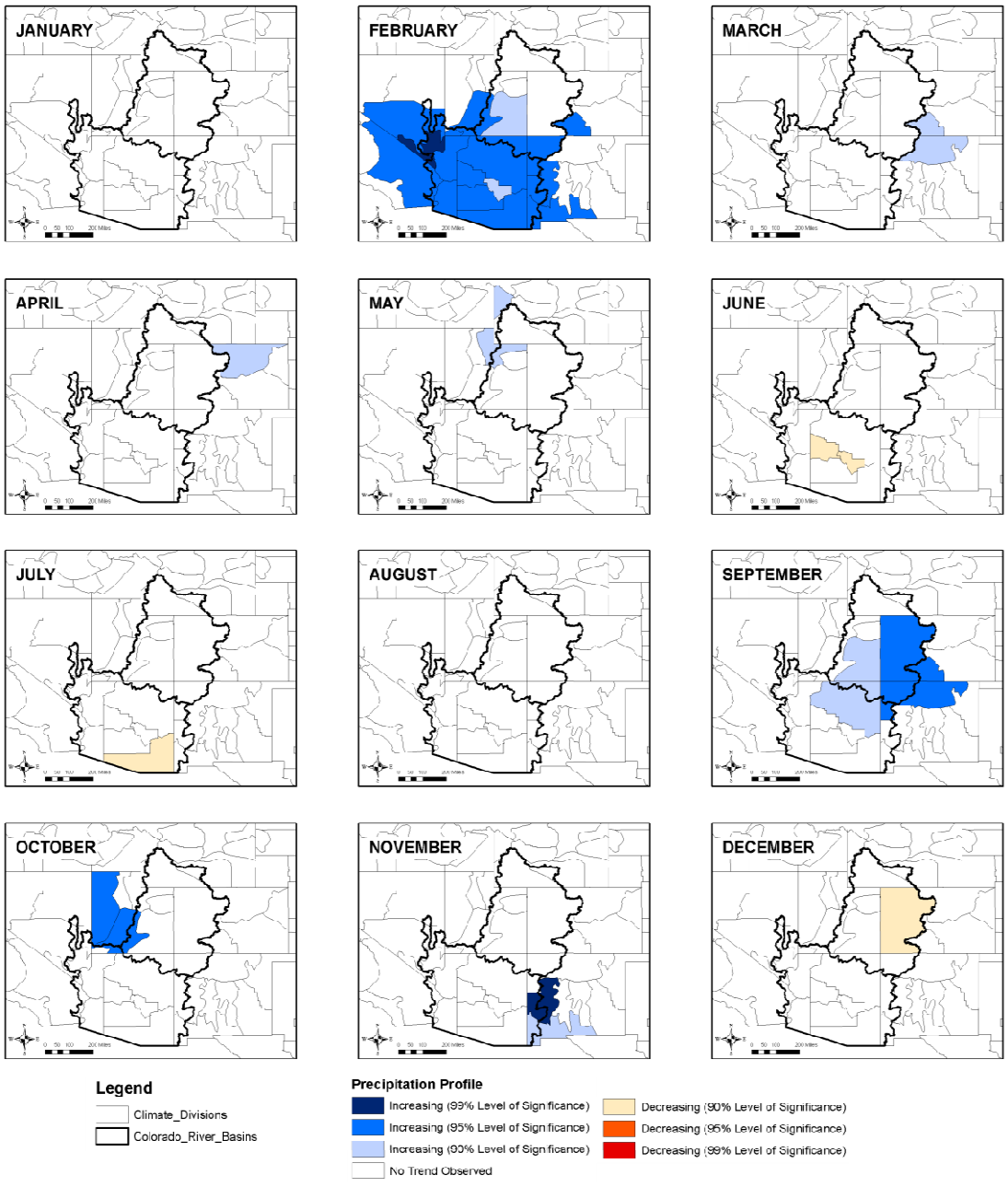

Figure 5: Trends in precipitation data over each climate division intersecting the Colorado River Basin.

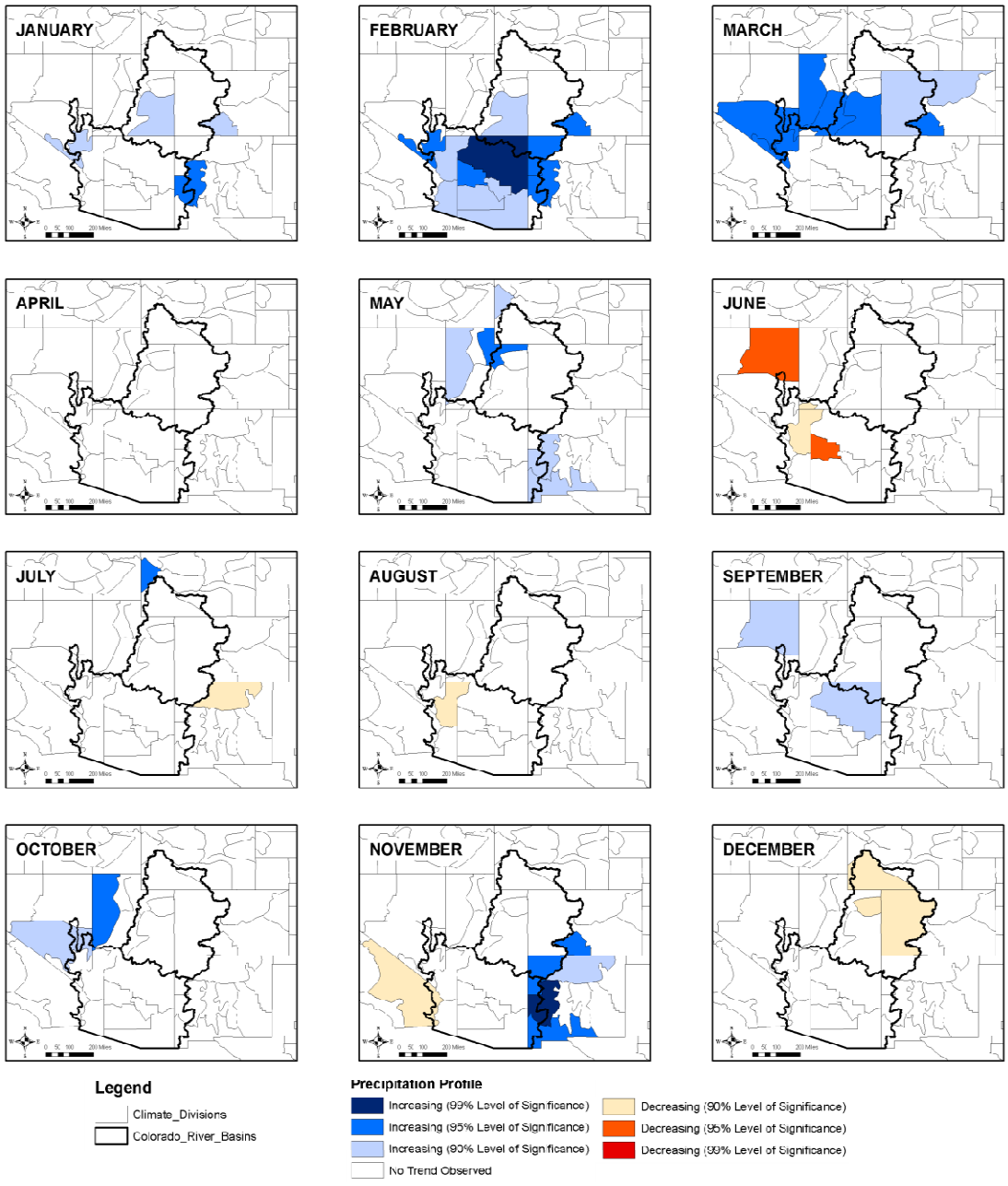

Figure 6: Step Changes in precipitation data over each climate division intersecting the Colorado River Basin.

3.4.3 Streamflow Results

Resource managers depend on accurate inflow forecasts to plan delivery schedules, hydropower generation, agricultural requirements, and the continued sustainability of environmental projects and programs. Lins and Slack (1999) note that streamflow has increased across the majority of the United States, which correlates to increasing trends in precipitation and temperature observations noted by Huntington (2006) and Groisman et al. (2001).

Figure 7 and Figure 8 illustrate trend and step changes in streamflow observed at USGS gages with naturalized flow data. Increasing trends and step changes were observed consistently in the Upper Colorado River Basin in the early part of the year, particularly in January through March. This corresponds well with trends and step changes observed in precipitation and temperature data observed in the same region over the same time frame. These results agree with previous studies published by Lins and Slack (1999), McCabe and Wolock (2002), and Regonda et al. (2005). Interestingly, a corresponding decreasing trend in streamflow in later months is not prevalent in this study. However, this may be due to a high degree of streamflow variability in the Colorado River Basin, particularly during the peak runoff season (e.g., Pagano & Garen, 2005). Increased variability of streamflow in the spring and summer months may impede the detection of trends or step changes within data by relatively simple statistical tests. Streamflow in fall and winter months is much less variable; thus, changes in observational data can be detected easier.

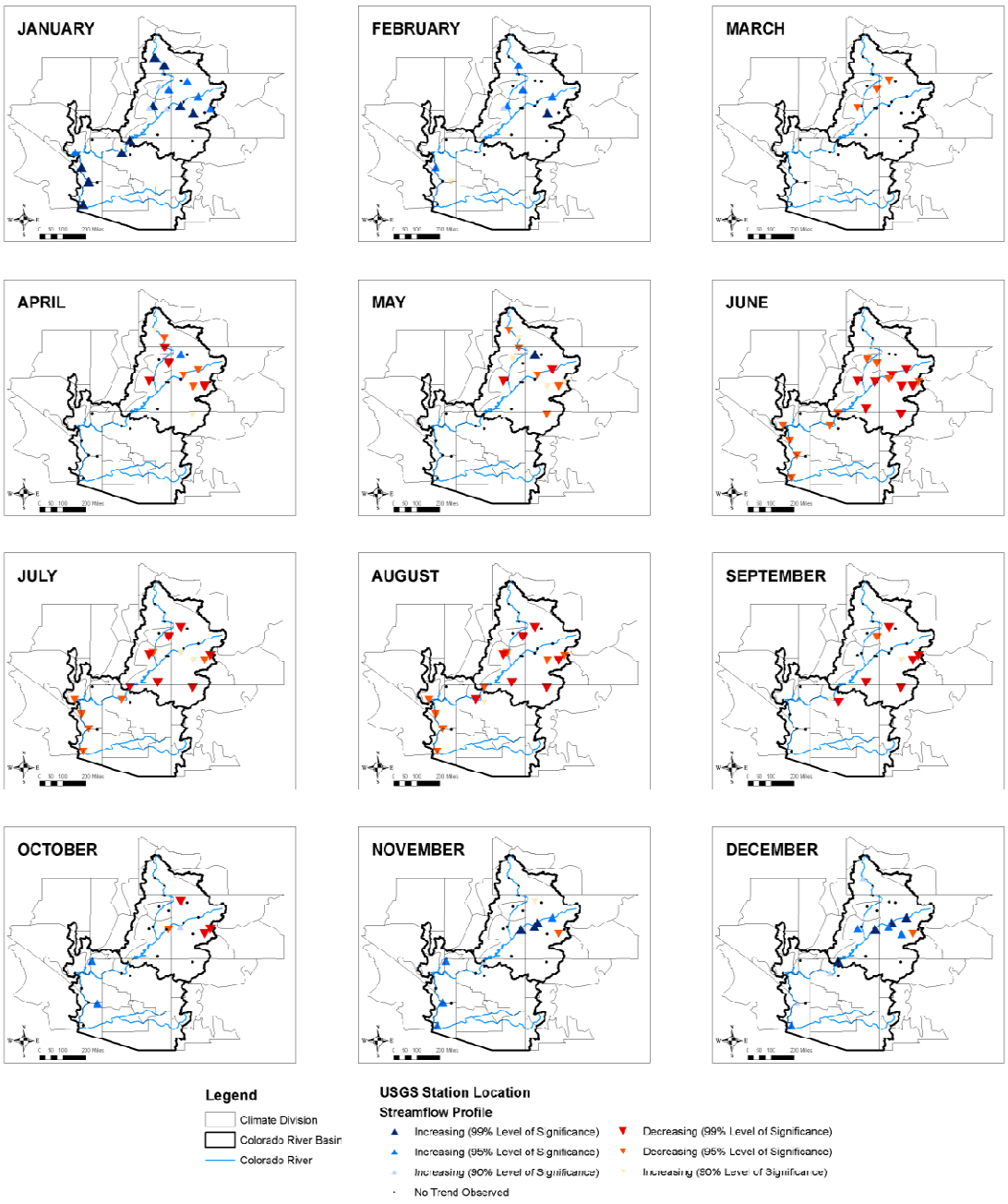

Figure 7: Trends in naturalized streamflow data at each USGS gage location within the Colorado River Basin.

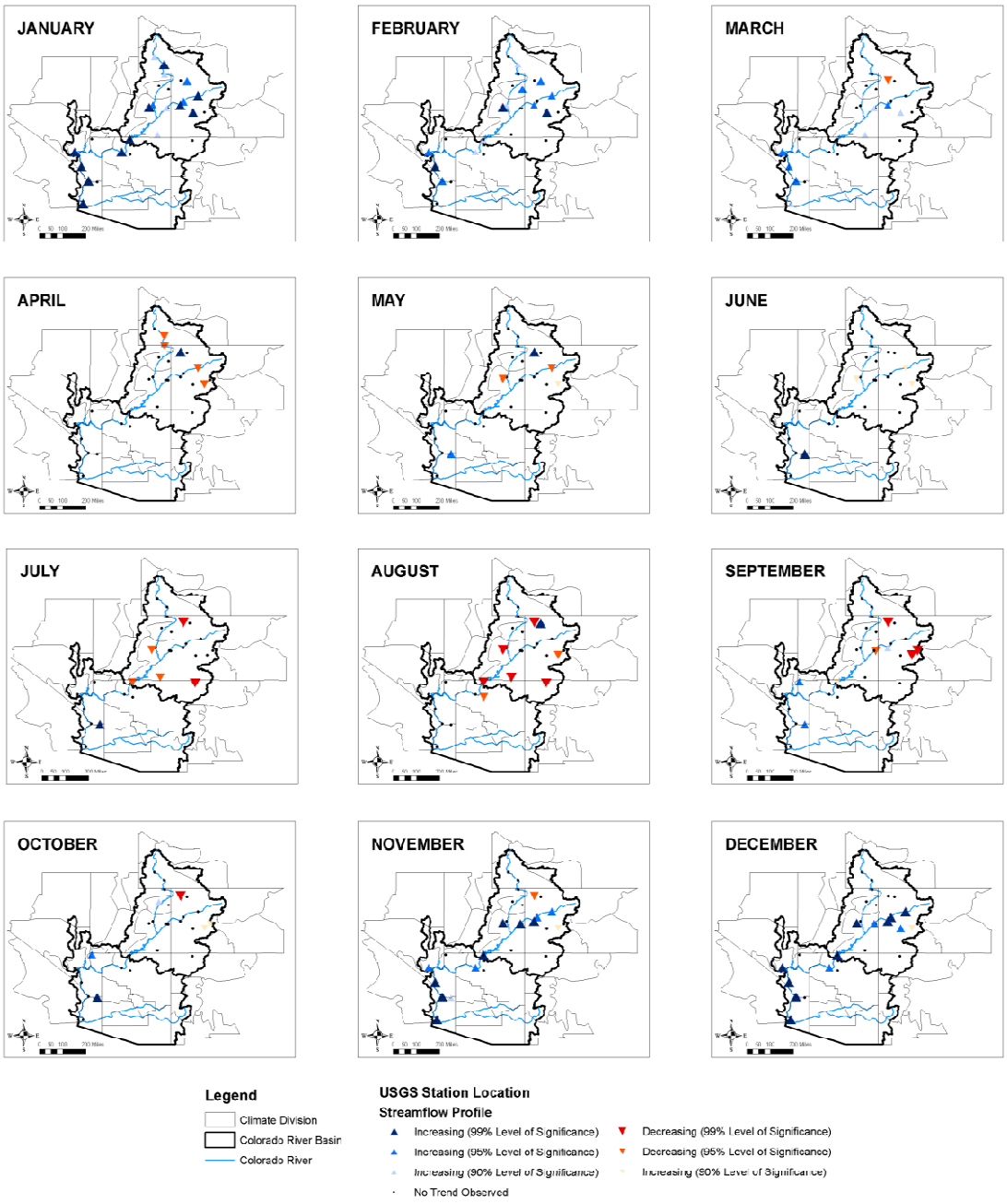

Figure 8: Step Changes in naturalized streamflow data at each USGS gage location within the Colorado River Basin.

3.5 Interdependency of Variables

The hydrologic cycle is known to be an interconnected and dependent system, whose complexity is only bounded by the scale at which the system is studied. In this study, three variables were studied within a complex river basin that is subject to varying and changing hydroclimatic conditions. It is acknowledged that this study does not address such variables as snowpack, groundwater, or evapotranspiration. However, the interdependency between temperature, precipitation, and streamflow appears to be particularly strong. Figure 9 summarizes the frequency of increasing and decreasing trends for each variable over the course of the year. Increasing trends in streamflow correspond to increasing trends in temperature and precipitation, particularly during the end and beginning of the water year (October through January). The results indicate that increasing trends in temperature in the Colorado River Basin coincided with increases in precipitation, particularly during the early part of the year. In addition, an increase in precipitation coincides with increased streamflow.

The prospect of prolonged and extreme drought and potential adverse impacts due to climate change are of primary importance to water resource managers in the Southwest and Reclamation (U.S. Department of the Interior, Bureau of Reclamation, Upper and Lower Colorado Regions, 2007) who depend on resources provided by the Colorado River and associated reservoirs. Increasing temperature trends, such as those shown in this study, have been associated with increasing trends in drought duration and drought severity in the Southwest and parts of the interior West (Andreadis & Lettenmaier, 2006). Easterling et al. (2007) suggests that increased precipitation since 1980 in the contiguous United States has “masked” drought events predominantly driven by increasing

temperature trends. While increasing temperature trends are apparent in this study, precipitation trends are not. Consequently, droughts have not been "masked" in the Colorado River Basin, as the basin is currently enduring the aforementioned longest drought on the observed record (Timilsena et al., 2007).

Recent research, such as Huntington (2006), propose that climate change will lead to an "intensification" of hydrologic processes, such as higher peak streamflow rates, in response to more frequent and intense rainfall events. While streamflow trends in this study support Huntington (2006), precipitation trends do not. Since precipitation trends are not readily apparent in this study, it is possible that the state (i.e., rain or snow) and interaction of precipitation (e.g., evaporation and seepage losses) are changing. Thus, more attention and research must be focused on the character of precipitation events (e.g., Trenberth et al., 2003).

Although snowpack is not considered in this study, it is possible that decreasing trends in streamflow that are prevalent during the traditional peak runoff season (April through July) are due to a lack of snowmelt contributing to spring runoff. Because there are increasing trends in precipitation during the winter months, it is possible that increasing temperature trends have contributed to an environment that is not conducive to maintaining snowpack reserves.

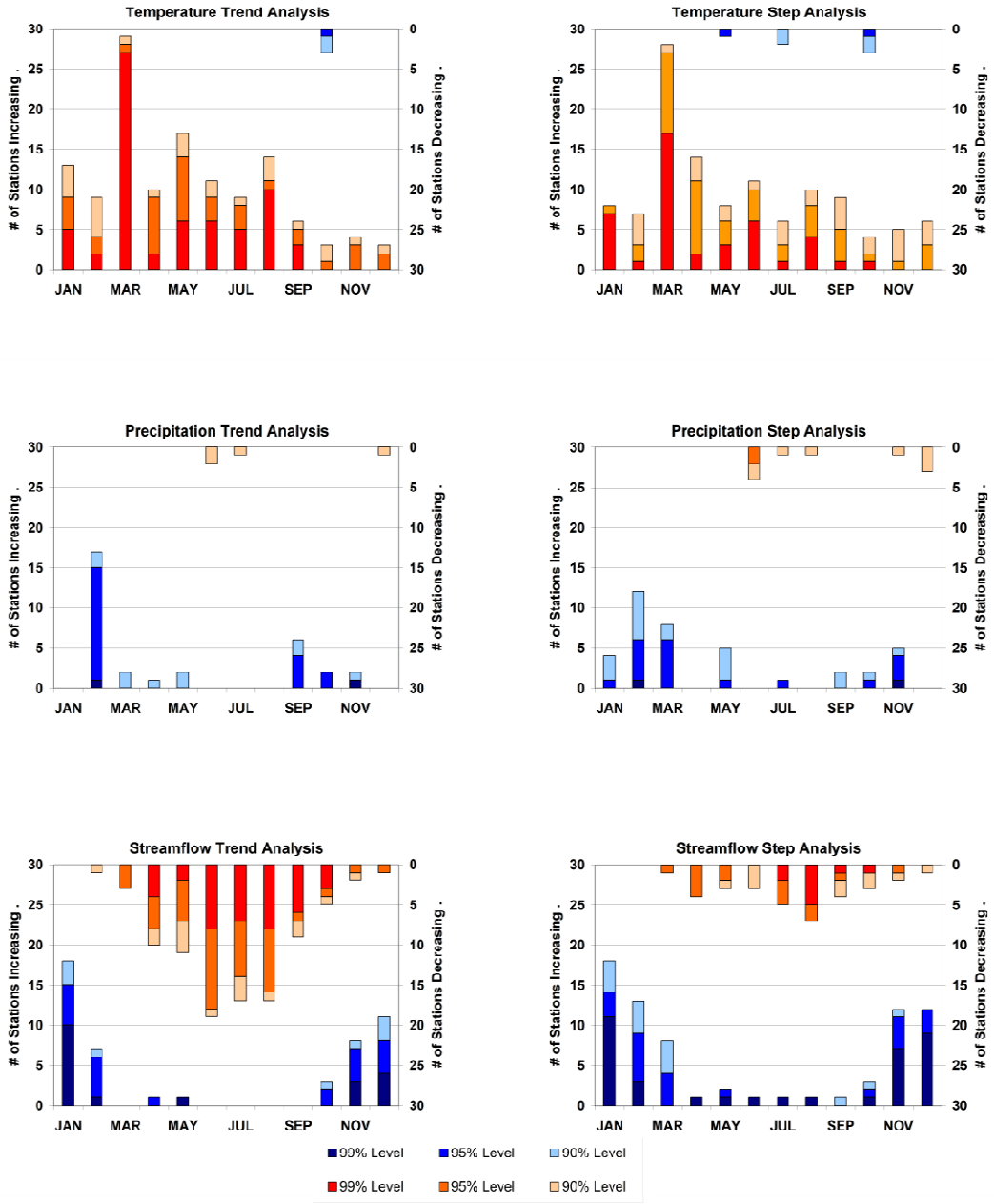

Figure 9: Plots showing the number of stations (29 climate divisions or 29 naturalized flow gage locations) having increasing or decreasing trends or step changes in the Colorado River Basin. Observations from trend analysis are on the left; observations from step change analysis are on the right. In each plot, bars along the lower horizontal axis correspond to the number of stations with increasing trend measured on the left vertical axis. Likewise, bars along the upper horizontal axis correspond to the number of stations with decreasing trend measured on the right vertical axis.

3.6 Conclusion of Preliminary Study

The nature of trends and changes in key hydrologic parameters is critical for long-term water management in the Colorado River Basin. In this study, temperature, precipitation, and streamflow data were investigated in an effort to identify trends and step changes apparent between 1951 and 2005. Each parameter was studied over climate divisions or USGS gage locations encompassing the entire Colorado River Basin.

Increasing temperature trends were evident across much of the Colorado River Basin. While increasing temperature trends are evident over the entire year, temperature trends were most significant in the first quarter of the year, January through March. Increasing temperature trends correspond well spatially with trends observed in the precipitation record, as increasing precipitation trends were most prevalent in January through March. These findings agree with previous studies which indicate a correlation between increasing temperatures and increasing precipitation consistent with global warming and climate change research (Hamlet et al., 2005; Hamlet & Lettenmaier, 2007; Hamlet et al., 2007; Huntington, 2006; Metz & Intergovernmental Panel on Climate Change, Working Group III, 2007; Parry & Intergovernmental Panel on Climate Change, Working Group II, 2007).

Increasing streamflow trends in January through March and decreasing streamflow trends during peak runoff months (April through July) were seen in this study. This correlates well with findings in Regonda et al. (2005) which indicate peak streamflow rates occurring earlier in the year. Streamflow trends, when taken within the context of these results and previous study, agree with precipitation and temperature trends observed in this study. These results are reasonable when considering the dynamic relationship

between the parameters and the possible changing character of precipitation in the Colorado River Basin. It is interesting to note that decreasing streamflow trends are apparent at the 99% confidence interval throughout the Colorado River Basin during the traditional peak flow months, despite the high variability of streamflow rates that have historically occurred in the Colorado River Basin (e.g., Pagano & Garen, 2005; Woodhouse & Lukas, 2006). Should the current severe drought continue, perhaps streamflow trends would become more prevalent in the winter months, where streamflow rates have been traditionally less variable. Further research needs to be done regarding the changing character and state of precipitation to better assess the impacts to streamflow in the Colorado River Basin.

CHAPTER 4

REGIONAL ANALYSIS OF TRENDS IN WESTERN U.S. SNOWPACK AND CORRESPONDING IMPACTS TO STREAMFLOW IN THE COLORADO RIVER BASIN (SUBMITTED TO JOURNAL OF HYDROMETEOROLOGY)

4.1 Introduction

Trends in both the magnitude and timing of streamflow are of principal interest to water resource managers (Lins & Slack, 1999; McCabe & Wolock, 2002). The magnitude of runoff is important to assess water availability and reservoir storage; timing of runoff is important to assess flood control regulations, hydropower generation, and irrigation demands. Due to increasing temperatures, research has shown a trend towards earlier spring runoff in both observed data (e.g., Cayan et al., 2001; Kalra et al., 2008; Mauget, 2003; Miller & Piechota, 2008; Regonda et al., 2005) and modeled data (Hamlet et al., 2005; Hamlet et al., 2007; Maurer & Duffy, 2005; Stewart et al., 2005). Miller and Piechota (2008) have previously shown a shift in the timing of naturalized flow over the Colorado River Basin. Flow trends have decreased during the traditional peak runoff season (April through July) and increased in fall and winter months. As previously described in Chapter 2, Miller and Piechota (2008) hypothesized that increasing streamflow trends in the fall and winter were due to more frequent winter rain events and less frequent snow events; less snow events may contribute to decreased mountain snowpack and a resultant decrease in spring snowmelt runoff.

Trends in precipitation and snowpack characteristics have also been the subject of research and interest to water resource managers, particularly with regards to the

snowmelt driven hydrology of the Upper Colorado River Basin. Decreasing trends in SWE have been noted in the Western U.S. and Colorado River Basin (e.g., Feng & Hu, 2007; Kalra et al., 2008). More interestingly, decreasing trends in SWE have correlated with the changing character of precipitation; that is, changes in the frequency and magnitude of rainfall and snowfall events (Trenberth et al., 2003). Knowles et al. (2006) noted a reduction in the ratio between the winter SWE and total winter precipitation between water year 1949 and 2004 that correlated with changing temperature trends over the Western U.S. Knowles et al. (2006) further found the largest changes to winter precipitation typically occurred in March and agrees with other studies indicating a shift in changing character of precipitation (e.g., Mote, 2003; Mote et al., 2005; Mote, 2006; Serreze et al., 1999).

It is clear that streamflow and snowpack are vitally important to water resource availability in the Western U.S., particularly in snowmelt driven basins such as the Colorado River Basin. Research has indicated that climate change may significantly impact snowpack and streamflow in snowmelt dominated basins (Cooley, 1990; Maurer, 2007; Metz & Intergovernmental Panel on Climate Change, Working Group III, 2007; Salathé Jr., 2005) and are indicative of drought and arid conditions in the American Southwest (Seager et al., 2007; Timilsena & Piechota, 2008). While current research has focused on the identification of trends in either observed streamflow or snowpack, there has been significantly less investigation of the impact of observed trends that are coincident in both SWE and streamflow, particularly over the Colorado River Basin. Presumably, this is due to the relatively short period of record of snowpack observations in the mountainous Western U.S., which is why most studies have focused on long term

model projections of snowpack and streamflow. In this research, trends in the observed snowpack in the Western U.S. are investigated. Furthermore, these trends are compared to observed streamflow trends over Colorado River headwater basins (Figure 10) in an attempt to quantify the impact of changing precipitation characteristics to streamflow in the basin and to improve understanding of the linkage between snowpack and streamflow over the basin.

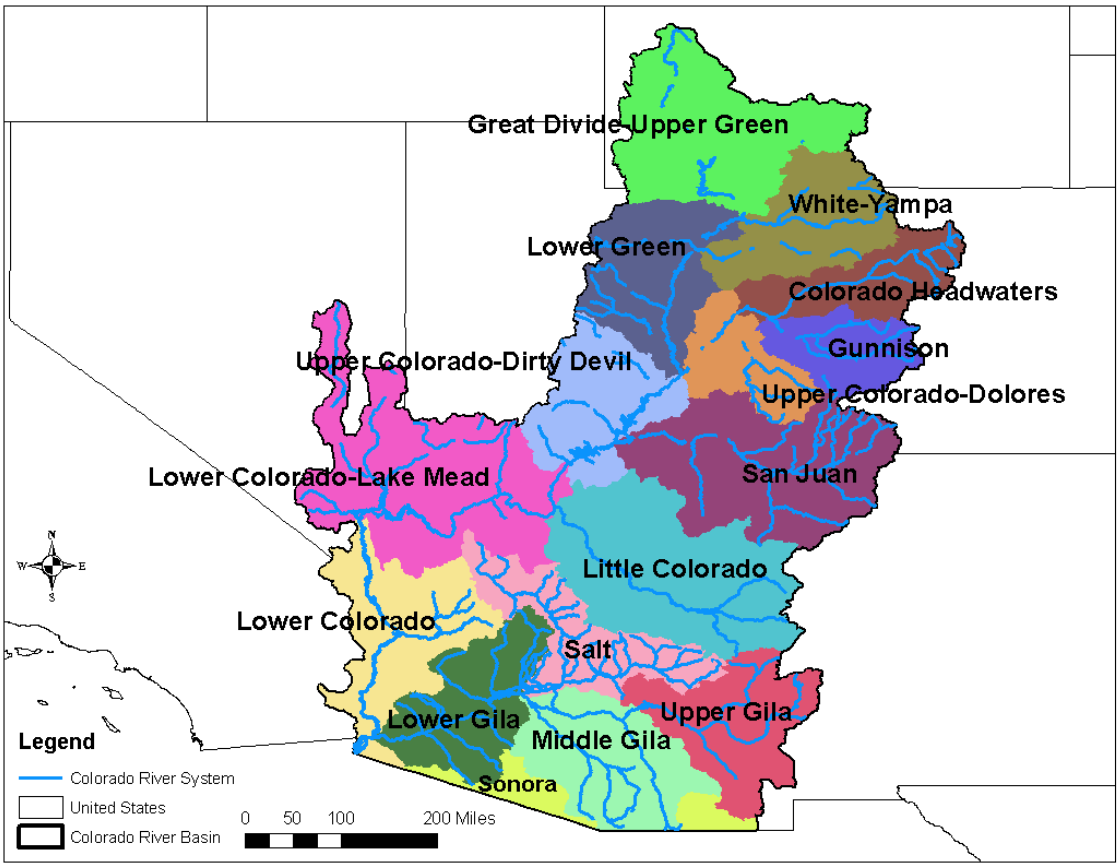

Figure 10: Subbasins of the Colorado River Basin

4.2 Data and Methods

4.2.1 Precipitation and Snow Water Equivalent

Data used in analysis for this research came from various government agencies and included both daily and monthly gage data, typically incorporating gage data from inception through water year 2008. Daily snowpack and precipitation observations are obtained from the NRCS SNOTEL network. NRCS SNOTEL stations subjected to analysis in this study span the western U.S. and Alaska (Figure 11a). Monthly SWE data are derived from daily observations by using the first day of the month; April 1 SWE is commonly used in streamflow forecasting and typically regarded as the date of peak snowpack (e.g., Mote et al., 2005). For inclusion in this study, SNOTEL stations are required to have a period of record of at least 20 years, and at least 50% complete over any given year period. These data requirements are slightly more stringent than those described in Huntington et al. (2004) and Knowles et al. (2006).

Currently, the NRCS operates 761 SNOTEL stations in 13 states, the farthest east being located in South Dakota and the farthest west located in Alaska. Of the 761 total SNOTEL stations, 398 stations met the aforementioned completeness criteria to be included in this study. Of the stations included in this study, the furthest east is located in Southern Utah, and the furthest west is located in Central Alaska. Of interest, studies have noted a relationship between elevation and snowpack. Mote (2003) found that below 5900 feet, declining SWE observations coincide with increasing temperature trends. Of the stations included in this study, the lowest is located at 375 feet in Alaska, and the highest is located at 11600 feet in Colorado. In the continental U.S., the lowest station is located at 2600 feet in Oregon.

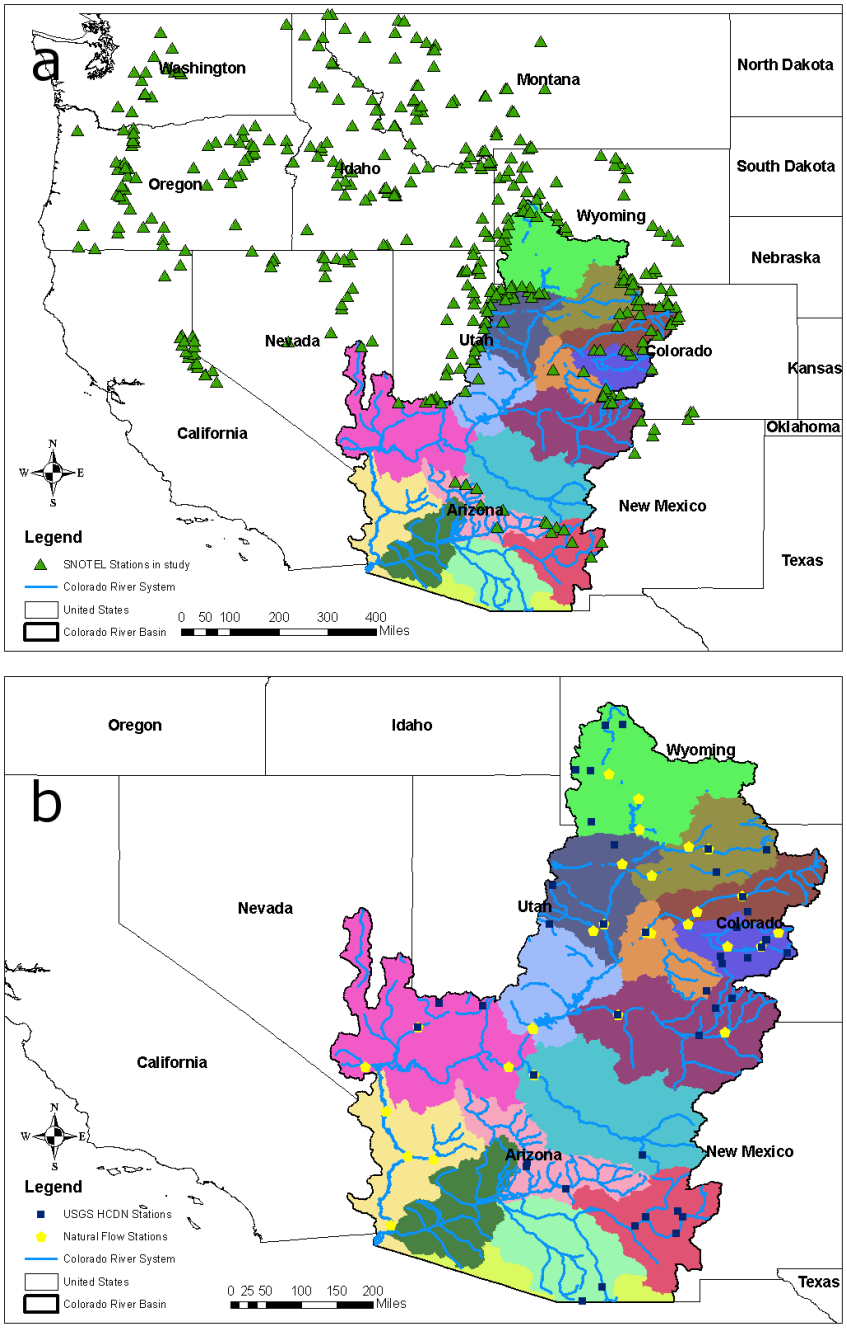

Figure 11: The spatial distribution of a) SNOTEL gages over the Western U.S. and b) USGS HCDN and Reclamation Natural Flow stations over the Colorado River Basin included in this study. It is important to note that analysis over SNOTEL gages in Alaska is considered, though they are not pictured.

4.2.3 Streamflow Data

Daily streamflow data provided by the USGS are used in this study, provided the gage is part of the Hydro-Climatic Data Network (HCDN) and located within the Colorado River Basin (Figure 11b). These USGS HCDN gages are selected, as they are predominantly free of anthropogenic influence and have a length of record usually greater than 30 years as described in Slack and Landwehr (1992). For the purposes of this study, monthly streamflow data is obtained from the natural streamflow record developed and distributed by the Reclamation. Natural flow data is calculated using historical information from USGS stream gaging locations, reservoir operations, and depletion histories of Colorado River water users (J. Prairie & Callejo, 2005). The period of natural flow records provided by Reclamation spans October 1905 to December 2006 (i.e., water year 1906 through the end of calendar year 2006) and was used in the development of the Colorado River Interim Guidelines (U.S. Department of the Interior, Bureau of Reclamation, Upper and Lower Colorado Regions, 2007).

Prior to 1971, consistent and complete records for many of the 29 USGS streamflow stations used in development of Reclamation's natural flow record did not exist. In summary, Reclamation creates the historical monthly natural flow record by using robust statistical methods (e.g., K-Nearest Neighbor Bootstrapping) to derive cumulative annual streamflow values in the Colorado River Basin. Through multiple linear regression and statistical analysis of the error term, these annual flows are temporally disaggregated to the monthly timescale. The extended streamflow record and historical record have similar statistical properties (Lee & Salas, 2006, In review; Salas et al., 2005).

4.3 Methodology

Trends in hydroclimatic observations from SNOTEL and USGS stations, as well as naturalized flow derived by Reclamation, are investigated using Kendall's tau (τ) nonparametric test for monotonic trend with a correction for ties. Kendall's τ is well-suited for applications to water resources, as it is a rank-based procedure that is resistant to outliers in time series (Helsel & Hirsch, 1992). Kendall's τ test has successfully been used in previous research investigating the trends in precipitation and streamflow observations (e.g., Huntington, 2006; Knowles et al., 2006; Rood et al., 2005). The significance of monotonic trends detected in SWE observations are calculated through comparison of the Kendall's τ test statistic to a standard two-sided Student's *t* table. For completeness and to ensure the accuracy and applicability of Kendall's τ to the collected observations, Spearman's Rho (ρ) test for monotonic trend is also applied to hydroclimatic time series investigated in this study. Like Kendall's τ, Spearman's ρ is a rank-based statistical test; however, Spearman's ρ weights the magnitude of differences in time series ordinates more heavily. Kendall's τ and Spearman's ρ measure the same correlation at different scales of magnitude (Helsel & Hirsch, 1992).

The interaction between changing snowpack characteristics and streamflow is investigated over basins within the Colorado River Basin. That is, the interdependency of snowpack and streamflow is examined such that observations from SNOTEL stations are compared only to naturalized or observational streamflow within the same geographic subbasin within the Colorado River Basin.

4.4 SNOTEL Observations

4.4.1 Daily SNOTEL Trends

Trends in daily SWE and cumulative water year precipitation are investigated using Kendall's τ over standardized observations. Miller and Piechota (2008) previously noted the lack of significant precipitation trends over the Colorado River Basin using climate division data. While the vast majority of stations (342 stations or 86%) exhibit a decreasing linear trend over a broad elevation range (Figure 12), there is a lack of statistical significance perhaps due to the relatively small time series available at each station and the presence of drought over a large portion of the station's record; that is, the lack of a significantly long gage record to adequately capture long term station averages and the natural variability of the hydrology in the Western U.S. impedes the ability to find statistical significance through the use of a monotonic trend test. Cumulative precipitation trends over the Western U.S. are similar to those observed over the Colorado River Basin (Table 2). The average change in cumulative water year precipitation over the basin is approximately -0.14 inches per year.

Figure 13 shows the results of Kendall's τ test over daily observational SWE time series derived from each of the SNOTEL stations included in this study over the continental U.S. Of the 398 stations for which the Kendall's τ test is applied, approximately 72% (287 stations) indicate a decreasing trend at the 90% confidence interval; 69% (275 stations) indicate a decreasing trend at the 99% confidence interval. In contrast, only 17% of those stations indicated an increasing trend at least at the 90% confidence interval.

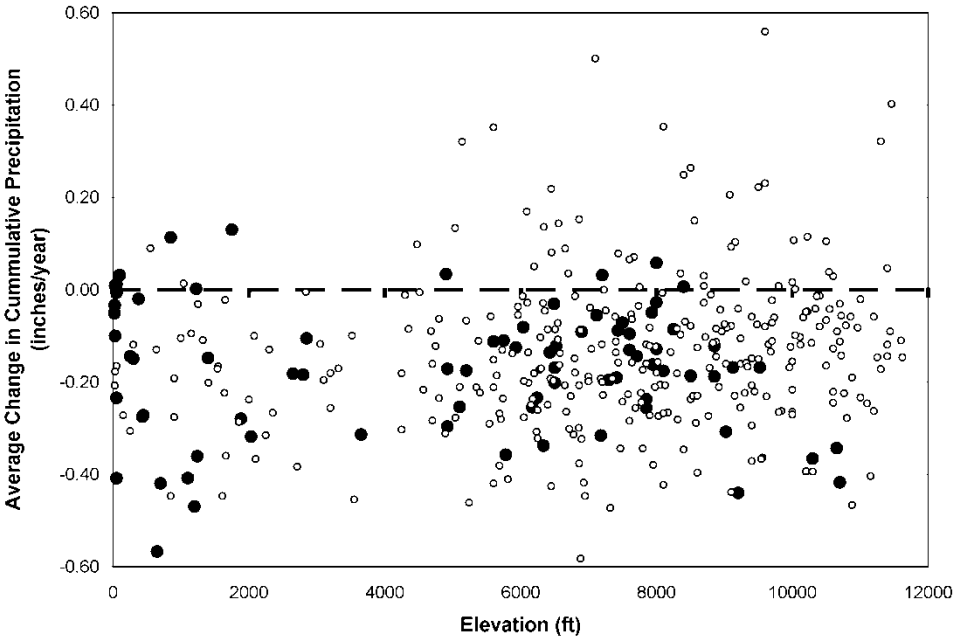

Figure 12: For each of the 398 SNOTEL stations included in this study, the linear trend in cumulative water year precipitation over the station's period of record is plotted against the elevation at the station location. Dark circles are indicative of a gage located within the Colorado River Basin; open circles indicate a station outside of the Colorado River Basin.

Increasing trends are concentrated mostly over the Cascade Mountain Range in the Pacific Northwest and the Southern Rocky Mountain Region in the Yampa and Colorado Headwater River Basins. Decreasing snowpack is prevalent over the Sierra Nevada Mountain Range, which suggests additional strain on California's water resources. Although the Sierra Nevada Mountains are located outside of the Colorado River Basin, changes to California's water supply system from any source will impact Colorado River usage in the southern portion of the state. For instance, as the availability of water resources for the state decreases, it is less likely that California will have the flexibility to participate in Reclamation sponsored conservation programs which allow for states to store water resources in Lake Mead, to the benefit of the Colorado River System.

Table 2: SNOTEL station results for the entire Western U.S. and Colorado River Basin.

SNOTEL Station Characteristics		
	Western U.S.	**Colorado River Basin**
	398 Stations	*79 Stations*
Decreasing Water Year Precipitation	342 (86%)	69 (87%)
Increasing Water Year Precipitation	56 (14%)	10 (13%)
Decreasing Peak SWE / Earlier Peak	227 (57%)	46 (58%)
Decreasing Peak SWE / Later Peak	69 (17%)	18 (23%)
Increasing Peak SWE / Earlier Peak	57 (14%)	10 (13%)
Increasing Peak SWE / Later Peak	45 (11%)	4 (5%)
Earlier Snow / Earlier Melt	179 (45%)	41 (52%)
Later Snow / Earlier Melt	119 (30%)	30 (38%)
Earlier Snow / Later Melt	68 (17%)	5 (6%)
Later Snow / Later Melt	32 (8%)	3 (4%)

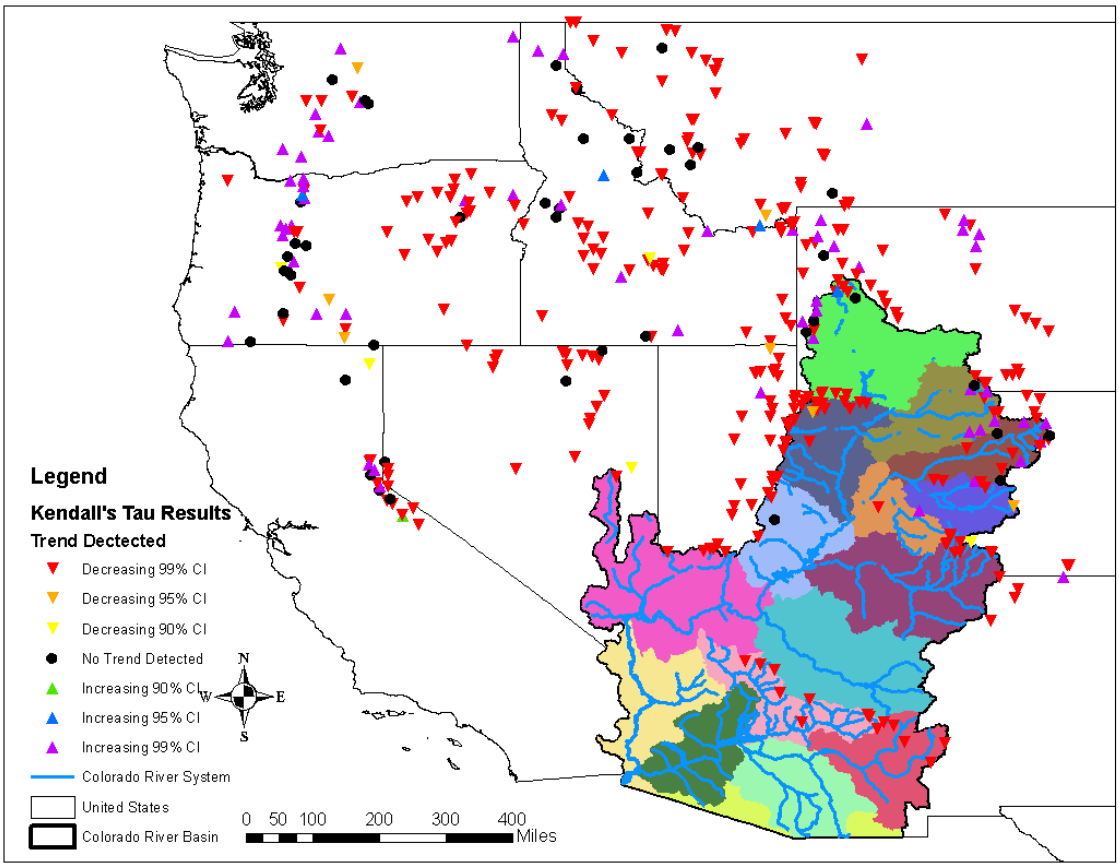

Figure 13: Trend results and confidence intervals from Kendall's τ statistical test run over the period of record at each site. The map shows the spatial distribution of daily SWE trends over the Western U.S. where the vast majority of stations are located.

Whereas Mote (2003) observed less change in SWE at higher elevations (greater than approximately 5900 feet) in the Pacific Northwest, the results of this study indicate no less potential impacts to SWE at high elevations over the Western U.S. The magnitude of decreasing trends throughout the SNOTEL record are relatively small; however, it is important to interpret these observations as point measurements that are representative of broad spatial areas where a small change in a point SWE observation may represent a large accumulated change in actual volume of potential snowmelt runoff from a vast area.

4.4.2 Trends in the Timing Characteristics of Snow Season

In this study, it is assumed that a reported SWE measurement greater than 0.0 inches indicates the presence of snowpack at a particular station; as such, the first indication of snowpack during the water year is interpreted from reported SNOTEL measurements. Similarly, the first day after April 1 when a reported SWE measurement of 0.0 inches is observed signals the "melt day," or the end of the snow season during the course of a water year. Additionally, for each water year, the peak SWE and days since the beginning of the water year (October 1) to reach peak SWE are investigated for linear trends. Table 2 summarizes the results of this analysis. Most stations tend to show declining peak SWE observations in conjunction with occurrence at an earlier date in the water year. Table 2 also summarizes the amount of stations that exhibit earlier or later initial starts to the snow season and those stations that exhibit earlier or later melt days.

For the purposes of this study, the length of the snow season at a particular SNOTEL gage is defined as the duration of time in days since the first observation of SWE after the beginning of the water year to the first observation of 0.0 inches of SWE after April 1. Of the SNOTEL gages included in this study, approximately 60% (238 stations) of the gages exhibited a decreasing linear trend in the length of the snow season (Figure 14). Of those gages located within the Colorado River Basin, 66% (52 stations) exhibited a decreasing linear trend in the length of the snow season. The Cascade station in Colorado lost approximately 1.4 days of its snow season over the course of its gage record; conversely, the Hams Fork station in southern Wyoming gained approximately 1.3 days to its snow season over the course of its gage record. The median loss to the length of the snow season over each gage in the Colorado River Basin is approximately 0.2 days.

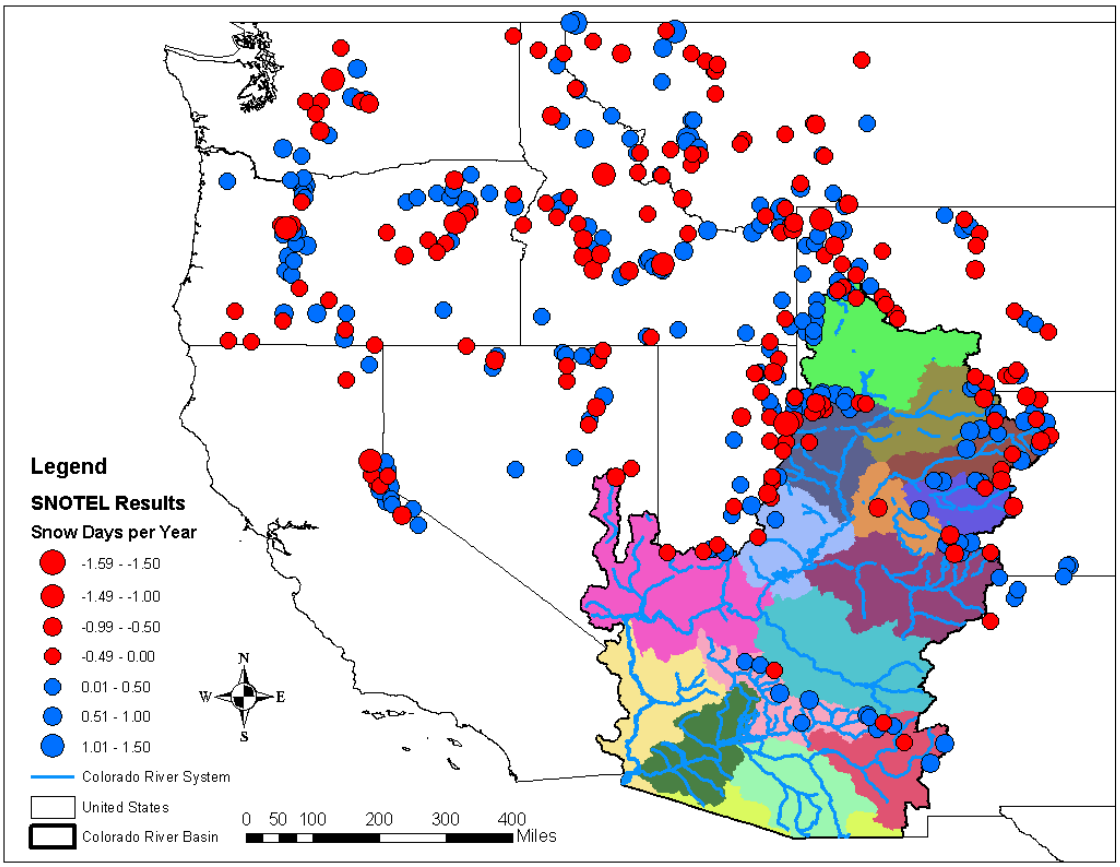

Figure 14: The length of the snow season at each SNOTEL station. Red circles indicate a decrease in the length of the snow season over the life of the station. Blue circles indicate longer snow seasons over the length of record for the station.

Table 2 summarizes the potential shift in timing of the snow season throughout the Western U.S. and Colorado River Basin. Those stations showing earlier starts to the snow season and later ends to the snow season also tend to trend towards higher peak annual SWE; conversely, those showing later starts to the snow season and earlier ends to the snow season also tend to trend towards lower peak annual SWE regardless of elevation. Most SNOTEL stations in this study (235 or 60%) and those in the Colorado River Basin (49 or 62%) reporting an earlier end to the snowpack season also show a trend towards earlier peak annual SWE as well (Table 2). As stated previously, most stations report an earlier end to the snowpack season; of the 238 stations reporting an

earlier melting of the snowpack, 119 (50%) stations also report a later start to the snowpack season.

4.4.3 Trends in Snowfall and Rainfall Frequency

Most stations record daily SWE and daily precipitation, regardless of whether that precipitation occurs as snow or rain. The assumption was made that a recording of precipitation coupled with an increase to or stationary SWE observation would indicate a snow event, whereas a recording of precipitation coupled with a decrease to the station's SWE observation indicate a rain or rain-on-snow event. Miller and Piechota (2008) hypothesized that an increase in rain events was prevalent over the Colorado River Basin region due to increasing temperature trends in the basin; in turn, a corresponding decrease in snowfall frequency would also be apparent. However, the results of the current study do not support that hypothesis.

Seasonal trends in rainfall and snowfall events were not apparent in the current study. At the annual time scale, moderate increases in rainfall frequency were observed, as approximately 74% of SNOTEL stations showed an increasing trend (67% of SNOTEL stations located in the Colorado River Basin). The average increase in rainfall frequency was approximately 0.1 days per water year. No consistent trends in snowfall frequency were observed throughout the dataset, although some decreasing trends were detected in eastern Utah just inside the Lower Green Headwater Basin on the Wasatch Front Range. The Daniels-Strawberry station at the mouth of the Strawberry River showed a decrease of approximately 1.6 days per water year and contributes to flow in the Green River, a major tributary to the Colorado River.

While the results of the current study do not support the hypothesis proposed by Miller and Piechota (2008), the results do support those proposed by Huntington (Huntington, 2006) and others regarding hydrologic intensification. The results of the current study do support that the volume of inflow as precipitation over the Western U.S. and Colorado River Basin has decreased over approximately the last 25 years.

4.5 Streamflow Observations

The USGS currently operates 43 stations within the Colorado River Basin that are within the HCDN as described by Slack et al. (United States Geological Survey et al., 1992). It is important to note that while Slack et al. (United States Geological Survey et al., 1992) identified periods of the streamflow record as minimally affected by anthropogenic factors, this study uses the entire period of record at each of these stations. Applying the Kendall's τ statistical test to daily USGS HCDN time series data revealed interesting trends throughout the Upper Colorado River Basin (Figure 15). Gages in the northern area of the basin located within the Upper Green, Lower Green, and Yampa subbasins yielded frequent decreasing trends at the 99% confidence interval. However, a small cluster of gages in the Gunnison and northern portion of the San Juan subbasins yielded frequent increasing trends at the 99% confidence interval.

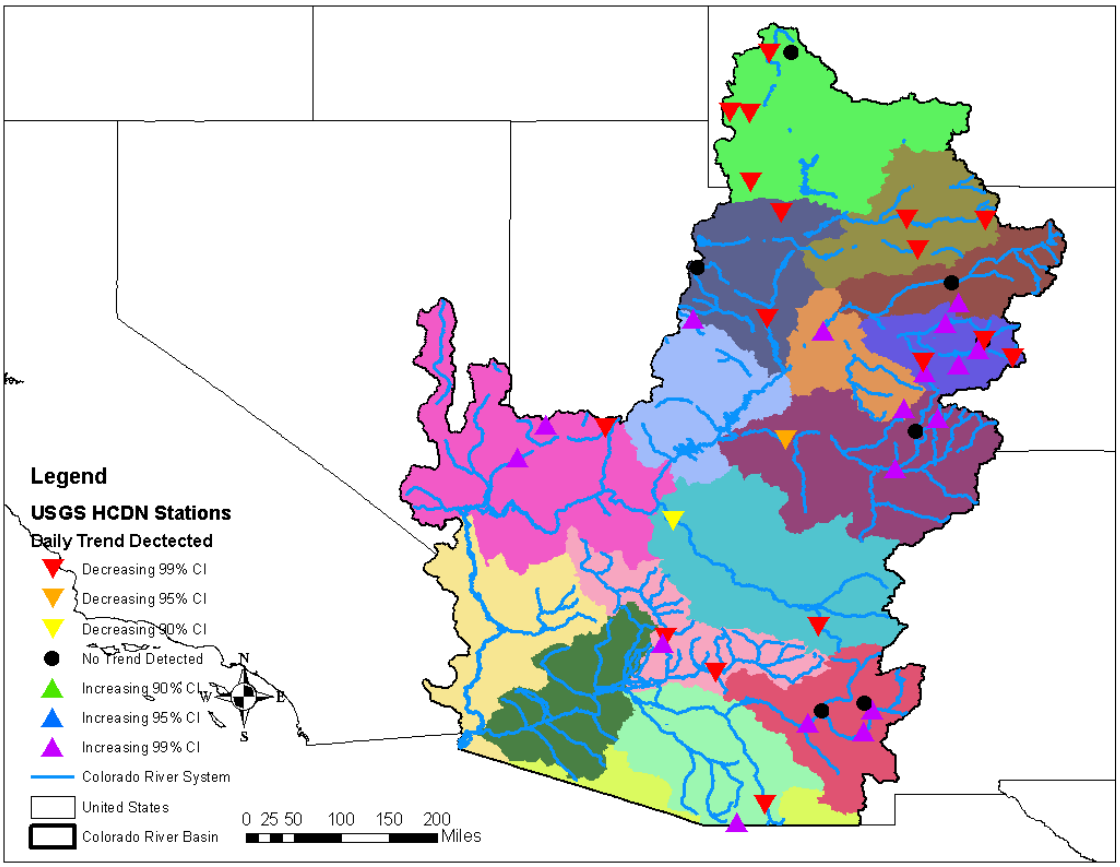

Figure 15: Trend results and confidence intervals from Kendall's τ statistical test run over the period of daily record at each USGS HCDN gage.

Naturalized flow stations distributed by Reclamation (J. Prairie & Callejo, 2005) are utilized in this study when investigating time series at a monthly or longer time step due to the long, complete nature of the dataset and removal of anthropogenic influence. For comparison, seasonal (monthly) trends in both the Natural Flow and USGS HCDN network were investigated using the Kendall's tau statistical test. The results compare very similarly to those presented in Miller and Piechota (2008), which did not utilize the Kendall's tau test for monotonic trends. Most Natural Flow stations show decreasing trends through the traditional peak runoff period (April – July) and increasing trends over the winter months (Figure 16). Similar results were noted throughout the USGS HCDN record as well.

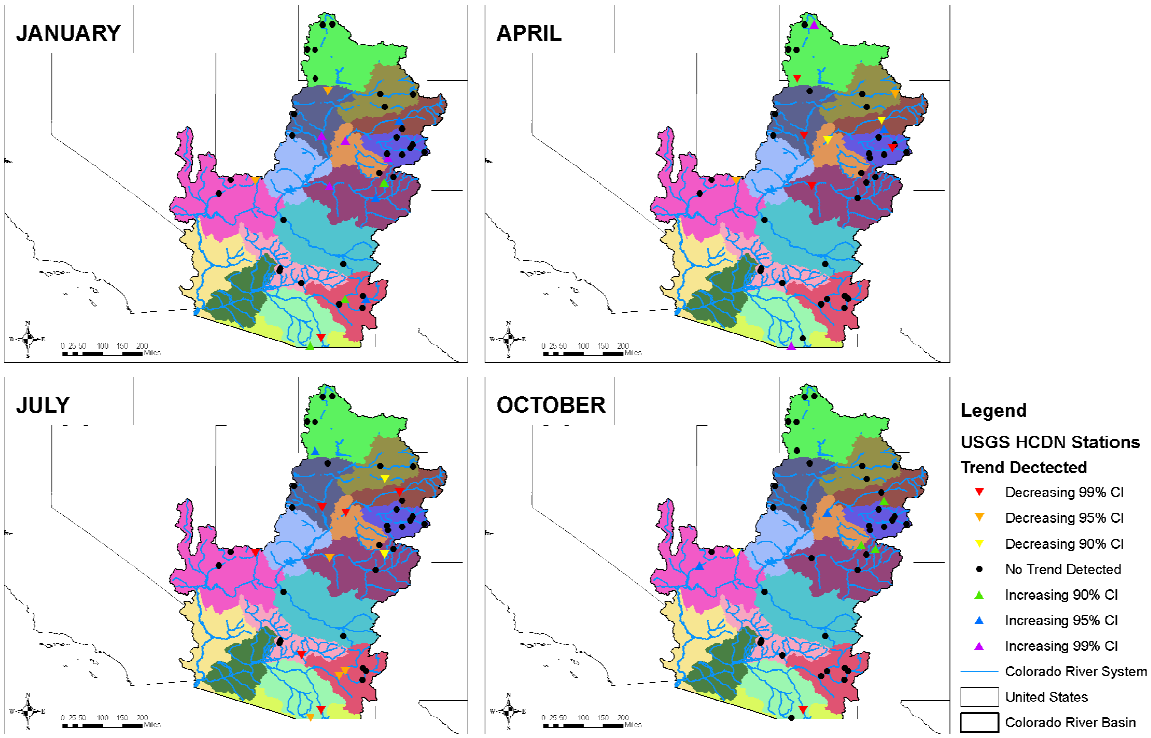

Figure 16: Quarterly trend results and confidence intervals from Kendall's t statistical test run over the period of monthly records at each Reclamation Natural Flow station.

4.5.1 Daily Streamflow Trends

Daily time series are investigated over the operational record of the gage for linear trends in annual water year flow volume. Of the 43 stations investigated, 29 (67%) exhibit a decreasing trend in water year flow volume. While the magnitude of decreasing volume ranges between approximately 4 acre-feet and 20,300 acre-feet, the average decrease in flow relative to each station is approximately 0.3% per year. More interestingly were trends in the April through July volume observed at each station. Over the Colorado River Basin, 34 stations (79%) exhibited decreasing linear trends in April through July runoff. Again, the average decrease in April through July runoff relative to each station is relatively small and is approximately 0.5% per year. Table 3 shows that most stations (67%) in the Colorado River Basin exhibit decreasing April through July runoff in conjunction with decreasing water year runoff. Of the 14 stations with

increasing trends in water year runoff volume, 9 stations also exhibit increasing April through July runoff; over the Colorado River Basin, the majority of annual runoff has traditionally been observed during these months. There is no station within the Colorado River Basin that exhibits increasing April through July runoff and decreasing water year runoff.

4.5.2 Trends in the Timing of Daily Runoff

The timing of inflow in the Colorado River Basin is not only important to water resource managers, but also to those who benefit from timely inflows impacting hydroelectric and environmental endeavors. For the purposes of this study, the maximum daily flow observed over the course of a water year is referred to as the "peak flow." Also considered is the number of days since the beginning of the water year to reach half of that water year's annual flow volume. Most stations over the Colorado River Basin tend to show trends towards earlier peak flows and also tend to show trends towards reaching 50% of the annual water year flow earlier. For both parameters, the average amount of days to reach each date decreased by approximately a tenth of day per year. Table 3 summarizes the number of stations experiencing changes to the timing of peak flows and changes to the timing of reaching 50% of the annual water year total. The majority of stations (74%) yield earlier peak flows and reach 50% of the annual flow earlier, which supports various other studies which have noted a trend towards earlier runoff in the Colorado River Basin (e.g., McCabe & Clark, 2005; Miller & Piechota, 2008; Regonda et al., 2005; Stewart et al., 2005).

Table 3: USGS HCDN and Reclamation Natural Flow station results. Non-applicable (N/A) designations indicate an analysis not included in this current study. USGS HCDN data is used in correlation analysis with SNOTEL events at a daily timescale; Reclamation data is used in correlation analysis with SNOTEL data that has been aggregated to a monthly or greater time step.

Streamflow Station Characteristics		
	USGS HCDN	**Reclamation Natural Flow Dataset**
	43 Stations	*29 Stations*
Decreasing Water Year Volume	N/A	28 (97%)
Increasing Water Year Volume	N/A	1 (3%)
Decreasing April - July Volume	N/A	26 (90%)
Increasing April - July Volume	N/A	3 (10%)
Increasing Water Year / Increasing April - July Volume	N/A	1 (3%)
Increasing Water Year / Decreasing April - July Volume	N/A	0 (0%)
Decreasing Water Year / Increasing April - July Volume	N/A	2 (7%)
Decreasing Water Year / Decreasing April - July Volume	N/A	26 (90%)
Earlier Peak Flow / Earlier Date to 50% Annual Flow	32 (74%)	N/A
Earlier Peak Flow / Later Date to 50% Annual Flow	1 (2%)	N/A
Later Peak Flow / Earlier Date to 50% Annual Flow	3 (7%)	N/A
Later Peak Flow / Later Date to 50% Annual Flow	7 (16%)	N/A

4.5.3 Trends in Monthly Streamflow

Kendall's tau statistical analysis was used to check for monotonic trends in the Natural Flow record from 29 stations over the Colorado River Basin. Of the stations, 17 (58%) exhibited decreasing trends, most of which at the 99% confidence interval (Figure 17). None of the Natural Flow stations showed any statistical significance of an increasing trend.

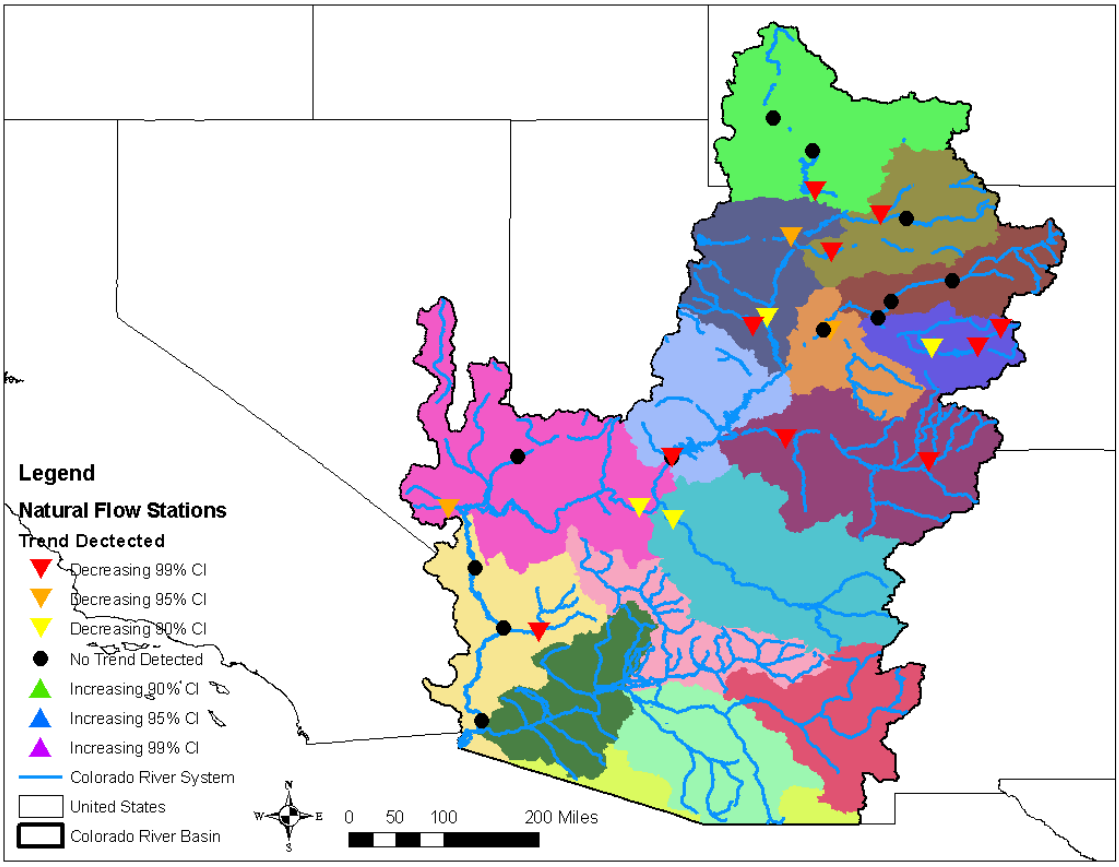

Figure 17: Trend results and confidence intervals from Kendall's τ statistical test run over the period of daily record at each Reclamation Natural Flow station.

Annual and April through July Natural Flow at each station was also considered. Of the 29 stations, nearly all exhibited decreasing trends in annual water year runoff volume (28 stations) and April through July runoff volume (26 stations). Similarly to those

trends observed over the USGS HCDN dataset, the magnitude of trends was relatively small when compared to average station data. Variability in monthly and annual flows over the Colorado River Basin disproportionally impacts linear analysis of runoff time series. Table 3 summarizes the frequency of trends observed over the Natural Flow record.

4.6 Correlation Between Snowpack and Streamflow in Colorado River Basin

Trends in snowpack and streamflow observed in this study tend to support other recently published work (e.g., Knowles et al., 2006; Mote, 2003; Regonda et al., 2005; Stewart et al., 2004). This study proposes to further address the correlation between observed snowpack and runoff within the Colorado River Basin and impacts to the magnitude and timing of flows. Characteristics of Natural Flow and SNOTEL observations within Colorado River Headwater Basins are considered. For the purposes of this research, the Colorado Headwaters, Upper Green, Lower Green, Yampa, Gunnison, and San Juan headwater river basins are considered.

Correlation between the date to peak SWE observation and peak streamflow as well as correlation between the date to peak SWE observation and the date to 50% of annual water year volume was done using daily data from USGS HCDN gages. Correlations between SNOTEL information and total water year or April through July runoff was done using monthly data from Reclamation's Natural Flow dataset.

Results are similar for each headwater basin in this study; as such, the results have been graphically shown for the Gunnison River Basin as summarized below.

4.6.1 Gunnison River Basin

The Gunnison River Basin is located West Central Colorado and contributes approximately 14.1% of the total annual runoff to the Colorado River from the Upper Colorado River Basin (Hoerling & Eischeid, Unpublished). Reclamation operates the Aspinall Unit (i.e. the system of three dams, Blue Mesa, Crystal, and Morrow Point and their associated reservoirs) within this subbasin to protect endangered fish species within the Gunnison River while also providing water for municipal and agricultural use in accordance with the Aspinall Unit Operations Draft Environmental Impact Statement (U.S. Department of the Interior, Bureau of Reclamation, Upper Colorado Region, 2009).

Figure 18 and Figure 19 illustrate recent snowpack and streamflow characteristics over the Gunnison River Basin. The relationship between annual April through July runoff with observations of SWE is similar when SWE is compared to total annual runoff. Over the past 10 water years, the date at which 50% of the annual water year volume is observed has consistently occurred earlier than the historical average of all USGS stations within the basin. This shift in timing appears in conjunction with earlier observations of peak aggregate SWE, the timing of the melt day, and to a lesser extent, the first day of observed snowfall.

Over the last 10 years, the average water year total runoff and April through July runoff have been below average consistently as the length of snow season has been below average (Figure 19). Since 1979, April through July runoff in the basin has consistently been above or below average with peak SWE observations from SNOTEL stations. Over the last decade, earlier dates to the timing of the end of the snowpack season have corresponded well with decreased average streamflow in the Gunnison River Basin.

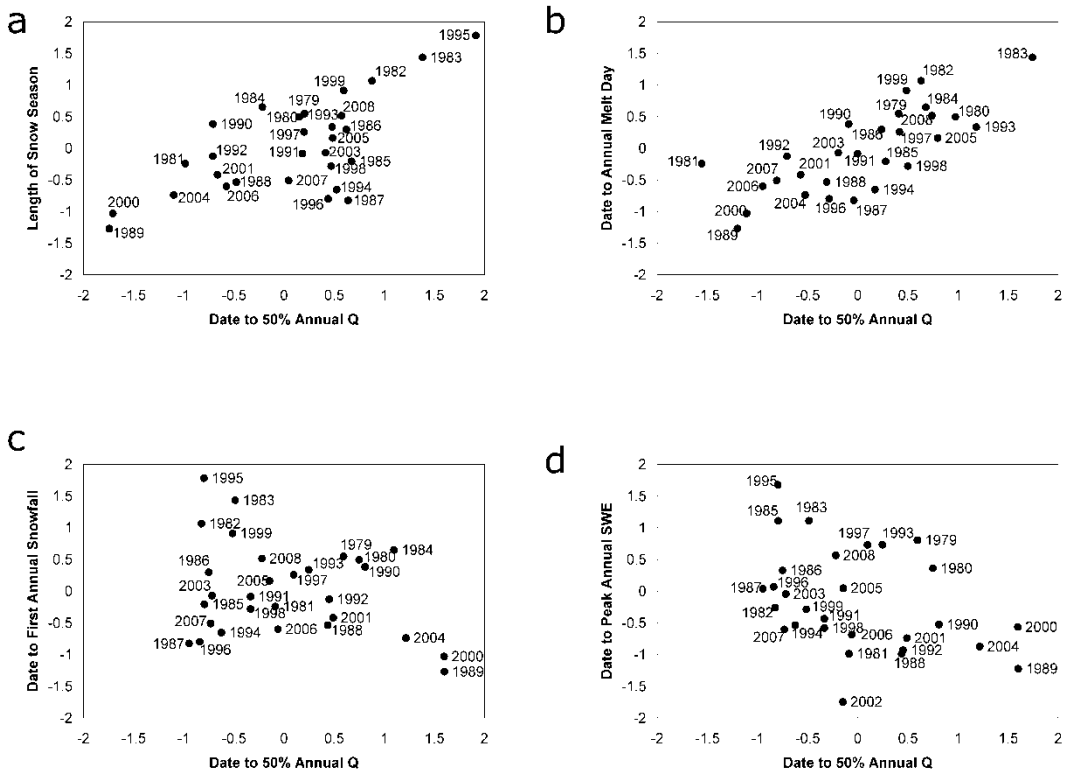

Figure 18: In each plot, the years are indicated as dots. On the x-axis, the standardized average date when 50% of the observed annual runoff (date to 50% annual Q) from daily USGS station data is described. On the y-axis, the standardized average a) length of the annual snow season (length of snow season), b) date when the melt day is observed (date to annual melt day), c) date when the first snowfall is observed (date to first annual snowfall), and d) date when the peak SWE (date to peak annual SWE) is observed from daily NRCS SNOTEL station data.

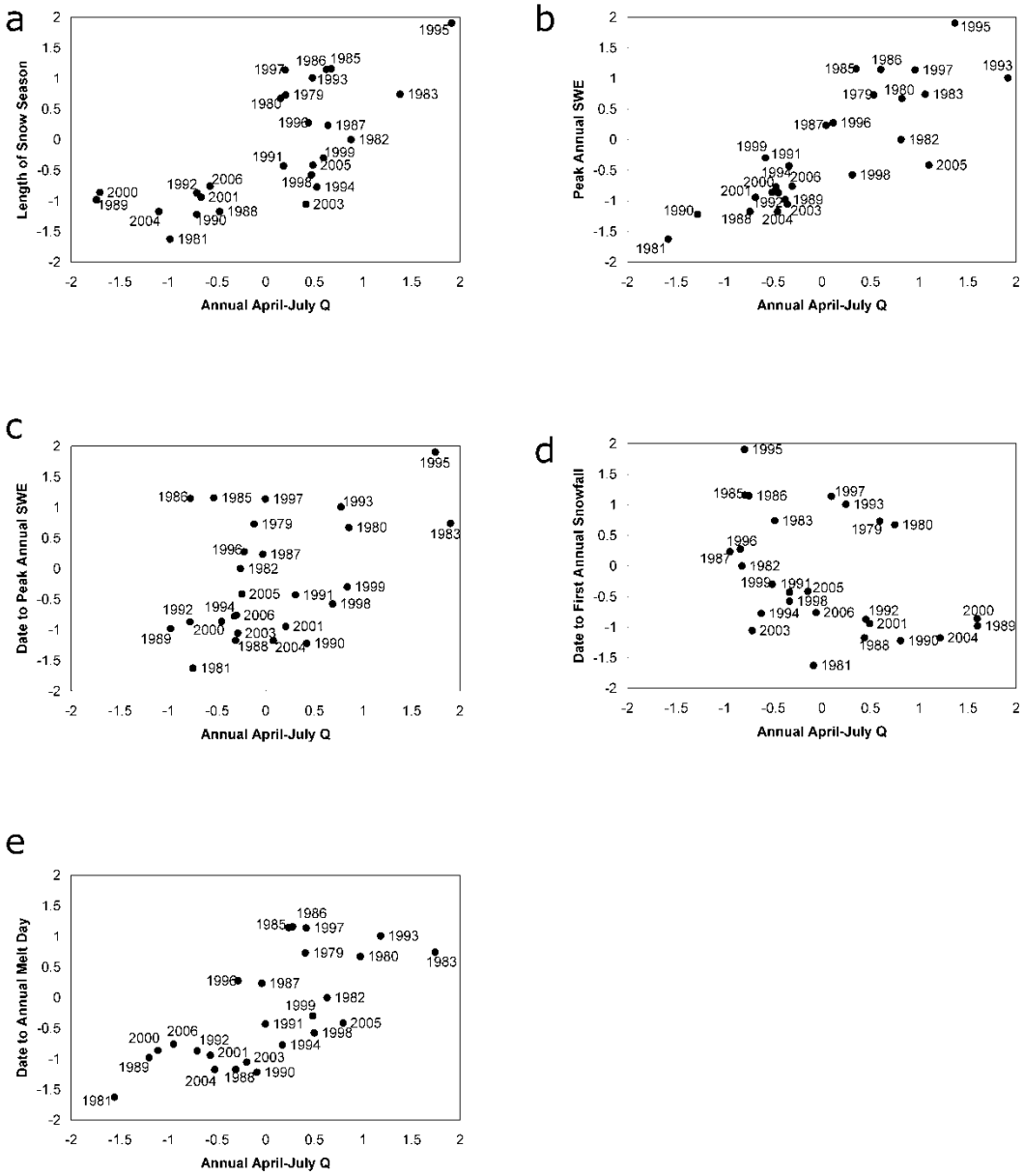

Figure 19: In each plot, the years are indicated as dots. On the x-axis, the standardized average annual April through July runoff (Annual April-July Q) from daily USGS station data is described. On the y-axis, the standardized average a) length of the annual snow season (length of snow season), b) peak annual SWE, c) date when the peak SWE (date to peak annual SWE) is observed, d) date when the first snowfall is observed (date to first annual snowfall), and e) date when the melt day is observed (date to annual melt day) from daily NRCS SNOTEL station data.

4.6.2 Colorado Headwaters River Basin

The Colorado Headwaters River Basin is located north of the Gunnison River Basin in Northwest Colorado. Of the subbasins within the Upper Colorado River Basin, the Colorado Headwaters contributes nearly a quarter of the annual streamflow to the Colorado River mainstem (Hoerling & Eischeid, Unpublished). Streamflow in the basin is largely unregulated, with no major regulatory dams or diversions.

Over the past decade, below average aggregate date to 50% annual water year streamflow corresponds well with earlier average aggregate dates to peak SWE and the end of the snowpack season. To a lesser extent, the below average aggregate date to 50% annual water year streamflow corresponds well with the length of the snowpack season (Figure 20).

Water year volume characteristics correlate well with April through July volume characteristics. Both the aggregate average date to Peak SWE measurement and the aggregate average magnitude of peak SWE correspond well with aggregate average April through July runoff in the basin (Figure 21). Like the Gunnison River Basin, April through July Runoff corresponds better to date signaling the end of the snowpack season than to the date signaling the beginning of the snowpack season.

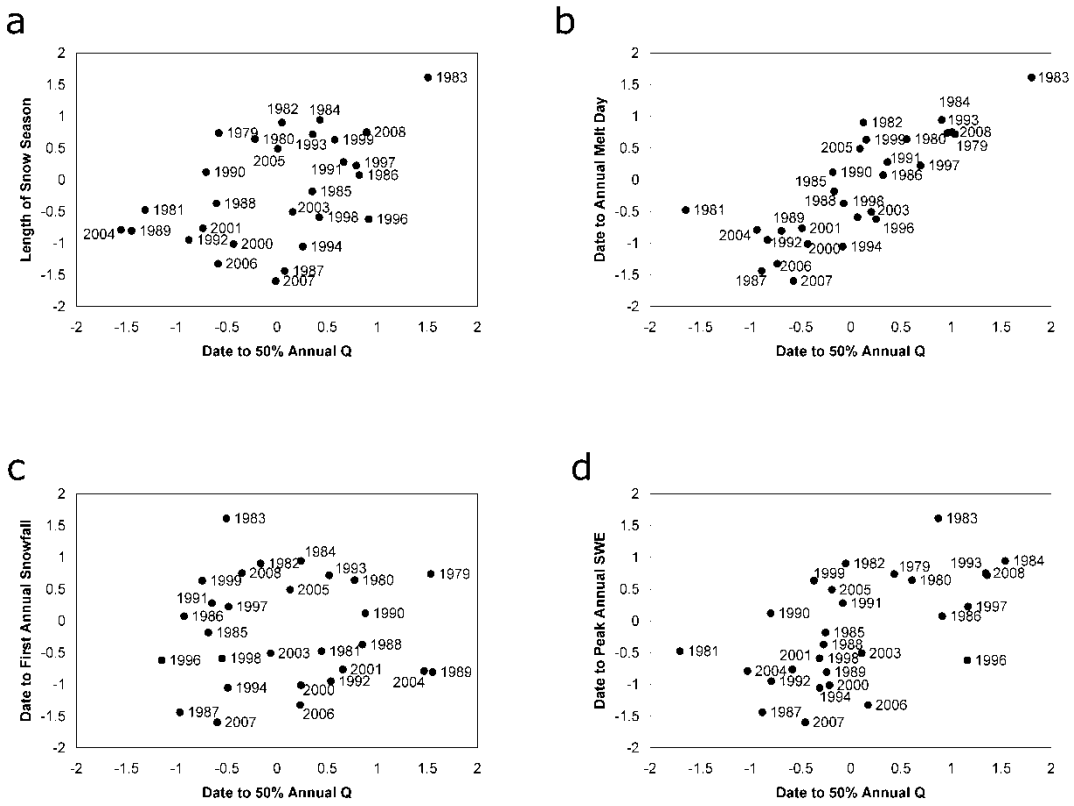

Figure 20: As described in Figure 18, for the Colorado Headwaters Basin.

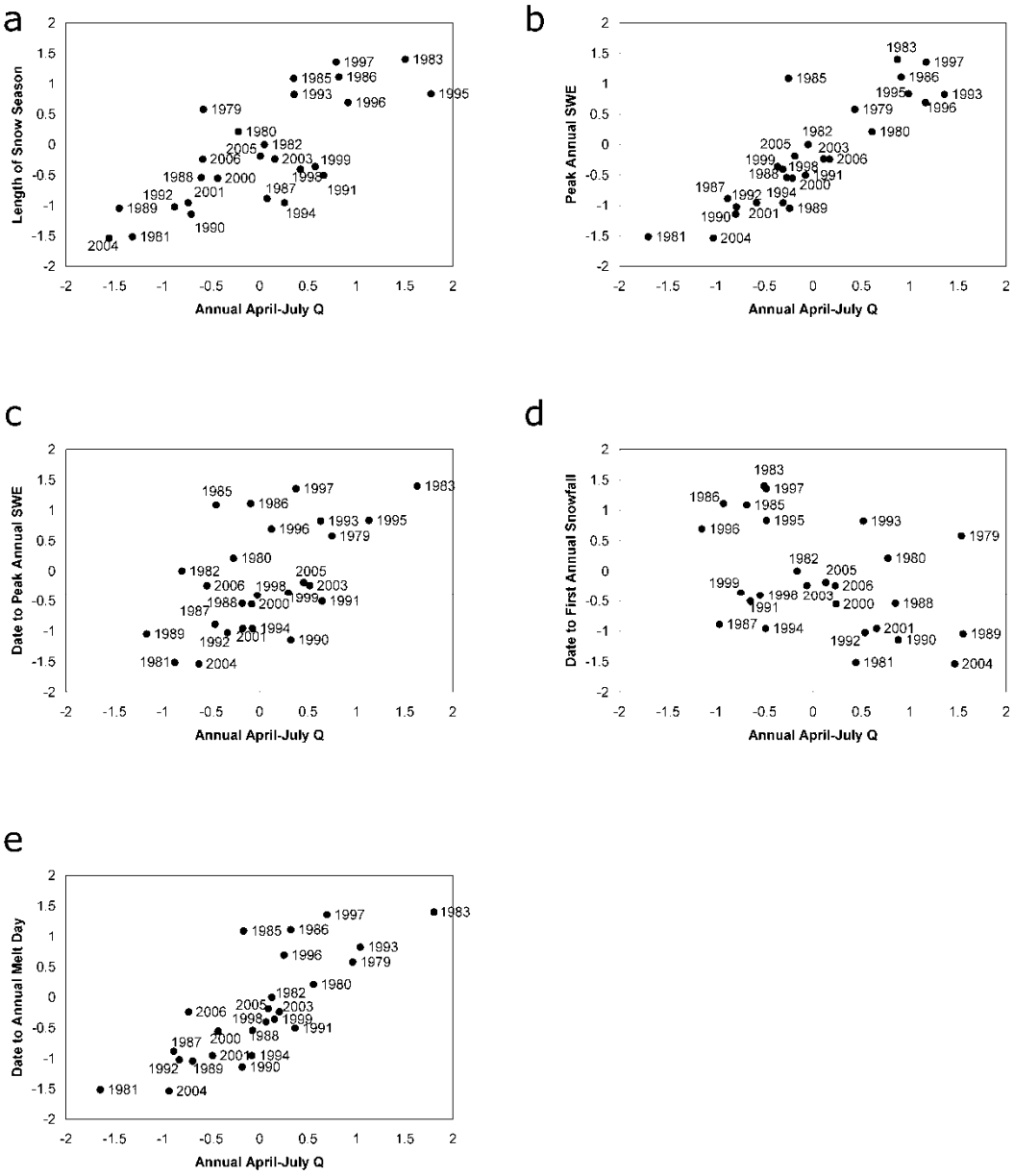

Figure 21: As described in Figure 19, for the Colorado Headwaters Basin.

4.6.3 Upper Green River Basin

The Upper Green River Basin is the northern most subbasin in the Upper Colorado River Basin, the bulk of which is located in southwest Wyoming. The subbasin contributes approximately 14.4% of the annual water year runoff to the Colorado River (Hoerling & Eischeid, Unpublished) and is primarily regulated by Reclamation through the Fontenelle and Flaming Gorge Dams. Flaming Gorge Dam is operated in accordance with the EIS published by Reclamation (U.S. Department of the Interior, Bureau of Reclamation, Upper Colorado Region, 2005) in order to protect critical habitat for endangered fish species in the region while maintaining water use development goals under the Colorado River Storage Project.

Like previous subbasins discussed here, decreasing (increasing) aggregate average streamflow corresponds with an average aggregate earlier (later) end to the snowpack season. Shorter average snowpack seasons tend to correspond well with earlier timing associated with 50% of the annual water year runoff. Similarly to the Gunnison and Colorado River Headwaters subbasins, there does not seem to be a strong agreement between the beginning of the snowpack season and the date to the 50% of the annual water year runoff (Figure 22).

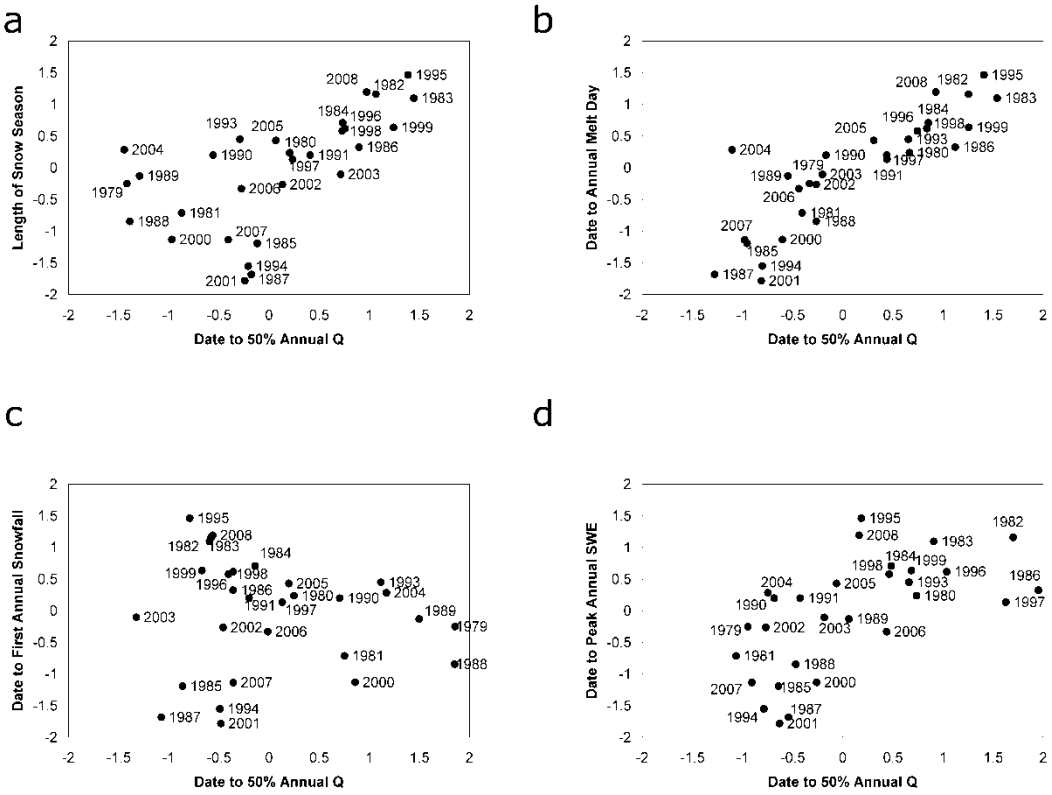

Figure 22: As described in Figure 18, for the Upper Green Basin.

April through July runoff in the Upper Green River Basin is representative of the total annual water year flow. Throughout the period of shared observations, there is good correspondence between observed aggregate average peak SWE and April through July runoff. The average aggregate date to the peak SWE observation also agrees with April through July runoff, where earlier (later) peak SWE observations typically indicate below (above) average aggregate April through July runoff. Again, average aggregate April through July runoff corresponds more strongly with the end of the snowpack season than with the beginning of the snowpack season (Figure 23).

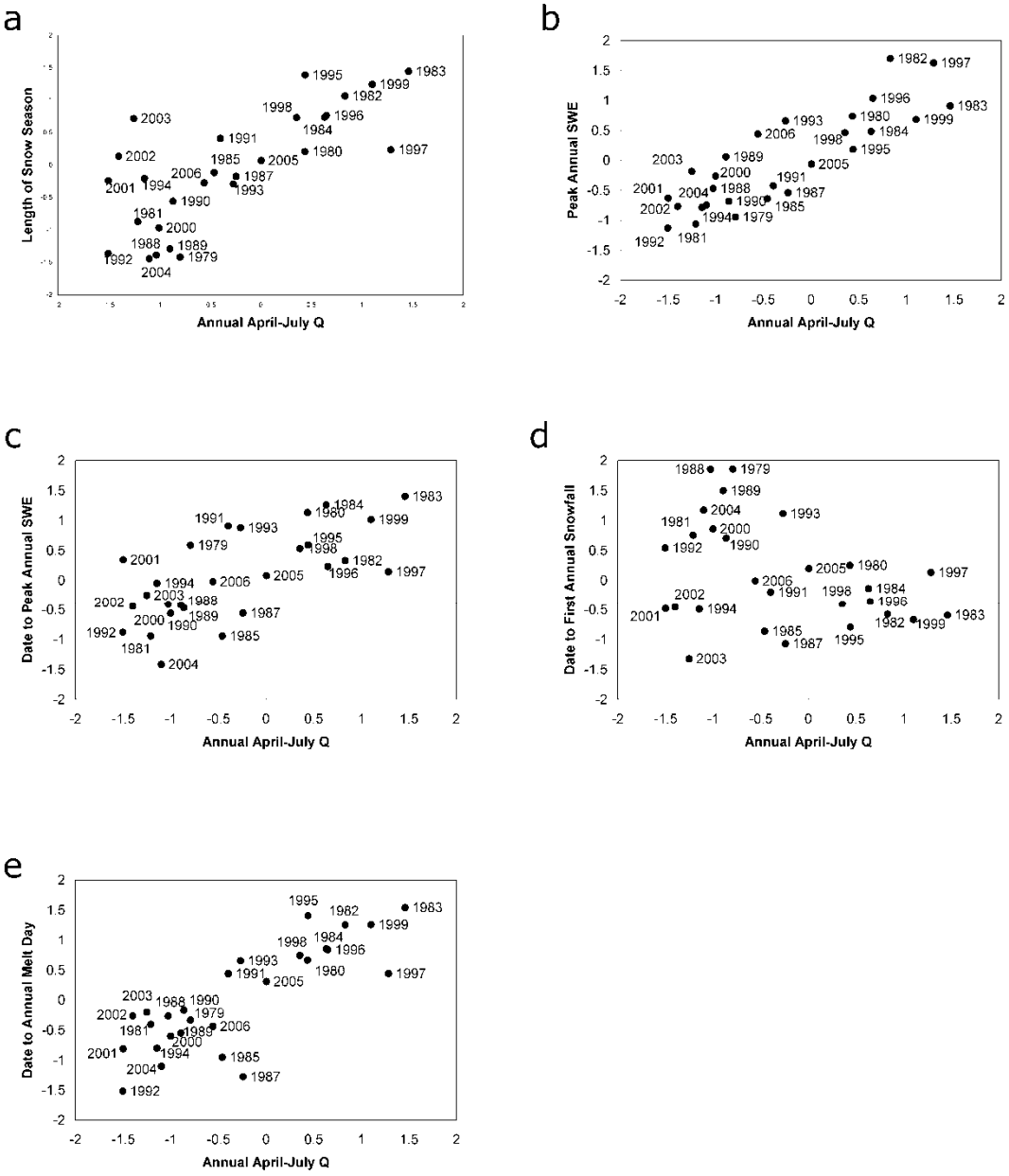

Figure 23: As described in Figure 19, for the Upper Green Basin.

4.6.4 Lower Green River Basin

The Lower Green River Basin contributes approximately 10% (Hoerling & Eischeid, Unpublished) of the annual water year streamflow to the mainstem Colorado River in the Upper Colorado River Basin. The basin covers the majority of eastern Utah and is largely unregulated by major dams or diversions.

Like previous subbasins discussed here, decreasing (increasing) aggregate average streamflow corresponds with an average aggregate earlier (later) end to the snowpack season. Shorter average snowpack seasons tend to correspond well with earlier timing associated with 50% of the annual water year runoff. There does not seem to be a strong agreement between the beginning of the snowpack season and the date to the 50% of the annual water year runoff (Figure 24).

Aggregate average peak SWE observations correspond well with aggregate average April through July runoff in the basin, and, to a lesser extent, the average aggregate date to the peak SWE corresponds well to April through July runoff in the basin as well. As with other previously discussed river basins, the end of the snowpack season corresponds well with the April through July runoff, whereas an earlier end to the snowpack season corresponds well with below average April through July runoff. Water year streamflow volume correlates well with April through July runoff in the basin (Figure 25).

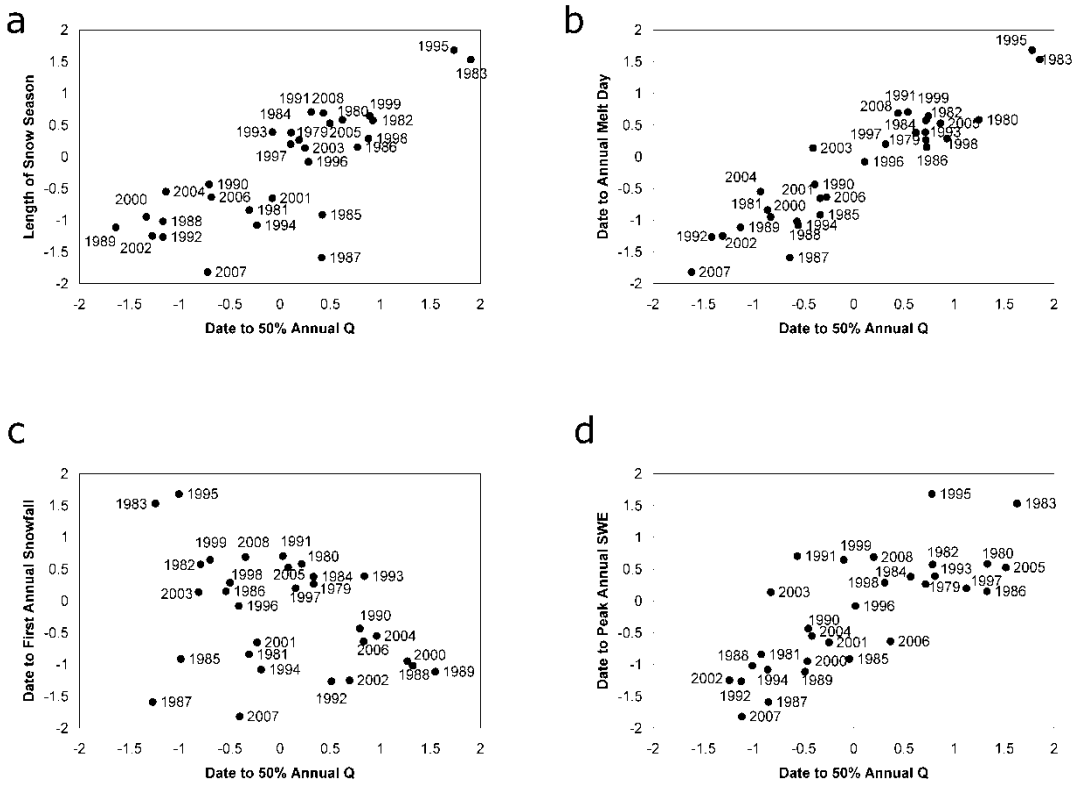

Figure 24: As described in Figure 18, for the Lower Green Basin.

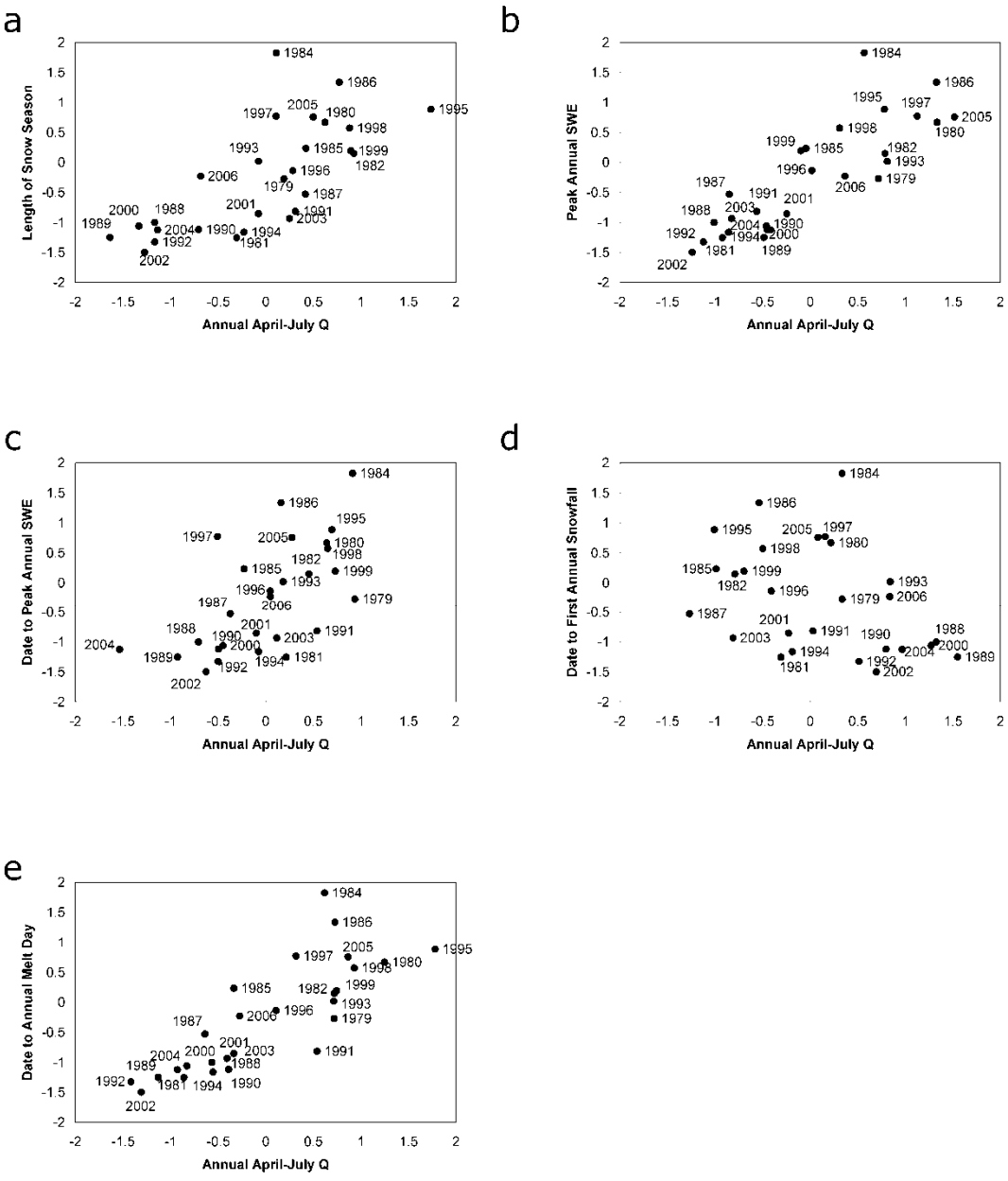

Figure 25: As described in Figure 19, for the Lower Green Basin.

4.6.5 San Juan River Basin

The San Juan River Basin contributes nearly 12% of the average annual runoff to the mainstem Colorado from the Upper Colorado River Basin (Hoerling & Eischeid, Unpublished). The San Juan River within the basin is regulated primarily by Reclamation through the operation of the Vallecito and Navajo Dams and reservoirs. The Navajo reservoir is part of the aforementioned Colorado River Storage Project and is operated to aid the continued development of water resources in the Upper Colorado River Basin. The Navajo reservoir in operated under accordance with Environmental Impact Statement published by Reclamation (2006) and in conjunction with the Fish and Wildlife Service's (FWS) San Juan River Basin Recovery Implementation Program (U.S. Fish and Wildlife Service, 2006) in an effort to protect critical habitat to endangered fish species in the basin.

Average aggregate snowpack characteristics compared with the average aggregate date to 50% annual streamflow similarly to those comparisons made to previous basins. Over the past decade earlier dates to average aggregate peak SWE correspond well with earlier average aggregate date to 50% water year streamflow (Figure 26).

Average aggregate snowpack characteristics correspond with average aggregate April through July runoff characteristics in a similar fashion as previously discussed river basins. In particular, there is strong correspondence between average aggregate peak SWE and the timing of the end of snowpack season with average aggregate April through July runoff (Figure 27).

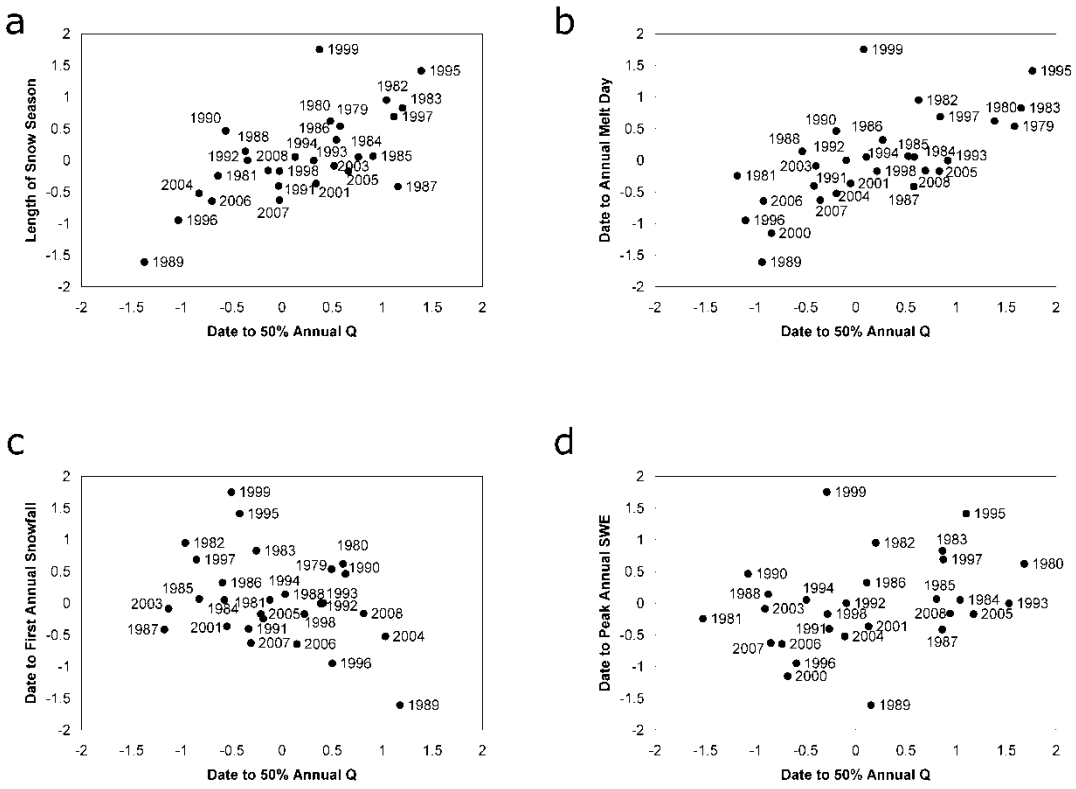

Figure 26: As described in Figure 18, for the San Juan Basin.

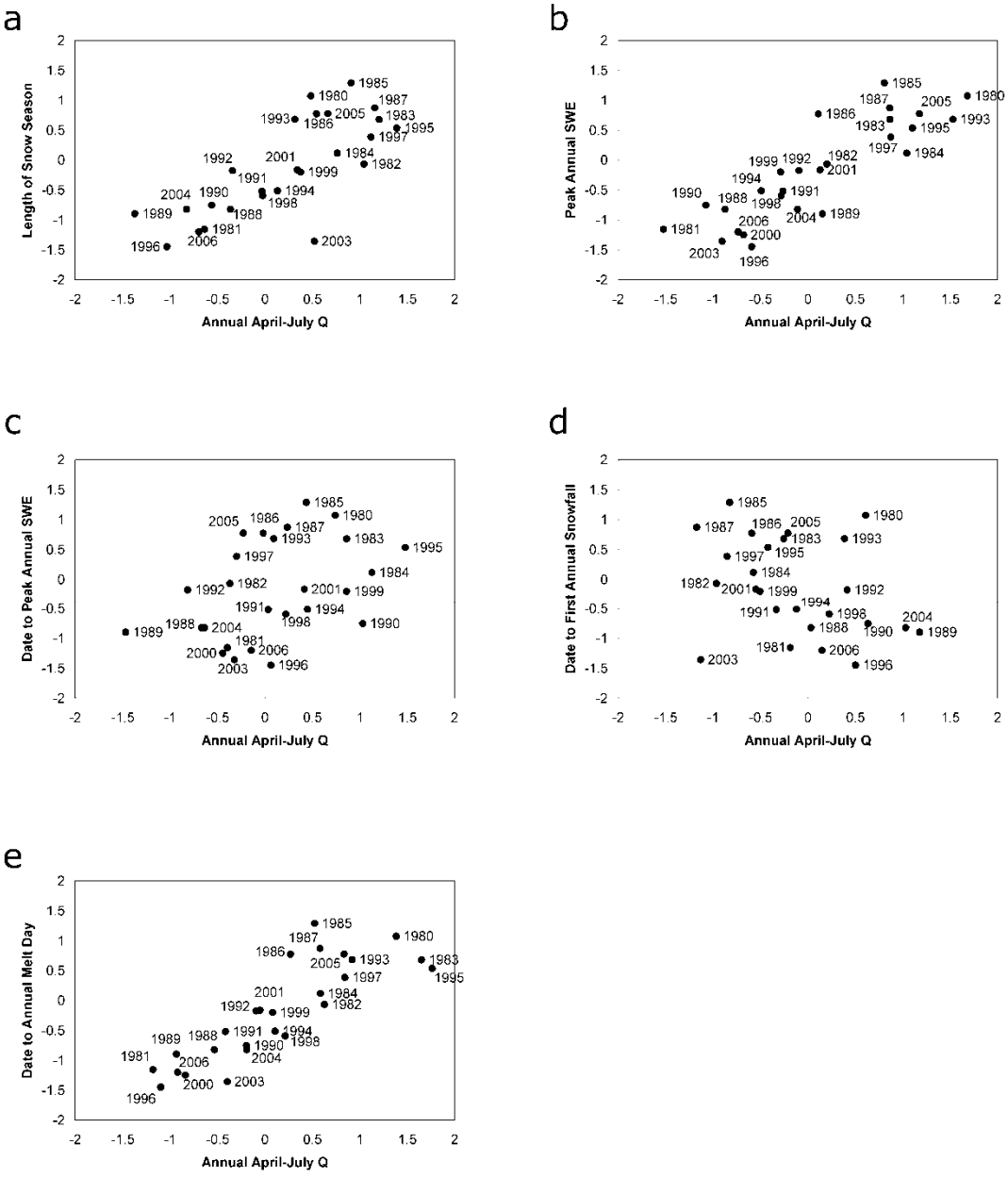

Figure 27: As described in Figure 19, for the San Juan Basin.

4.6.6 Yampa River Basin

The Yampa River Basin extends from southern Wyoming through northwest Colorado and northeast Utah and contributes approximately 16% of the annual water year inflow to the Colorado River mainstem (Hoerling & Eischeid, Unpublished) through the White, Snake, and Yampa tributaries.

Average aggregate snowpack characteristics compared with the average aggregate date to 50% annual streamflow similarly to those comparisons made to previous basins. Over the past decade earlier dates to average aggregate peak SWE correspond well with earlier average aggregate date to 50% water year streamflow. Like other subbasins in the Upper Colorado River Basins, there is little correlation between the date to start of the snowpack season and the date to 50% of the annual water year runoff (Figure 28).

In the Yampa River Basin, average aggregate snowpack characteristics correspond with average aggregate April through July runoff characteristics in a similar fashion as previously discussed river basins. April through July runoff continues to be representative of water year snowpack.

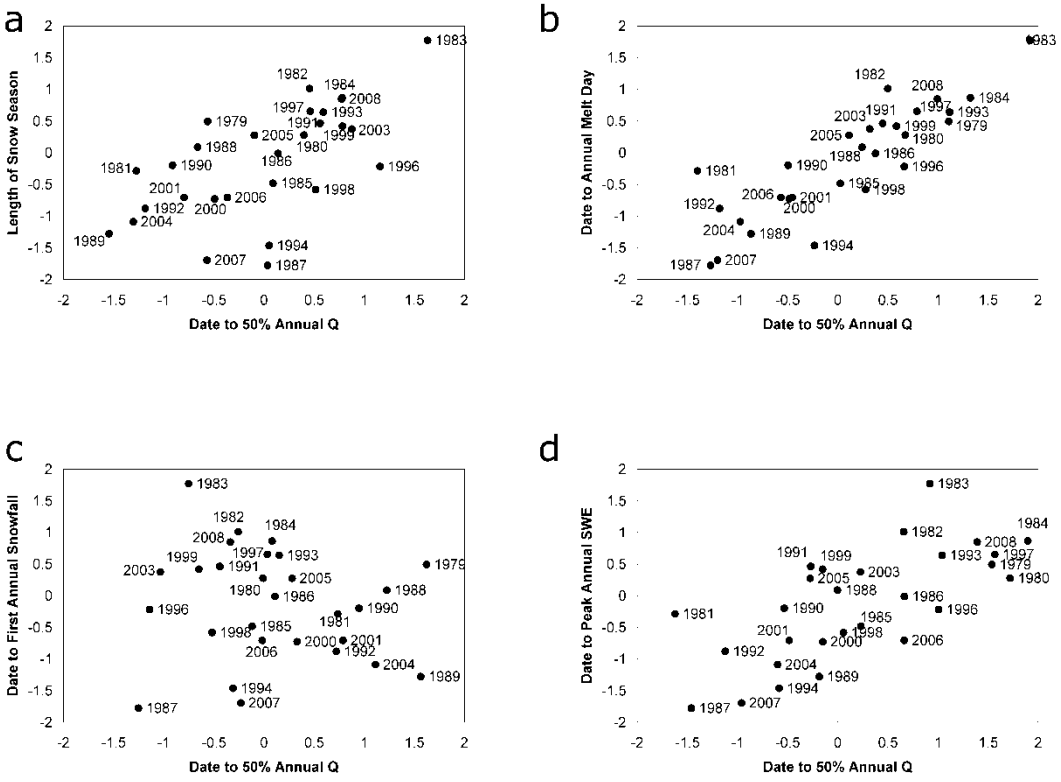

Figure 28: As described in Figure 18, for the Yampa Basin.

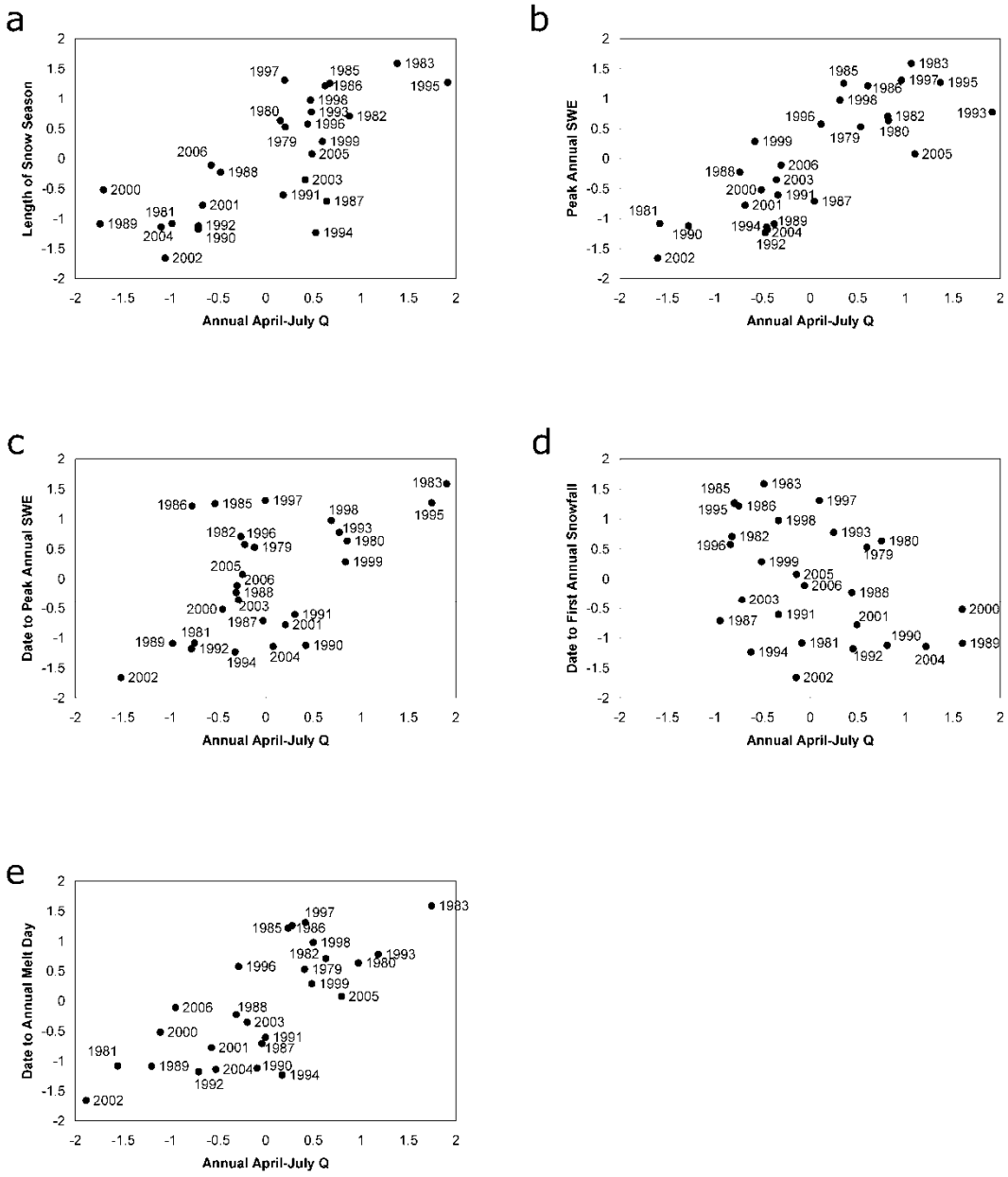

Figure 29: As described in Figure 19, for the Yampa Basin.

4.7 Discussion Regarding Precipitation and Streamflow Characteristics in the Colorado River Basin

Basin scale hydroclimatology has become an important consideration of water resource managers, particularly as it relates to streamflow within a river system (e.g., Grantz et al., 2005). As such, consideration of hydroclimatic trends within the Colorado River Basin has become important, particularly in light of the recent historic drought. In this study, there is evidence to suggest significant decreasing trends in snowpack, particularly during the current drought period. In the snow driven hydrology of the Upper Colorado River Basin, this correlates well with decreasing trends in both observed and natural streamflow in the basin.

Based on daily SNOTEL observations, the length of snowpack season has shortened during this period of drought, and corresponds to below average aggregate April through July runoff in Colorado headwater river basins. Interestingly, there is a much stronger correspondence between runoff characteristics and the timing of the end of the snowpack season than correspondence between runoff characteristics and the timing of the beginning of the snowpack season.

While these results agree and provide support for previous studies showing a shift in the timing and magnitude of runoff in the Colorado River Basin, this study does not support an earlier hypothesis by Miller and Piechota (2008) suggesting that the timing of runoff in the Colorado River Basin is due to the changing characteristics of precipitation in the basin. This study did not observe any significant trends in the frequency of snowfall and rainfall events. Investigation into the frequency of precipitation events with a more robust gaging network (e.g. COOP stations) in conjunction with temperature

observations may provide improved insight as to the changing character of precipitation in the basin. However, this study does support that over this period of drought, the Colorado River Basin is experiencing decreased snowpack and shorter snowpack seasons due to earlier snowmelt.

As this period of drought continues in the Colorado River Basin, water resource managers and forecasters should continue to expect shorter snowpack seasons and resultant decreased and earlier runoff in the basin. It is possible that earlier snowmelt runoff is more susceptible to infiltration and evaporative losses throughout the basin, as increasing temperatures may increase both potential and actual evapotranspiration rates. With continued drought and decreased spring runoff, water resource managers must continue effective water management policies and conservation practices.

CHAPTER 5

DEVELOPMENT OF STREAMFLOW PROJECTIONS UNDER CHANGING CLIMATE CONDITIONS OVER COLORADO RIVER BASIN HEADWATERS

5.1 Introduction

As detailed in previous chapters, the Colorado River Basin is currently experiencing the worst drought over the observed record (e.g, Timilsena et al., 2007). At the beginning of water year 1999 (October 1998), water storage in the Colorado River Basin was at 94% capacity; in particular, the two largest reservoirs within the system, Lake Powell and Lake Mead, were at 98% and 91% capacity, respectively. Since 1999, water storage in the Colorado River Basin has decreased to 56% capacity; Lake Powell and Lake Mead are currently at 44% and 58% capacity, respectively. The current drought has increased concerns on the ability of Reclamation to continue to meet water delivery requirements (Barnett & Pierce, 2008; Barnett & Pierce, 2009; Barsugli et al., 2009; Rajagopalan et al., 2009) and the impacts of climate change to hydroclimatology over the Colorado River Basin and the American West (e.g., Balling Jr. & Goodrich, 2007; L. D. Brekke et al., 2008; Christensen & Lettenmaier, 2007; Fassnacht, 2006; Matter et al., 2010; Maurer, 2007; Meko et al., 2007; Miller & Piechota, 2008). In previous study, Miller and Piechota (2008), enforced previous research indicating warming temperature trends over the Colorado River Basin region and corresponding changes in the timing of streamflow within the basin (e.g., Christensen & Lettenmaier, 2007; Hamlet et al., 2005; Hamlet & Lettenmaier, 2007; Hidalgo et al., 2009; Kalra et al., 2008; Regonda et al., 2005; Timilsena & Piechota, 2008). In Chapter 4, decreasing trends in snowpack over the

Colorado River Basin and the American West were shown to correspond with decreasing annual streamflow within the Colorado River Basin. It was suggested that current streamflow prediction models predominantly driven by observed snowpack conditions and utilized by the CBRFC may need to be investigated in light of changing climate conditions.

Traditionally, Reclamation has used historical data to project future streamflow conditions and associated reservoir operations. Implicit in this practice is the assumption that the distribution of past data (e.g., mean, variance, standard deviation) is representative of future conditions. Under changing climate conditions, the past may no longer be representative of the future (e.g., L. D. Brekke et al., 2008). Climate change caused by anthropogenic influences has influenced global climate and hydrology such that past hydroclimatic means and extremes are no longer representative of expected hydroclimatology (Solomon & Intergovernmental Panel on Climate Change, Working Group I, 2007). Milly et al. (2008) defines stationarity as the idea that natural systems fluctuate within an unchanging envelope of variability. As such, the assumption of hydroclimatic stationarity over the Colorado River Basin under climate change may not be correct.

Streamflow in the Lower Colorado River Basin has been shown to exhibit signs of nonstationarity and climatic teleconnection phases such as the AMO, PDO, and SOI (e.g., Thomas, 2007). Mauget (2003) investigated multidecadal trends in streamflow, precipitation, and temperature over a 106 year period (1861 – 2001) using parametric Mann – Whitney U and Z statistical techniques. It was noted that precipitation displayed nonstationary behavior after 1972. Over the 106 year observational period, 8 of the 10

wettest years occurred between 1973 and 1999, particularly over the southwestern, central, and eastern regions of the United States. Drier conditions in the American West have persisted since 1999. In contrast, 6 of the 10 warmest years occurred between 1986 and 2000 and have continued to persist throughout the southwest. Streamflow conditions are representative of nonstationary behavior in the precipitation and temperature record and have decreased with drier, warmer conditions. These results are supported by later studies indicating nonstationary behavior in the streamflow record using nonparametric statistical tests (i.e., Kendall's τ and Spearman's ρ) to changes in climate teleconnection indices (e.g., AMO, PDO, SOI) (e.g., Thomas, 2007). Under changing climate conditions, the Colorado River Basin exhibits nonstationary behavior in temperature and precipitation characteristics, contributing to a hydrologic deficit in the basin, especially in the southwest.

Water managers have traditionally relied on the assumption of hydroclimatic stationarity to efficiently manage water resources and environmental operations. The timing and magnitude of runoff events is of particular importance, as actual and forecasted runoff events can impact the operation of reservoirs; however, climate change and anthropogenic alterations to basin characteristics increase the difficulty in accurately projecting streamflow conditions within hydrologic systems (e.g., Villarini et al., 2009). Raff et al. (2009) developed a methodology to assess flood risk and runoff projections using projections of future climate. Raff et al. (2009) utilized temperature and precipitation data from 112 GCMs within the WCRP CMIP3 dataset (Meehl et al., 2007) subjected to statistical downscaling and bias-correction (Maurer et al., 2007) to drive the NWS RFS hydrologic model over the Boise River above Lucky Peak Dam in Idaho,

James River above Jamestown Dam in North Dakota, San Joaquin River above Friant Dam in California, and the Gunnison River Basin above Blue Mesa Dam in Colorado. Each of the four basins investigated in Raff et al. (2009) exhibited the potential for increased flood frequency under changing climate conditions, although the authors to acknowledge the need for further study to more fully understand these results. Other recent studies have developed alternative methodologies for incorporating temperature and precipitation patterns over the Upper Colorado River Basin (Matter et al., 2010). The models and data sources presented in Raff et al. (2009) are very similar to the models and data sources utilized in this focus of the study.

Hydrologic studies such as the one presented here and others (e.g., Maurer & Duffy, 2005; Maurer, 2007; Raff et al., 2009; VanRheenen et al., 2004) are typically developed over regional, basin scales, so there exists a disconnect between the large spatial scale of the output from GCMs and their usability in hydrologic studies. Furthermore, GCMs do not capture details important to regional hydrologic studies such as local climate circulation or the orographic character of the basin (e.g., Metz & Intergovernmental Panel on Climate Change, Working Group III, 2007; Wigley, 2004).

Statistical downscaling utilized observed data at the desired level of resolution to derive relationships between high resolution output from GCMs and the regional climate scale of interest. Although computationally inexpensive, statistical downscaling does require a sufficiently long record of observational data to develop satisfactory cross scale relationships; most statistical downscaling methods also assume some measure of stationarity over the climate record; under changing climate conditions, the assumption of stationarity may not be valid (e.g., Koutsoyiannis et al., 2007; Matter et al., 2010; Milly

et al., 2008; Thomas, 2007). Despite this limitation, statistical downscaling methods are computationally inexpensive and are able to develop higher scales of resolution of climate data over a longer period of time than most regional climate models. When properly applied, the level of uncertainty and the quality of downscaled data derived using dynamical and statistical methods is comparable (Solomon & Intergovernmental Panel on Climate Change, Working Group I, 2007; Wigley, 2004; Wood et al., 2004).

In this research, statistically downscaled data derived using the BCSD method developed by Wood et al. (2004) is used. The method is documented in numerous peer-reviewed academic studies (Cayan et al., 2007; Christensen et al., 2004; Hayhoe et al., 2004; Hayhoe et al., 2007; Maurer & Duffy, 2005; Maurer, 2007; Payne et al., 2004; VanRheenen et al., 2004; Wood et al., 2004) and produces downscaled temperature and precipitation data that statistically matches the historical period.

The BCSD technique developed by Wood et al. (2004) is unique from other statistical downscaling methods in that the method is able to simultaneously produce gridded time series of precipitation and temperature data; most statistical downscaling methods are limited to a single variable, with some exceptions (Harpham & Wilby, 2005; e.g., Wilks, 1999). For regional hydroclimatic studies, it is important that the variables of interest (precipitation and temperature) are developed simultaneously to develop realistic spatial and temporal climate relationships. It is important to note that any biases over the historical period within the climate data that are a result of the GCM itself will be projected into the future, but the BCSD method compares very well with other statistical downscaling methods (Wood et al., 2004).

In this study, the development of a methodology to develop streamflow projections for use in Reclamation river and reservoir management models is described. This study will examine the impacts of changing climate to evapotranspiration rates, which has not yet been fully addressed in this area of research, and much less over the Colorado River Basin. The need to address evapotranspiration rates in climate study over the Colorado River Basin has been documented (e.g., L. Brekke & Prairie, 2009). The impact to evapotranspiration rates are taken into consideration and incorporated into the development of streamflow projections over Colorado River headwater basins in this study. The results of this study further the goals of the Colorado River Basin Water Supply and Demand Study (U.S. Department of the Interior, Bureau of Reclamation, Lower Colorado Region, 2009).

Streamflow projections are examined for evidence of nonstationarity within the projected period through the use of the Kolmogorov-Smirnov Test (KS – Test). Currently, there is debate regarding the validity and degree of nonstationarity within the Colorado River Basin. Through consideration of the distribution of streamflow over Colorado River headwater basins and results of the KS – Test, this study attempts to further this discussion.

5.2 Study Area

In this study, projections of streamflow are developed over the Gunnison, Green, and San Juan River Basins (Figure 30). Collectively, the three basins contribute approximately 40% of the annual runoff in the Upper Colorado River Basin (Hoerling & Eischeid, Unpublished).

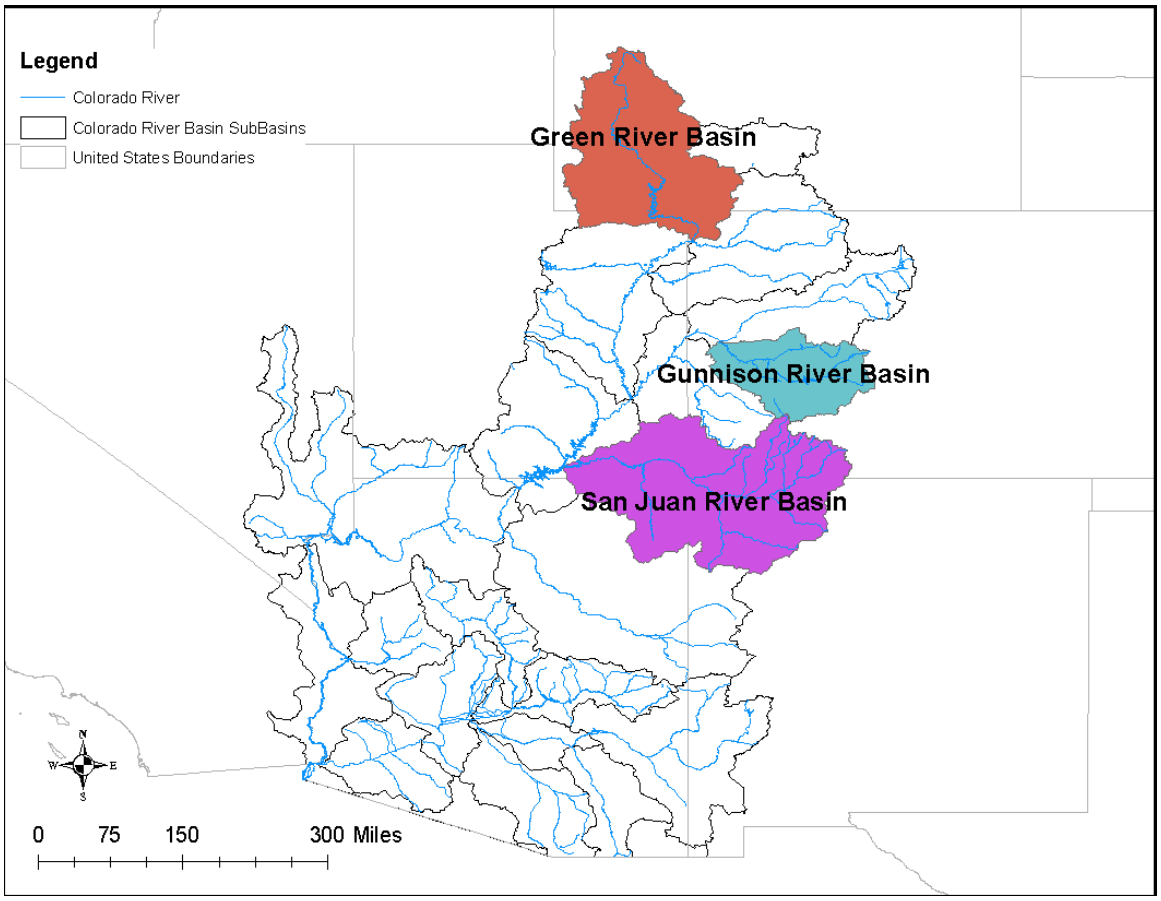

Figure 30: The Colorado River headwater basins considered in this study.

The basins in this study provide an opportunity to cover a broad latitudinal range of the Upper Colorado River Basin and compare results to other research efforts in the area. The Gunnison River Basin has been the subject of numerous studies, particularly for the application of downscaled climate projections (e.g., L. Brekke & Prairie, 2009; McCabe Jr., 1994; Raff et al., 2009; U.S. Department of the Interior, Bureau of Reclamation, Upper Colorado Region, 2009). Research on the impacts of teleconnection events on drought and streamflow conditions in the Green River Basin have provided some insight as to the role of climate variability over the Colorado River Basin (G. A. Tootle & Piechota, 2003). Pursuant to the National Environmental Protection Act (NEPA) of 1969, an Environmental Impact Statement (EIS) and Record of Decision (ROD) were

published in 2006 defining the operations of the Navajo Reservoir within the San Juan River Basin to aid in the conservation of endangered fish species, habitat, and continue to meet Reclamation's obligations to water delivery requirements and Native American water rights (U.S. Department of the Interior, Bureau of Reclamation, Upper Colorado Region, 2006).

5.3 Data

5.3.1 Bias Corrected Spatially Downscaled Precipitation and Temperature Data

Reclamation, in cooperation with Lawrence Livermore National Labs and Santa Clara University, has made available BCSD precipitation and temperature data from the WCRP CMIP3 dataset over the continental United States (available at: http://gdo-dcp.ucllnl.org/downscaled_cmip3_projections). This climate data has been downscaled to 1/8th degree (approximately 7.5 miles or 12 kilometers) grid cell resolution, making it more useful for regional hydrologic analysis. As previously described, this data have been downscaled using the BCSD technique described in Wood et al. (2004) and is available at a monthly timestep. Figure 31 illustrates the impact of the BCSD method.

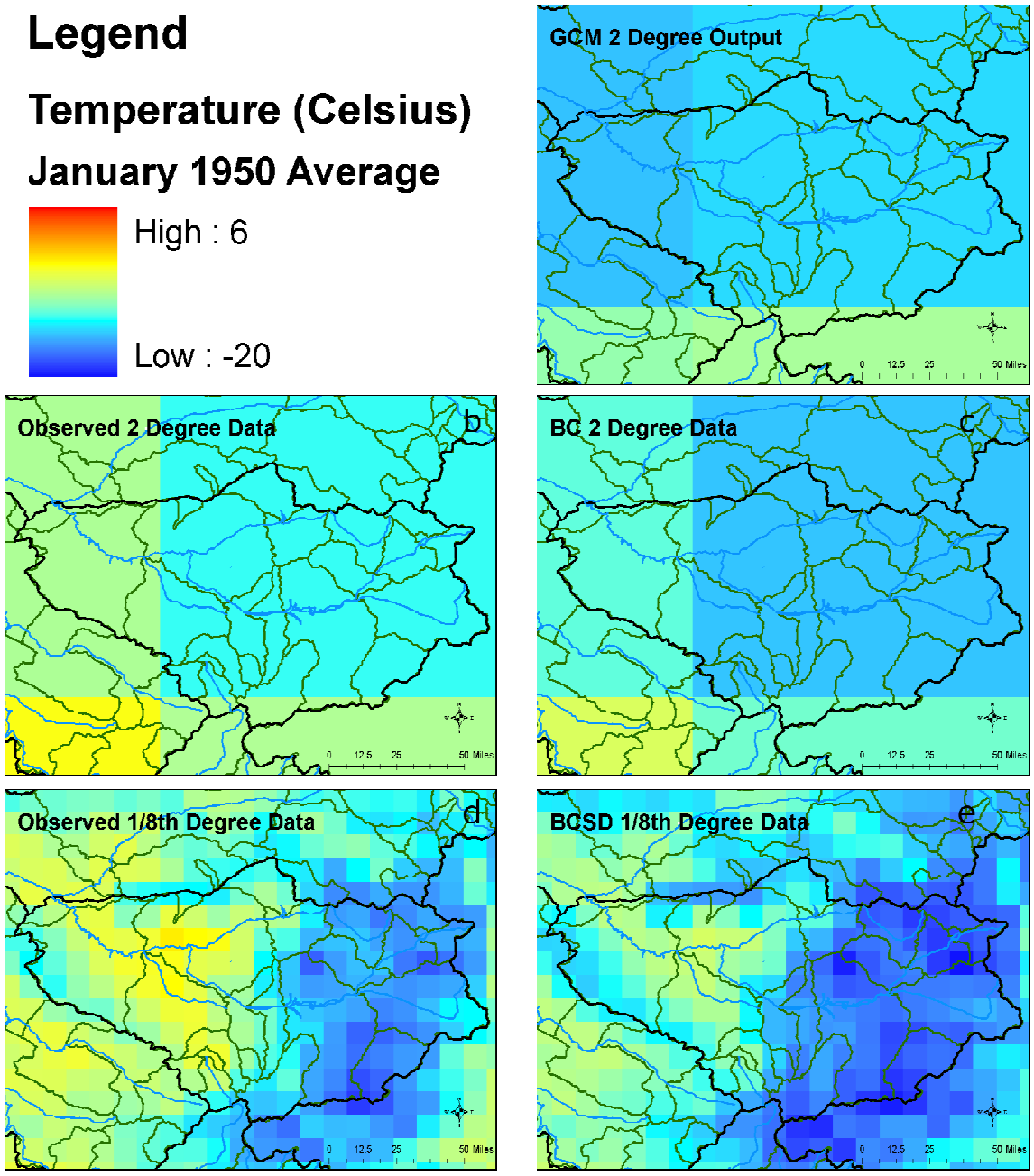

Figure 31: Observed and modeled average monthly temperature in January 1950 was obtained over the Gunnison River Basin. a) displays raw, 2 degree output from the Canadian Centre for Climate Modeling and Analysis GCM under emissions scenario A2. b) displays observed temperature at the 2 degree scale. c) displays modeled temperature at the 2 degree scale that has been bias corrected. d) displays observed temperature at the 1/8th degree scale. e) displays modeled temperature data at the 1/8th degree scale that has been bias corrected and spatially downscaled.

Reclamation is also currently developing streamflow projections over the Upper Colorado River Basin using the Variable Infiltration Capacity (VIC) model and the BCSD dataset described in this study in the Colorado River Basin Water Supply and Demand Study (U.S. Department of the Interior, Bureau of Reclamation, Lower Colorado Region, 2009). The VIC model being used by Reclamation is being run at a daily timestep; as such, temporal disaggregation of data from the monthly BCSD dataset over the Colorado River Basin is required. Temporal disaggregation of the monthly data was accomplished by scaling historical daily precipitation or shifting historical daily temperature data to match monthly time series data (Wood et al., 2004). This study utilizes the daily precipitation and temperature time series derived for that study. Future work will aim to reconcile differences between Reclamation's research efforts with the VIC hydrologic model and this study's effort with the NWS CBRFC RFS model.

5.3.2 Emissions Scenarios

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

emphasis placed on the sharing or exchange of information. For this study, it may be interpreted as the most pessimistic storyline and more apparent increasing temperatures.

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

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

5.3.3 Projections of Evapotranspiration

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

$$E = \frac{1}{\lambda}\left[\frac{\Delta A + \rho_a c_P \, D/r_a}{\Delta + \gamma\left(1 + r_s/r_a\right)}\right] \tag{19}$$

where E is evapotranspiration in mm/day, Δ is the gradient of the saturated vapor pressure with respect to temperature, A is the energy available for partitioning into latent or sensible heat, D is the vapor pressure deficit, r_a is the aerodynamic resistance, r_s is the surface resistance of land cover, and γ is the psychrometric constant in kPa/^{o}C and defined by:

$$\gamma = \frac{c_P P}{\in \lambda} * 10^{-3} \tag{20}$$

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

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

$$ET_R = \frac{\left(ET_1 - ET_0\right)}{ET_0} \tag{21}$$

where ET_R is a ratio representing change in evapotranspiration demand per degree Celsius. ET_1 is the evapotranspiration rate calculated by the VIC model after the increase in temperature, and ET_o is the original evapotranspiration rate prior to the change in temperature parameters.

Results were then averaged over a monthly timestep. In practice, monthly evapotranspiration rates are adjusted as a calibration parameter in the RFS by the CBRFC. Although this study was unable to use the calibration model used by the CBRFC, calibration of streamflow projections was achieved through the use of a ratio method in post-processing of streamflow output (see Section 5.4.4 and 5.6).

5.4 Methodology

5.4.1 Hydrologic Model

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

calibration model run at the CBRFC is dependent on infrastructure unique to the CBRFC; thus, this study does not operate the NWS RFS model exactly as it is run at the CBRFC.

The NWS CBRFC RFS model used in this study incorporates mean areal temperature (MAT) and mean areal precipitation (MAP) input files. Over the water year 1976 through water year 2005 calibration period, the CBRFC derives these files through the use of gage measurements provided by a variety of sources (e.g., NOAA, NRCS, NCDC, USGS, and Reclamation). In this study, MAT and MAP files are developed using BCSD, temporally disaggregated climate data from the WCRP CMIP3 dataset.

The NWS RFS model provided by the CBRFC relied on values of evapotranspiration demand unique to each month; that is, evapotranspiration demand in any given month is identical throughout the length of the model run. This evapotranspiration demand, though reasonable and comparable to evapotranspiration measurements over any given area, was derived through the use of a separate calibration model to more closely align forecasted streamflow output with observations of streamflow over the calibration period. In this study, evapotranspiration is a function of monthly average projected temperature. As such, a third input file describing mean areal evapotranspiration (MAE) was derived in this study.

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

upstream local catchments in addition to precipitation and temperature input. Figure 32 illustrates the CBRFC catchments over the Gunnison River Basin and surrounding Colorado River Basin area.

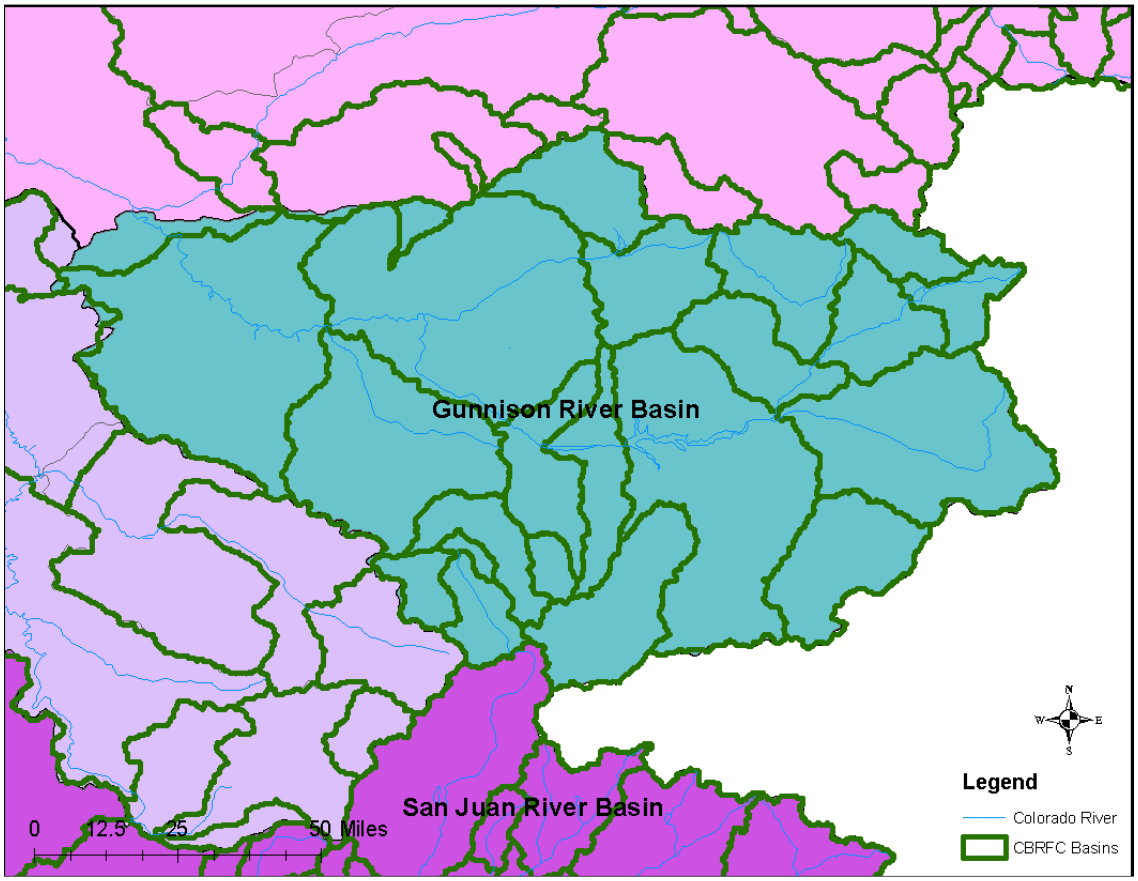

Figure 32: Catchments over the Gunnison River Basin and the surrounding Colorado River Basin are outlined in dark green.

5.4.2 Derivation of MAT Input Files

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

CBRFC, the empirical relationships derived over the Colorado River Basin are as follows:

$$\begin{aligned} 00Z &= 0.950 * T_{\min} + 0.050 * T_{\max-1} \\ 06Z &= 0.400 * T_{\min} + 0.600 * T_{\max} \\ 12Z &= 0.025 * T_{\min} + 0.925 * T_{\max} \\ 18Z &= 0.670 * T_{\min} + 0.330 * T_{\max} \end{aligned} \quad (22)$$

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

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

Each catchment is divided into up to three elevation bands as defined by the CBRFC. For each catchment and elevation band within that catchment, a daily time series of minimum and maximum temperature data was derived by taking the average of daily minimum and maximum temperature values from each 1/8th degree grid cell from the

temporally downscaled BCSD dataset. By applying the empirical formulations described in equation (19), a time series of 6-hourly temperature values was derived for each elevation band within each catchment. A MAT file containing this information for each elevation band within each catchment is used as input for the NWS CBRFC RFS.

5.4.3 Derivation of MAP Input Files

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

In this study, time series of precipitation at a 6-hour timestep were derived by first comparing the daily rainfall depth from the temporally disaggregated BCSD dataset to the 30-year record of aggregated daily observations of precipitation used by the CBRFC. The aggregated daily precipitation event occurring in the same month and nearest to the daily precipitation event from the temporally disaggregated BCSD dataset was then identified. The daily precipitation value from the temporally disaggregated BCSD dataset was then disaggregated to a 6-hourly time step proportional to the identified event within the CBRFC observed dataset. A MAP file containing this information for each elevation band within each catchment is used as input for the NWS CBRFC RFS.

5.4.4 Derivation of MAE Input Files

The NWS CBRFC RFS model provided for this study relied on static, monthly evapotranspiration demand within the SAC-SMA process. For this study, the model was

modified to require daily evapotranspiration input. Daily evapotranspiration data was derived by first averaging the rate of evapotranspiration change per 1 degree Celsius derived through the use of the VIC model over each elevation band within each catchment for each month over the 30-year calibration period (1976 – 2005). In addition, 12 base average temperatures were derived for each month using the 30-year calibration period.

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

$$ET_t = ET_{orig} + (T_t - T_{base}) * \overline{ET_R} \quad (23)$$

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

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

CBRFC RFS. See Appendix A for a more detailed explanation of the derivation of evapotranspiration data within this study.

5.4.5 Post-Run Bias Correction

As described previously, the CBRFC runs the NWS RFS in parallel with a separate calibration model. This calibration model is not immediately transferable from the CBRFC to outside agencies; as a result, this study was not able to replicate the calibration process in practice by the CBRFC. Instead, this study uses a ratio method to adjust streamflow projections such that the long term mean over the CBRFC calibration period is equal to the long term mean derived through the use of the temporally disaggregated BCSD data over the calibration period.

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

5.4.6 Model and Data Integration

In this study, numerous data sets were created and integrated to produce projections of streamflow under changing climate conditions. In addition, two models, the NWS CBRFC RFS and the VIC model, were utilized to develop unregulated streamflow projections and relative changes to evapotranspiration with respect to temperature, respectively. Figure 33 illustrates how these models and data sets were derived and integrated to produce the projections of unregulated streamflow presented in this study.

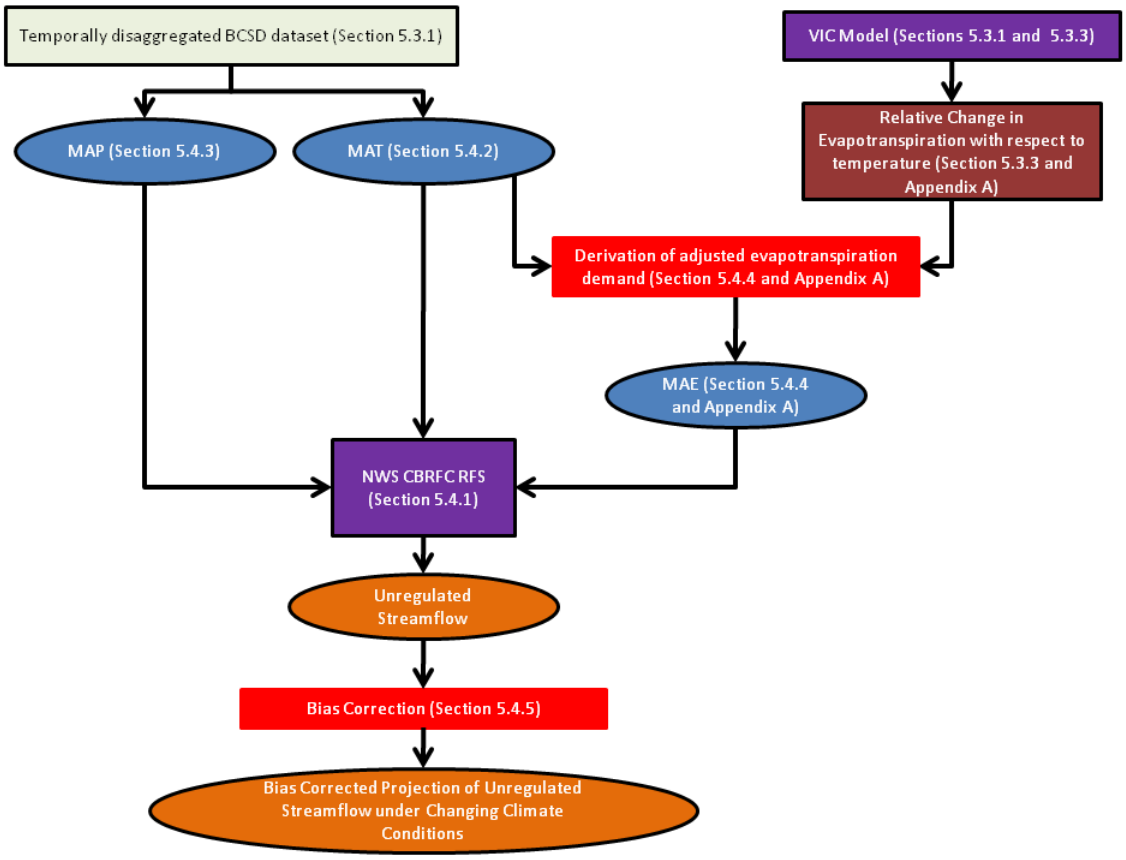

Figure 33: This flow chart illustrates how information from the temporally disaggregated BCSD dataset and information from the VIC model were used to develop precipitation, temperature, and evapotranspiration demand input to drive the NWS CBRFC RFS model. Unregulated streamflow output from the NWS CBRFC RFS model was then bias corrected. It is important to note that the environmental consulting firm AMEC operated the VIC model and evapotranspiration output was provided for use in this study.

5.4.7 Test for Stationarity

The KS – Test is a nonparametric test for determining if the distributions of two samples are the same. The KS –Test compares empirical distributions of two sample sets of data and determining the maximum distance between the two sets of data. This maximum distance is a value from which the hypothesis that the underlying distribution is the same for both samples may be rejected if the value of the maximum distance exceeds a critical value defined by the size of the samples. The KS – Test has been used

to compare ensemble streamflow projections between lumped and distributed hydrologic models (Carpenter & Georgakakos, 2006) as well as detecting changes in the probability distributions associated with precipitation and streamflow events (W. Wang et al., 2008). In this study, the KS – Test is utilized to compare probability distributions of multi-decadal streamflow projections.

5.5 Results of RFS Model Runs

5.5.1 Impact of Evapotranspiration Incorporation

The NWS CBRFC RFS model derives monthly evapotranspiration demand through the use of a separate calibration model. Streamflow response to evapotranspiration is significant and in defining an evapotranspiration time series based on temperature, it is acknowledged that this study has deviated appreciably from how the CBRFC currently derives unregulated inflow forecasts. However, current research has not incorporated climate change impacts to evapotranspiration despite its important role in the hydrologic cycle.

Figure 34 illustrates the impact of taking into account climate change impacts to evapotranspiration. Whereas the 10^{th} and 90^{th} percentiles over the 90 year projection period are approximately equal, the mean of the 112 climate projections is different. Over the 2010 – 2039 time period, adjusting evapotranspiration in response to temperature change results in a decrease of approximately 121,000 acre-feet (approximately 6%) than projections made without an adjustment to temperature. This difference increases over time, with a decrease of approximately 209,000 acre-feet (approximately 10%) and approximately 267,000 acre-feet (approximately 13%) over the 2040 – 2069 and 2070 – 2099 time periods, respectively.

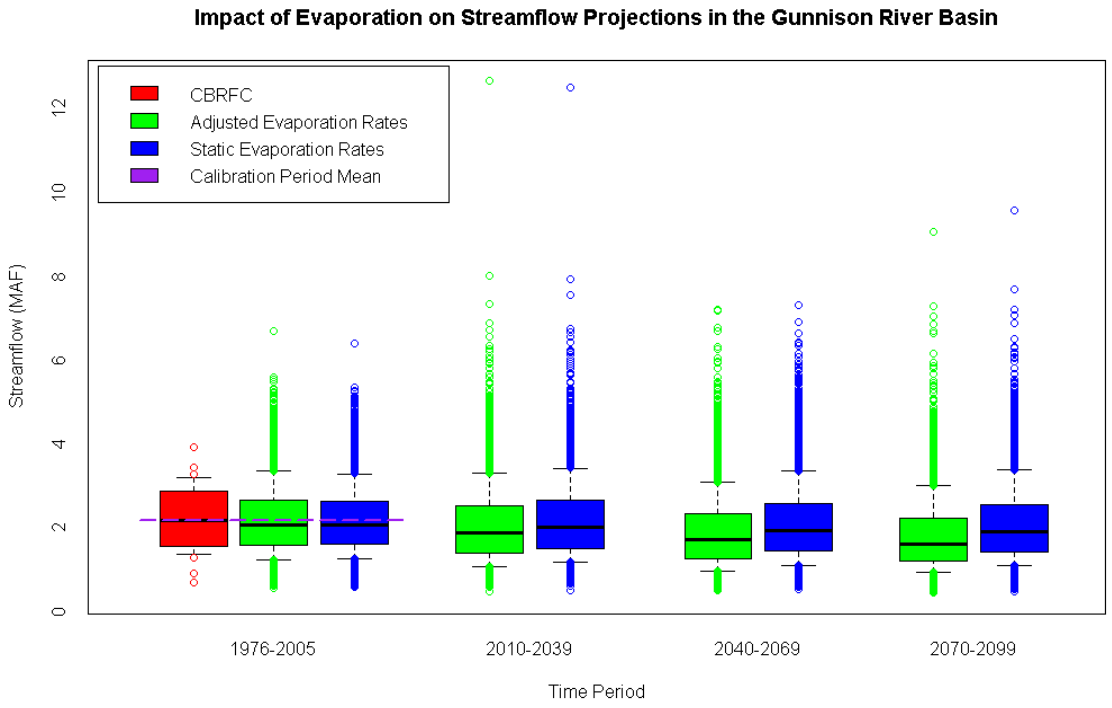

Figure 34: Modified boxplots illustrating the impact of incorporating climate change impacts to evapotranspiration rates in the Gunnison River Basin. Boxplots in this study define the outer whiskers at the 10% and 90% exceedance values. The red boxplot illustrates results derived using data from the CBRFC over the calibration period. Green boxplots illustrate results derived using the temporally downscaled BCSD dataset and adjusting evapotranspiration in response to temperature change. Blue boxplots illustrate results derived using the temporally downscaled BCSD dataset without adjusting evapotranspiration in response to temperature change.

Evapotranspiration and associated impacts to projections of streamflow over the Gunnison River Basin is spatially distributed (Figure 35). Adjusting evapotranspiration with changing temperature impacts the Gunnison River Basin across all catchments, particularly those in the southern portion of the basin which is typically characterized by flatter topography and contributes less flow to the Gunnison River tributary.

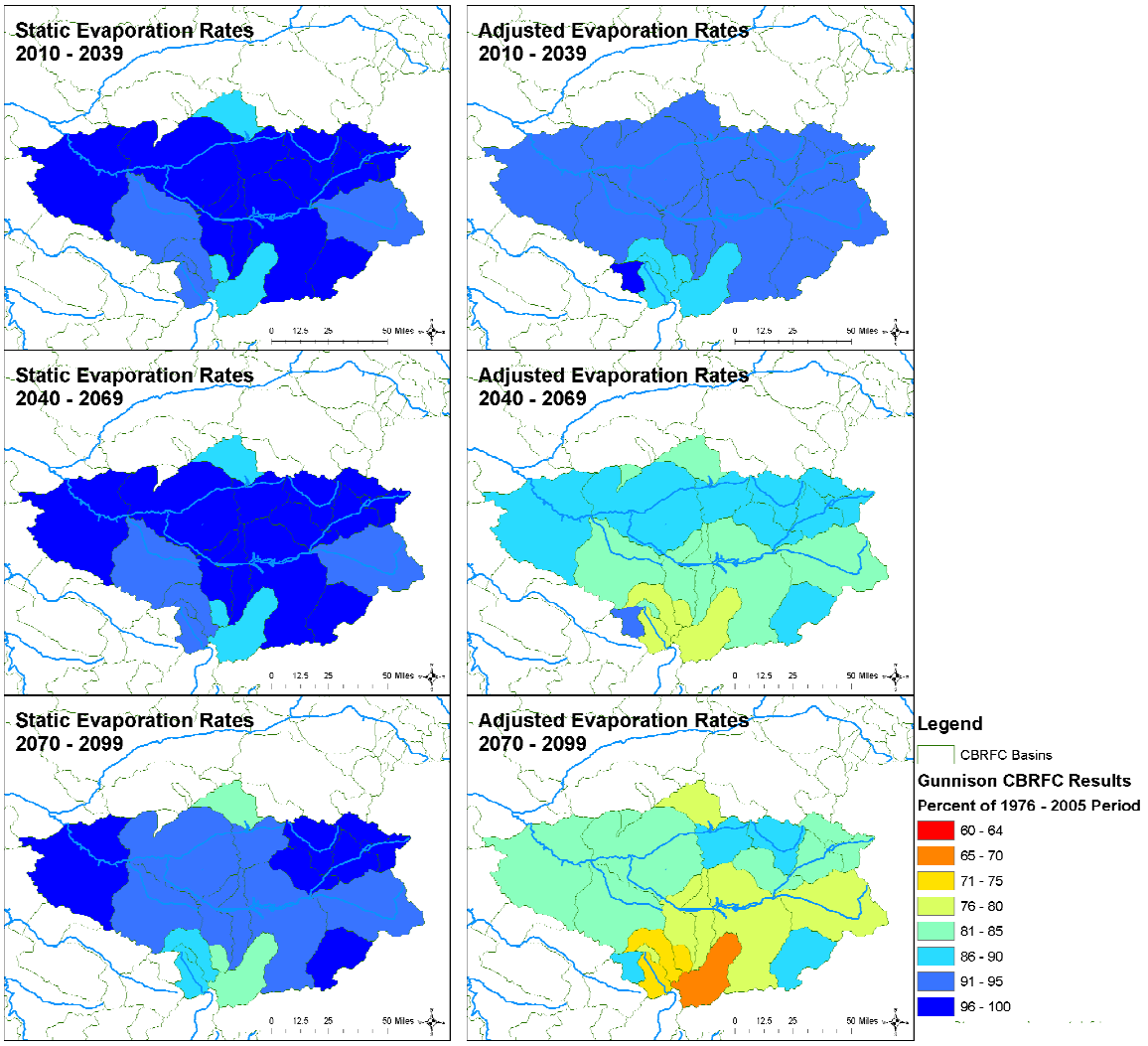

Figure 35: Impact of adjusting evapotranspiration with changes in temperature at the catchment scale over the Gunnison River Basin. Panels on the left reflect average model output when evapotranspiration is not adjusted with temperature over the 2010-2039 time period (top left), the 2040 – 2069 time period (middle left), and the 2070 – 2099 time period (bottom left). Panels on the right reflect average model output when evapotranspiration is adjusted with temperature over the 2010-2039 time period (top right), the 2040 – 2069 time period (middle right), and the 2070 – 2099 time period (bottom right). Decreasing streamflow projections are more pronounced throughout latitudinal and elevation bands when evapotranspiration is adjusted for changing temperatures.

For the purposes of this study, streamflow projections are derived for each of the three headwater basins with evapotranspiration adjusted for temperature changes. This decision is made for two reasons; firstly, recent study of climate change impacts to streamflow over the Colorado River Basin typically indicate decreasing flow within the basin between 10% and 20% (e.g., Barnett & Pierce, 2009; Christensen & Lettenmaier, 2007; Hamlet et al., 2007; Hoerling & Eischeid, 2007). The second reason is to maintain a methodology similar to that of parallel work being done by Reclamation with VIC model; future study will attempt to reconcile streamflow differences between the studies.

5.6 Post Bias Correction

As described previously, this study is limited in that it can not reproduce the current calibration in practice at the CBRFC. In an attempt to limit the impact of lack of a parallel calibration model, streamflow projections derived through the use of the modified NWS CBRFC RFS model were bias corrected such that the average streamflow over the 30-year calibration period were identical. This was accomplished through the use of a ratio method described in Section 5.5.4. This was accomplished by first deriving the average streamflow associated with each month over the 30-year calibration period defined by the CBRFC. For each of the 112 climate projections within the temporally disaggregated BCSD dataset, the average streamflow projection associated with each month over the 30-year calibration period was calculated. A bias correction factor for each climate projection was defined and applied over the projected time series such that the average streamflow over the 30-year calibration period is exactly equal to that derived by the CBRFC. Summary statistics comparing pre- and post-bias corrected streamflow projection data are presented in Table 4. It is important to note that the mean for each

climate projection was bias corrected to match the calibration period; that is the average for each of the 112 climate projections is equal to the mean of the results over the CBRFC calibration period. In contrast, the pre-bias corrected mean presented in Table 4 is the average of all mean streamflow derived using the 112 climate projections.

Table 4: Statistics of streamflow projections pre- and post-bias correction.

Statistic	CBRFC Streamflow Projection (1976 - 2005)	Average of 112 Climate Projections (1976 - 2005) Pre-Bias Correction	Average of 112 Climate Projections (1976 - 2005) Post-Bias Correction
Mean	2.183	1.804	2.183
Average Median	2.163	1.716	2.050
Average Standard Deviation	0.809	0.635	0.851
Average Variance	0.655	0.411	0.737
Average Maximum	3.935	3.400	4.382
Average Minimum	0.701	0.814	0.917
Average Skew	0.258	0.704	0.818

5.7 Streamflow Projections

5.7.1 Gunnison River Basin

The Gunnison River Basin contributes approximately 14% of the Upper Colorado River Basin's annual runoff to the Colorado River (Hoerling & Eischeid, Unpublished). Over the 30-year calibration period, the average runoff from the Gunnison is

approximately 2.18 MAF. Each of the 112 climate projections was used to force the NWS CBRFC RFS (Figure 36). Over the model run period (1950 – 2099), average streamflow from the Gunnison River Basin is approximately 2.05 MAF. Table 5 summarizes the results of the streamflow projections over the Gunnison River Basin. Reclamation operates the Blue Mesa, Morrow Point, and Crystal Dams and Reservoirs, collectively known as the Aspinall Unit, as part of the Colorado River Storage Project (CRSP) (U.S. Department of the Interior, Bureau of Reclamation, Upper Colorado Region, 2009). Reclamation manages the CRSP to meet downstream flow requirements, hydroelectric power needs, and provide for endangered fish and their habitat, along with other approved uses.

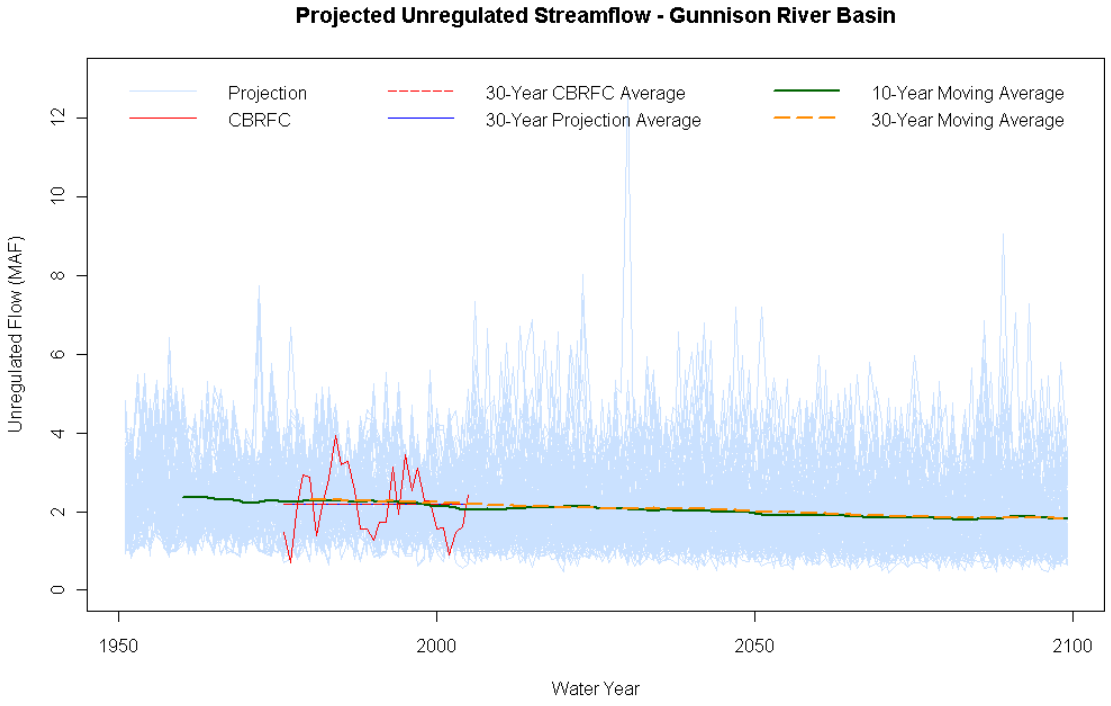

Figure 36: Streamflow projections from each of the 112 climate projections over the Gunnison River Basin. Results from the CBRFC's calibrated model are included as well as long-term averages.

Table 5: Average streamflow projections from the Gunnison River Basin. Projections are separated by SRES emissions scenarios and future multi-decadal periods.

Average streamflow projection (MAF) from the Gunnison River Basin				
Time Period	**All**	**A2**	**B1**	**A1B**
2010 - 2039	2.07	2.10	2.09	2.02
2040 - 2069	1.91	1.89	1.92	1.92
2070 - 2099	1.83	1.76	1.90	1.82

On average, streamflow over the Gunnison River Basin decreases over future multi-decadal periods. Of interest, one climate projection results in a streamflow projection in excess of 12 MAF in the year 2030. This projection is made by the Canadian Centre for Climate Modeling and Analysis GCM (Flato & Boer, 2001) under an A1B emissions scenario, which, on average, is the more moderate emissions scenario considered in this study. The minimum annual flow projection is approximately 0.44 MAF in 2071. This minimum flow is a product of the GCM from the Institut Pierre Simon in Laplace, France (O et al., 2005); more intuitively, this projection falls under the A2 emissions scenario which describes, on average, a more aggressive warming trend. Figure 37 separates streamflow projections over the Gunnison River Basin by emission scenarios included in this study.

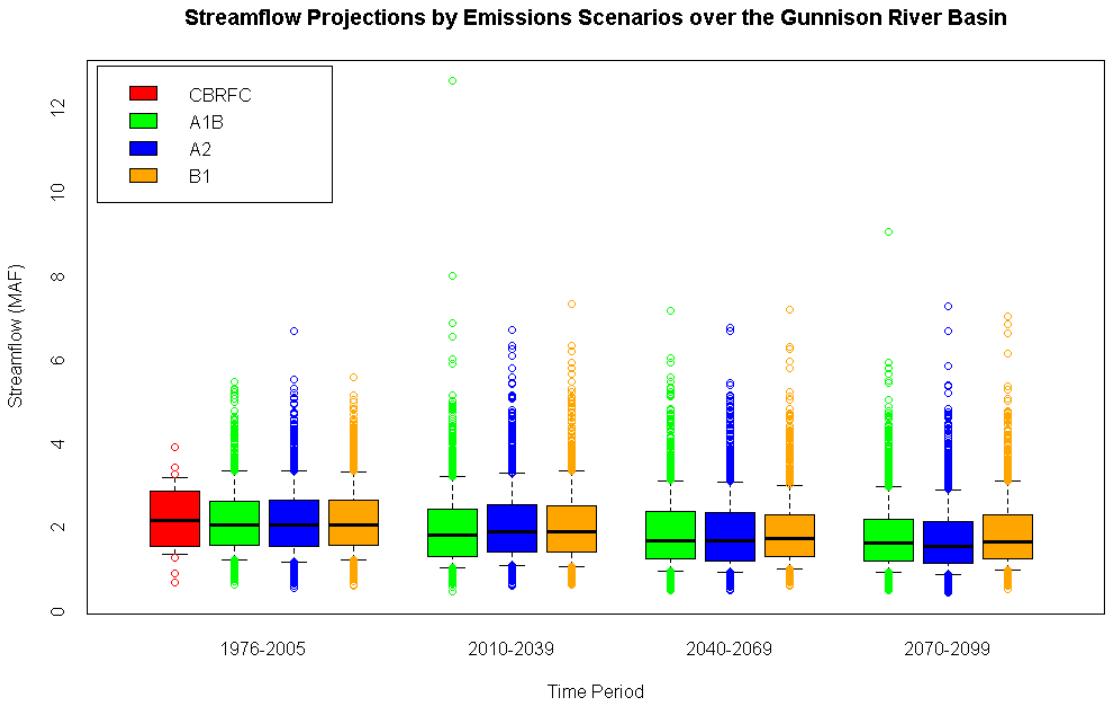

Figure 37: Streamflow Projections over the Gunnison River Basin separated by emissions scenarios.

As shown in Figure 38, the southern portion of the Gunnison River Basin exhibits the greatest percent reduction in projected streamflow from the calibration period. This area encompasses the southern portion of the Rocky Mountains. Previous work has shown that snowpack in this area has declined with warming trends over the Colorado River Basin and contribute decreased streamflow in the region (Mote et al., 2005; Mote, 2006).

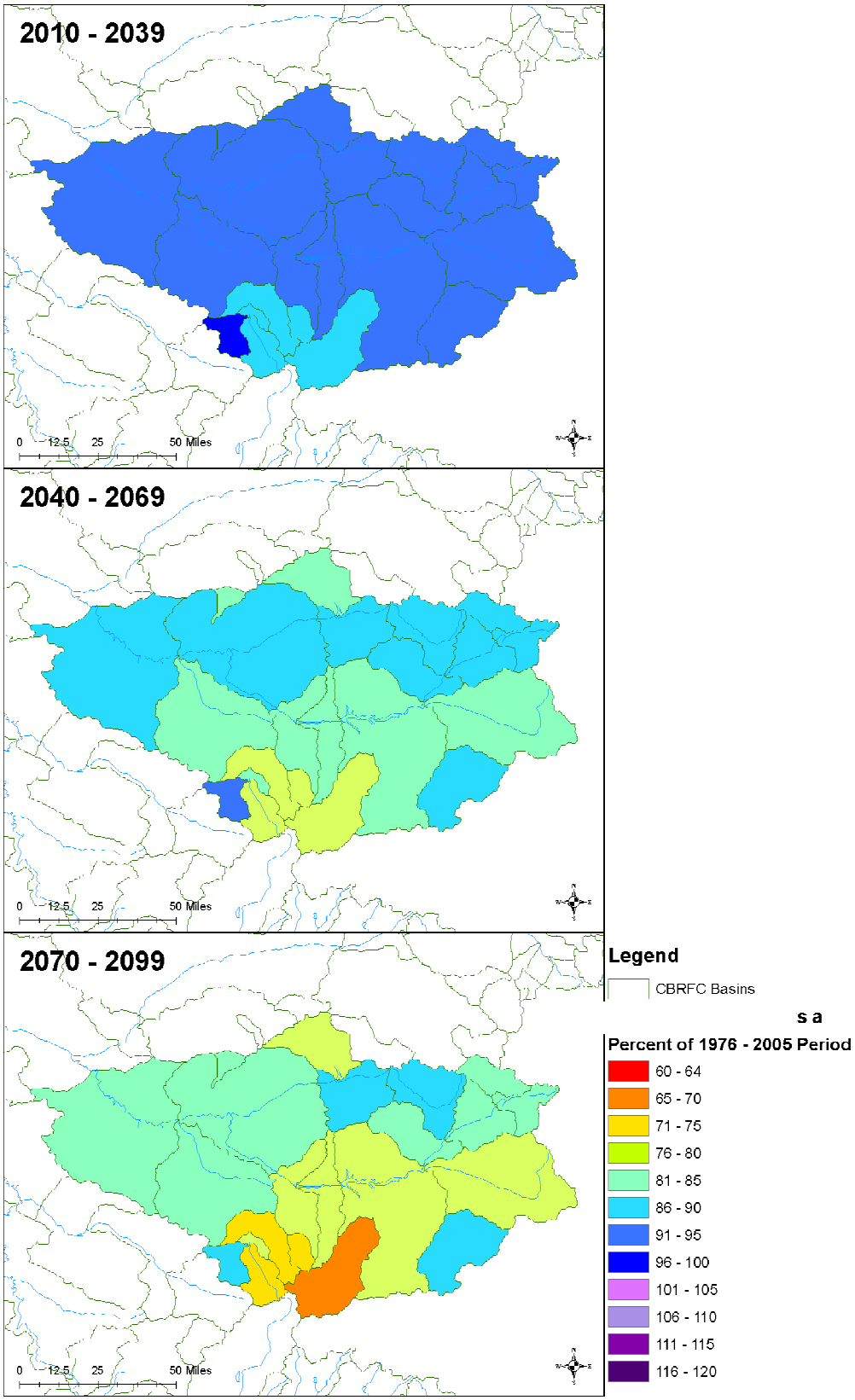

Figure 38: Multi-decadal averages of streamflow projections over the Gunnison River Basin.

5.7.2 Green River Basin

As derived by Hoerling and Eischeid(Unpublished), the Green River Basin contributes approximately 14.5% of the Upper Colorado River Basin's annual runoff to the Colorado River. It is important to note that unlike Hoerling and Eischeid (Unpublished) the CBRFC model does not account for runoff from the Great Divide subwatershed just to the east of the Green River Basin. The region accounted for in this study contributes approximately 12.5% of the Upper Colorado River Basin's annual runoff.

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

Over the 30-year calibration period, the average runoff from the Green River Basin is approximately 1.93 MAF. Each of the 112 climate projections was used to force the NWS CBRFC RFS (Figure 39). Over the model run period (1950 – 2099), average streamflow from the Green River Basin is approximately 1.92 MAF. Table 6 summarizes the results of the streamflow projections over the Green River Basin.

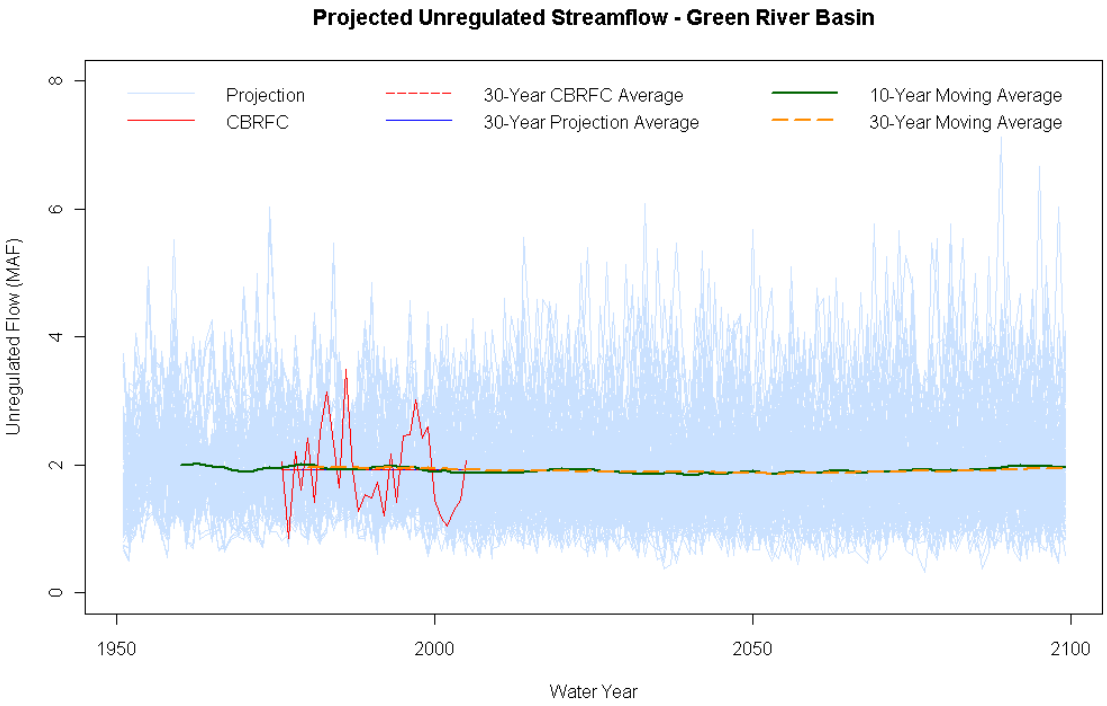

Figure 39: Streamflow projections from each of the 112 climate projections over the Green River Basin. Results from the CBRFC's calibrated model are included as well as long-term averages.

Table 6: Average streamflow projections from the Green River Basin. Projections are separated by SRES emissions scenarios and future multi-decadal periods.

Average streamflow projection (MAF) from the Green River Basin				
Time Period	**All**	**A2**	**B1**	**A1B**
2010 - 2039	1.89	1.93	1.89	1.86
2040 - 2069	1.89	1.92	1.87	1.89
2070 - 2099	1.95	1.97	1.92	1.96

On average, streamflow over the Green Basin increases slightly over future multi-decadal periods. Figure 40 separates streamflow projections over the Green River Basin by emission scenarios included in this study.

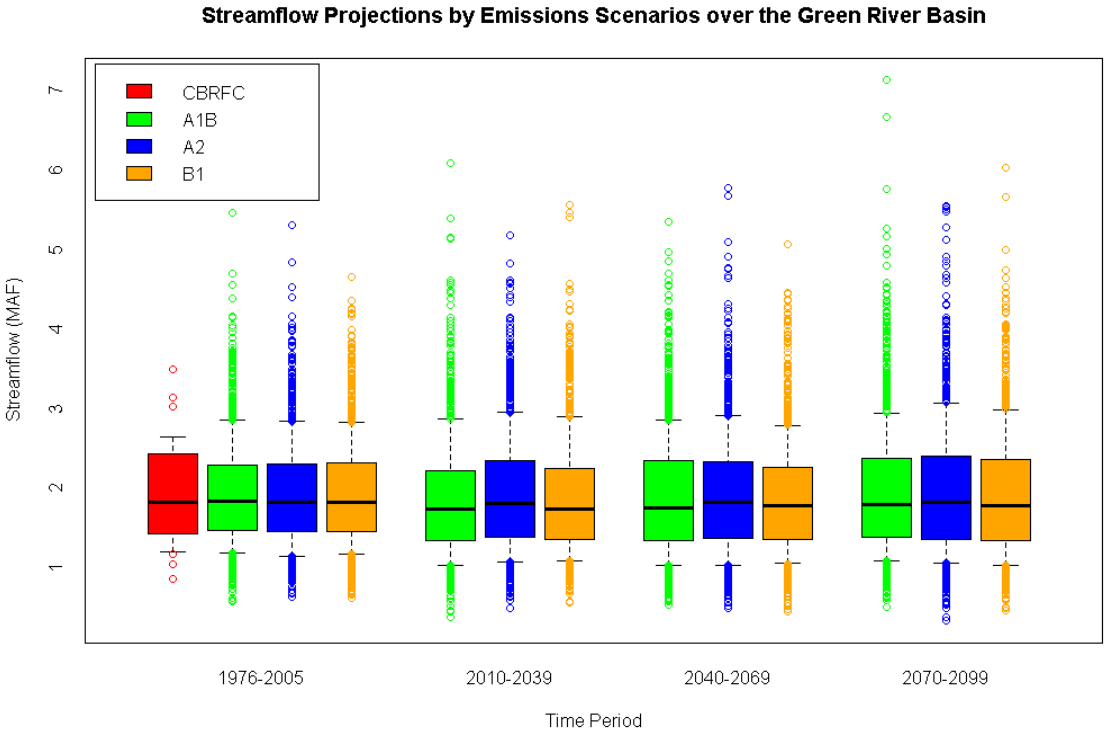

Figure 40: Streamflow Projections over the Green River Basin separated by emissions scenarios.

As shown in Figure 41, much of the central portion of Green River Basin exhibits slightly increased streamflow when compared to the calibration period. This is somewhat consistent with results noted by Mote (2006). Mote (2006) describes increasing trends in SWE when using a regression describing SWE in terms of precipitation and temperature. The SNOW-17 model derives snowpack conditions in a similar fashion (E. A. Anderson, 2006). Under these climate conditions, increased model snowpack conditions would yield increased runoff throughout the basin.

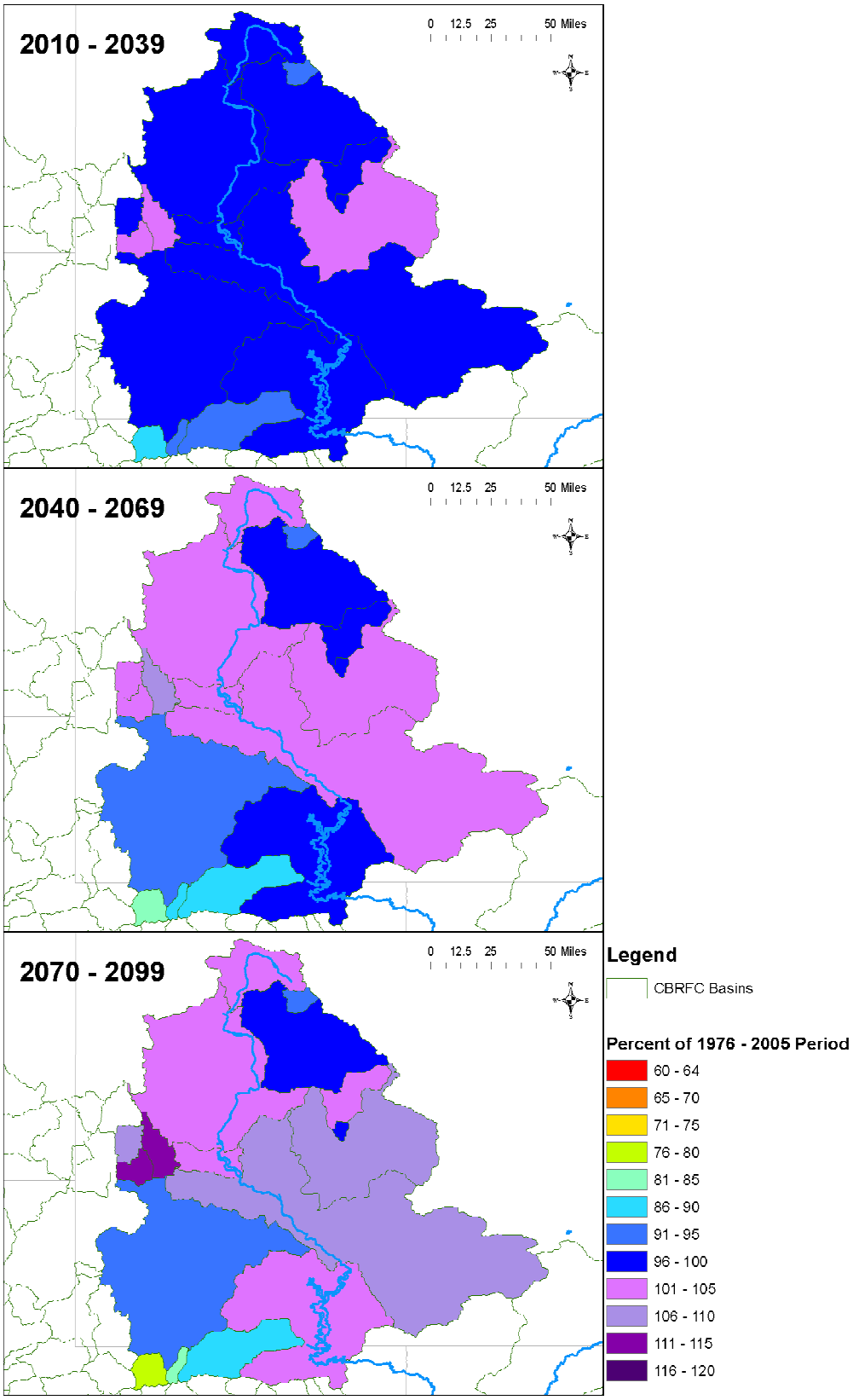

Figure 41: Multi-decadal averages of streamflow projections over the Green River Basin.

5.7.3 San Juan River Basin

Since 1992, Reclamation has been working in collaboration with the San Juan River Basin Recovery Implementation Program to protect the Colorado pikeminnow and the razorback sucker and their respective habitat (U.S. Fish and Wildlife Service, 2006). Reclamation operates the Vallecito and Navajo reservoirs within the San Juan River Basin to manage approximately 16% of the annual runoff to the Colorado River (Hoerling & Eischeid, Unpublished); this value does not include the western most portion of the San Juan River Basin, rather, the model developed by the CBRFC terminates near the confluence of Chinle Creek and the San Juan River and contributes approximately 12% of the annual runoff to the Colorado River. Reservoirs within the San Juan River Basin are also part of the CRSP.

Over the 30-year calibration period, the average runoff from the San Juan River Basin is approximately 1.81 MAF. Each of the 112 climate projections was used to force the NWS CBRFC RFS (Figure 42). Over the model run period (1950 – 2099), average streamflow from the San Juan River Basin is approximately 1.67 MAF. Table 7 summarizes the results of the streamflow projections over the San Juan River Basin.

For the San Juan River Basin Recovery Implementation Program, a model within the RiverWare framework is utilized. In the next chapter, this model will be used to investigate the impacts climate change may have on Reclamation's ability to meet San Juan River Basin Recovery Implementation Program goals.

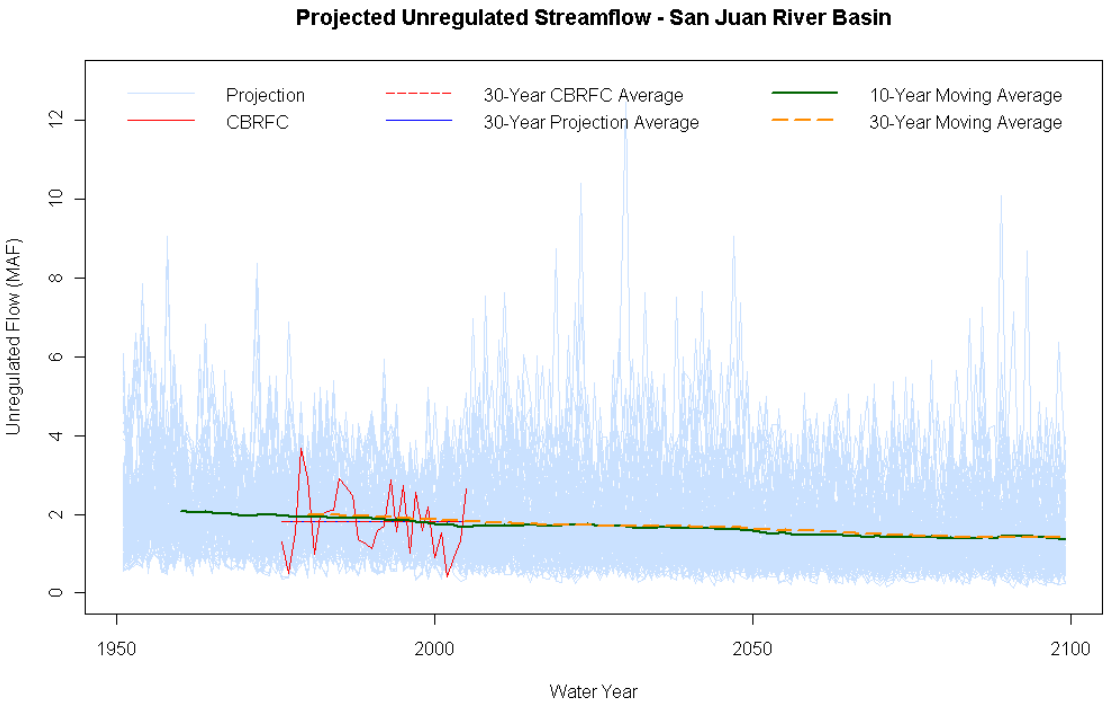

Figure 42: Streamflow projections from each of the 112 climate projections over the San Juan River Basin. Results from the CBRFC's calibrated model are included as well as long-term averages.

Table 7: Average streamflow projections from the San Juan River Basin. Projections are separated by SRES emissions scenarios and future multi-decadal periods.

Average streamflow projection from the San Juan River Basin				
Time Period	**All**	**A2**	**B1**	**A1B**
2010 - 2039	1.69	1.71	1.74	1.62
2040 - 2069	1.50	1.47	1.54	1.49
2070 - 2099	1.40	1.32	1.50	1.39

On average, streamflow over the San Juan River Basin decreases over future multi-decadal periods. Of interest, one climate projection results in a streamflow projection in excess of 9 MAF in the year 2030. Like the Gunnison River Basin, this projection is made by the Canadian Centre for Climate Modeling and Analysis GCM (Flato & Boer, 2001) under an A1B emissions scenario. The minimum annual flow projection is approximately 0.10 MAF in 2091. This minimum flow is also a product of the GCM from the Institut Pierre Simon in Laplace, France (O et al., 2005) under the A2 emissions scenario. Figure 43 separates streamflow projections over the San Juan River Basin by emission scenarios included in this study.

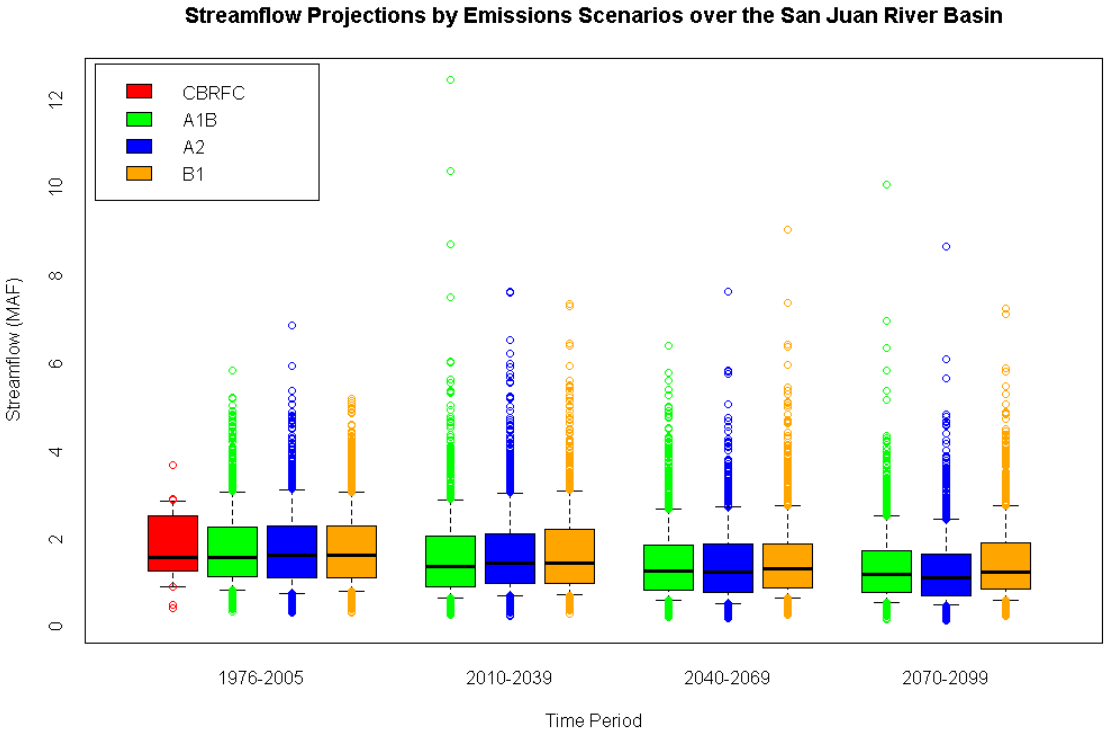

Figure 43: Streamflow Projections over the San Juan River Basin separated by emissions scenarios.

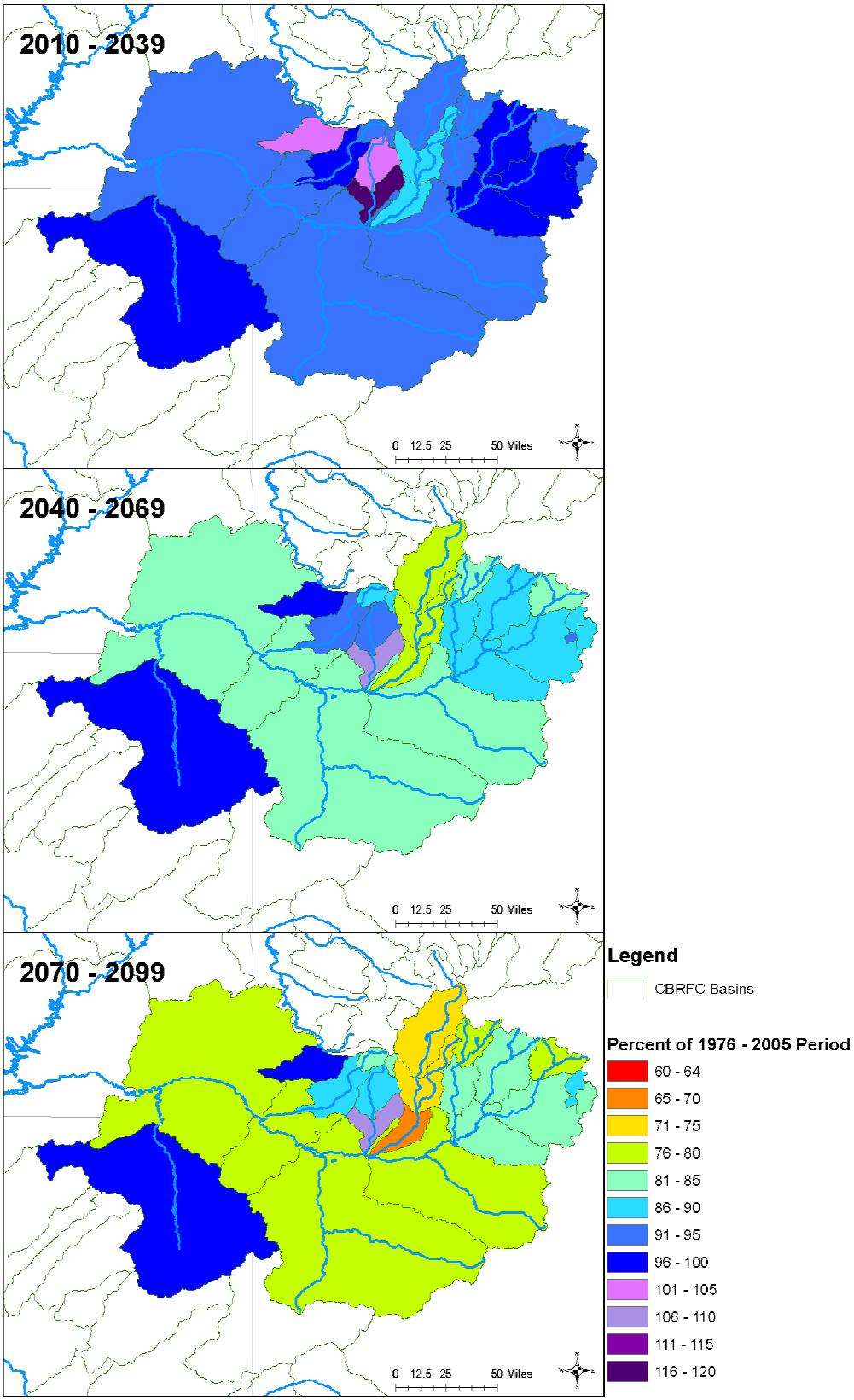

Figure 44: Multi-decadal averages of streamflow projections over the San Juan River Basin.

As shown in Figure 44, the vast majority of the San Juan River Basin exhibits reduced streamflow when compared to the calibration period. Reduced streamflow in the region results in less flexibility in the management of Reclamation's reservoir system. With reduced flows, it is more difficult for Reclamation to manage reservoir releases to protect endangered fish in the area, particularly as it relates to the regulation of river temperatures and the protection of habitat area.

5.8 Stationarity in Projected Streamflow Forecasts

Summary statistics and the KS – Test are used in this study to assess the stationarity of streamflow projections over each of the headwater basins considered in this study. The definition of stationarity, particularly with regards to climate change, is often under debate (e.g., Matter et al., 2010; Milly et al., 2008; Raff et al., 2009; Villarini et al., 2009; Wilby et al., 1999). Summary statistics have been used in past studies to investigate the distribution and change of hydroclimatic indices (e.g., J. Prairie et al., 2007; J. R. Prairie & Rajagopalan, 2007) and the KS – Test has been used as a test for change over historical hydroclimatic time series (e.g., Koutsoyiannis & Montanari, 2007; W. Wang et al., 2008) hydrologic model forecasts (Carpenter & Georgakakos, 2006).

5.8.1 Gunnison River Basin Results

Summary statistics for streamflow projections over the Gunnison River Basin are presented in

Table 8. While there is an appreciable change in summary statistics between multi-decadal periods, these changes may be attributed to natural hydroclimatic variability within the Colorado River Basin as evidenced by tree-ring reconstructions over the region

(e.g., Meko et al., 2007; Woodhouse & Lukas, 2006; Woodhouse et al., 2006). A cumulative distribution of streamflow over each multidecadal period and separated by emissions scenario is presented in Figure 45. The cumulative distribution functions (CDF) of streamflow, regardless of emission scenario, tend to be close, though separation is more apparent over the time period spanning 2070 - 2099.

Table 8: Gunnison River Basin summary statistics.

Summary Statistics of Streamflow Projections Over the Gunnison River Basin (MAF)												
	1976 - 2005			2010 - 2039			2040 - 2069			2070 - 2099		
Statistic	**A2**	**B1**	**A1B**	**A2**	**B1**	**A1B**	**A2**	**B1**	**A1B**	**A2**	**B1**	**A1B**
Min	0.54	0.61	0.63	0.61	0.64	0.47	0.49	0.61	0.51	0.43	0.53	0.50
1st Quantile	1.56	1.57	1.57	1.42	1.42	1.31	1.21	1.30	1.25	1.14	1.26	1.21
Median	2.06	2.08	2.06	1.91	1.91	1.83	1.70	1.73	1.69	1.54	1.67	1.64
Mean	2.18	2.18	2.18	2.10	2.09	2.01	1.89	1.92	1.91	1.76	1.90	1.82
3rd Quantile	2.65	2.66	2.63	2.56	2.53	2.45	2.35	2.30	2.40	2.16	2.31	2.21
Max	6.70	5.60	5.49	6.72	7.36	12.67	6.79	7.20	7.19	7.29	7.05	9.06

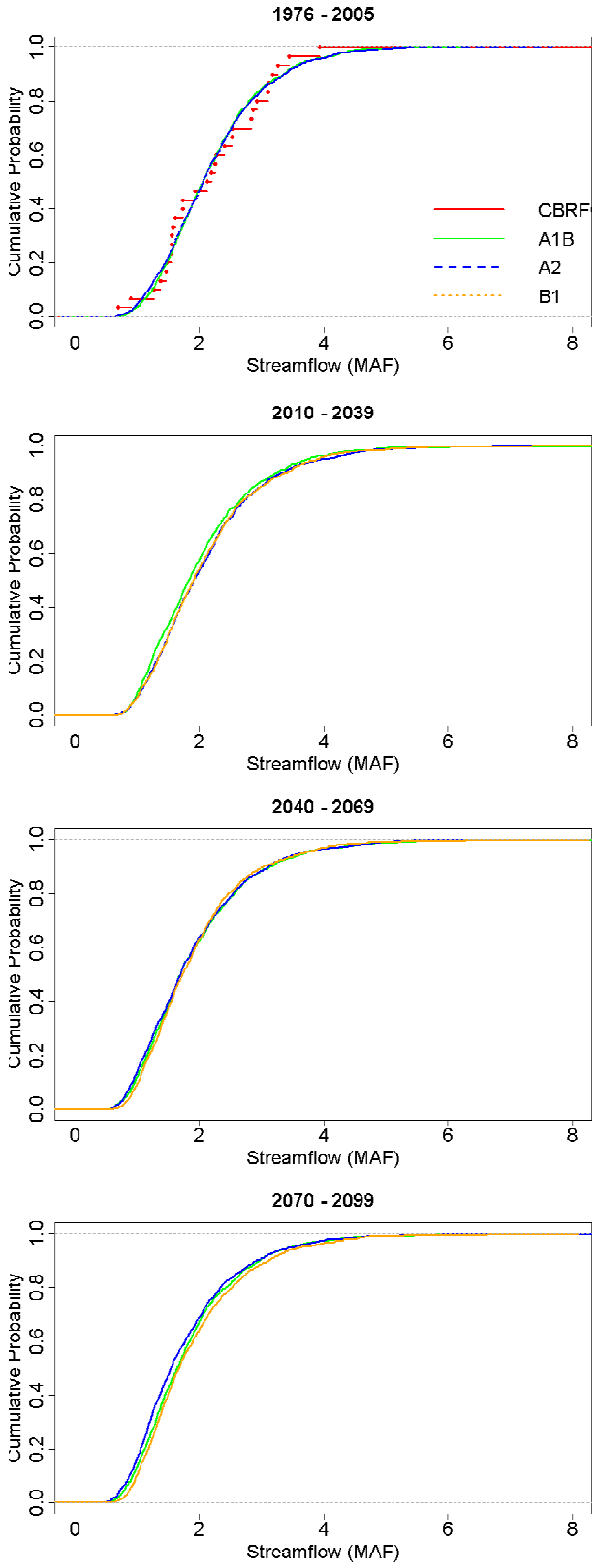

Figure 45: Plots of CDFs of projected streamflow over the Gunnison River Basin.

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

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

The KS – Test was then applied between streamflow projections derived by the CBRFC over the calibration period and streamflow projections derived using climate data from the 112 temporally downscaled BCSD dataset over the period from 2010 to 2099, separated by emissions scenario and multi-decadal period. For each emissions scenario and projected streamflow over the period spanning 2010 to 2039, the test statistic was less than the critical value and the null hypothesis could not be rejected. However, for each emissions scenario and projected streamflow over the period spanning either 2040 to 2069 or 2070 to 2099, the null hypothesis could be rejected. Table 9 summarizes results of the KS – Tests performed over the Gunnison River Basin.

Table 9: Results of the KS - Test over the Gunnison River Basin

	Test Statistic	Critical or p-Value	Null Hypothesis
All Climate - Driven Projections 1976-2005	0.108	0.878	Not Rejected
All Climate - Driven Projections 2010 - 2099	0.221	0.109	Rejected
A1B Projections 1976 - 2005	0.111	0.863	Not Rejected
A1B Projections 2010 - 2039	0.192	0.234	Not Rejected
A1B Projections 2040 - 2069	0.235	0.079	Rejected
A1B Projections 2070 - 2099	0.280	0.021	Rejected
A2 Projections 1976 - 2005	0.105	0.907	Not Rejected
A2 Projections 2010 - 2039	0.143	0.593	Not Rejected
A2 Projections 2040 - 2069	0.244	0.063	Rejected
A2 Projections 2070 - 2099	0.321	0.005	Rejected
B1 Projections 1976 - 2005	0.108	0.884	Not Rejected
B1 Projections 2010 - 2039	0.137	0.644	Not Rejected
B1 Projections 2040 - 2069	0.220	0.119	Rejected
B1 Projections 2070 - 2099	0.251	0.050	Rejected

5.8.2 Green River Basin Results

Summary statistics for streamflow projections over the Green River Basin are presented in Table 10. Unlike the Gunnison River Basin there is not an appreciable change in summary statistics between multi-decadal periods. There is less deviation from the 1976 – 2005 mean over each multi-decadal period than that observed over the Gunnison River Basin. CDFs of Green River Basin streamflows share similar characteristics with those over the Gunnison River Basin (Figure 46).

Table 10: Green River Basin summary statistics.

Summary Statistics of Streamflow Projections Over the Green River Basin												
	1976 - 2005			**2010 - 2039**			**2040 - 2069**			**2070 - 2099**		
Statistic	**A2**	**B1**	**A1B**	**A2**	**B1**	**A1B**	**A2**	**B1**	**A1B**	**A2**	**B1**	**A1B**
Min	0.63	0.61	0.58	0.49	0.56	0.38	0.50	0.45	0.53	0.33	0.47	0.51
1st Quantile	1.45	1.46	1.47	1.38	1.36	1.34	1.37	1.35	1.34	1.36	1.34	1.38
Median	1.82	1.82	1.83	1.81	1.73	1.73	1.82	1.78	1.76	1.83	1.78	1.80
Mean	1.93	1.93	1.93	1.93	1.88	1.86	1.92	1.87	1.89	1.97	1.92	1.96
3rd Quantile	2.31	2.32	2.30	2.34	2.25	2.22	2.33	2.26	2.35	2.41	2.36	2.37
Max	5.31	4.65	5.47	5.17	5.56	6.09	5.78	5.07	5.35	5.54	6.03	7.13

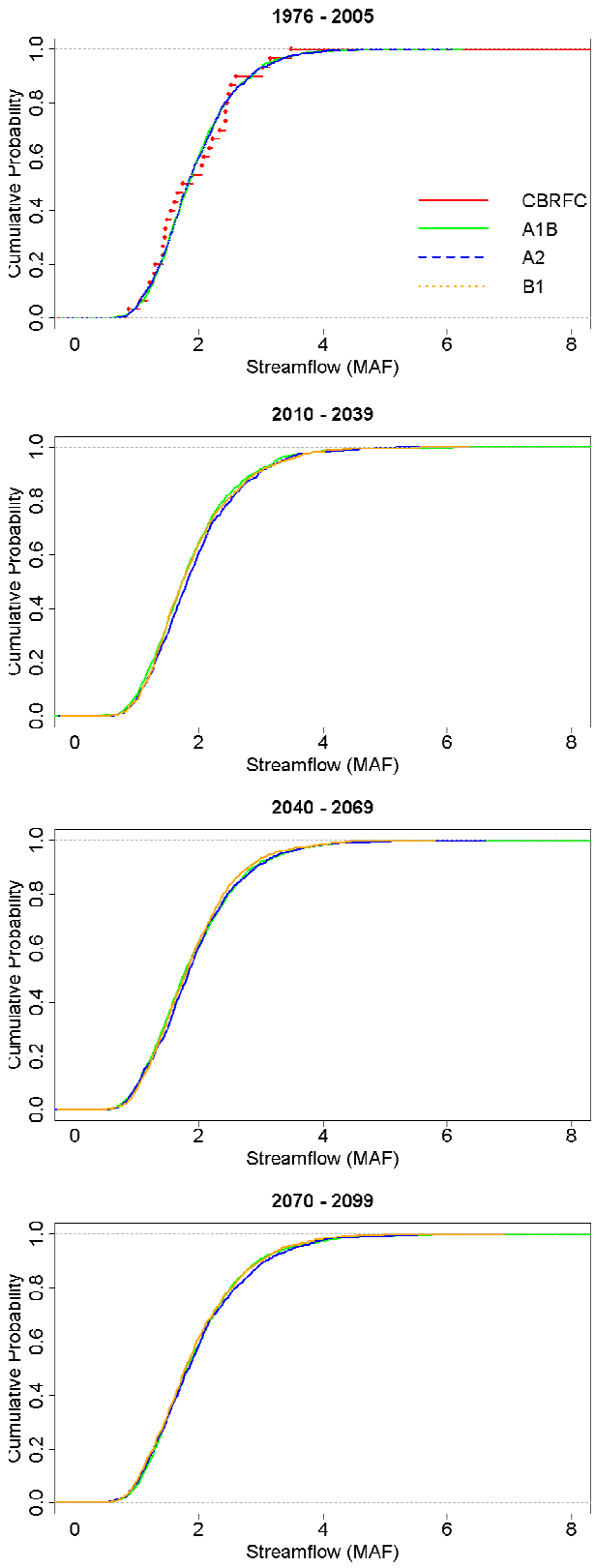

Figure 46: Plots of CDFs of projected streamflow over the Green River Basin.

KS – Test results were developed in an identical fashion to those over the Gunnison River Basin. The results of each KS – Test indicated that the null hypothesis could not be rejected; that is, each multi-decadal period did not come from a statistically different distribution. As a result, it is not possible to state that streamflow projections statistically exhibit nonstationary behavior. The topography of the Green River Basin is generally more mountainous and at higher elevations than those in the San Juan and Gunnison River Basins. As warming temperature impacts are more prevalent at lower elevations, projected climate over the Green River Basin may exhibit more stationary characteristics since climate change impacts are not as realized at higher elevations and latitudes (e.g., Mote et al., 2005; Mote, 2006). Table 11 summarizes the results of the KS – Tests over the Green River Basin.

Table 11: Results of the KS - Test over the Green River Basin.

	Test Statistic	Critical or p-Value	Null Hypothesis
All Climate - Driven Projections 1976-2005	0.102	0.919	Not Rejected
All Climate - Driven Projections 2010 - 2099	0.103	0.911	Not Rejected
A1B Projections 1976 - 2005	0.109	0.881	Not Rejected
A1B Projections 2010 - 2039	0.132	0.691	Not Rejected
A1B Projections 2040 - 2069	0.102	0.923	Not Rejected
A1B Projections 2070 - 2099	0.077	0.995	Not Rejected
A2 Projections 1976 - 2005	0.104	0.912	Not Rejected
A2 Projections 2010 - 2039	0.096	0.950	Not Rejected
A2 Projections 2040 - 2069	0.097	0.946	Not Rejected
A2 Projections 2070 - 2099	0.099	0.937	Not Rejected
B1 Projections 1976 - 2005	0.100	0.932	Not Rejected
B1 Projections 2010 - 2039	0.127	0.734	Not Rejected
B1 Projections 2040 - 2069	0.116	0.825	Not Rejected
B1 Projections 2070 - 2099	0.100	0.932	Not Rejected

5.8.3 San Juan River Basin Results

Summary statistics for streamflow projections over the Green River Basin are presented in Table 12. Like the Gunnison River Basin there is an appreciable change in summary statistics between multi-decadal periods. CDFs of San Juan River Basin streamflows share similar characteristics with those over the Gunnison River Basin (Figure 47).

Table 12: Summary statistics over the San Juan River Basin.

Summary Statistics of Streamflow Projections Over the San Juan River Basin												
	1976 - 2005			**2010 - 2039**			**2040 - 2069**			**2070 - 2099**		
Statistic	**A2**	**B1**	**A1B**	**A2**	**B1**	**A1B**	**A2**	**B1**	**A1B**	**A2**	**B1**	**A1B**
Min	0.31	0.32	0.34	0.23	0.30	0.27	0.19	0.26	0.21	0.13	0.25	0.17
1st Quantile	1.11	1.13	1.14	1.00	1.00	0.90	0.79	0.89	0.83	0.69	0.85	0.78
Median	1.64	1.62	1.59	1.44	1.45	1.37	1.24	1.33	1.26	1.11	1.24	1.18
Mean	1.81	1.81	1.81	1.71	1.74	1.62	1.47	1.54	1.49	1.32	1.50	1.39
3rd Quantile	2.29	2.29	2.27	2.13	2.21	2.07	1.88	1.88	1.85	1.66	1.92	1.74
Max	6.87	5.21	5.84	7.64	7.36	12.47	7.66	9.06	6.42	8.68	7.25	10.10

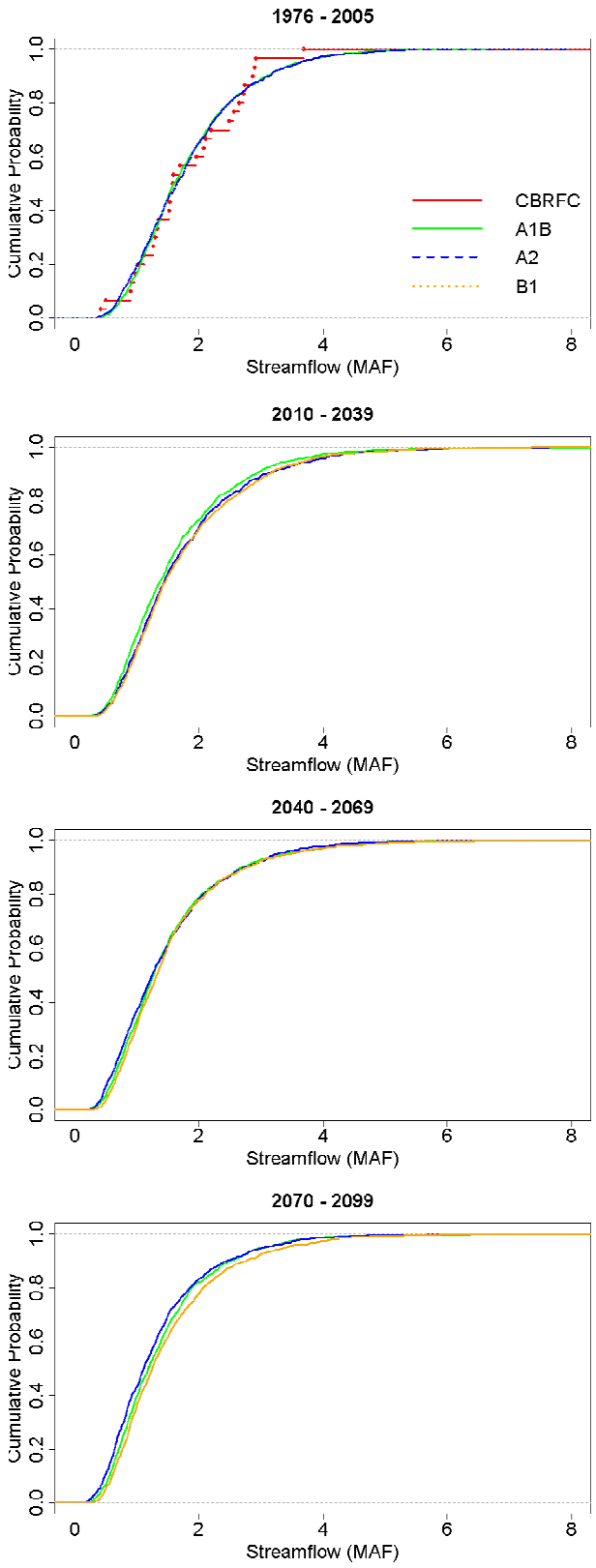

Figure 47: Plots of CDFs of projected streamflow over the San Juan River Basin.

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

Table 13: Results of the KS - Test over the San Juan River Basin

	Test Statistic	Critical or p-Value	Null Hypothesis
All Climate - Driven Projections 1976-2005	0.102	0.916	Not Rejected
All Climate - Driven Projections 2010 - 2099	0.247	0.053	Rejected
A1B Projections 1976 - 2005	0.103	0.918	Not Rejected
A1B Projections 2010 - 2039	0.216	0.130	Rejected
A1B Projections 2040 - 2069	0.265	0.033	Rejected
A1B Projections 2070 - 2099	0.309	0.007	Rejected
A2 Projections 1976 - 2005	0.099	0.937	Not Rejected
A2 Projections 2010 - 2039	0.175	0.333	Not Rejected
A2 Projections 2040 - 2069	0.279	0.021	Rejected
A2 Projections 2070 - 2099	0.349	0.002	Rejected
B1 Projections 1976 - 2005	0.105	0.907	Not Rejected
B1 Projections 2010 - 2039	0.162	0.426	Not Rejected
B1 Projections 2040 - 2069	0.251	0.050	Rejected
B1 Projections 2070 - 2099	0.278	0.022	Rejected

5.9 Discussion

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

Evapotranspiration under changing climate conditions is not trivial in hydrologic modeling efforts or water resource management studies. A major contribution of this study is that by adjusting evapotranspiration with temperature, catchment streamflow projections are decreased by as much as 20% over a 30 year multi-decadal period. The CBRFC currently adjusts evapotranspiration demand within the SAC-SMA model within the NWS RFS to calibrate the model to observed streamflow in the basin. This methodology highlights both the importance and uncertainty regarding evapotranspiration in hydrologic modeling studies. Evapotranspiration is a sensitive and important parameter that must be accounted for; however, due to limited observational data, it is often implicitly calculated through calibration efforts or as part of a mass balance formulation. Under changing climate conditions, this uncertainty increases. This study presents a progressive methodology through which changes to evapotranspiration may be addressed when dealing with uncertainty associated with climate change. Previous studies have presented progressive automated calibration schemes but do not address evapotranspiration (e.g., Hogue et al., 2000; Hogue et al., 2006; Sorooshian et al., 1993).

Regardless, under changing climate conditions, accurate estimates and measurements of evapotranspiration will become increasingly important.

The use of the KS – Test (and other goodness of fit tests) when testing hydrologic frequency distributions has, at times, been discouraged since the probability of accepting the null hypothesis when it is false is relatively high (Haan, 2002). This is more true when testing small samples of data and indicative of the conservative and insensitive nature of the KS – Test. As such, the rejection of the null hypothesis in this study can be reported with high confidence since the null hypothesis was rarely rejected and sample sizes of data were consistently over 1000 projections. Table 14 summarizes the results of the KS – Test applied to streamflow distributions in this study.

Table 14: Summary of results of the KS – Test performed in this study. Shaded boxes indicate significantly different distributions from the calibration period. Unshaded boxes indicate reflect not enough evidence to make a determination.

Time Period / Emissions Scenario	Gunnison River Basin			Green River Basin			San Juan River Basin		
	A1B	A2	B1	A1B	A2	B1	A1B	A2	B1
1976 - 2005									
2010 - 2039									
2040 - 2069									
2070 - 2099									

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

scale to determine potential shifts in the timing and magnitude of streamflow runoff under changing climate conditions.

Chapter 6 applies streamflow projections developed in this study over the San Juan River Basin to a Reclamation planning model in an attempt to examine climate change impacts to Reclamation reservoir operations.

CHAPTER 6

APPLICATION OF STREAMFLOW PROJECTIONS UNDER CHANGING CLIMATE CONDITIONS TO RECLAMATION'S PLANNING MODEL OVER THE SAN JUAN RIVER BASIN

6.1 Introduction

The San Juan River Basin spans over the Four Corners area of the United States, and inhabits regions of Colorado, Utah, Arizona, and New Mexico (Figure 48) within the Upper Colorado River Basin. Reclamation operates the Navajo and Vallecito Dams and Reservoirs within the basin to regulate flow from the San Juan, Animas, and La Plata Rivers, as well as other tributaries to the Colorado River. The projected operations of Navajo and Vallecito are included in Reclamation's widely used and circulated monthly projection of reservoir operations.

In this chapter, streamflow projections derived through the use of temporally disaggregated and BCSD climate data are used to force a Reclamation planning model. By forcing a Reclamation planning model with projections of streamflow under changing climate conditions, the impact of climate change on Reclamation operations may be assessed through analysis of Reclamation's projected operations of Navajo Dam and Reclamation's ability to meet the flow recommendations established by the San Juan River Basin Recovery Implementation Program (SJRBRIP). This study represents the first attempt by Reclamation to incorporate climate change information into a planning model over the San Juan River Basin.

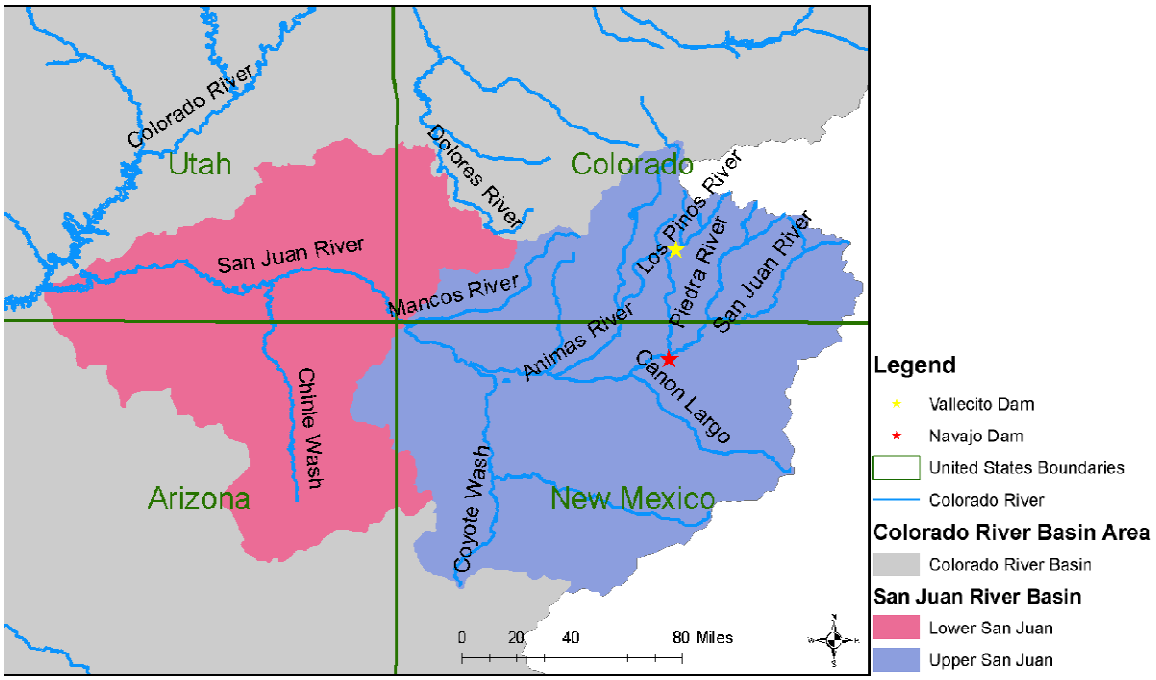

Figure 48: San Juan River Basin.

6.1.1 24 Month Study for the Entire Colorado River Basin

As described in a previous chapter, the Secretary of the Interior implemented the Interim Guidelines (U.S. Department of the Interior, Bureau of Reclamation, Upper and Lower Colorado Regions, 2007), which fully defined the operational range of Lake Powell and Lake Mead and defined coordinated operation between the two reservoirs, particularly in times of shortage. Specification of the coordination of operations between the two reservoirs is dependent upon the forecasted inflow and resulting projections of reservoir storages and elevations. Those projections are currently done using Reclamation's mid-term, deterministic model, commonly referred to as "The 24-Month Study." As the name implies, the 24-Month Study is a projection of monthly operations of Colorado River system reservoirs over a two year period. The 24-Month study is driven by unregulated inflow forecasts provided to Reclamation by the CBRFC and is updated each month. The Interim Guidelines describe two time periods in which the

annual operation of Glen Canyon Dam and Hoover Dam (the dams which create Lake Powell and Lake Mead, respectively) are explicitly defined and possibly subject to adjustment.

The first is during the process of developing Reclamation's Annual Operating Plan (AOP). The AOP is a summary of the past year's hydrology and dam operations in the Upper and Lower Colorado River Basins and a projection of the upcoming year's hydrology and dam operations. The plan is developed by Reclamation in cooperation with Colorado River water stakeholders. Reclamation establishes the operational tier and associated annual release for the upcoming year from Lake Powell and Lake Mead based on the results of the 24-Month Study published in August and as prescribed in the Interim Guidelines and reports these results in the AOP. Depending on the characteristics of the operational tier, the operations of Glen Canyon Dam may be adjusted based on the results of the April 24-Month Study.

For instance, in August 2008, results of Reclamation's 24-Month study projected operation at Glen Canyon Dam to be consistent with Section 6.B of the Interim Guidelines; that is, Glen Canyon Dam would release 8.23 MAF of water, but would be subject to a possible adjustment in the April 2009 24-Month Study, resulting in increased releases. Based on projections of Colorado River Basin hydrology, the August 2008 24-Month study projected such an April adjustment would occur and would result in a water year 2009 release from Glen Canyon Dam of approximately 9.394 MAF. As a result of this increased release from Glen Canyon Dam, the surface water elevation of Lake Mead was projected to be 1105.00 feet at the end of water year 2009.

Forecasts of unregulated inflow into the Upper Colorado River Basin provided by the CBRFC steadily decreased due to drier than expected conditions and decreased snowpack throughout the basin; despite this, subsequent monthly updates of the 24-Month Study by Reclamation continued to project that the results of the April 2009 24-Month Study would result in an increase to the release from Glen Canyon Dam. However, In April 2009, continued dry conditions and a subsequent decreased unregulated inflow forecast resulted in no April adjustment occurring at Glen Canyon Dam. As a result, pursuant to the Interim Guidelines, Glen Canyon Dam released 8.23 MAF of water for water year 2009 and the surface water elevation of Lake Mead ended water year 2009 at 1093.68 feet. This decline in water surface elevation resulted in operational and financial hardship to concessionaires and recreationalists at Lake Mead and highlighted uncertainty within Reclamation's mid-term deterministic model.

6.1.2 San Juan River Basin Operations and Daily Decision Model

Upper Basin reservoirs, such as the Navajo Reservoir, are operated independently of operations at Lake Powell and Glen Canyon Dam; these reservoirs are operated to meet water delivery and environmental flow requirements. In consideration of changing climate conditions, traditional assumptions by Reclamation and the CBRFC may be subject to increased uncertainty.

The San Juan River Basin is operated in accordance with the preferred alternative to the extent possible described in Reclamation's final environmental impact statement on the operation of Navajo Reservoir, Colorado River Storage Project, San Juan River, New Mexico, Colorado, and Utah (U.S. Department of the Interior, Bureau of Reclamation, Upper Colorado Region, 2006). These operations are in agreement with flow

recommendations made by the SJRBRIP. The SJRBRIP is a cooperative effort between Reclamation, FWS, Bureau of Indian Affairs, Bureau of Land Management, Southern Ute Indian Tribe, Ute Mountain Ute Tribe, Navajo Nation, Jicarilla Apache Nation, river stakeholders, and the states of Colorado and New Mexico (U.S. Department of the Interior, Bureau of Reclamation, Upper Colorado Region, 2006; U.S. Fish and Wildlife Service, 2006). The goals of the SJRBRIP is to protect tribal water interests and water use and development in the area while also maintaining water releases to recover two endangered fish, the Colorado pikeminnow and razorback sucker, and their habitat in accordance with flow recommendations on the San Juan River and the Endangered Species Act (San Juan River Basin Recovery Implementation Program Biology Committee, 1999). Streamflow is monitored at the confluence of the San Juan River and Animas River near Farmington, New Mexico.

The preferred alternative implemented by Reclamation is also considered the environmentally preferred alternative. This alternative most closely imitates a natural hydrograph and constrains the release from the Navajo Reservoir between 250 and 5,000 cfs. The natural hydrograph was derived using gage measurements of streamflow over a 65-year period of record (1929 – 1993) in the San Juan River Basin. Flow recommendations established by the SJRBRIP are followed while also protecting the purposes of the Colorado River Storage Project Act and Indian trust assets. The flow recommendations are summarized in Table 15 (U.S. Department of the Interior, Bureau of Reclamation, Upper Colorado Region, 2006; U.S. Fish and Wildlife Service, 2006).

Table 15: Summary of San Juan Flow Recommendations. Flow duration is between March 1st and July 31st.

Category	Duration	Frequency	Purpose
1. Flows > 10,000 cfs	At least 5 days	Needs to occur in 20% of the years on average, with a maximum interval of 11 years	Provide significant out-of-bank flow, generate new cobble sources, change channel morphology, provide nutrient loading, increase channel complexity and diversity
2. Flows > 8,000 cfs	At least 10 days	Needs to occur in 33% of the years on average, with a maximum interval of 7 years	Maintain channel cross-section, move and build cobble bars for fish spawning, provide habitat for larval fish
3. Flows > 5,000 cfs	At least 21 days	Needs to occur in 50% of the years on average, with a maximum interval of 5 years	Clean backwater areas, maintain low flow velocity habitats, maximize nursery habitats
4. Flows > 2,500 cfs	At least 10 days	Needs to occur in 80% of the years on average, with a maximum interval of 3 years	Move cobble into higher gradient areas on spawning bars, clean cobble for spawning areas
Category	**Timing**	**Variability**	**Purpose**
Timing of must be similar to historical conditions	Within 5 days of the historical mean date of May 31	Standard deviation of date of peak to be 12 to 25 days from the mean date of May 31	Maintain similar ascending and descending natural hydrograph limbs which are important for fish spawning
Category	**Level**	**Purpose**	
Mean weekly target base flow	500 cfs from Farmington to Lake Powell; minimum of 250 cfs from Navajo Dam	Low, stable base flows enhance nursery conditions. Flows between 500 and 1,000 cfs optimize backwater habitats	
Category	**Control**	**Purpose**	
Flood control release	Release as a spike, and do not release prior to September 1st unless necessary	Periodic high magnitude, short duration (spike) flows improve low-velocity habitats by flushing sediment and discouraging the presence of non-native species	

The maximum interval is defined as the maximum amount of time between category flow events to remain in compliance with the flow recommendations. For instance, category 1 in Table 15 describes a flow event of at least 10,000 cfs for at least 5 consecutive days between March 1st and July 31st. The maximum amount of time that may lapse before the next flow event, the maximum interval, is 11 years to remain in compliance with the flow recommendations.

Construction of Navajo Dam began with the signing of the 1956 Colorado River Storage Project Act, which authorized a number of projects to allow for the development of water resources within the Upper Colorado River Basin. Construction of Navajo Dam was completed in 1963 and has a maximum content of approximately 1.7 MAF, supporting a number of water development projects in New Mexico and Colorado. The Navajo Indian Irrigation Project diverts water from the reservoir at an intake elevation of 5,990 feet when storage is approximately 0.662 MAF. During the winter, the reservoir can be lowered to 5,985 feet with approximately 0.626 MAF in storage as long as the reservoir recovers prior the beginning of the irrigation season (U.S. Department of the Interior, Bureau of Reclamation, Upper Colorado Region, 2006). Like other Colorado River Storage Project Act projects, Navajo Dam produces hydroelectric power through a plant owned and operated by the city of Farmington, New Mexico. Reclamation operates Navajo Dam to meet the flow recommendations outlined in Table 15. Water resource development planning and Reclamation's ability to comply with section 7 of the Endangered Species Act (ESA) within the San Juan River Basin and subsequent impacts to the SJRBRIP flow recommendations is evaluated using multiple hydrologic models,

one of them being the San Juan Daily Decision Model (SJDDM). From the SJRBRIP (2006):

> *The [SJDDM] is used to support [SJRBRIP] goals to recover populations of the endangered razorback sucker and Colorado pikeminnow in the San Juan River while proceeding with water development in the Basin. The model is used in ESA section 7 consultations to determine the level of impact, if any, of a proposed water development or water management action on Reclamation's ability to operate Navajo Dam to meet the [SJRBRIP's] flow recommendations for the San Juan River below Farmington, or a reasonable alternative. Model results are not the sole criteria used to determine the level of a proposed water project's impact, and model assumptions and model uncertainty are considered when interpreting results. The model was used to evaluate and develop the current flow recommendations, and will be used in developing future revisions to the flow recommendations. In addition, the model will be used to develop and evaluate revisions to the hydrologic baseline.*

6.2 Hydrologic Model

To aid in the planning of water development projects and their impact to Reclamation's ability to meet flow recommendations in the San Juan River Basin, Reclamation utilizes a hydrologic model created within the RiverWare framework (Zagona et al., 2001) referred to as the San Juan Daily Decision Model (SJDDM). Figure 49 illustrates the SJDDM within the RiverWare framework which is operated at a daily timestep. RiverWare is a versatile object-based hydrologic model that allows for rule-based simulation. Being a rule-based model, the operation of reservoirs and flow recommendation goals and requirements can be incorporated into the model in the form of prioritized logic. The SJDDM has been developed with rules to operate the Navajo Reservoir to meet the flow recommendations developed by the SJRBRIP.

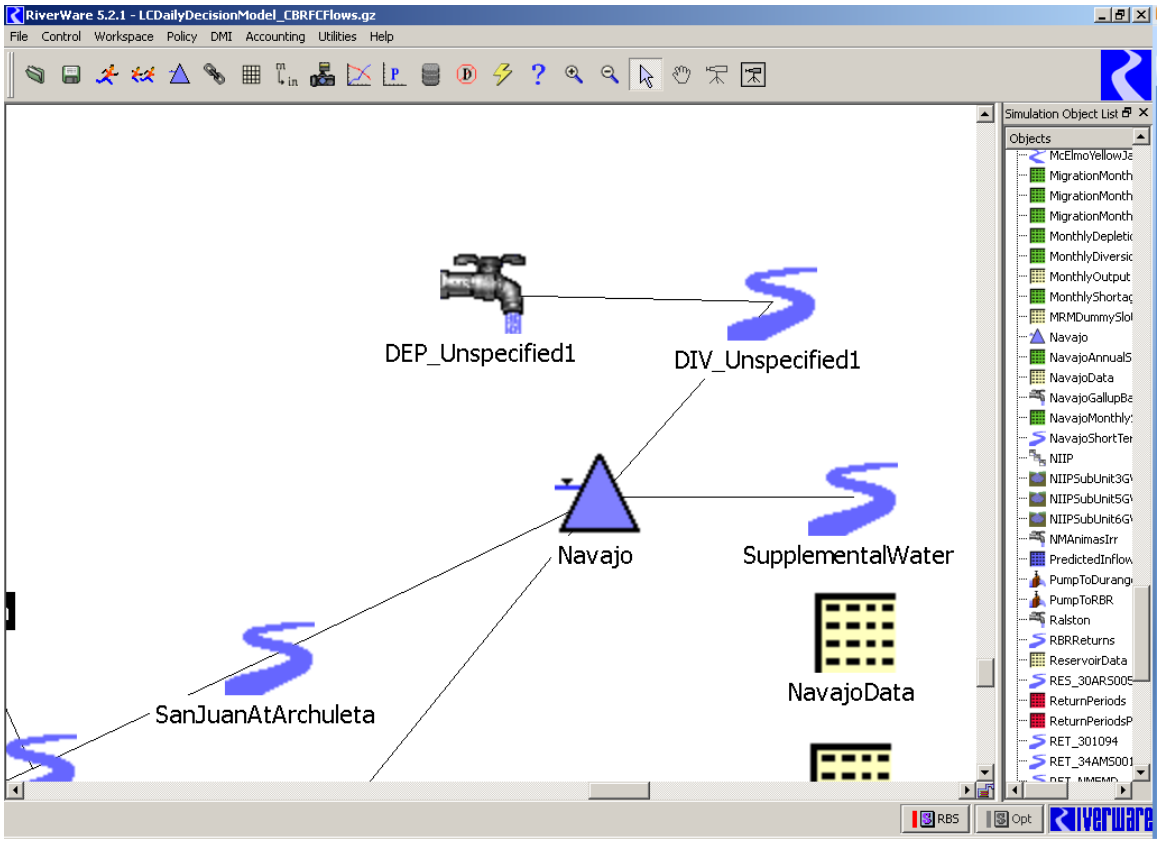

Figure 49: The SJDDM within the RiverWare framework

The SJDDM is just one planning model in a series of models and forecasts utilized by Reclamation to evaluate how efficiently flow recommendations may be met under historical hydrologic scenarios. Prior to the running of the SJDDM, unregulated (naturalized) flows within the San Juan River Basin are computed using the state of Colorado's Water Resource Model, commonly referred to as StateMod (Bennett, 2000). From this model, Colorado's monthly baseline water supply is computed. A subsequent model takes monthly unregulated flow from the StateMod model and computes daily regulated flow that can be input into the SJDDM. The goal of the SJDDM is to optimize flushing releases to avoid unnecessary releases such that water can be used to meet future flow recommendations, meet baseflow requirements for endangered fish and their habitat,

and conserve water for future water development projects while staying compliant with the ESA and SJRBRIP flow recommendations.

Being a regulated flow model, the SJDDM implicitly takes into account reservoir operations upstream of Navajo Reservoir in addition to diversions and return flows within the San Juan River Basin. Upstream reservoir operations and diversions are not explicitly simulated. As such, unregulated streamflow projections can not be directly input into this model; regulated streamflow is required as input.

For this study, the SJDDM was run at a daily timestep over water years 1976 through water year 2069 using information from unregulated streamflow projections derived through temporally disaggregated BCSD climate data. This is discussed in further detail in Section 5.3.

6.3 Data

6.3.1 Consumptive Use Within the San Juan River Basin

The SJDDM is a regulated flow model which implicitly takes into account diversion requests from water users within the San Juan River Basin as well as return flows to the San Juan River Basin system. As such, projections of future consumptive use within the San Juan River Basin had to be derived. The Upper Colorado River Commission recently issued a hydrologic determination in which an estimate of water use in the Upper Colorado River Basin was defined through 2060 (Upper Colorado River Commission, 2007). Projected use in the Upper Colorado River Basin is a departure from observed consumptive use in the Upper Colorado River Basin and is representative of projected development of water resources and projects over the upper basin (Figure 50). Current

use in the basin is more dependent on both socio-economic factors and hydrology, compared with projected use.

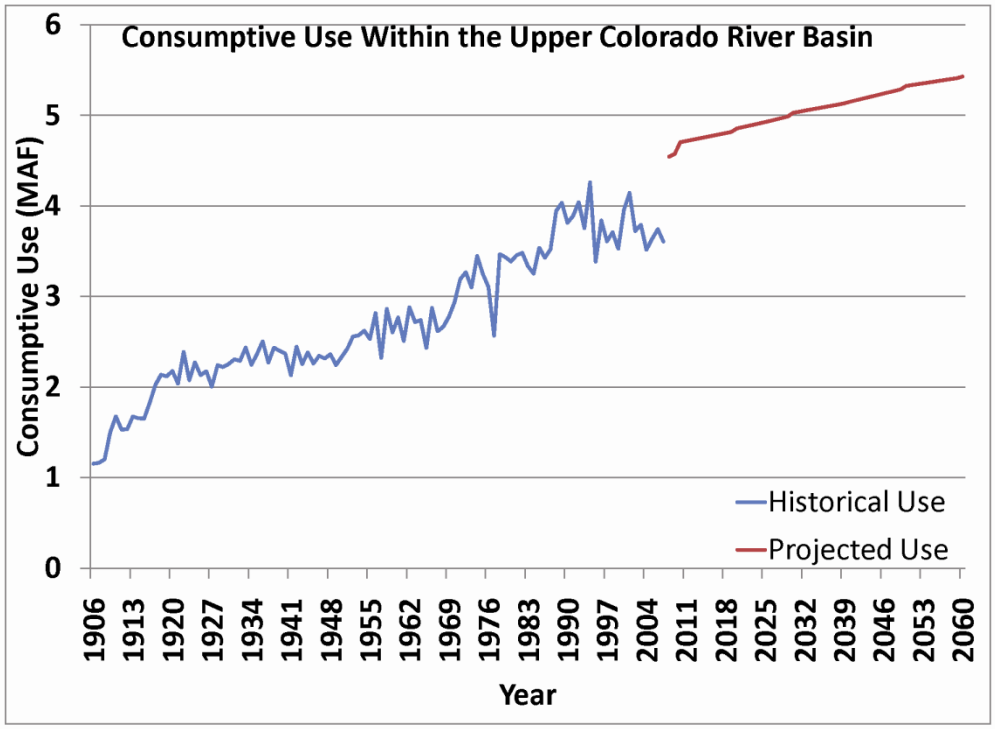

Figure 50: Upper Colorado River Basin Historical and Consumptive Use

Projected future water use in the San Juan River Basin was estimated by first computing a daily average for each day over the calendar year over the calibration period spanning 1976 through 2005. A ratio of projected annual consumptive use to average historical consumptive annual use over the calibration period was defined for each year from 2008 through 2069. Projected daily consumptive use was then calculated by adjusting the daily average consumptive use at a particular diversion within the SJDDM by multiplying this daily average by the projected annual consumptive use to average annual consumptive use ratio previously derived. This may be expressed as:

$$CU_T = \overline{CU} * \frac{PU_T}{\overline{AAU}} \qquad (24)$$

where CU_T is the daily projected consumptive use at timestep T at that diversion point, $\overline{CU}$ is the long – term average consumptive use at time T over the calibration period (1976 – 2005), PU_T is the projected annual use at time T, and $\overline{AAU}$ is the long term average annual consumptive use for that diversion point over the calibration period.

Annual consumptive use for the years 2061 through 2069 was linearly increased by the average annual increase over the projected period, approximately 9,000 acre-feet per year. It is important to note that this study did not assume changes to consumptive use within the San Juan River Basin due to climate change or other socio-economic impacts (i.e., changing water use due to changing demographic or economic conditions within a region).

6.3.2 Projected Inflow Conditions

Projections of unregulated inflow under changing climate conditions over the San Juan River Basin were incorporated into Reclamation's SJDDM. As stated in section 6.2, projected unregulated inflow can not be directly incorporated into the SJDDM. As a result, a methodology was developed to incorporate information from these climate change projections into the SJDDM.

Within the SJDDM, there are 17 objects (or nodes) to which streamflow can be input into the model. For each of these objects, unregulated streamflow projections were identified which correspond approximately to the physical location of each node within the San Juan River Basin. At each of these nodes projections of daily streamflow were made over the period from 2008 to 2069. This time period was selected to be consistent with thirty year periods presented in previous chapters and due to constraints of projected consumptive use over the Upper Colorado River Basin.

Projected streamflow at each inflow object within the SJDDM was estimated by first computing a daily average of historic streamflow at each object for each day over the calendar year over the calibration period spanning 1976 through 2005. A ratio of projected annual streamflow to average annual projected streamflow over the calibration period was defined for each object and each year from 2008 through 2069 for each of the 112 climate scenarios. Projected daily regulated streamflow was then calculated for each inflow node in the SJDDM by multiplying the node's daily average by the projected annual streamflow to average annual projected streamflow ratio previously derived. This may be expressed as:

$$Q_P = \overline{Q} * \frac{q_A}{\overline{q}} \tag{25}$$

where Q_P is the daily projected streamflow at time P, $\overline{Q}$ is the average regulated daily streamflow, q_A is the annual projected unregulated streamflow at year A corresponding with time P for a particular emissions scenario, and $\overline{q}$ is the average annual streamflow projection over the calibration period for a particular emissions scenario. Through this process, annual consumptive use data in the Upper Colorado River Basin is effectively temporally and spatially disaggregated.

Initial conditions of reservoir storage within the model were set to observed conditions at the end of the day on September 30, 1975. Default initial model parameter conditions relating to initial groundwater storage conditions and coefficients, return flow rates, and routing coefficients were retained.

6.4 Results

The SJDDM was initially run using historical initial reservoir conditions and historical consumptive use values from water year 1976 through 2005. This was done for two reasons:

1. Model results over 1976 through 2005 could be compared to historical observations over the same time period.
2. Initial conditions within in the model needed to be developed before projecting the model further into the future under the 112 streamflow scenarios.

The SJDDM was then subsequently run using 2005 modeled initial conditions from water year 2006 through 2069 using information from the 112 streamflow projections derived using temporally disaggregated, BCSD climate data as described in Chapter 5. In this study, reservoir and flow characteristics are compared over three periods within the San Juan River Basin. The first period is a single hydrologic trace that spans water year 1976 through 2005 and is modeled using initial conditions and historical consumptive use values within the San Juan River Basin. The second period spans water year 2010 through 2039 and uses streamflow information over that time period from 112 hydrologic traces. The third period spans water year 2040 to 2069 and uses streamflow information over that time period using those same 112 hydrologic traces utilized in the previous time period.

6.4.1 Navajo Reservoir Operations

Figure 51 illustrates Navajo Reservoir as modeled by the SJDDM over water years 1976 through 2005 and observed storage at the reservoir. It should be noted that the flow

recommendations by the SJRBRIP were not implemented until 1992, so releases prior to then are not indicative of Reclamation operations in response to the SJRBRIP. Average observed and modeled storage within the Navajo Reservoir during this time period is approximately 1.3 MAF, though the timing of environmental releases is different. The minimum end of month pool elevation over this range is 5974.57 feet in October of 2004, which is below the minimum operating level for the Navajo Indian Irrigation Project (5990 feet), but outside of the growing season. The maximum end of month pool elevation is 6085.22 feet in April of 2004. Mean monthly inflow into the Navajo Reservoir is approximately 79 KAF. Over the 1976 through 2005 period, the Navajo pool elevation was below the minimum Navajo Indian Irrigation Project operating elevation from July 8, 2004 through April 4, 2005 and from September 5, 2005 through October 31, 2005. The Navajo Reservoir pool elevation is below 5990 feet approximately 3% of the time over the 30-year period, or an average of 3% per year. In 2005, Navajo Reservoir pool elevation was below 5990 feet approximately 58% of the time.

It is important to note that while seasonal and annual variations in hydrology and reservoir operations are important to Reclamation, the focus of this study is on long-term planning and operational impacts. It is acknowledged that month to month and annual variability in Reclamation operations is not represented consistently within the SJDDM; however, as mentioned previously, the long-term historical and modeled operations at Navajo Dam are equal. Furthermore, long term trends in storage, release, and flow within the San Juan River Basin are captured in the SJDDM. Additional study and

improvement to the SJDDM may better capture seasonal and annual operations within the San Juan River Basin in the future.

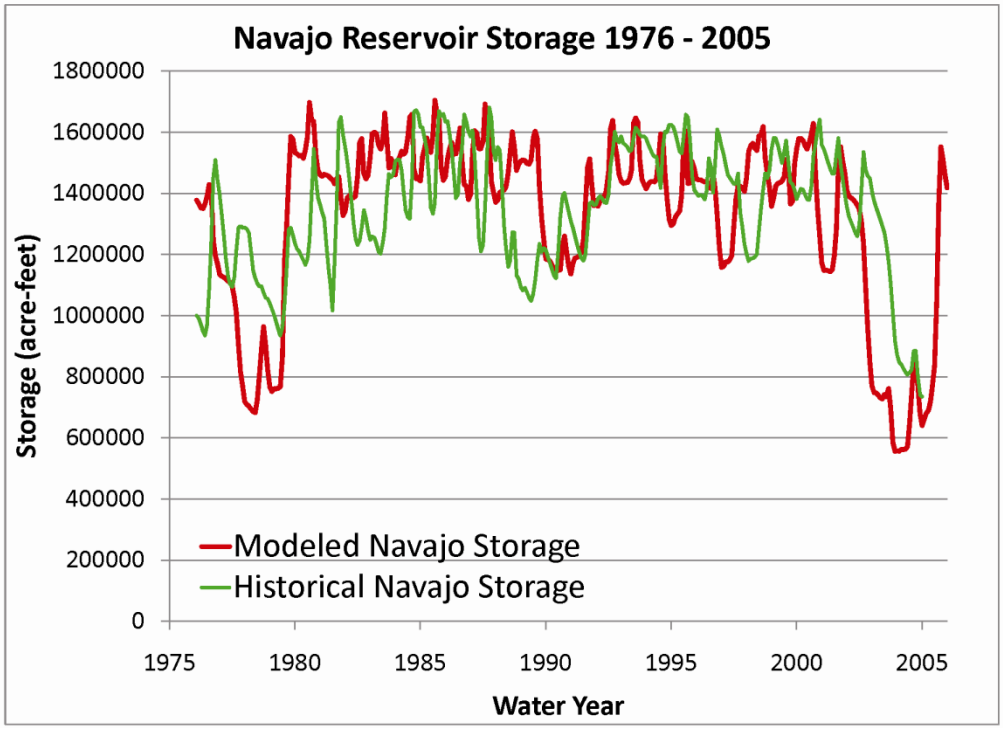

Figure 51: Navajo Reservoir observed and modeled end of month storage from water 1976 through 2005. The long term average storage of both modeled and historical storage is approximately 1.3 MAF.

The SJDDM operates the Navajo Reservoir to meet flow recommendations as described by the SJRBRIP. The SJDDM was run using information from 112 streamflow projections derived using projections of future climate conditions from water year 2010 through 2039 (Figure 52). The average Navajo Reservoir storage over this period is approximately 1.4 MAF. Over the 30 year period, the 10-year average water year storage decreases approximately 2.8 KAF per year.

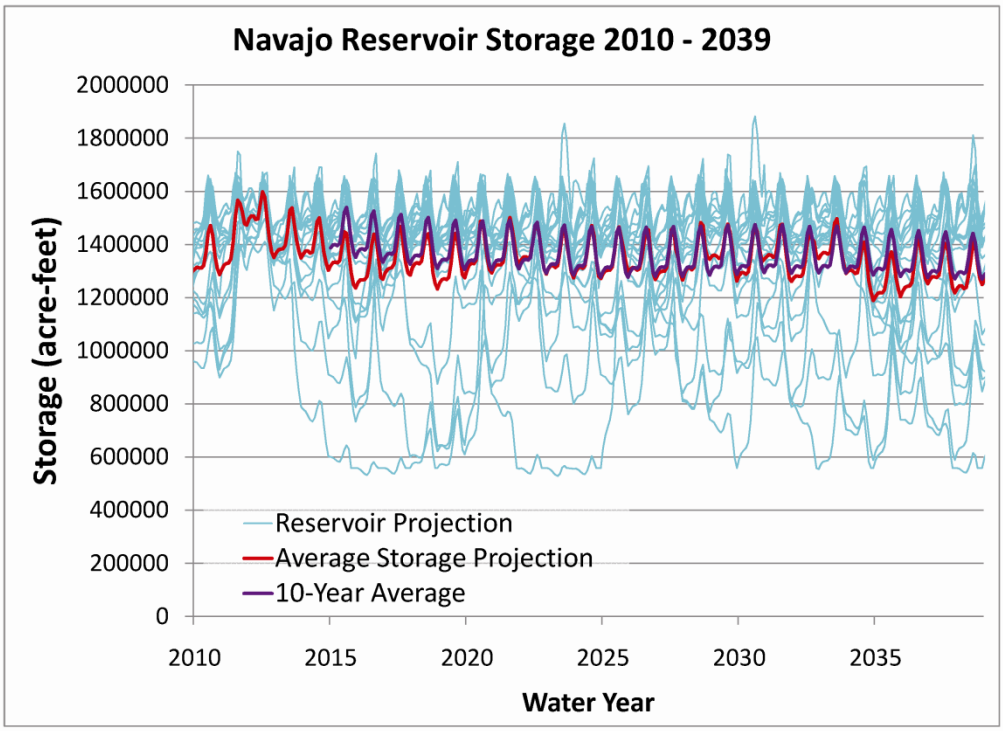

Figure 52: Projection of Navajo Reservoir Storage from water year 2010 through 2039. The red line illustrates the average of the 112 reservoir storage projections at any given time. The purple line illustrates the moving 10-year average reservoir storage projection at any given time.

On average, the pool elevation at Navajo Reservoir is above 5990 feet 97% of the time.

Decreases in average Navajo Reservoir storage are more stark as consumptive use is increased to meet projected Upper Colorado River Basin projections (Figure 53). Average Navajo Reservoir storage is 1.1 MAF. Over the 30 year period, the 10-year average water year storage decreases approximately 1.4 KAF per year. Decreased water in the reservoir limits Reclamation flexibility to operate Navajo Dam to meet consumptive use requirements and flow recommendations.

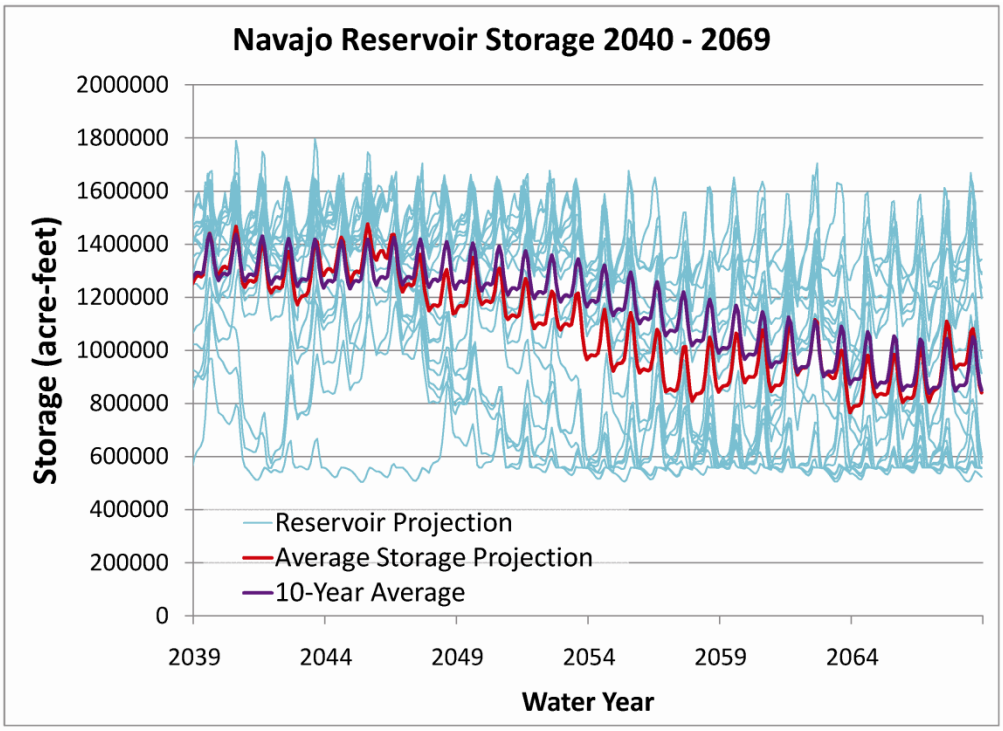

Figure 53: Projection of Navajo Reservoir Storage from water year 2040 through 2069. The red line illustrates the average of the 112 reservoir storage projections at any given time. The purple line illustrates the moving 10-year average reservoir storage projection at any given time.

Reflective of the increase in consumptive use throughout the basin, the pool elevation at Navajo Reservoir is above 5990 feet approximately 80% of the time during the 2040 to 2069 time period. This potentially may impact operations of the Navajo Indian Irrigation Project. These results indicate that consumptive use, combined with potential impacts due to climate change, may adversely impact Reclamation's ability to meet both flow recommendations and water delivery requirements efficiently.

6.4.2 Performance of Flow Recommendations at the San Juan River and Animas River Confluence Near Farmington, NM

The San Juan River flow recommendations are monitored at the confluence of the San Juan and Animas Rivers near Farmington, New Mexico (confluence). Analysis of flows at the confluence is performed over the same time period as analysis of the Navajo

Reservoir (Section 6.4.1). Figure 54 illustrates monthly flow volumes spanning the 1976 through 2005 water year at the confluence. Average monthly projected streamflow at the confluence is approximately 92 KAF. It is interesting to note high flow months that are typically representative of high flows released to meet flow recommendations for endangered fish. It is also important to note the minimum baseflow of approximately 500 cfs (approximately 30,000 acre-feet monthly).

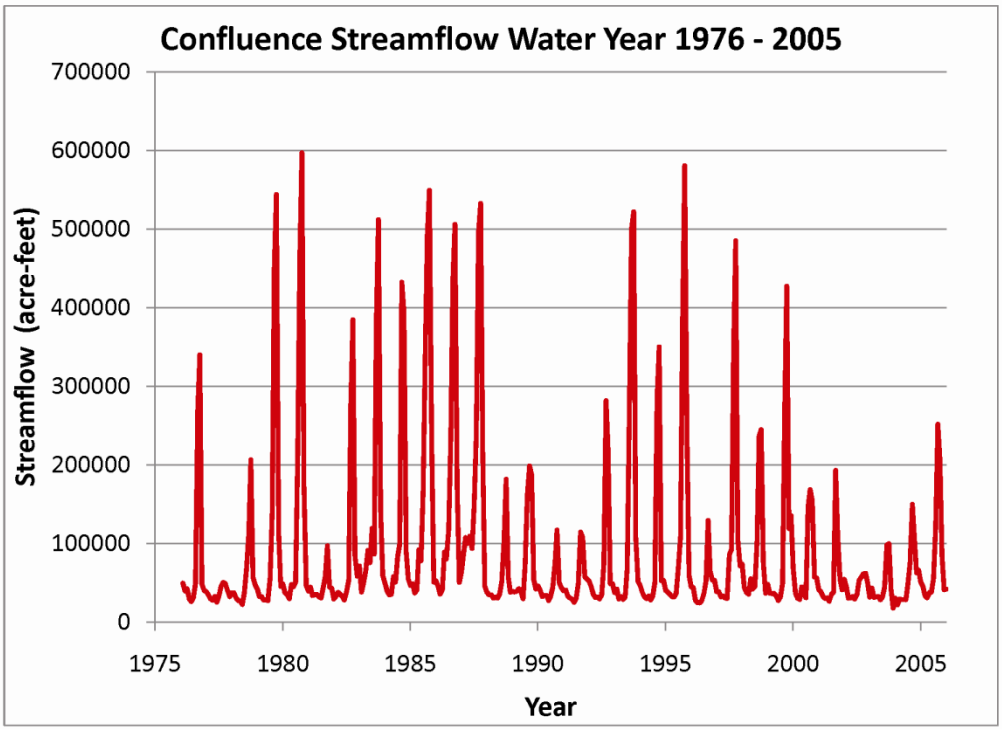

Figure 54: Monthly streamflow at the confluence of the San Juan and Animas Rivers.

Each year was analyzed for its ability to meet the enumerated flow recommendations in Table 15. The occurrence of a particular flow recommendation within the 30 year period, along with the maximum interval between a particular flow recommendation. A summary of these results is presented in Table 16.

Table 16: Summary of modeled ability to meet flow recommendations over the water years 1976 - 2005. Maximum Interval is the time between flow recommendation events, Occurrence is the number of years a particular flow recommedation could be met.

Flow Recommendation	Occurrence	Maximum Interval
1	8	8
2	10	8
3	14	6
4	26	1

Nearly all the water years over the 30 year period have a flow regime able to meet the 2500 cfs for 10 days requirement during spring runoff (flow recommendation #4, Table 15). The only recommendation frequency that is not fully met is requiring 5000 cfs for at least 21 days for 50% of the years (flow recommendation #3, Table 15); in this model, it is met 47% of the time. The maximum interval for flows of 8000 cfs and 5000 cfs were also each exceeded by one year. Streamflow at the confluence of the Animas and the San Juan Rivers was modeled over water years 2010 through 2039 (Figure 55).

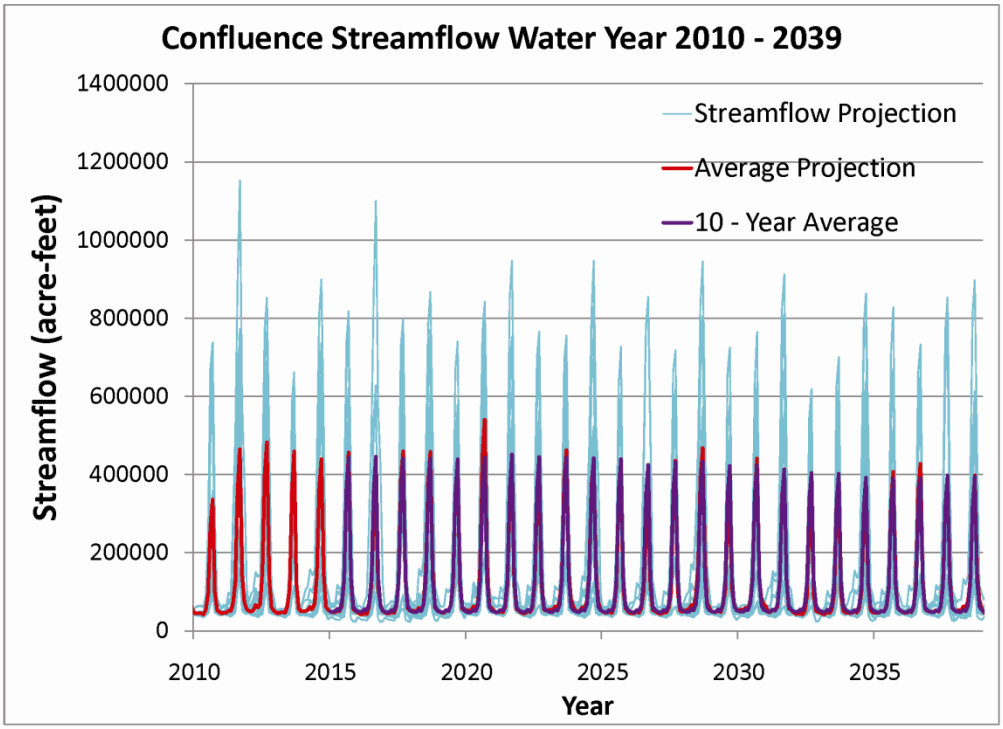

Figure 55: Monthly streamflow projections at the confluence of the San Juan and Animas Rivers.

Seasonal peaks are retained throughout the flow series despite increasing consumptive use and decreasing streamflow within the basin. Increased releases from the Navajo Reservoir due to higher consumptive use contribute to high flows at the confluence. However, over the projected 30 year period, average streamflow is approximately 100 KAF; slightly above that modeled over the 1976 – 2005 period. This may be due to increased return flows to the San Juan River due to increased water demand.

Table 17 summarizes the average ability to meet flow recommendations within the San Juan River Basin. Overall characteristics of the model's ability to meet the flow recommendations over the 2010 through 2039 period are slightly increased when compared with the 1976 through 2005 period. This is due to the fact that Navajo Reservoir releases more water to meet water delivery demands during the spring months, and thus, higher flows are observed. While the ability to better meet flow recommendations may appear slightly improved, there is less total storage in the Navajo Reservoir during the 2010 through 2039 period.

Table 17: Summary of modeled ability to meet flow recommendations over the water years 2010 - 2039. Maximum Interval is the time between flow recommendation events, Occurrence is the number of years a particular flow recommedation could be met.

Flow Recommendation	Occurrence	Maximum Interval
1	12.9	6.7
2	15.6	5.5
3	16.1	4.3
4	26.4	1.9

Figure 56 illustrates projected streamflow at the confluence over the 2040 through 2069 time period. Like the previous 30-year period, there are occasional high flows in excess of those observed over the 1976 through 2005 modeled period. Unlike the

previous multi-decadal period, average monthly streamflow at the confluence of the Animas and San Juan Rivers is slightly lower than that simulated in the 1976 through 2005 period, approximately 90 KAF.

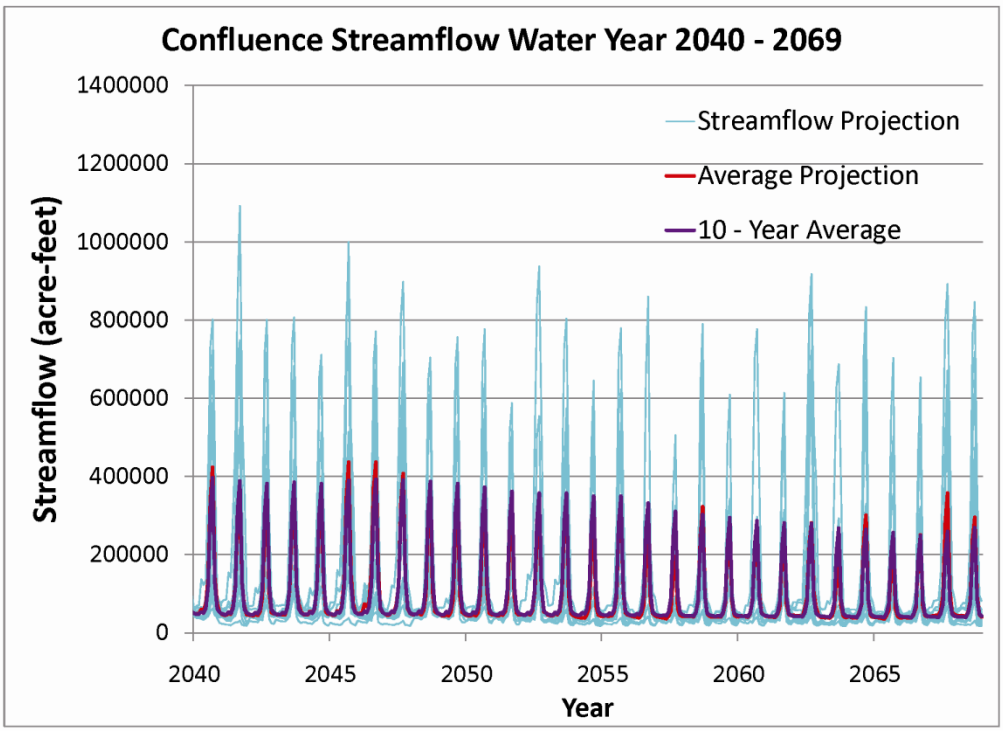

Figure 56: Monthly streamflow projections at the confluence of the San Juan and Animas Rivers.

Table 18 summarizes the average ability to meet flow recommendations within the San Juan River Basin. Overall characteristics of the model's ability to meet the flow recommendations decreased in efficiency from those modeled over the 1976 – 2005 period. In all cases, the average maximum interval increased between flow events, and the occurrence of events decreased in all cases. The total number of flow events decreased on average over the 2040 – 2069 period, and the maximum interval between events increased.

Table 18: Summary of modeled ability to meet flow recommendations over the water years 2040 - 2069. Maximum Interval is the time between flow recommendation events, Occurrence is the number of years a particular flow recommedation could be met.

Flow Recommendation	Occurrence	Maximum Interval
1	7.9	12.4
2	9.4	11.8
3	10.7	9.7
4	22.6	2.7

6.4.3 Distribution of Navajo Reservoir Storage

The cumulative distribution of storage within Navajo Reservoir over the water years 1976 through 2005, 2010 through 2039, and 2040 through 2069 are compared (Figure 57). The storage values spanning water year 1976 through 2005 are derived using historically modeled consumptive use and streamflow in the San Juan River Basin. Storage values spanning water year 2010 through 2069 are derived using projections of consumptive use and streamflow that has been adjusted using information from streamflow projections developed using temporally disaggregated, BCSD climate data. In the SJDDM, storage within Navajo Reservoir is directly influenced by inflow, predominantly unregulated, into the San Juan River Basin.

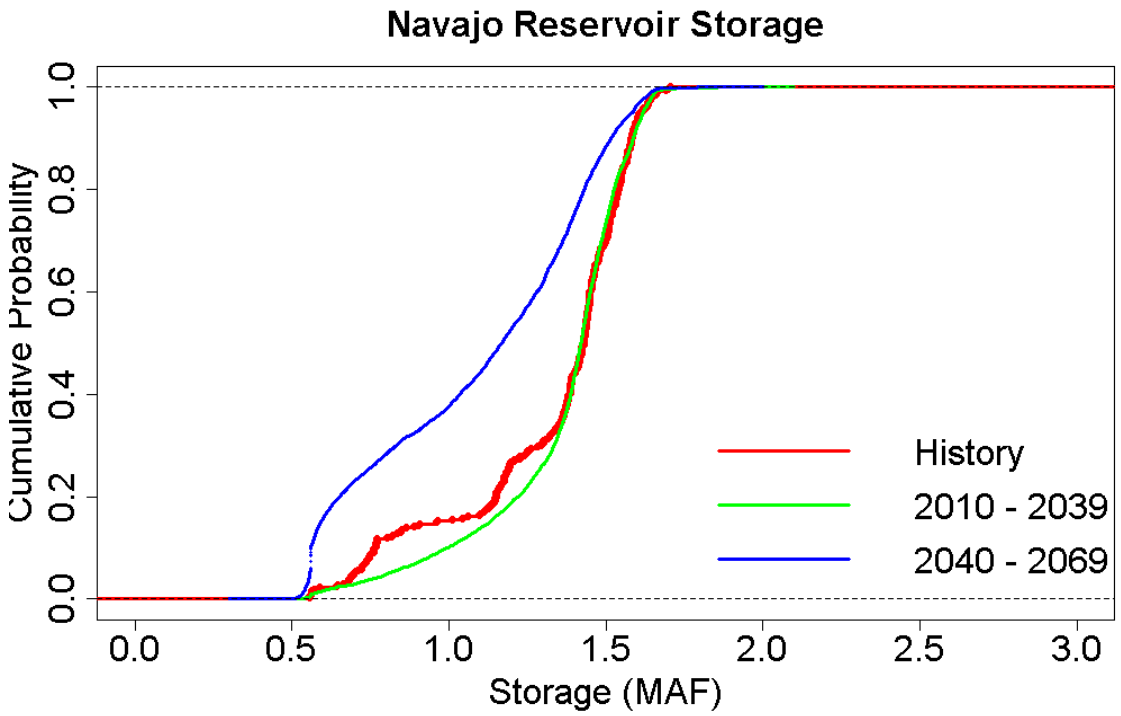

Figure 57: Navajo Reservoir storage output from the SJDDM. The red line illustrates the cumulative probability distribution of monthly reservoir storages derived using historical consumptive use and streamflow conditions within the San Juan River Basin. The green and blue lines represent the cumulative probability distribution of monthly reservoir storage derived using information from projected streamflow under changing climate conditions and projected consumptive use within the San Juan River Basin.

The KS – Test was used to compare each of the two projected cumulative probability distributions of reservoir storage with historically modeled projections of storage within Navajo Reservoir. For the projected period spanning 2010 – 2039, the projection exhibits a test statistic greater than the critical value when compared to the historical projection such that the null hypothesis could be rejected. The same result was found when comparing the projected period spanning 2040 – 2069 to the historical period. This indicates that the model results from the future projections are statistically significantly different than those from the modeled historic. Table 19 summarizes these results.

Table 19: Results of the KS - Test over the Navajo Storage results from the SJDDM.

	Test Statistic	Critical or p-Value	Null Hypothesis
Navajo Storage Projections 2010 - 2039	0.080	0.022	Rejected
Navajo Storage Projections 2010 - 2039	0.349	≈0.00	Rejected

6.4.4 Distribution of Streamflow at the Confluence

The cumulative distribution of streamflow at the confluence over the water years 1976 through 2005, 2010 through 2039, and 2040 through 2069 are compared (Figure 58). The streamflow values are derived using identical methodology as Navajo Reservoir storage values for respective time periods. However, in the SJDDM, streamflow at the confluence is regulated within the model to meet consumptive use demands and flow recommendations. Streamflow at the confluence is more directly influenced by consumptive use within the San Juan River Basin; storage, if available, within Navajo Reservoir is released to meet these demands regardless of inflow into the reservoir system.

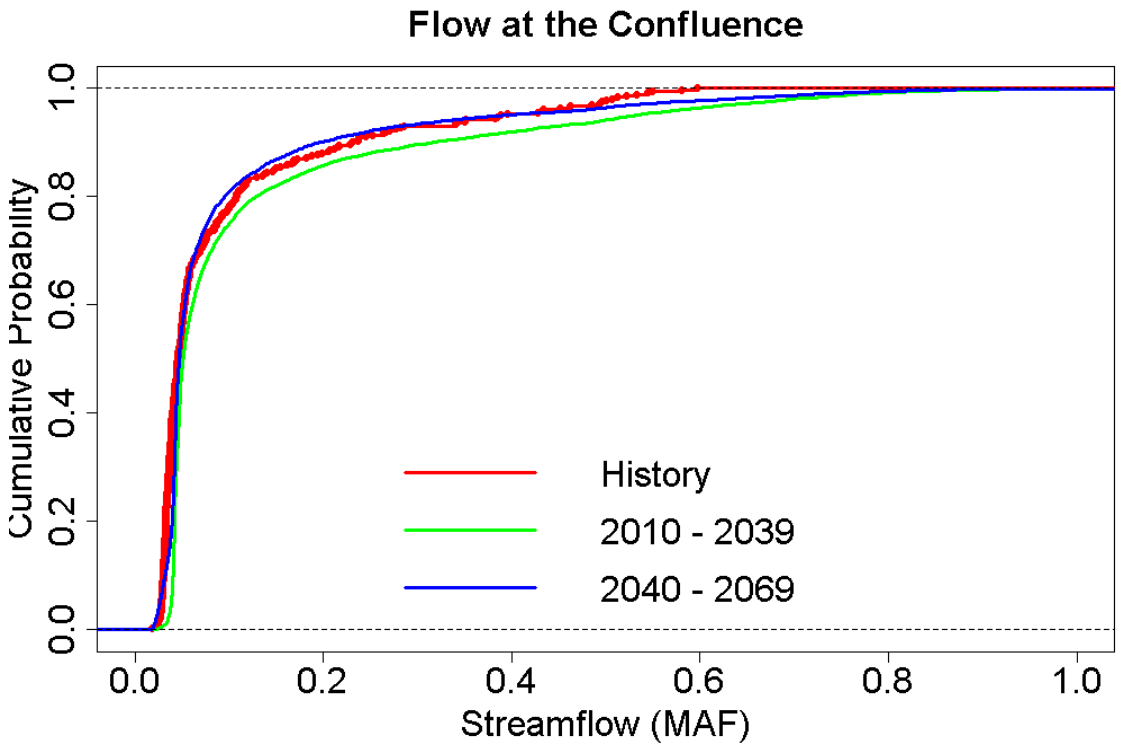

Figure 58: Flow at the confluence output from the SJDDM. The red line illustrates the cumulative probability distribution of streamflow derived using historical consumptive use and streamflow conditions within the San Juan River Basin. The green and blue lines represent the cumulative probability distribution of monthly streamflow derived using information from projected streamflow under changing climate conditions and projected consumptive use within the San Juan River Basin.

The KS – Test was used to compare projected distributions of streamflow at the confluence with historically modeled projections of streamflow at the confluence. For the projected period spanning 2010 – 2039, the projection exhibits a test statistic greater than the critical value when compared to the historical projection such that the null hypothesis could be rejected. The same result was found when comparing the projected period spanning 2040 – 2069 to the historical period, again indicating a statistically significant distribution from the modeled historic output. Table 20 summarizes these results.

Table 20: Results of the KS - Test over the streamflow at the confluence results from the SJDDM.

	Test Statistic	Critical or p-Value	Null Hypothesis
Confluence Flow 2010 - 2039	0.328	≈0.00	Rejected
Confluence Flow 2010 - 2039	0.200	≈0.00	Rejected

Despite flow at the confluence being regulated at the model, there exists more frequent peak flows, with larger magnitudes, in future model projections than those historically modeled. These results may be more representative of significant changes in the consumptive use of water within the basin than water supply.

6.5 Discussion

In this study, information from streamflow projections derived using projections of future climate was incorporated into a Reclamation planning model, namely, the SJDDM. This study also proposed a methodology by which projections of unregulated flow may be incorporated into a regulated flow model. Based on the multidecadal projections studied here, it is apparent that consideration of future unregulated streamflow projections enables water resource managers to account for hydrologic variability, but does not take into account socio-economic variability and large potential impacts to watershed hydrology.

This study assumed consumptive use within the San Juan River Basin will increase coincident with projections of consumptive use over the Upper Colorado River Basin. Considering the current recession of the U.S. economy, development of water resources in the Upper Colorado River Basin has lagged behind projections. Simulated increased

consumptive use over the San Juan River Basin resulted in increased demand from Navajo Reservoir and subsequent diversion and return flows within the basin. As a result, modeled future streamflow at the confluence of the Animas and San Juan Rivers may have been augmented by return flow. While this consequence may assuage concerns related to the future ability to meet the flow recommendations set forth by the SJRBRIP, it does not address water quality issues that may arise with increased return flow to the river. In future study, it would be beneficial to examine consumptive use from a more probabilistic, rather than deterministic, vantage. Despite this limitation, this study successfully incorporated climate change information into a Reclamation planning model; the first such attempt within the Colorado River Basin. Future work will attempt to reconcile differences in streamflow projections between Reclamation planning models such as the Colorado River Simulation System (CRSS); similar hydrologic studies have focused on the reconciliation of streamflow projections from hydrologic models (e.g., Hoerling et al., 2009).

In fulfilling water delivery requirements and flow recommendations, a number of considerations must be taken into account, and prioritized. As such, the SJDDM may evolve into an operational model from which daily Navajo Reservoir operations may be determined with increased accuracy and benefit to endangered species in the area. Future Reclamation efforts will continue to incorporate climate change information into both operational and planning models. Regardless of model evolution, it is clear that proactive conservation efforts, transparent river management, and continued incorporation of the best science available are essential to managing the Colorado River and its tributaries effectively and efficiently.

CHAPTER 7

CONCLUSIONS, CONTRIBUTIONS, AND FUTURE DIRECTION

7.1 Conclusions and Contributions

The research presented in this study contributes to the discipline of hydrology and water resources, the science of climate change, and advances the goals of Reclamation, particularly in the Colorado River Basin. In this study, climate change impacts over the Colorado River Basin were addressed through the investigation of the changing nature of precipitation and hydrologic intensification and how those impacts may affect future Colorado River Basin streamflow and reservoir management within the basin. Future impacts of climate change to the Colorado River Basin were then investigated using temporally disaggregated, BCSD projections of future climate (i.e., temperature and precipitation) conditions. Temporally disaggregated, BCSD climate data were used to derive unregulated streamflow projections at three headwater basins within the Upper Colorado River Basin: the Gunnison River Basin, the Green River Basin, and the San Juan River Basin. This research also represents Reclamation's first effort to incorporate climate change information from GCMs into a river management planning model on the Colorado River Basin, specifically within the San Juan River Basin.

7.1.1 Chapter 4 Contributions

In Chapter 4, characteristics of precipitation and corresponding changes to streamflow over the Colorado River Basin were investigated to evaluate potential impacts of climate change to the hydrology of the Colorado River Basin. The research presented in Chapter 4 demonstrated that over the current period of drought within the Colorado River Basin, the length of the snowpack season has shortened and corresponds with

decreased annual streamflow. Due to increasing temperature trends, earlier snowmelt has contributed to changes in the magnitude and timing of runoff within the Colorado River Basin. As this period of drought continues in the Colorado River Basin, water resource managers and forecasters should continue to expect shorter snowpack seasons and resultant decreased and earlier runoff in the basin. It is possible that earlier snowmelt runoff is more susceptible to infiltration and evaporative losses throughout the basin, as increasing temperatures may increase both potential and actual evapotranspiration rates. With continued drought and decreased spring runoff, water resource managers must continue effective water management policies and conservation practices. While this study allowed for the general characterization of hydroclimatic trends over the Colorado River Basin, the nature of the data (i.e., relatively short period of record) analyzed did not allow for a more extensive investigation into changing precipitation characteristics. Chapter 3 presented research published in the Journal of Hydrometeorology (Miller & Piechota, 2008) and was a precursor to work presented in Chapter 4.

Contribution #1 – Chapter 4 related trends in snowpack and streamflow conditions throughout the Colorado River Basin. Shorter snowpack seasons and decreased precipitation, particularly in this time of drought, have contributed to decreased streamflow within the basin.

7.1.2 Chapter 5 Contributions

The goal of Chapter 5 was to derive projections of unregulated streamflow under changing climate scenarios over the Gunnison, Green, and San Juan River headwater basins. Temporally disaggregated BCSD climate data was used to force the NWS RFS developed by the CBRFC over the three Colorado River headwater basins for 112

projections of future climates based on projections of future greenhouse gas emissions. Although the NWS RFS model was unable to be calibrated by methods used at the CBRFC, a post-bias correction was applied to address this limitation. Furthermore, the impact of changing temperature to evapotranspiration rates was investigated. It was observed that adjusting evapotranspiration to changing temperature significantly impacted streamflow projections. Over the Gunnison River Basin, adjusting evapotranspiration with changing temperature decreased projected streamflow by as much as 13% or nearly 300,000 acre-feet. It is acknowledged that evapotranspiration was represented as a linear function of temperature; future research may attempt to develop alternative functions to describe evapotranspiration demand.

Results of multi-decadal analysis of streamflow projections over Colorado River headwater basins yielded interesting results. Encompassing the northern portion of the Colorado River Basin, the Green River Basin did not exhibit significant change under climate change conditions and actually showed an increase in runoff on average of 3% over the projected 90 year period. In contrast, the Gunnison and San Juan River Basins exhibited significant negative change in runoff. Over the Gunnison River Basin, average streamflow decreased approximately 15% over the 90 year projection period; the San Juan River Basin average streamflow decreased nearly 20%.

Contribution #2 – A methodology was developed to incorporate changes to evapotranspiration rate with changing temperature conditions over the Colorado River Basin. Evapotranspiration changes due to climate change were accounted for in the derivation of streamflow projections.

Contribution #3 – The NWS CBRFC RFS was forced using projections of future climate from temporally disaggregated, BCSD data from large-scale GCMs over Colorado River headwater basins. These streamflow projections present a range of streamflows that Reclamation may use to plan for the future under changing climate conditions.

7.1.3 Chapter 6 Contributions

Chapter 6 represented Reclamation's first effort to apply climate change information from GCMs to a planning model in the Colorado River Basin. Information from unregulated streamflow projections were used to derive regulated streamflow time series over the San Juan River Basin. These time series were then used to drive the SJDDM through the year 2069. Continued drought and decreasing streamflow within the basin would impact Reclamation's efforts to meet water demands as efficiently and effectively as has been done historically. It was observed that projected streamflow volumes decreased within the San Juan River Basin. When coupled with the assumption that consumptive use within the Upper Colorado River Basin will increase, the flexibility to meet environmental releases was impacted. These results indicate the need for continued conservation efforts and efficient management of the river system.

Contribution #4 – This work represents Reclamation's first effort to incorporate climate change information from GCMs into a planning model within the Colorado River Basin.

Contribution #5 – This work provides a "proof-of-concept" for incorporating climate change data from multiple sources and models over the Colorado River Basin.

7.2 Research Utility

The research presented in this dissertation advances and contributes to the understanding of hydroclimatic impacts due to climate change over the Colorado River Basin and is of great utility to the academic, Reclamation, and general water resource management communities. It is important that research, as it pertains to climate change and subsequent impacts to people and the environment, is effectually communicated, transparent, and accessible to a broad range of professionals, as well as the general public. Whereas research in other fields may strive to only advance scientific theory, or pertain to a relatively small population, it is important that climate change research advance the understanding of the entire community.

This study provides a framework from which water resource managers and researchers may incorporate relatively complex projections of future climate into hydrologic models to develop streamflow projections which may not have necessarily been observed in the past. These streamflow projections provide for a range of scenarios from which risk assessment and planning endeavors may be undertaken.

This research describes a methodology in which the limitation of one hydrologic model, in this case the NWS CBRFC RFS, to account for changes to a hydroclimatic variable (i.e., evapotranspiration) due to climatic change is overcome through the use of another hydrologic model (i.e., the VIC model). This methodology is relatively flexible, and may be applied to different hydrologic models and hydroclimatic variables not considered here.

With regards to the utility of this research to Reclamation operations, this research provides a "proof-of-concept" study which may be applied to other subbasins within the

Colorado River Basin, or, with the cooperation of other agencies and Colorado River Basin stakeholders, may be applied over the entire Colorado River Basin. Future efforts by Reclamation will attempt to reconcile streamflow projections derived in this study with streamflow projections derived in parallel with the Colorado River Basin Water Supply and Demand Study. Additionally, this research highlights the need for Reclamation to continue investigation into future uncertainties and risks of meeting multiple objectives of the reservoir system within the Colorado River Basin.

7.3 Future Work and Direction

The fields of hydrology and water resources and the science of climate change are constantly evolving as researchers and scientists continue to develop new ideas, new methodologies, and make new observations. While the research presented in this study contributes to the field of hydrological sciences and to the goals of Reclamation, it represents only the beginning of my career study; this dissertation is a foundation, not a culmination, of future efforts to improve the overall understanding of climate change impacts to the Colorado River Basin. In that vein, future study and direction may include, but is not limited to:

1. As temperature continues to increase as global warming continues over the Colorado River Basin, streamflow characteristics will continue to change, altering future streamflow conditions from those expected based on past observations. In Chapters 3 and 4, as well as other studies, evidence is presented illustrating a change in the timing and magnitude of basin runoff. It is important to understand in more detail how streamflow conditions are impacted, particularly during times of drought. For instance, as land surface cover changes with increased urbanization and

desertification, infiltration characteristics within the basin will undoubtedly be impacted. As drought persists, decreased soil moisture conditions may impede surface runoff; or, warmer temperatures may cause snowpack to melt more quickly which may increase surface runoff efficiency. As streamflow characteristics change, the susceptibility of runoff to evaporative loss may change as well. A greater understanding of climatic impacts to streamflow hydrology, particularly in times of drought, over the Colorado River Basin would be beneficial.

2. In Chapter 4, the character of precipitation was investigated. It would be interesting to use the NWS RFS developed by the CBRFC over the Colorado River Basin to examine projections of future snowpack conditions in Colorado River headwater basins and corresponding impacts to unregulated streamflow projections. In particular, assumptions within the SAC-SMA and SNOW-17 model may need to be addressed in light changing climate conditions. Hydrologic intensification has been characterized more fully at the global and regional scale. It may be interesting to investigate localized realizations of hydrologic intensification and possible relationships with teleconnection indices.
3. Evapotranspiration rates as a function of temperature were described in Chapter 5. Evapotranspiration rates were adjusted linearly with temperature; this linear relationship was invariant with elevation bands and uniform across temperature. Future research may investigate other methods from which evapotranspiration rates may be estimated from temperature, perhaps including regional topography.
4. Information from streamflow projections under changing climate conditions was incorporated into a Reclamation planning model in Chapter 6. The SJDDM was

selected for this study because it modeled a headwater basin for which streamflow projections under changing climate conditions were derived, had a direct impact to a reservoir (Navajo Reservoir) published in Reclamation's 24-Month Study, and offered metrics to compare operational impacts over time in the SJRBRIP flow recommendations. Whereas unregulated streamflow projections were adjusted to force this regulated model, it would advantageous to use a Reclamation model explicitly forced with unregulated, or natural, streamflow projections. Efforts by the Colorado River Basin Study will pursue this using the VIC hydrologic model.

5. As climate change is realized on the hydrology of the Colorado River Basin, consumptive use of water resources within the basin will change as well. Future study should investigate the socio-economic implications of climate change in the Colorado River Basin. For example, changing consumptive use patterns may exacerbate water resource management problems, or may aid in the mitigation of negative climate change impacts.

APPENDIX A

DEVELOPMENT OF EVAPOTRANSPIRATION DATA FOR USE IN CLIMATE CHANGE ANALYSIS

A.1 Introduction

Due to limitations of some hydrologic models, it is sometimes beneficial for water resource managers to utilize multiple hydrologic models to accomplish particular goals or advance research efforts. In this study the NWS RFS was used to develop streamflow projections under changing climate conditions. The SAC – SMA model within the NWS RFS accounts for evapotranspiration in one of two ways:

1. Evapotranspiration demand may be set by the user for the 16th of each month. That is, the user may set 12 monthly evapotranspiration demand values from which the SAC – SMA model will linearly interpolate between to define evapotranspiration at shorter time scales. Over the model run period, these 12 values may not be adjusted. The CBRFC currently operates the NWS RFS model in this way.
2. A time series of evapotranspiration demand may be defined by the user, much like a precipitation or temperature time series may be defined.

The SAC – SMA model, as it is currently implemented within the NWS RFS model, does not allow for evapotranspiration demand to be a defined as a function of temperature, or any other hydroclimatic variable.

One of the major contributions of this study is an attempt to account for climate change impacts to evapotranspiration and resultant impacts to streamflow within the

Colorado River Basin. Due to limitations of the NWS RFS model, results from the VIC model, a hydrologic model separate from the NWS RFS, were employed in this research.

A.2 Incorporation of information from the VIC model

As part of the Colorado River Basin Water Supply and Demand Study (U.S. Department of the Interior, Bureau of Reclamation, Lower Colorado Region, 2009), Reclamation has contracted with AMEC to develop and run the VIC model over the Upper Colorado River Basin using the temporally disaggregated, BCSD climate data also utilized in this study. For this study, AMEC generated evapotranspiration rates from the VIC model as first described in Section 5.3.3 and in more detail in Section XXX. Those results were then shared with this study and used to develop time series of evapotranspiration demand for input into the NWS RFS model.

A.2.1 Penman-Monteith Equation

As described in Chapter 5, the VIC model computes evapotranspiration throught he use of the Penman-Monteith equation. The Penman-Monteith equation is defined as:

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

where E is evapotranspiration in mm/day, Δ is the gradient of the saturated vapor pressure with respect to temperature, A is the energy available for partitioning into latent or sensible heat, D is the vapor pressure deficit, r_a is the aerodynamic resistance, r_s is the surface resistance of land cover, and γ is the psychrometric constant in kPa/^{o}C and defined by:

$$\gamma = \frac{c_P P}{\in \lambda} * 10^{-3} \quad \text{(A-2)}$$

where c_P is the specific heat of moist air, P is the atmospheric pressure, $\in$ is the ratio of the molecular weight of water vapor to that of dry air, and λ is the latent heat of vaporization of water (Maidment, 1993; Xu et al., 1994).

A.2.2 Development of Evapotranspiration Rate of Change With Respect to Temperature

It is important to note that the VIC model is a distributed model and, for this study, the resolution is equivalent to the resolution of the temporally disaggregated, BCSD climate data (i.e., 1/8th degree or approximately 12 km or 7.5 miles). In comparison, the NWS RFS model is a lumped model over which the SAC-SMA model is run over each elevation band within each catchment area. The NWS RFS model incorporates separate and different metrics to define land cover and vegetation characteristics over a catchment area than the VIC model uses to define land cover and vegetation characteristics over each 1/8th degree grid cell. Due to differences between the two models, evapotranspiration data is not directly translated from the VIC model to the NWS RFS model. As such, an evapotranspiration rate was derived using the VIC model.

In order to develop an evapotranspiration rate, the VIC model was run over the 30-year base period of 1976 – 2005 using the temporally disaggregated, BCSD data. For each grid cell, a resultant evapotranspiration value, ET_0, was derived.

The VIC model was then run a second time over the 30-year base period; however, both minimum and maximum temperature values were increased by 1 degree Celsius. A value of 1 degree Celsius was chosen for ease of use and be within a reasonable range of temperature variation such that the VIC model would not operate outside of the

calibrated, operational range for which the model was developed by AMEC. For each grid cell, a resultant evapotranspiration value, ET_1, was derived. The relative change in evapotranspiration demand due to temperature, ET_R, at each grid cell is then defined as:

$$ET_R = \frac{\frac{(ET_1 - ET_0)}{ET_0}}{\Delta T} \tag{A-3}$$

where ΔT is the change in temperature between the two VIC model runs. In this case, ΔT is equal to 1 ^{o}C, and equation A-3 simplifies to:

$$ET_R = \frac{(ET_1 - ET_0)}{ET_0} \tag{A-4}$$

For each grid cell, the relative change in evapotranspiration per degree change in temperature is derived over the 30 year base period for each month; that is, 12 monthly values expressing the relative change in evapotranspiration per degree change in temperature are derived for each grid cell.

As previously described, there exists a discrepancy between the spatial discretization of the lumped NWS RFS and the distributed VIC model. As such, the relative change in evapotranspiration per degree change in temperature was averaged over each elevation band within each catchment to derive a single ET_R value for each elevation based on the number of gridded cells within a particular elevation band within each catchment for each month.

The original evapotranspiration demand within the NWS CBRFC RFS model was used as a base evapotranspiration value. For each month over the model run (1950 – 2099), an average monthly temperature was derived. This monthly average temperature was then compared to the base temperature derived over the same month over the 30-year

calibration period (1976 – 2005). The original evapotranspiration value was then adjusted based on the difference between average monthly temperature and the base monthly temperature:

$$ET_t = ET_{orig} + (T_t - T_{base}) * \overline{ET_R} \quad \text{(A-5)}$$

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

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

A.3 Sample Calculation

Derivation of evapotranspiration for a particular month was derived using the methodology described here.

A.3.1 Derivation of Relative Change in Evapotranspiration Demand Due to Temperature

The VIC model was first run by AMEC using base conditions over the Colorado River Basin developed by AMEC. For the purposes of this appendix, calculation of evapotranspiration demand under base conditions will be denoted by the subscript "0."

Variables which are functions of air temperature will share this subscript. Using equation A-1, we define:

$$E_0 = \frac{1}{\lambda}\left[\frac{\Delta_0 A + \rho_a c_P D/r_a}{\Delta_0 + \gamma_0\left(1 + r_s/r_a\right)}\right] \tag{A-6}$$

It is important to note that only the gradient of the saturated vapor pressure with respect to temperature (Δ) and the psychrometric constant (γ), are functions of air temperature. Other variables are functions of radiation flux, land surface, wind conditions, or hydrologic constants. The latent heat of vaporization of water, λ, is a function of water surface temperature.

The VIC model was then run by AMEC using base conditions; however, both minimum and maximum air temperature input was increased by 1 ^{o}C. For the purposes of this appendix, calculation of evapotranspiration demand under altered temperature conditions will be denoted by the subscript "1." Variables which are functions of air temperature will share this subscript. Again, using equation A-1, we define:

$$E_1 = \frac{1}{\lambda}\left[\frac{\Delta_1 A + \rho_a c_P D/r_a}{\Delta_1 + \gamma_1\left(1 + r_s/r_a\right)}\right] \tag{A-7}$$

Using equation A-3, the relative change in evapotranspiration demand due to temperature, ET_R, is then:

$$ET_R = \frac{\dfrac{\left(E_1 - E_0\right)}{E_0}}{\Delta T} \tag{A-8}$$

where ΔT is the change in temperature between the base and altered VIC model runs. In this case, ΔT is equal to 1 ^{o}C. and simplifies to:

$$ET_R = \frac{(E_1 - E_0)}{E_0} \quad \text{(A-9)}$$

It is important to note that minimum and maximum air temperature within the VIC model could have been increased (or decreased) by an amount not equal to 1 ^{o}C. This would have impacted ΔT in equation A-8 such that it would equal a constant other than 1 ^{o}C. By choosing 1 ^{o}C, other variables which are not direct functions of air temperature were not impacted significantly within the VIC model. The impact of changing parameters within the VIC model to evapotranspiration over various regions has been the subject of recent study (e.g., Hurkmans et al., 2008; Hurkmans et al., 2009; Lakshmi & Wood, 1998; Ziegler et al., 2003).

ET_R was derived for each grid cell over the study area. For each elevation band within each catchment area, an average relative change in evapotranspiration demand due to temperature, $\overline{ET_R}$, was derived as:

$$\overline{ET_R} = \frac{\sum_{1}^{n} ET_{R_n}}{n} \quad \text{(A-10)}$$

where n is the number of grid cells within a given elevation band within a given catchment. For instance, assume an upper elevation band within a small catchment over the San Juan River Basin. Three grid cells with three values of ET_R are within the catchment. Then by equation A-10, ET_R for this particular elevation band within this particular catchment is:

$$\overline{ET_R} = \frac{ET_{R1} + ET_{R2} + ET_{R3}}{3} \quad \text{(A-11)}$$

A.3.2 Derivation of Monthly Evapotranspiration Demand Time Series

The NWS RFS model provided by the CBRFC for this study relied on static, monthly evapotranspiration demand within the SAC-SMA process. To account for impacts to evapotranspiration due to climate change, the model was modified to require daily evapotranspiration input. For each elevation band within each catchment, a static evapotranspiration demand value is provided for each month; that is, the CBRFC has derived 12 monthly evapotranspiration demand values for each elevation band within each catchment. Each of the 12 monthly evapotranspiration demand values is constant over the course of the run, and is not adjusted through time or based on other hydroclimatic input or variables within the NWS RFS.

Each of the 12 original static evapotranspiration demand values within the NWS CBRFC RFS model were used as a base evapotranspiration value depending on the month of interest. For each month over the model run (1950 – 2099), an average monthly temperature was derived. This monthly average temperature was then compared to the base average temperature derived over the same month over the 30-year calibration period used for the VIC model. The original evapotranspiration value was then adjusted based on the difference between average monthly temperature and the base monthly temperature:

$$ET_t = ET_{orig} + (T_t - T_{base}) * \overline{ET_R} \quad \text{(A-12)}$$

where ET_t is the adjusted monthly evapotranspiration demand at a given time, ET_{orig} is the original evapotranspiration demand employed by the CBRFC, T_t is the average

temperature over any given month in the derived time series, and T_{base} is the 30-year calibration period average temperature for any given month. ET_t is derived for each month over the entire period of the model run for each elevation band within each catchment within the study area.

Daily evapotranspiration demand was assumed to be constant and uniform over the course of any given month. Thus, to derive a daily time series for input into the NWS CBRFC RFS, the value of ET_t derived from equation A-12 was distributed uniformly for each month. As such, there is no variation of daily evapotranspiration demand within any given month over a particular elevation band within a particular catchment in this study.

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VITA

Graduate College
University of Nevada, Las Vegas

William Paul Miller

Degrees:

Bachelor of Science, Environmental Hydrology and Water Resources, 2003
University of Arizona

Master of Science, Environmental Engineering, 2005
University of Notre Dame

Publications:

Miller, S. N., Kepner, W. G., Mehaffey, M. H., Hernandez, M., Miller, R. C., Goodrich, D. C., Devonald, K. K., Heggem, D. T., & **Miller, W. P.** (2002). Integrating Landscape Assessment and Hydrologic Modeling for Land Cover Change Analysis. *Journal of the American Water Resources Association, 38*(4), 915-929.

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Dissertation Examination Committee:

Chairperson, Thomas C. Piechota, Ph. D.
Committee Member, Jacimaria R. Batista, Ph. D.
Committee Member, Sajjad Ahmad, Ph. D., P.E.
Committee Member, Terrance J. Fulp, Ph. D.
Graduate Faculty Representative, William J. Smith Jr., Ph. D.