Technical Memorandum No. 86-68210–2015-04

Niobrara River Basin Study Appendix A — Climate Change Analysis

U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Denver, Colorado

March 2015
Revised February 2016

Mission Statements

The U.S. Department of the Interior protects America's natural resources and heritage, honors our cultures and tribal communities, and supplies the energy to power our future.

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

On cover: Aerial view of the Wild and Scenic portion of the Niobrara River. Photo by Michael Melford (http://www.michaelmelford.com/); used by permission.

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Niobrara River Basin Study Appendix A — Climate Change Analysis

Prepared by:

Technical Service Center
Water and Environmental Resources Division (86-68200)
Water Resources Planning and Operations Support Group (86-68210)
Marketa M. Elsner, PE, Hydrologic Engineer

Peer reviewed by:

Subhrendu Gangopadhyay, PE, PhD, Supervisory Hydrologic Engineer

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Executive Summary

Purpose, Scope and Objectives

The Niobrara River Basin Study (Basin Study) is a collaborative effort by the Nebraska Department of Natural Resources (DNR) and the US Bureau of Reclamation (Reclamation), which is authorized under the SECURE Water Act (Title IX, Subtitle F of Public Law 111-11). The purpose of the Basin Study is to evaluate current and projected future water supply and demand and to collaborate with stakeholders in the region on identification and evaluation of potential adaptation strategies which may reduce any identified gaps. Projections of future water supply and demand are based on Reclamation's West-Wide Climate Risk Assessments ([WWCRA]; Reclamation, 2011; Reclamation, 2015) but contain additional information, if available.

The purpose of this report is to summarize the climate change analysis for the Basin Study and discuss development of climate related inputs for various modeling components of the Basin Study by Reclamation's Technical Service Center. The executive summary provides a general basin scale assessment of historical and future water supply. The following report provides additional details of the water supply assessment and also summarizes ways in which linkages between various Basin Study modeling components were developed to incorporate historical and projected climate and hydrologic information. Additional Basin Study technical reports supplement this analysis and contribute to the overall Basin Study report.

Interrelated Activities — Federal WaterSMART Program

The federal Water Sustain and Manage America's Resources for Tomorrow (WaterSMART) Program provides the underlying mechanism for initiating the Basin Study. The WaterSMART Program was established by the Secretary of Interior under Secretarial Order 3297 to address an increasing set of water supply challenges, including chronic water supply shortages due to increased population growth, climate variability and change, and heightened competition for finite water supplies. The WaterSMART Program was developed as means of implementing the SECURE Water Act of 2009 (Public Law 111-11). Through WaterSMART, Reclamation is making use of the best available science in the assessments it conducts and the policies it employs, with the goal of securing future water supplies.

Summary of Previous and Current Studies

Climate in Nebraska, as well as in the Niobrara River Basin, is well known for its climate extremes and for having a substantial moisture gradient from west to east, with the western portion being semiarid and the eastern portion being more humid. Annual precipitation totals for Nebraska range from 36 inches in the southeast to less than 15 inches in the northwest (University of Nebraska-Lincoln, 2014). As one example of its climate variability, an average of 40 percent of the annual precipitation typically falls from May through July, while only 5 to 7 percent of the annual total normally falls from December through February. In addition, the 1930s and 1950s saw widespread droughts, while the last 50 years have generally been wetter than average.

Nebraska has experienced an overall warming trend of about 1 degree F since 1895. Seasonally, the trends show greater warming in winter (defined as December - February) and spring (defined as March - May), 2.0 degrees F and 1.8 degrees F, respectively. The length of the frost-free season in Nebraska has increased, anywhere from 5 to 25 days and on average by more than one week since 1895 (University of Nebraska-Lincoln, 2014). Although it is difficult to attribute historical precipitation variability to human induced change (Hoerling et al., 2010), there is growing evidence of a linkage between the warming of the globe, arctic sea ice decline and extreme winters across the GP Region (Reclamation, 2013).

Reclamation's WWCRA (Reclamation, 2011) indicates the Great Plains region will continue to experience the kind of interannual to interdecadal variations in precipitation that it has experienced historically. In addition, climate change will further exacerbate climate hazards such as tornadoes, droughts, floods and increase economic losses in the future (University of Nebraska-Lincoln, 2014). According to Nebraska's climate change impacts assessment (University of Nebraska-Lincoln, 2014), projected changes in temperature for Nebraska range from 4 - 5 degrees F (low emission scenarios) to 8 - 9 degrees F (high emission scenarios) by the late twenty-first century (2071-2099). Projected changes in temperature and precipitation are expected to coincide with a decreasing trend in spring snow water equivalent (SWE), a decreasing trend in April–July runoff volume, increasing trends in December–March and annual runoff volumes, and reduced soil moisture levels (Reclamation, 2013). However, it should be noted that uncertainties associated with the hydrologic analysis may impact results of climate change impacts studies (Vano et al., 2012).

Future climate and hydrologic projections in the Niobrara River Basin will impact various environmental resources pertinent to the Basin Study to varying degrees, including water resources, agriculture, aquatic ecosystems, invasive species, and other related resources. Irrigators may face allocation restrictions that set limits on the amount of water that can be applied on an annual basis. By the year 2100, the Third National Climate Assessment (Shafer et al., 2014) indicates that the frost-free season will increase by 30 to 40 days for Nebraska. The assessment also suggests that changes to crop growth cycles due to warming winters and alterations in the timing and magnitude of rainfall events have already been observed; and as these trends continue, they will require new agriculture and livestock management practices (Shafer et al., 2014).

Climate changes are anticipated to alter both water quality and quantity. Increases in the frequency and intensity of high precipitation events, particularly in a landscape such as the Niobrara River basin that is dominated by agriculture, will lead to increased runoff of sediments, fertilizers, and pesticides into water bodies. Increased frequency of drought and heat waves, combined with increased human demand for water, will result in lower stream flows and an increase in the frequency of stream segments being de-watered and wetlands drying up (University of Nebraska-Lincoln, 2014).

Historical Surface Water Availability

The Variable Infiltration Capacity Model ([VIC], described in detail in Section 2.1) was employed over the historical period 1950-2010 to quantify historical trends in surface water availability. The VIC model is an advantageous tool for this type of evaluation since this model has been applied over the continental United States and beyond, and is the basis for assessments under Reclamation's WWCRA (Reclamation, 2011). The VIC model may be implemented at any spatial resolution, adhering to a latitude-longitude grid. For this Basin Study, and for consistency with Reclamation's WWCRA, the model was implemented over the study area at 1/8 degree, or approximately 12 kilometer resolution. VIC provides a wide array of hydrologic outputs, typically including runoff, snow-water equivalent and evapotranspiration, which are routinely analyzed to assess climate change impacts on watershed hydrology.

Historical trend analysis over the period 1950-2010 indicates an increasing trend in mean annual temperature and precipitation during this period, along with increases in evapotranspiration and runoff. Historical trends in precipitation and temperature computed using the Maurer et al. (2002) meteorological dataset, whose extended dataset through 2010 was used as input to the VIC model, are generally consistent with historical trends reported by the University of Nebraska-Lincoln (2014) study as well as by Reclamation's 2013 Literature Synthesis. Table ES-1 summarizes computed historical trends in mean annual precipitation, temperature and runoff.

Table ES-1. Summary of Historical Trends in Precipitation, Daily Average Temperature, and Annual Runoff, Computed from VIC Model Simulations Over 1950–2010

	Basinwide Change	Percent Change
Precipitation	+ 2.2 in	+ 12%
Daily Average Temperature	+ 0.56 °F	--
Annual Runoff	+ 0.55 in	+ 45%

Data and Models Used to Evaluate Climate Change Effects on Water Supply

Climate may be generally described as average weather (for example, temperature and precipitation), typically considered over time periods of decades, as opposed to days or weeks. Arguably the most common approach for developing scenarios of future climate involves downscaling information (in space and time) from native scale GCM resolution to a finer resolution suitable for long term planning studies such as the Basin Study.

Development of climate scenarios for the Basin Study relies on projections of future climate and hydrologic conditions developed under Reclamation's WWCRA (Reclamation, 2011). The Basin Study involves numerous modeling components which are brought together to evaluate watershed response to projected future climate conditions and to various water management alternatives. There is a need to adequately represent the projected range of future climate conditions, while also limiting the number of required simulations to maintain a manageable project scope. Therefore, three future climate change scenarios were developed as input to the hydrologic and management modeling framework to encompass range of projected water availability in the watershed, defined as mean annual difference between precipitation and evapotranspiration, for the 2030-2059 future time horizon.

Climate change scenarios were developed based on individual climate projections selected directly from the 112 available CMIP3-based projections (further described in Section 3.1) to represent low projected water availability (hereafter called the Low scenario), median projected water availability (hereafter called the Central Tendency scenario), and high projected water availability (hereafter called the High scenario), as well as a range of projected change in summer temperature and precipitation. The selected Low scenario corresponds with a decrease in water availability by approximately -9 percent. The select Central Tendency scenario corresponds with an increase in water availability of approximately 6 percent. The select High scenario corresponds with an increase in water availability of approximately 37 percent.

Historical climate data is also used along with assumed current water demands (in this case set at 2010 levels) to establish a Baseline No Action scenario, to be used as a benchmark for evaluation of climate change impacts by the Basin Study integrated models. Future climate change scenario data (representing a future time horizon of 2030-2059) is used along with assumed current water demands (set at 2010 levels) to explore future water supply and demand under a range of future climates. These scenarios are termed Future No Action (Low, Central Tendency, and High). The Basin Study also explores two selected management alternatives under the same future change scenario data and assumed future demands. Generally, the first alternative includes changing the location of surface water diversion from the Niobrara River to the Mirage Flats Irrigation District to reduce conveyance losses in the current canal system. The second alternative includes using existing canal systems to recharge the groundwater system during periods of excess available water. These alternative scenarios are termed Future with Alternative (Low, Central Tendency, and High). Together, the Future No Action scenarios may be used to evaluate how climate change might impact current water management. Further, the Future with Alternative scenarios may be used to evaluate how alternatives may reduce projected water supply/demand gaps identified by the Future No Action scenarios.

Effects of Climate Variability and Change on Water Supply

Historical and projected changes in climate and water balance variables are summarized for each of the three climate change scenarios developed for the Basin Study. Specifically, the Low scenario represents projected low water availability and generally corresponds with hotter and drier future climate. The Central Tendency scenario represents the middle-of-the-road water availability and generally corresponds with the central tendency of all available GCM projections for the chosen future time horizon. The High scenario represents high projected water availability and generally corresponds with wetter and less warm future climate. Together, the climate change scenarios are intended to represent a range of projected future conditions.

The following figure (Figure ES-1) summarizes historical and projected mean annual precipitation, temperature, and runoff averaged over select zones for the Central Tendency scenario and 2030-2059 future time horizon. The zones, which are illustrated in Figure 9 Section 3.2.2 by colored polygons, correspond with the modeled runoff zones by the watershed model and groundwater models for the Upper Niobrara White (UNW) and Central Nebraska (CENEB) subregions. Zones represent major Niobrara River subbasins and correspond with the contributing drainage area to selected USGS gages. Projected changes basin wide for the Central Tendency scenario indicate an increase in mean annual precipitation by about 8 percent, an increase in mean annual temperature by about 3 degrees F, and an increase in mean annual runoff by about 13 percent (refer to Table 7 for additional details).

The VIC model, along with a separate streamflow routing routine, was used to develop historical and projected natural (unimpaired) streamflow for the chosen future time horizon at model nodes used throughout the Basin Study (refer to Table 1 in Section 1.1.2). Historically, unimpaired streamflow in the basin has a seasonal peak in May and June, corresponding with the seasonality of precipitation. Projected mean monthly unimpaired streamflow for the Central Tendency scenario indicates a substantial increase in seasonal peak flow for all Basin Study model nodes, on the order of 50 percent for nodes in the upper basin and on the order of 30 percent for the Niobrara River near Spencer, Nebraska. For the low flow season (generally defined as August through November), reductions in mean monthly unimpaired flow on the order of 10 to 20 percent are projected for the Central Tendency scenario.

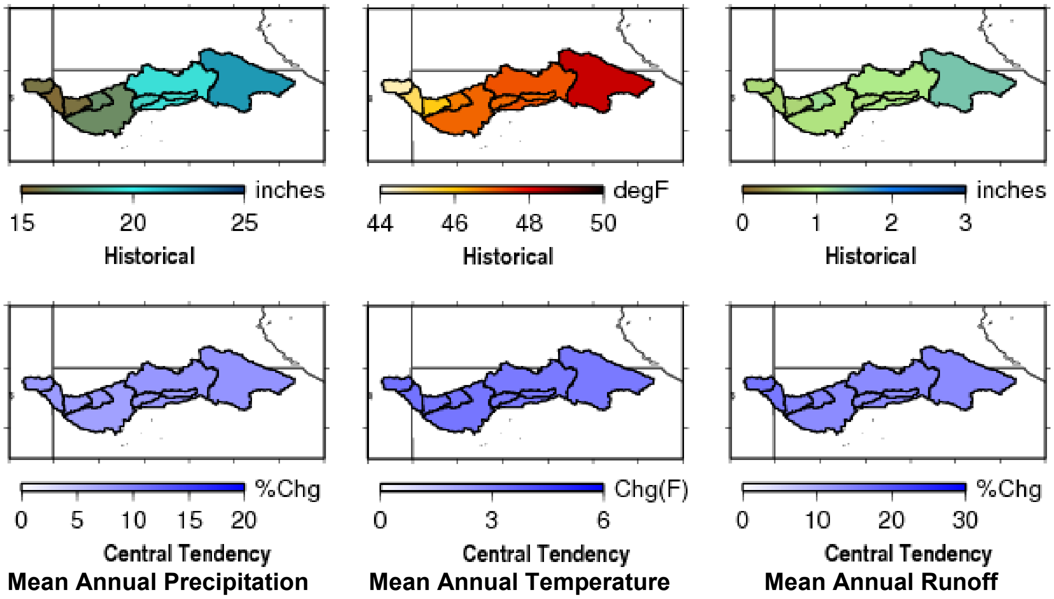
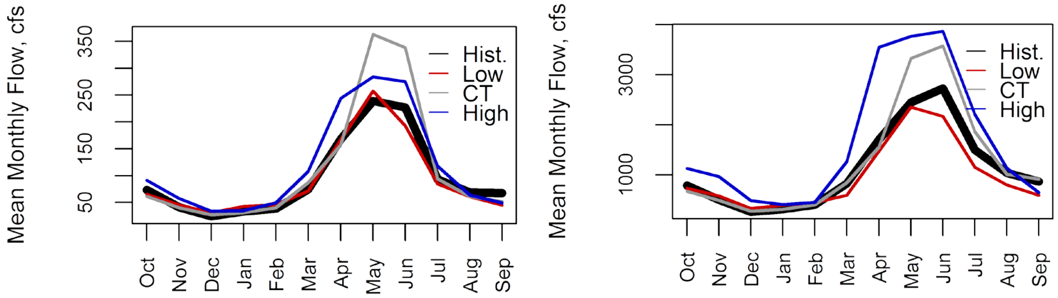


Figure ES-1. Historical (1960-2010) and projected changes in mean annual precipitation (inches), temperature (degrees F), and runoff (inches) for the Central Tendency climate change scenario (2050s compared with historical).



Niobrara River above Box Butte (06454500)

Niobrara River near Spencer (06465000)

Figure ES-2. Summary of historical and projected mean monthly hydrographs of simulated natural streamflow by the VIC model.

Linkages of Climate Change Scenarios and Basin Study Models

The modeling framework for the Basin Study consists of two integrated models, namely encompassing UNW and CENEB portions of the study area (see illustrations of these modeled areas in Figure 1 in Section 1.1.2). Each of the integrated models (UNW and CENEB) is comprised of a series of models which interact through data transfer. In each modeled region, a watershed model simulates surface water hydrology and agricultural water demands, a groundwater hydrology model simulates groundwater levels and baseflow contributions to streamflow, and a surface water operations model simulates the management of water in the region. The following paragraph outlines historical and climate change scenario data developed for various modeling components of the Basin Study by Reclamation's Technical Service Center. It should be noted that although the Technical Service Center provided inputs for modeling components, it did not implement them.

The watershed models for the UNW and CENEB subregions of the study area ingest daily precipitation, daily minimum and maximum air temperature, and daily reference evapotranspiration at select climate stations. Reclamation's Technical Service Center developed historical and climate change scenario inputs of these variables. In addition, the UNW and CENEB subregion surface water operations models incorporate computed net evaporation rates for Box Butte and Merritt reservoirs as part of the water balance. Reclamation utilized the Complementary Relationship Lake Evaporation (CRLE) model (Morton et al., 1985) to compute historical and projected reservoir net evaporation. This methodology is consistent with Reclamation's WWCRA (2015). For Box Butte, the Central Tendency scenario indicates an increase of about 15 percent in net evaporation for the future time horizon 2030-2059. For Merritt, the Central Tendency indicates a median increase of about 2 percent.

Reclamation's Technical Service Center developed adjusted historical Merritt Reservoir inflows for the purpose of calibrating the CENEB surface water operations model, as well as adjusted Merritt Reservoir inflows for the Future No Action scenarios. Other model inputs were provided by DNR and its contractors. Finally, Reclamation provided historical and projected temperature at NWS/Co-Op stations closest to Box Butte and Merritt reservoirs, which are relevant to the recreation benefits analysis. Additional details regarding development of individual inputs are discussed in Section 4 of this technical report (also referred to as Appendix A to the Niobrara River Basin Study report).

Contents

Tables

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Acronyms

°C	degrees Celsius
°F	degrees Fahrenheit
ASCE-EWRI	Environmental and Water Resources Institute of the American Society of Civil Engineers
BCSD	bias correction and spatial disaggregation or bias-corrected and spatially downscaled
cfs	cubic feet per second
CMIP3	Coupled Model Intercomparison Project Phase 3
CMIP5	Couple Model Intercomparison Project Phase 5
CENEB	Central Nebraska model region (includes Middle Niobrara, Lower Niobrara, Upper Elkhorn, Lower Elkhorn, Upper Loup, and Lower Loup Natural Resources Districts)
CO_2	carbon dioxide
Co-Op	cooperative observer
deg	degrees
DNR	Nebraska Department of Natural Resources
EPA	Environmental Protection Agency
ET	evapotranspiration
GCM	General Circulation Model, or Global Climate Model
GHG	greenhouse gas
ID	identification number
in	inches
IPCC	Intergovernmental Panel on Climate Change
km	kilometer
NCA	National Climate Assessment
NOAA	National Oceanic and Atmospheric Association
NWR	National Wildlife Refuge
NWS	National Weather Service
P	precipitation
PDSI	Palmer Drought Severity Index
Prcp	precipitation
Reclamation	U.S. Department of the Interior, Bureau of Reclamation
SECURE	Science and Engineering to Comprehensively Understand and Responsibly Enhance
SWE	snow water equivalent
T	temperature
Tavg	average temperature
UNW	Upper Niobrara–White model region (includes Upper Niobrara–White Natural Resources Districts)
U.S.	United States
USGS	U.S. Geological Survey
VIC	Variable Infiltration Capacity hydrologic model
WaterSMART	Water Sustain and Manage America's Resources for Tomorrow

WWCRA	West-Wide Climate Risk Assessment

1 Introduction

1.1 Purpose, Scope, and Objective of Study

The Niobrara River Basin Study (Basin Study) is a collaborative effort by the Nebraska Department of Natural Resources (DNR) and the US Bureau of Reclamation (Reclamation), which is authorized under the SECURE Water Act (Title IX, Subtitle F of Public Law 111-11).

The purpose of the Basin Study is to evaluate current and projected future water supply and demand and to collaborate with stakeholders in the region on identification and evaluation of potential adaptation strategies which may reduce any identified gaps. Projections of future water supply and demand are based on Reclamation's West-Wide Climate Risk Assessment ([WWCRA]; Reclamation, 2011; Reclamation, 2015) but contain additional information, if available. The WWCRA is an ongoing complementary activity in the Basin Studies Program in which Reclamation is developing a comprehensive and consistent set of hydro-climate data resources for the western United States (US) by incorporating the best available science. These data resources provide a baseline for climate change adaptation planning.

More specifically, basin studies seek to build upon existing knowledge through studies, reports, and stakeholder collaboration. The following objectives are key components of each basin study:

- Assess current and projected future water supply
- Assess current and projected future water demand
- Evaluate current and projected future system reliability with respect to chosen evaluation metrics
- Identify and evaluate potential adaptation strategies that may reduce any imbalances

The purpose of this report is to summarize the climate change analysis for the Basin Study and discuss development of climate related inputs by Reclamation's Technical Service Center for various modeling components of the Basin Study. It first provides a general basin scale assessment of historical and future water supply. The report then summarizes ways in which linkages between various Basin Study modeling components were developed to incorporate historical and projected climate and hydrologic information. Additional Basin Study technical reports supplement this analysis and contribute to the overall Basin Study report.

1.1.1 Federal WaterSMART Program

This section briefly discusses the ongoing federal Water Sustain and Manage America's Resources for Tomorrow (WaterSMART) Program, which provides the underlying mechanism for conducting the Basin Study. The WaterSMART Program, established by the Secretary of Interior under Secretarial Order 3297, addresses an increasing set of water supply challenges, including chronic water supply shortages due to increased population growth, climate variability and change, and heightened competition for finite water supplies. The WaterSMART Program was developed as means of implementing the SECURE Water Act of 2009 (Public Law 111-11). The WaterSMART Program provides the scientific and financial tools and the collaborative environment needed to help balance water supply and demand through the efficient use of current supplies and the development of new supplies. Through WaterSMART, Reclamation is making use of the best available science in the assessments it conducts and the policies it employs. Results coming from this work have and will continue to inform the decisions of water managers who need reliable estimates of current conditions in the hydrologic cycle and projections of supply and demand in watersheds throughout the nation. Many examples of best available science are being developed through the WaterSMART Program. Much of that science can be accessed through the WaterSMART Clearinghouse, an online collaborative site where best practices and cost-effective technologies for water conservation and sustainable water strategies are shared with the public (http://www.doi.gov/watersmart/html/index.php).

1.1.2 Location and Description of Study Area

The Niobrara River Basin is located almost entirely within the state of Nebraska. Only small portions of its tributary area are located in Wyoming and South Dakota (approximately 4 and 12 percent, respectively). Each basin study is unique with respect to addressing relevant water supply and demand issues in its watershed. In the Niobrara River Basin, surface water and groundwater resources are used to supply water for agricultural uses, primarily. However, additional uses of the basin’s water resources include municipal use, hydropower, recreation, and ecosystem services.

Figure 1 illustrates the Basin Study area and includes other notable features within the basin. The basin has two Bureau of Reclamation irrigation projections: the Mirage Flats Project (11,662 acres) located in the upper basin (near US Geological Survey [USGS] gage ID [identification] 0645450, see Figure 1) and the Ainsworth Unit (35,000 acres) located in the lower basin (near USGS gage ID 0649500, see Figure 1). Spencer Hydropower is the single (private) hydropower facility in the basin, located near USGS gage ID 06465000 (see Figure 1). In addition, a reach of the lower Niobrara River was designated as a National Wild and Scenic River in 1991. This Wild and Scenic River is located near the Fort Niobrara National Wildlife Refuge ([NWR], see Figure 1).

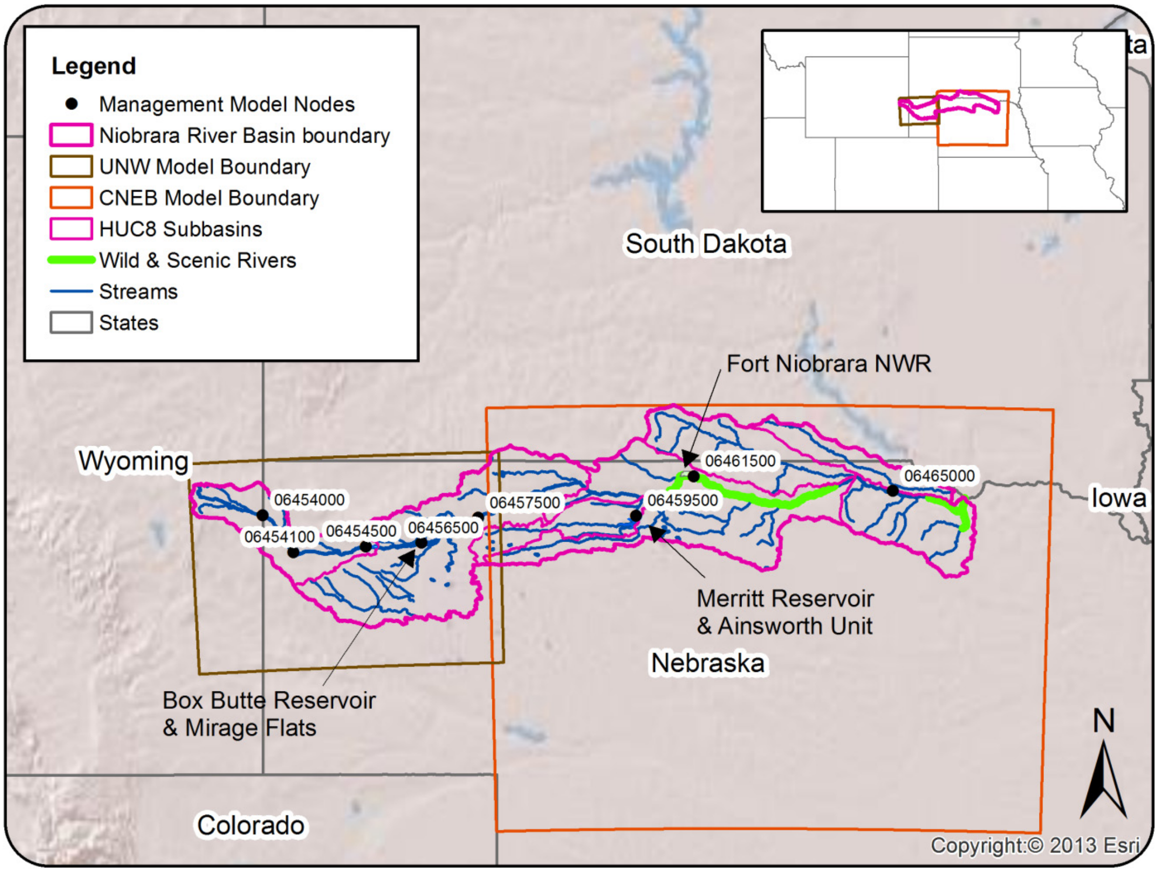


Figure 1. Overview map of Niobrara River Basin.

Figure 1 also includes points which indicate the locations of model nodes for the water management models used as part of the Basin Study modeling framework. These nodes correspond with selected USGS streamflow gaging locations. These gaging locations are described in more detail in Table 1.

1.2 Summary of Previous and Current Studies

A large body of research has been conducted over the past ten or more years on climate change and how various regions of the US might be affected. Most of this research has focused on large scale implications while providing limited regional scale information. The following section summarizes research that is relevant to the Niobrara River Basin, and shows that this analysis adds value to our understanding of climate change impacts in the region. The section relies on four primary sources which are comprised of synthesis reports of a wide range of climate change related research in the region. These sources are identified in Table 2.

Table 1. Summary of Management Model Locations

USGS ID	Management Model Location	Latitude	Longitude
06454000	Niobrara River at Wyoming-Nebraska State Line	42.66	–104.07
06454100	Niobrara River at Agate, Nebraska	42.42	–103.79
06454500	Niobrara River above Box Butte Reservoir, Nebraska	42.46	–103.17
06456500	Niobrara River near Hay Springs, Nebraska	42.48	–102.69
06457500	Niobrara River near Gordon, Nebraska	42.64	–102.21
06461500	Niobrara River near Sparks, Nebraska	42.90	–100.36
06459500	Snake River near Burge, Nebraska	42.65	–100.86
06465000	Niobrara River near Spencer, Nebraska	42.81	–98.66

Table 2. References Supporting Summary of Previous and Current Studies

Citation	Title of Existing Synthesis Report
Reclamation (2013)	Third Edition Literature Synthesis on Climate Change Implications for Water and Environmental Resources
Shafer et al. (2014)	Climate Change Impacts in the United States: The Third National Climate Assessment, Chapter 19, Great Plains
US Environmental Protection Agency (2014)	Climate Change Indicators in the United States, 2014, Third Edition
University of Nebraska-Lincoln (2014)	Understanding and Assessing Climate Change Implications for Nebraska

Together, these sources provide a broad summary of existing scientific knowledge of historical climate and climate change impacts on the Niobrara River Basin and surrounding region. Information from these sources is summarized further in the sections below.

1.2.1 Historical Trends

The Niobrara River Basin extends across much of northern Nebraska, extending into southern South Dakota and into eastern Wyoming. Climate in Nebraska, as well as in the Niobrara River Basin, is well known for having a substantial moisture gradient from west to east, with the western portion being semiarid and the eastern portion being more humid. Annual precipitation totals for Nebraska range from 36 inches in the southeast to less than 15 inches in the northwest (University of Nebraska-Lincoln, 2014), while average annual temperatures range from about 55 degrees Fahrenheit (F) in the southeast to about 46 degrees F in the northwest. Reclamation's 2013 literature synthesis, which summarizes existing literature (published between 1994 and 2012) on historical trends in climate and hydrology, as well as projected future changes in the Great Plains region, summarizes trend analysis using the US Historical Climatology Network. The analysis indicates an increase in annual precipitation of more than 4 percent in the northern Great Plains and 10 percent in the southern Great Plains over the same period. The trend was more consistent in the southern Great Plains (Reclamation, 2013).

Historical climate trends reported by University of Nebraska-Lincoln (2014) indicate Nebraska has experienced an overall warming of about 1 degree F since 1895. Seasonally, the trends show greater warming in winter (defined as December - February) and spring (defined as March - May), 2.0 degrees F and 1.8 degrees F, respectively. Summer (defined as June – August) has a 1.0 degree F warming trend, while fall (defined as September – November) has no discernable historical temperature trend. This assessment reports no discernable trend in mean annual precipitation in Nebraska. However, trends in seasonal precipitation show a general increase in spring across the state, a small decrease in summer, and essentially no trend in fall and winter. Reclamation's 2013 literature synthesis indicates that, based on data from the US Historical Climatology Network, temperatures increased approximately 1.85 degrees F (1.02 degrees Celsius [C]) in the northern Great Plains to approximately 0.63 degrees F (0.35 degrees C) in the southern Great Plains between 1901 and 2008.

The University of Nebraska-Lincoln (2014) assessment indicates the length of the frost-free season in Nebraska has increased, anywhere from 5 to 25 days and on average by more than one week since 1895. In an analysis of the paleo-record, multiple lines of evidence suggest that drought was a dominant feature of climate during the period from 900 to 1300 A.D. The more recent 150 year period of record has been largely a wet period, which may exacerbate any overall drying and loss of water due to climate change in coming decades.

In addition to its west-east wetter climate gradient, Nebraska's climate is also variable and subject to extremes. As one example of its climate variability, an average of 40 percent of the annual precipitation typically falls from May through July, while only 5 to 7 percent of the annual total normally falls from December through February. In a typical winter across southeast Nebraska, 20 to 25 inches of snow are common, increasing to 40 to 45 inches across the northwestern corner of the state. As one example of its climate extremes, portions of the state experienced severe flooding in 2011 and the entire state was engulfed in an extreme drought in 2012, the driest and warmest year on record, when portions of the state recorded maximum daily temperatures exceeding 100 degrees F for 30 days or more (University of Nebraska-Lincoln, 2014).

Brown and Mote (2009) performed a snowpack sensitivity study across the entire Northern Hemisphere and compared the results to observed conditions (1966–2007 National Oceanic and Atmospheric Administration [NOAA] satellite dataset) and to snow cover simulations from the Coupled Model Intercomparison Project Phase 3 (CMIP3). The least sensitive areas were found to be in interior regions, such as the interior US, with relatively cold and dry winters where precipitation plays a larger role in snow cover variability. Kunkel et al. (2009) found snowfall declines from 1920–1921 to 2006–2007 in the central Great Plains and large percentage increases in the lee of the Rocky Mountains and parts of the north-central Great Plains. It should be noted, however, that it remains difficult to attribute historical precipitation variability to anthropogenic forcing (Hoerling et al., 2010). As an example, worldwide trends in observed mean and extreme precipitation trends show signs of the influence of human forcing of the climate, but climate models produce a notably weaker precipitation change signal than is seen in the observations. However, there is growing evidence of a linkage between the warming of the globe, arctic sea ice decline and extreme winters across the eastern two-thirds of the US, including the GP Region (Reclamation, 2013).

The Environmental Protection Agency (EPA) published a report titled "Climate Change Indicators in the United States" to communicate information about the science and impacts of climate change, assess trends in environmental quality, and inform decision-making. The third edition, published in 2014, indicates that average drought conditions across the nation have varied since records began in 1895. The 1930s and 1950s saw the most widespread droughts, while the period from about 1964-2013 has generally been wetter than average. However, specific trends vary by region. A more detailed index developed recently by US EPA shows that between 2000 and 2013, roughly 20 to 70 percent of the US experienced drought at any given time, but this index has not been in use for long enough to compare with historical drought patterns (US EPA, 2014).

Although pine forests are not characteristic throughout Nebraska, the Pine Ridge region in the western Niobrara River valley consists of Ponderosa pine forests. Repeated intense and uncharacteristic wildfires occurred in this region since 1994 and reduced forest cover from 250,000 acres to less than 100,000 acres. Intense burning has converted some of these forests to grassland, and projected increases in temperature and drought may threaten Nebraska's remaining pine forests. In addition, Nebraska's pine forests lost thousands of trees in the 2000s from Mountain Pine Beetle attacks, part of an outbreak affecting 35 million acres in North America. Engraver beetles (Ips species) are currently attacking and killing heat- and drought stressed pines across the Pine Ridge and Niobrara Valley (University of Nebraska-Lincoln, 2014).

1.2.2 Climate Projections

The Intergovernmental Panel on Climate Change (IPCC) projections of future climate have been utilized in assessing projecting climate change impacts, including over Nebraska and the Niobrara River Basin. Reclamation, in its WWCRA (2011), reported on climate change implications for water supplies and related water resources within eight major Western US river basins, including

Great Plains Region's Missouri River Basin. The Great Plains regions are likely to continue to experience the kind of interannual to interdecadal variations in precipitation that they have experienced in the past. For the next few decades, these variations are likely to be superimposed upon background trends that, in most cases, are likely to be subtle compared with the variations. Evapotranspiration demands and warm-season precipitation play a more prominent role in determining local hydrologic conditions in the Great Plains relative to water management and generally more so relative to the influence of headwaters snowpack and snowmelt timing. Future projections of precipitation for the southern Great Plains are further complicated by the limitations on the ability of climate models to portray the frequency and intensity of warm-season convection events or tropical storm systems tracking into the region (Reclamation, 2013).

According to Nebraska's climate change impacts assessment, which reports on analyses using climate projections from the World Climate Research Programme's Coupled Model Intercomparison Project Phase 5 (CMIP5, described in Section 3.1), projected changes in temperature for Nebraska range from 4 degrees F to 5 degrees F (low emission scenarios) to 8 degrees F to 9 degrees F (high emission scenarios) by the late twenty-first century (2071-2099). High temperature stress days are projected to increase to 13-16 additional days that exceed 100 degrees F across Nebraska, with a range from 10-21 days in the east to 21-37 days in the western part of the state. For Nebraska, the number of warm nights is expected to increase to an additional 20-25 nights for the lower emissions scenario and 25- 40 nights for the higher emissions scenario (where warm nights are defined as having a minimum temperature above 60 degrees F). Winter and spring precipitation is expected to increase in the more northern states, with little change in precipitation for these two seasons for Nebraska. Projected changes in summer and fall precipitation are expected to be small in the Great Plains, with some possibility of reduced summer precipitation in the central Plains states (University of Nebraska-Lincoln, 2014).

The region frequently experiences a wide range of weather and climate hazards such as tornadoes, droughts, floods, and other severe weather events that result in significant economic losses and stresses to a fragile ecosystem. Climate change will further exacerbate those stresses and increase economic losses in the future (University of Nebraska-Lincoln, 2014). Gutowski et al. (2008) suggest that climate change likely will cause precipitation to be less frequent but more intense in many areas and suggests that precipitation extremes are very likely to increase, an effect already that is already observed (Min et al., 2011). In another study, the Palmer Drought Severity Index (PDSI) gives indications of a semi-permanent state of severe drought over the Great Plains in coming decades with climate change projections of rising temperatures and decreasing precipitation amounts (Reclamation, 2013). Hoerling et al. (2012) looked at the difference between projections of PDSI and soil moisture through the 21st century and found that the PDSI projections do lead to prolonged severe drought conditions. The soil moisture projections, however, point to a more modest drying with a much smaller change in drought frequency. In their view, if prolonged severe drought occurs in the near future, it will be due to lengthy periods of precipitation deficits.

Groundwater irrigation accounts for about 95 percent of all groundwater withdrawals, and Nebraska leads the nation in irrigated acres, the vast majority of which is sourced from groundwater (University of Nebraska-Lincoln, 2014). Groundwater levels in Nebraska are closely related to climate variability, predominately because of the changing demand for irrigation. In Nebraska, a northwest-southeast gradient of observed annual precipitation (15-36 inches per year) and projected changes in heavy precipitation (0.4 to 1 inches during the 7 wettest days) illustrate the sensitivity of the western portion of the state to recurrent dry conditions.

1.2.3 Hydrological Projections

Projected changes in climate have implications for hydrology. Warming trends contribute to a shift in cool season precipitation towards more rain and less snow, which causes increased rainfall-runoff volume during the cool season accompanied by less snowpack accumulation. Generally speaking, the ensemble-median changes in climate based on CMIP3 projections (described in Section 3.1) suggest that the greater Missouri River Basin (encompassing the Niobrara River Basin) will experience increasing mean-annual temperature and with precipitation change during the 21st century that varies from increases in more northerly subbasins to generally no change in more southerly subbasins. These changes are projected to be accompanied by decreasing trend in spring snow water equivalent (SWE), a decreasing trend in April–July runoff volume, increasing trends in December–March and annual runoff volumes, and reduced soil moisture levels (Reclamation, 2013).

It should be noted that uncertainties associated with the hydrologic analysis may impact results of climate change impacts studies. Vano et al. (2012) applied multiple land-surface hydrologic models in the Colorado River Basin under multiple, common climate change scenarios. Their results showed that runoff response to these scenarios varied by model and stemmed from how the models feature a collective of plausible hydrologic process portrayals, where a certain combination of process portrayal choices led to a model's simulated runoff being more or less sensitive to climate change. Although these results are most applicable to the Colorado River Basin, it is still expected that application of the models in Vano et al. (2012) to other Western US basins would likewise show model-dependent runoff sensitivity to climate change (Reclamation, 2013).

1.2.4 Climate Change Impacts

Future climate and hydrologic projections in the Niobrara River Basin will impact various environmental resources pertinent to the Basin Study to varying degrees, including water resources, agriculture, aquatic ecosystems, invasive species, and other related resources.

If temperatures do increase during the growing season and precipitation decreases as indicated by the Third National Climate Assessment (NCA) 2014 report (Shafer et al., 2014), rural water supplies will be more vulnerable to shortages because of competition from irrigation. Irrigators may face allocation restrictions that set limits on the amount of water that can be applied on an annual basis. The Third National Climate Assessment suggests that rising temperatures are leading to increased demand for water and energy. In parts of the region, this will constrain development, stress natural resources, and increase competition for water among communities, agriculture, energy production, and ecological needs (Shafer et al., 2014).

By the year 2100, the Third National Climate Assessment (Shafer et al., 2014) indicates that the frost-free season will increase by 30 to 40 days for Nebraska. Also, the Synthesis and Assessment Product 4.3 by the US Climate Change Science Program (Lettenmaier et al., 2008) discusses the effects of climate change on agriculture and water resources (Hatfield et al., 2008). Findings suggest significant irrigation requirement increases for corn and alfalfa due to increased temperatures and carbon dioxide (CO_2) and reduced precipitation. Further, agricultural water demand could decrease due to crop failures caused by pests and disease exacerbated by climate change. On the other hand, agricultural water demand could increase if growing seasons lengthen and, assuming that farming practices could adapt to this opportunity, by planting more crop cycles per growing season. However, a shift toward earlier planting dates may not be viable because of the continued vulnerability to freeze damage in the spring (University of Nebraska-Lincoln, 2014). For example, the 2012, 2013, and 2014 growing seasons produced hard freeze conditions during the first half of May, even as favorable soil temperatures are occurring two weeks earlier when compared to the early 1980s. If precipitation amounts remain steady or decrease by the year 2100, evapotranspiration demand will result in less moisture available to growing crops during their critical reproductive periods that occur in May (wheat), July (corn), and August (sorghum, soybean). During 2012, native vegetation broke dormancy a month earlier than normal and soil moisture reserves were depleted across most of the US Corn Belt well before the critical pollination period was reached.

The Third National Climate Assessment suggests that changes to crop growth cycles due to warming winters and alterations in the timing and magnitude of rainfall events have already been observed; as these trends continue, they will require new agriculture and livestock management practices (Shafer et al., 2014).

While all ecosystems in Nebraska will be affected by climate change, aquatic ecosystems (wetlands, lakes, streams, and rivers) may be the most highly impacted (University of Nebraska-Lincoln, 2014). Climate changes will alter both water quality and quantity. Increases in the frequency and intensity of high precipitation events, particularly in a landscape dominated by agriculture, will lead to increased runoff of sediments, fertilizers, and pesticides into water bodies. Increased frequency of drought and heat waves, combined with increased human demand for water, will result in lower stream flows and an increase in the frequency of stream segments being de-watered and wetlands drying up. Finally, increases in air temperature will result in increases in water temperature, causing a reduction in suitable habitat for cold-water dependent species such as trout.

Dunnell and Travers (2011) report that some spring flowering species have advanced their first flowering time, some fall species have delayed their first flowering, and some species have not changed. Given the importance of flowering timing for reproductive success, the changing climate in the Great Plains is expected to have long-term ecological and evolutionary consequences for native plant species.

Covich et al. (1997) summarize available information on patterns of spatial climate variability and identify subregions of importance to ecological processes within the Great Plains. Climate sensitive areas of the Great Plains range from cold water systems (springs and spring-fed streams) to warmer, temporary systems (intermittent streams, ponds, pothole wetlands, playas).

Warmer water temperatures also could exacerbate invasive species issues (e.g., quagga mussel reproduction cycles responding favorably to warmer water temperatures); moreover, climate changes could decrease the effectiveness of chemical or biological agents used to control invasive species (Hellman et al., 2008). Warmer water temperatures also could spur the growth of algae, which could result in eutrophic conditions in lakes, declines in water quality (Lettenmaier et al., 2008), and changes in species composition. In addition, landscape fragmentation is increasing, for example, in the context of energy development activities in the northern Great Plains. A highly fragmented landscape will hinder adaptation of species when climate change alters habitat composition and timing of plant development cycles (Shafer et al., 2014). The magnitude of expected changes will exceed those experienced in the last century. Existing adaptation and planning efforts are inadequate to respond to these projected impacts (Shafer et al., 2014).

2 Historical Surface Water Availability

2.1 Data and Models Used

The Basin Study utilizes regionalized soil water balance models (further referred to as watershed models), developed by the Upper Niobrara White (UNW) Natural Resources District, DNR, and their contractors, to characterize surface hydrology, crop yields and irrigation water requirements and to ensure that water supplies and water uses were accounted for within a balanced water budget. Together with groundwater (using MODFLOW) and surface water management models (using Stella and Excel software), these models were calibrated separately for the UNW region which includes UNW Natural Resources District and Central Nebraska (CENEB) to best represent simulated historical surface hydrology and crop dynamics in the watershed.

In this analysis, we employ the Variable Infiltration Capacity (VIC) surface hydrology model (Liang et al., 1994; Liang et al., 1996; Nijssen et al., 1997) to evaluate historical trends in various elements of the natural surface water hydrology budget, and projected changes based on the Basin Study climate change scenarios. The VIC model is an advantageous tool for this type of evaluation since this model has been applied over the continental United States and beyond, and has been used in Reclamation for assessments under the WaterSMART Basin Studies program (e.g., Reclamation, 2011).

The VIC model is a spatially distributed hydrology model that solves the water balance at each model grid cell. The model initially was designed as a land-surface model to be incorporated in a GCM so that land-surface processes could be more accurately simulated. However, the model now is run almost exclusively as a stand-alone hydrology model (not integrated with a GCM) and has been widely used in climate change impact and hydrologic variability studies. For climate change impact studies, VIC is run in what is termed the water balance mode that is less computationally demanding than an alternative energy balance mode, in which a surface temperature that closes both the water and energy balances is solved for iteratively. A schematic of the VIC hydrology and energy balance model is given in Figure 2.

The VIC model may be implemented at any spatial resolution, adhering to a latitude-longitude grid. For this Basin Study, and for consistency with Reclamation's West-Wide Climate Risk Assessment, the model was implemented over the study area at 1/8 degree, or approximately 12 kilometer resolution. Physical characteristics of each cell are predefined within the study area to simulate runoff and other water/land/atmosphere interactions at each model grid cell. The VIC hydrology model uses daily meteorological data (precipitation, maximum temperature, minimum temperature and wind) along with land cover, soils, and elevation information at 1/8 degree grid scale to simulate hydrologic processes. The meteorological data used as input to the VIC model in this Basin Study was developed by Maurer et al. (2002) and later extended through the year 2010. This dataset utilizes the National Weather Service (NWS) Cooperative Observer (Co-Op) network and Environment Canada daily station data as the primary sources for precipitation and temperature. The station data are processed to remove spatial and temporal inconsistencies and then interpolated to the 1/8 degree VIC model grid.

VIC provides a wide array of hydrologic outputs, including runoff, snow-water equivalent and evapotranspiration, which are routinely analyzed to assess climate change impacts on watershed hydrology. Also, note that all of these outputs are produced at the native VIC model grid cell resolution of 1/8 degree, or approximately 12 kilometers.

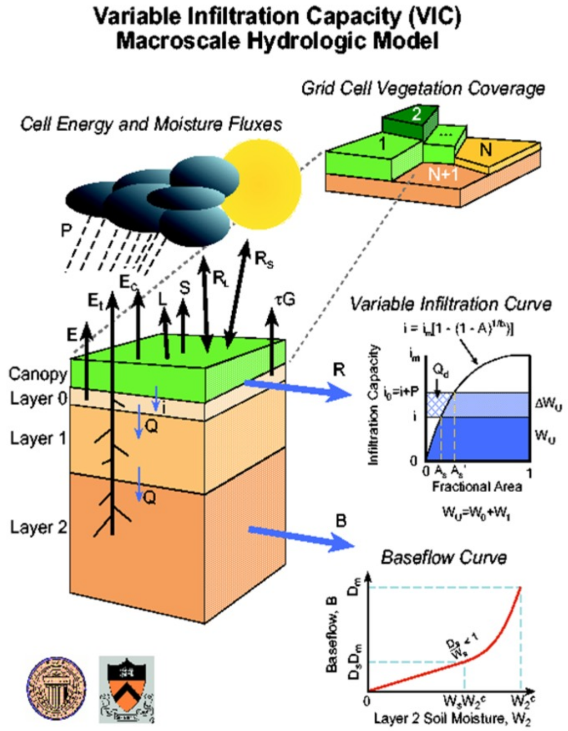
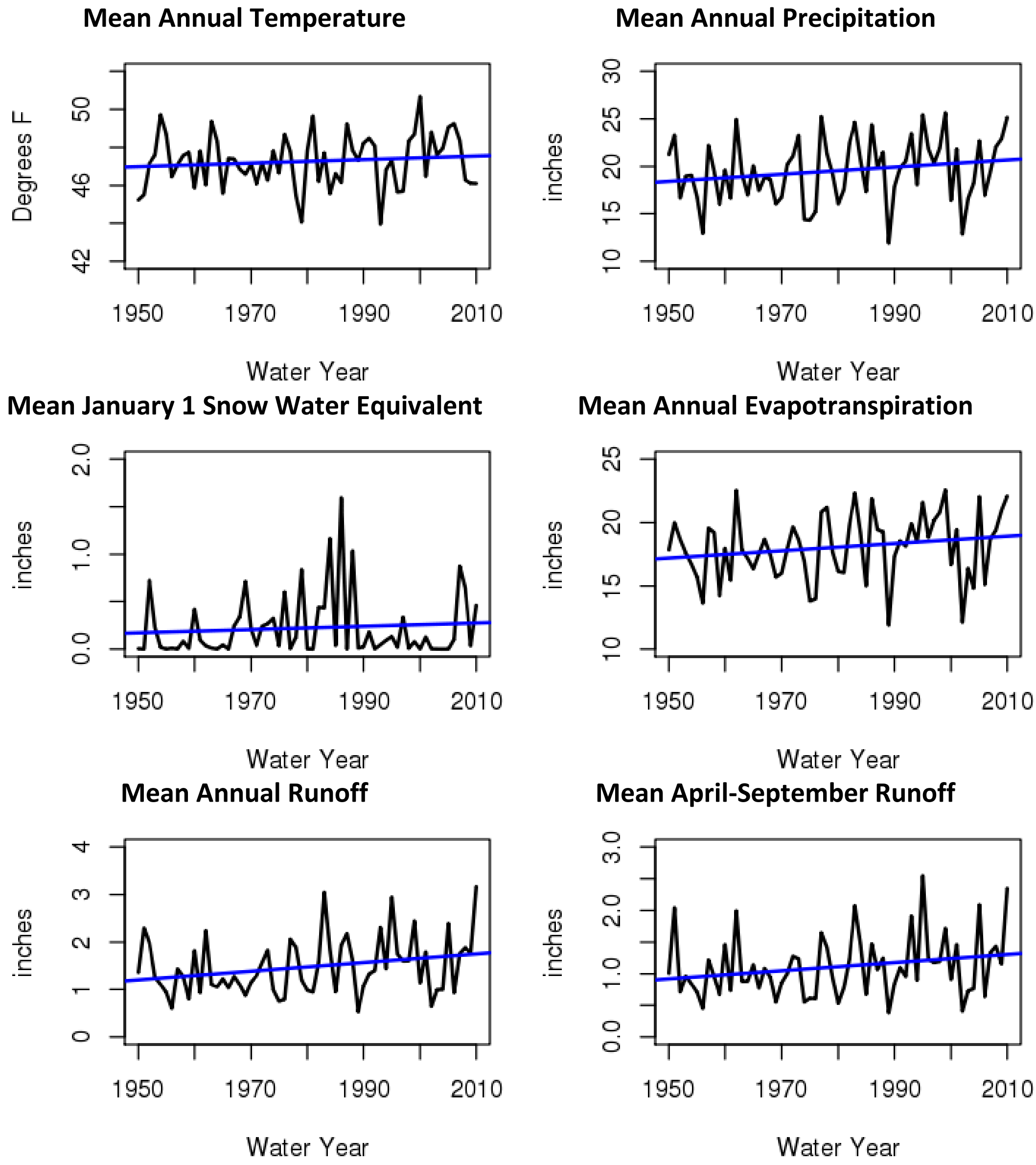


Figure 2: Illustration of VIC macroscale hydrologic model.

The following section summarizes present surface water availability in the Niobrara River Basin as a whole. Specifically, historical climate, snowpack, evapotranspiration, and runoff are presented as a way to characterize past trends and the basis for evaluating projected climate change impacts. It should be noted, however, that the Niobrara River Basin was divided into two regions, the UNW and the CENEB regions to enhance model computational efficiency (particularly for the groundwater models).

2.2 Present Availability

Figure 3 illustrates variability and historical trends in six basin averaged water balance variables, including mean annual temperature, mean annual precipitation, mean January 1 snow water equivalent (liquid content of the snowpack), mean annual evapotranspiration, mean annual runoff, and mean April-September runoff. SWE on January 1 was chosen for reporting due to the fact that the January 1 SWE has historically been the highest of any other month (comparing day 1 values for all months). The April – September runoff period was chosen because this period most generally corresponds with the irrigation season and represents the warmest half of the water year (typically October – September).


Mean Annual Temperature

Mean Annual Precipitation

Mean January 1 Snow Water Equivalent

Mean Annual Evapotranspiration

Mean Annual Runoff

Mean April-September Runoff

Figure 3. Summary of historical trends in the historical water balance in the Niobrara River Basin, 1950-2010.

Historical trend analysis over the period 1950-2010 indicates an increasing trend in mean annual temperature and precipitation during this period, along with increases in evapotranspiration and runoff (both annual and warm season, April – September, and an increase in January 1 SWE (month with historically highest computed snowpack). Table 3 summarizes these historical trends and computed change from 1950-2010. It should be noted that only the change in mean annual runoff is statistically significant, with a p-value less than or equal to 0.05. It should also be noted that the percent change in SWE and runoff between 1950 and 2010 are near or above 50 percent; however, the underlying values of SWE and runoff are small, generally less than 3 inches annually.

Table 3. Mean change over 1950-2010 period (water years) over the Niobrara River Basin

Numbers in bold indicate statistical significance of trend at the 95th percentile level.

	Basinwide Change	**Percent Change**	**P value**
Precip	+ 2.2 in	+ 12%	0.1253
Tavg	+ 0.56 °F	--	0.3599
January 1 SWE	+ 0.1 in	+ 61%	0.4852
Annual ET	+ 1.7 in	+10%	0.1264
Annual Runoff	**+ 0.55 in**	**+45%**	**0.0363**
Apr-Sep Runoff	+ 0.4in	+42%	0.0710

Historical trends in precipitation and temperature computed using the Maurer et al. (2002) meteorological dataset, extended through 2010, are generally consistent with historical trends reported by the University of Nebraska-Lincoln (2014) study as well as by Reclamation's 2013 Literature Synthesis. Computed historical trends in mean annual precipitation in this study consist of an approximate 12 percent increase, while Reclamation (2013) found between a 4 and 10 percent increase over the northern and southern Great Plains regions, respectively. Computed historical trends in annual daily average temperature consist of a change of approximately 0.6 degrees F, while the University of Nebraska-Lincoln report a statewide increase of about 1 degree F since 1895 and Reclamation (2013) reports an increase of approximately 1.85 degrees F in the northern Great Plains to approximately 0.63 degrees F in the southern Great Plains between 1901 and 2008. Although underlying station data used for analysis in the three studies may be the same, differences in results by these studies may be attributed to differences in processing of the data, as well as differences in reported spatial and temporal domains.

3 Effects of Climate Variability and Change on Supply

As a step toward greater understanding of the implications of climate change on the Niobrara River Basin, this section first describes the approach for development of climate scenarios for the Basin Study, followed by discussions of approaches for evaluation of climate change impacts on surface water supplies. The assessment focuses on projected changes in snowpack, timing and quantity of runoff, ET and soil moisture that have major implications for the watershed.

3.1 Data and Models Used

Climate may be generally described as average weather (for example, temperature and precipitation), typically considered over time periods of decades, as opposed to days or weeks. The climate system evolves in time under the influence of its own internal dynamics and because of external forcings, both natural (such as volcanic eruptions, solar variations) and anthropogenic (such as changing atmospheric composition and land-use change). Climate variability describes deviations from mean climate that may be due to natural internal processes or to variations in natural or anthropogenic forcings. Natural variability includes multi-year cycles in climate such as El Niño and La Niña, as well as cycles that can occur on even longer time scales. Changes in climate due to natural variability will continue to occur into the future, along with changes due to increased greenhouse gas (GHG) emissions from human activities. Climate change may be differentiated from climate variability as the persistence of anomalous conditions.

Arguably the most common approach for developing scenarios of future climate involves downscaling information (in space and time) from native scale GCM resolution to a finer resolution suitable for watershed-scale climate change impacts studies. This can be done using dynamical downscaling, which involves using GCM output to define boundary conditions for a finer scale regional climate model, or statistical downscaling, which involves using historical data as a way of statistically mapping GCM scale information to a finer resolution (in space and time). Statistical downscaling may involve delta method experiments, which involve computing period change values based on GCMs and applying them as perturbation factors to historical data. Numerous variations exist to this approach as well as hybrid approaches.

Climate projections are generally produced by internationally recognized climate modeling centers around the world and make use of greenhouse gas (GHG) emissions scenarios, which include assumptions of projected population growth and economic activities. GCMs used to develop projections of future climate conditions typically have spatial resolutions on the order of 1 degree latitude by 1 degree longitude (approximately 100km by 100km over mid-latitudes). However, water resources analysis and planning generally require information at much finer spatial scales. Many methods have been developed to downscale GCM projections to finer scales for use in water resources planning, all of which have strengths and weaknesses. Development of climate scenarios for the Basin Study relies on projections of future climate and hydrologic conditions developed under Reclamation's WWCRA (Reclamation, 2011). As part of the WWCRA, Reclamation, in collaboration with several other research groups, developed an archive of downscaled climate and hydrologic projections over the western US. The archive of downscaled climate projections developed under WWCRA is based on a statistical downscaling procedure, where GCM projections are spatially downscaled based on statistical relationships between large-scale climate features and fine scale climate for the region. The projections are publically available through an online data portal (see http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/dcpInterface.html).

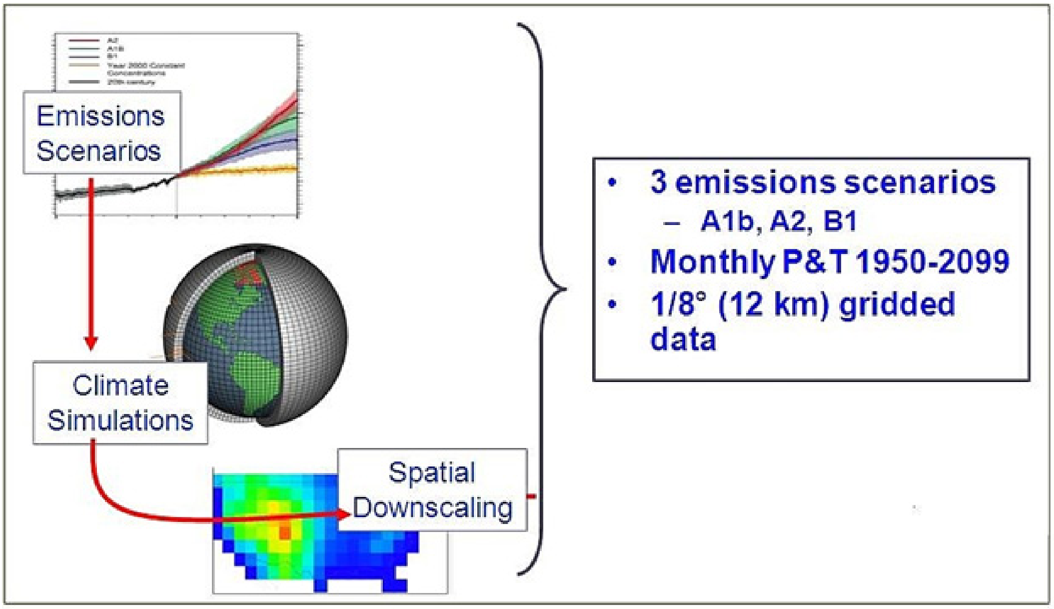


Figure 4. Summary of downscaled GCM key elements.

The statistical downscaling process is illustrated in Figure 4. The downscaled GCM projections used in the Basin Study are based on the CMIP3 (World Climate Research Programme's Coupled Model Intercomparison Project Phase 3; Meehl et al., 2007). These projections were the basis for analysis in the IPCC Fourth Assessment Report (IPCC, 2007).The emissions scenarios used in the downscaled GCM projections based on CMIP3 are A2 (high), A1b (medium), and B1 (low), and reflect a range of future GHG emissions. The emissions paths vary from lower to higher emissions rates, depending on assumptions of global technological and economic developments over the 21st century. Projections based on three CMIP3 emissions scenarios are available through the database mentioned above (A1B, A2, B1) for a total of 112 climate projections. Emission scenarios exist that have both higher and lower GHG emissions than those considered in this Basin Study (e.g. A1fi). However, the three scenarios included in the analysis span a wide range of projected GHG and there are more GCM projections available based on these three emissions scenarios than any others.

This Basin Study uses the downscaled CMIP3 climate projections; however, new projections from the CMIP5 were recently published in May 2013. CMIP5 climate projections are based on emission scenarios referred to as representative concentration pathways (RCPs; Taylor et al., 2012). Even though CMIP5 projections are more current, it has not been determined that they are a more reliable source of climate projections compared to existing CMIP3 climate projections. At this time, CMIP5 projections should be considered an addition to (not a replacement of) the existing CMIP3 projections unless the climate science community can offer an explanation as to why CMIP5 should be favored over CMIP3.

Many of Reclamation's basin studies, including this Basin Study, utilize the downscaled climate and hydrology projection archive as the basis for developing climate scenarios. It should be noted that throughout this report, the term *climate projections* refers to raw or downscaled projections of future climate conditions produced by GCMs, whereas the term *climate scenarios* refers to climate and hydrologic datasets—including inputs to hydrologic, operations, and resource models—derived from climate projections in combination with historical, paleo, and/or other data sources. Climate scenarios are used to support detailed analysis of regional or basin-scale water supplies, demands, and operations under future conditions for a specific water resources planning study.

Three climate scenarios were developed for the Niobrara River Basin representing a projected range of climate and hydrologic conditions for the future period from 2030-2059. Downscaled climate and hydrology projections were obtained from the WWCRA projection archive for a region encompassing the Niobrara River Basin (Figure 5). Note that this large-region view is only used to select projections to inform climate change scenarios. The large region is used to inform climate scenario development because of the coarser spatial scale of GCM projections. The region depicted in red in Figure 5 is based on the following bounding latitude by longitude box: 41.6875 North through 44.0625 North Latitude; -105.0625 East through -97.5625 East Longitude.

Consistent with many complex planning studies, the Basin Study involves numerous modeling components which are brought together to evaluate watershed response to projected future climate conditions and to various water management alternatives. There is a need to adequately represent the projected range of future climate conditions, while also limiting the number of required simulations to maintain a manageable project scope. Therefore, analysis of the watershed under all available climate projections (112) was not practically feasible for this study, as it would require the same number of simulations per modeling component, multiplied by the number of management alternatives to be considered by the study. To meet the needs of the Basin Study, three future climate change scenarios were developed as input to the hydrologic and management modeling framework to encompass range of projected water availability in the watershed in the 2030-2059 future time horizon. The following section describes the scenario development process for this study.

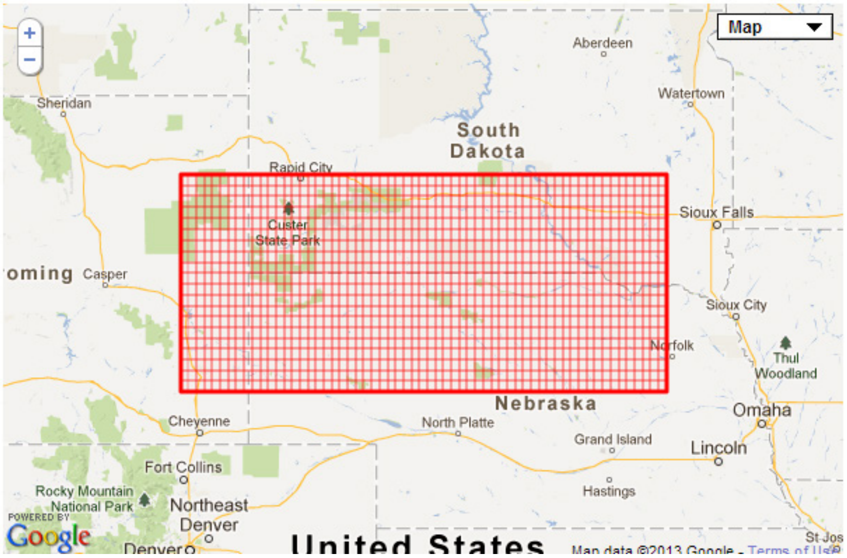


Figure 5. Map of region encompassing Niobrara River Basin that was used to develop climate scenarios.

Projected climate change scenarios developed for the Basin Study are based on projected changes in three variables, comparing the future period 2030-2059 to the historical period 1970-1999. The three variables include:

1. mean annual water availability
2. mean summer precipitation (including June, July, August)
3. mean summer temperature (including June, July, August)

Water availability is defined as the mean of the annual difference between precipitation and evapotranspiration. Mean summer (June – August) precipitation and temperature for the periods 1970-1999 and 2030-2059 were computed directly from the 112 statistically downscaled climate projections obtained from the WWCRA archive, while mean annual water availability is based on the corresponding hydrologic projections using the VIC model. VIC model simulations were completed as part of the WWCRA for each of the 112 CMIP3 future climate projections.

Depending on the preferences of a given study, the development of climate change scenarios may involve pooling of individual climate projections based on selected criteria or selection of individual climate projections for use as representative climate scenarios. Previous studies by Reclamation have explored the advantages and disadvantages of each approach (e.g. Reclamation, 2010;

Reclamation, 2011). For the Basin Study, climate change scenarios were developed based on three individual climate projections selected directly from the 112 available CMIP3-based projections to represent low projected water availability (hereafter called the low scenario), median projected water availability (hereafter called the central tendency scenario), and high projected water availability (hereafter called the high scenario), as well as a range of projected change in summer temperature and precipitation. The selected projections that represent the three scenarios are summarized in Table 4.

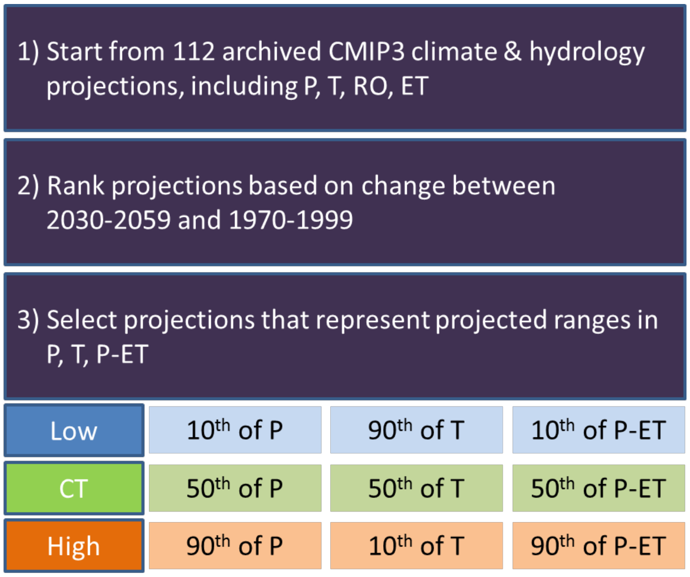
Table 4. Description of Niobrara River Basin Study Climate Change Scenarios

Climate Change Scenario	Description
Low	**giss_model_e_r.1.sresa2** Low projected water availability (10th percentile) combined with drier summers (10th percentile precipitation) and greater summer warming (90th percentile temperature)
Central Tendency	**cccma_cgcm3_1.3.sresb1** Central projected water availability (50th percentile) combined with central tendency of summer precipitation (50th percentile) and temperature (50th percentile)
High	**ncar_pcm1.1.sresa1b** High projected water availability (90th percentile) combined with wetter summers (90th percentile precipitation) and less summer warming (10th percentile temperature)

These scenarios were selected based on their ranked position with respect to projected change in mean annual water availability, summer precipitation (June – August), and temperature (June – August) from the historical period 1970-1999 to the future period 2030-2059. Projected change in precipitation and water availability were considered on a percent change basis, while temperature was considered based on difference in degrees Celsius. Projected changes in the above-mentioned variables were evaluated based on spatial means across the region (designated by region illustrated in Figure 5) for the selected historical and future time periods. Preliminary scenario selection was carried out based on select percentile ranks of water availability: the 10th percentile rank was chosen to represent the low end of the projected range of water availability (generally drier conditions); the 90th percentile rank was chosen to represent the high end (generally wetter conditions); and the 50th percentile rank was chosen to represent the central tendency of the range of projections. Final scenario selection was determined by the study team to ensure that the selected scenarios represent the projected ranges in all three variables. It should be noted that, although projections were selected based on projected changes computed as averages across a domain encompassing the Niobrara River Basin, the resulting climate scenarios maintain spatial variability across the domain. In other words, each scenario has potentially different projected climate changes from one portion of the watershed to another.

Figures 6 and 7 provide illustrations of the projection selection process. Specifically, Figure 6 provides a schematic view of the approach, while Figure 7 illustrates projected changes in mean summer (June – August) temperature and precipitation for the 2030-2059 period, compared with 1970-1999 for all 112 GCMs for which archive data are publicly available. Colored symbols in Figure 7 illustrate the selected projections that comprise the climate change scenarios for the Basin Study. The blue symbol represents the low climate change scenario; the green symbol represents the central tendency climate change scenario; and finally, the orange symbol represents the high climate change scenario. The 10th, 50th, and 90th percentile changes in summer precipitation and temperature are illustrated by red (10th and 90th) and black lines (50th) in Figure 7, to orient the reader.

Figure 7 shows that selected projections are close to the intersections of 10th, 50th, and 90th percentile change in summer precipitation and temperature. The projections closest to the intersections according to Figure 7 may not have been selected because projected changes in mean annual water availability (P-ET) were taken into consideration in the projection selection process, along with summer precipitation and temperature. Select projections were chosen based on their collective proximity to these percentile values.



1) Start from 112 archived CMIP3 climate & hydrology projections, including P, T, RO, ET

2) Rank projections based on change between 2030-2059 and 1970-1999

3) Select projections that represent projected ranges in P, T, P-ET

Low	10th of P	90th of T	10th of P-ET
CT	50th of P	50th of T	50th of P-ET
High	90th of P	10th of T	90th of P-ET

Figure 6. Overview of projection selection process.

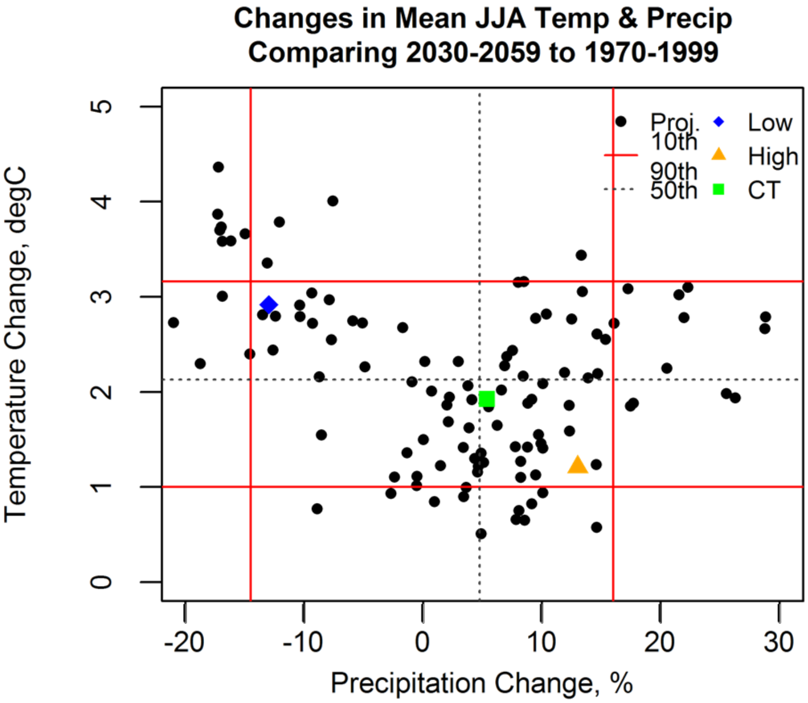


Figure 7. Projected change in mean summer (June – August) temperature and precipitation for 112 CMIP3 projections. Blue diamond indicates selected low scenario; green square indicates selected central tendency scenario; orange triangle indicates selected high scenario in terms of water availability.

The selected Low scenario corresponds with a decrease in water availability by approximately 9 percent. The selected Central Tendency scenario corresponds with an increase in water availability of approximately 6 percent. The selected High scenario corresponds with an increase in water availability of approximately 37 percent. In summary, the range of projected water availability spans a modest decrease in water availability to a substantial increase in water availability. The fact that the selected central tendency projection indicates an overall increase in water availability (6 percent) means that a majority of the 112 CMIP3 GCM projections suggest an increase in water availability as opposed to a decrease. However, it should be noted that each of the 112 projections is deemed equally likely. Table 5 summarizes the projected change in each of the scenario selection variables between future and historical periods (2030-2059 and 1970-1999).

It should be noted that there are limitations associated with the choice of single GCM projections to represent each climate change scenario (Low, Central Tendency, and High). For example, Harding et al. (2012) suggest that impact analyses relying on one or a few climate scenarios are unacceptably influenced by the choice of projections. Also, Desser et al. (2013) underscore the importance of including a large number of projections from a given model in an analysis of climate change impacts because each model realization may contain different superposition of unforced and forced trends.

Table 5. Summary of Projected Changes in Selected Scenario Variables

Results include those computed by the select projections for each scenario and those computed based on all 112 available CMIP3 projections.

Parameter	Projection	Low	Central Tendency	High
Mean Annual Water Availability	Select Projection	-9%	+6.1%	+37%
	Based on 112 Projections	–16%	+10%	+50%
Mean Summer Temperature (June–August)	Select Projection	+2.9°C	+1.9°C	+1.2°C
	Based on 112 Projections	+3.3°C	+2.1°C	+.96°C
Mean Summer Precipitation (June–August)	Select Projection	-13%	+5.4%	+13%
	Based on 112 Projections	-15%	+4.7%	+17%

Although it may be beneficial to evaluate climate change impacts based on numerous GCM projections, we found that projected changes in water availability, precipitation, and temperature computed based on the selected projections are comparable with corresponding 10th, 50th, and 90th percentile projections in these variables based on all 112 available CMIP3 projections. Table 5 illustrates the similarities in the projected changes. For each variable evaluated, projected changes based on selected projections (Low, Central Tendency, and High) are summarized along with projected changes based on all 112 projections. For summer precipitation, the ranges of these percentage values are less than 5 percent. For summer temperature, projected changes are within 0.5 degrees Celsius. For annual water availability, projected changes are more conservative than those based on all 112 projections (i.e. less change). It should be noted that projected changes for each variable based on all 112 projections are computed independently from each other, with the possibility of different ranks of GCMs for each variable.

The Basin Study utilizes historical and climate change scenario data to evaluate the implications of historical and future conditions on water supply and demand in a modeling framework, which is described in Section 4. Historical climate data (over a period 1960-2010), along with historical data and assumptions about water demands, allow for the tuning of individual models to observed historical conditions. Historical climate data is also used along with assumed current water demands (in this case set at 2010 levels) to establish a Baseline No Action scenario condition. The Baseline No Action scenario provides a benchmark to evaluate the effects of climate change on assumed future demands.

Future Low, Central Tendency, and High climate change scenario data (representing a future period of 2030-2059) is used along with assumed current water demands (set at 2010 levels) to explore future water supply and demand under a range of future climates. In the Basin Study, these future scenarios are termed Future No Action Low (FNA Low), Future No Action Central Tendency (FNA CT), and Future No Action High (FNA High).

The Basin Study also evaluates the effects to two implemented alternatives on future water supply and demand. The details of the management alternatives are described in detail in Appendix F, the integrated water management modeling report. Generally, the first alternative includes changing the location of surface water diversion from the Niobrara River to the Mirage Flats Irrigation District to reduce conveyance losses in the current canal system. The second alternative includes using existing canal systems to recharge the groundwater system during periods of excess available water. The same Future Low, Central Tendency, and High climate change scenario data described above (representing a future period of 2030-2059) are used along with assumed demands under the two selected management alternatives. In the Basin Study, these future scenarios are termed Future with Alternative Low (FA1 Low or FA2 Low), Future with Alternative Central Tendency (FA1 CT or FA2 CT), and Future with Alternative High (FA1 High or FA2 High). It should be noted that Future No Action and Future with Alternatives use same future climate scenarios.

3.2 Future Availability

Future water supply availability is described in this section by first evaluating projections of future temperature and precipitation, which drive hydrology. Following an assessment of projected future temperature and precipitation is an evaluation of projected future water balance variables pertinent to the Niobrara River Basin. Finally, an evaluation of projected changes in future unimpaired (or natural) streamflow is provided for selected locations in the basin that correspond with nodes in the groundwater, soil water balance, and surface water operations models.

3.2.1 Projections of Future Climate

Annual timeseries of mean annual precipitation (total) and temperature (average) are provided in Figure 8, covering the period 1950–2099 (water years 1951-2099) for all GCMs that were used to inform selection of Basin Study climate change scenarios. To estimate total annual precipitation for the basin, basin-wide average precipitation (average across the grid cells in the basin) was first calculated for each month of the water years 1950–2099. These basin average monthly precipitation values then were summed for each water year 1951-2099 to obtain the annual total precipitation. To estimate basin mean temperature, average monthly temperature was calculated from all the grid cells in the basin for each month of the water years 1951–2099. These monthly temperatures for any given year next were averaged across the grid cells in the basin to estimate the basin-wide annual mean temperature. The annual time series for all the 112 GCM projections were calculated and the results are presented to reflect the central tendency of the projections as well as the range. The central tendency is measured using the ensemble median. The 5th and 95th percentiles from the 112 GCM projections provide the lower and upper uncertainty bounds in the envelope of projections through time.

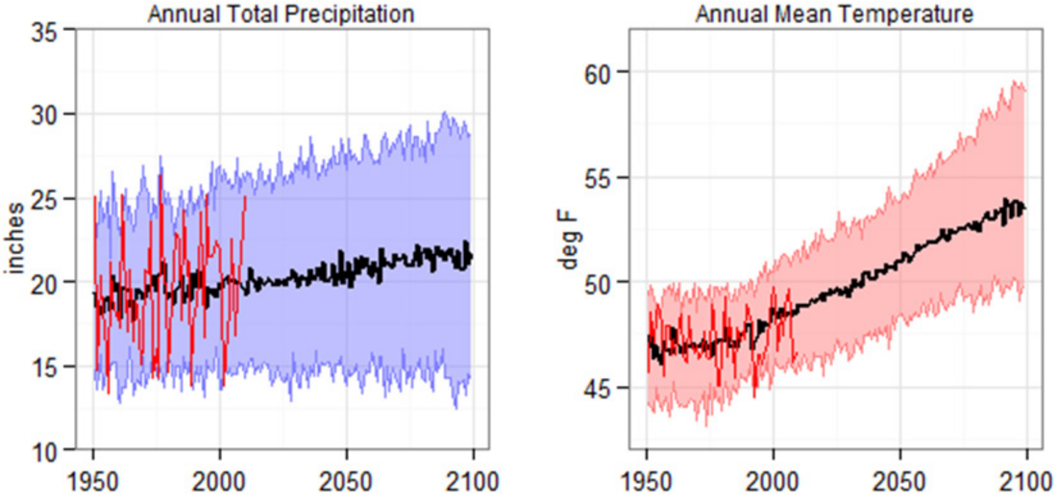


Figure 8. Projected mean annual precipitation (left) and temperature (right) averaged over the Niobrara River Basin for each of 112 archived CMIP3 climate projections from Reclamation's West-Wide Climate Risk Assessment. Heavy black line indicates annual median value. Heavy red line indicates basin averaged historical mean annual values based on Maurer et al. (2002) meteorological forcing dataset.

The heavy black line in Figure 8 is the annual time series of 50th percentile values (i.e., ensemble median). The shaded area is the annual time series of 5th to 95th percentiles. The heavy red line is the observed timeseries from the meteorological dataset used as the basis for historical model simulations for the Basin Study.

The annual total precipitation over the basin shows a somewhat increasing trend over the period from 1950 through 2099. The range of projections (as defined as the spread between 5th and 95th percentiles, or the width of the purple band) appears to expand through time indicating that model projections diverge into the future. The mean annual temperature over the basin shows an increasing trend and an expansion of the band of uncertainty over time. It should be noted that projected annual precipitation (particularly the median) is largely within the range of historical variability, whereas projected annual temperature at the end of this century is largely outside of the range of historical variability. The red lines showing observed mean annual precipitation and temperature highlights the year to year variability the Niobrara River Basin has experienced between 1950 and 2010, in part due to natural climate cycles outside of human induced climate change. This natural variability will continue in the future, as opposed to a monotonic or stepwise change through time.

3.2.2 Projections of Future Surface Hydrology

Historical and projected changes in climate and water balance variables are summarized in this section for each of the three climate change scenarios developed for the Basin Study. Climate change scenario development is described in detail in Section 3.1. Specifically, the Low scenario represents projected low water availability and generally corresponds with hotter and drier future climate. The Central Tendency scenario represents the middle-of-the-road water availability and generally corresponds with the central tendency of all available GCM projections for the chosen future time horizon. The High scenario represents high projected water availability and generally corresponds with wetter and less warm future climate. Together, the climate change scenarios are intended to represent a range of projected future conditions.

The following figures in this section consist of spatial plots that summarize climate and water balance variables averaged over select zones. The zones, which are illustrated in Figure 9 by colored polygons, correspond with the modeled runoff zones by the watershed and groundwater models (for UNW and CENEB subregions). Runoff zones represent major subbasins of the Niobrara River that correspond with USGS gage locations. There are five runoff zones in the UNW subregion of the study area, while there are three runoff zones in the CENEB subregion of the study area. Runoff zones are equivalent to the upstream contributing area to each of the model nodes from Table 1, subtracting any upstream zone areas. The Table 1 model nodes are included in Figure 9 for additional reference.

Figure 10 illustrates historical (1960-2010) and projected future (2030-2059) mean annual precipitation for the eight modeled zones within the basin. The figure indicates that the eastern part of the basin is historically wetter than the western part of the basin, which is consistent with analysis in Section 2.2. The Central Tendency climate change scenario indicates that the basin will experience an increase in mean annual precipitation of approximately 7 to 8 percent depending on the zone. The Low scenario indicates a change in precipitation from a decrease of 3 percent in the eastern part of the basin to an increase of 2 percent in the western part of the basin. The High scenario indicates an increase in mean annual precipitation by a range of 10 to 16 percent, with a greater increase in the eastern part of the basin. Data supporting the projected changes illustrated in Figure 10 are provided in Tables 6 and 7.

Figure 11 illustrates historical and projected changes in mean annual temperature for the eight modeled zones within the basin. The top panel showing historical temperature averaged from 1960-2010 for each zone indicates higher temperatures in the eastern part of the basin (approximately 48 degrees F on average) and lower temperatures in the western part of the basin (approximately 45 degrees F on average). Projected changes in temperature range from 2.5 degrees F (High scenario) to about 5.5 degrees F (Low scenario), without a substantial spatial gradient across zones.

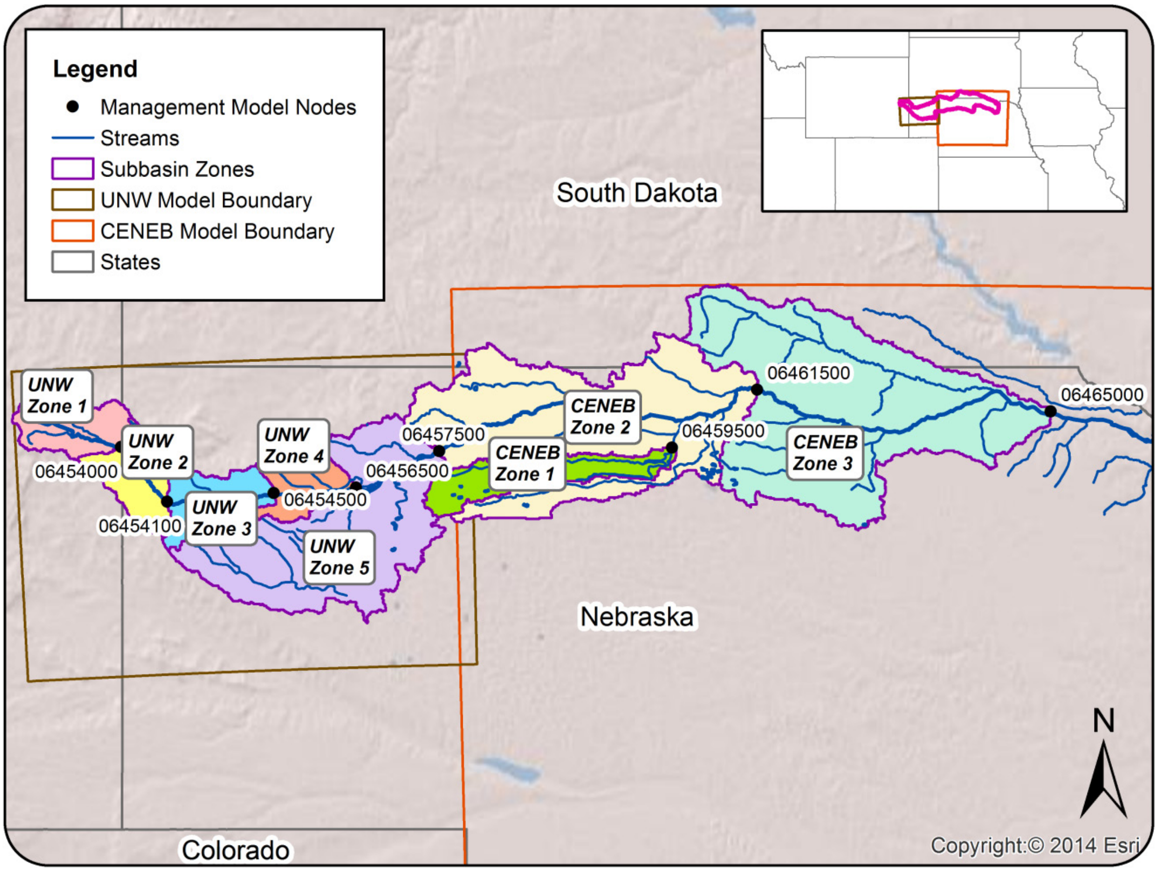


Figure 9. Summary zones (indicated by colored polygons) for climate change impact analysis.

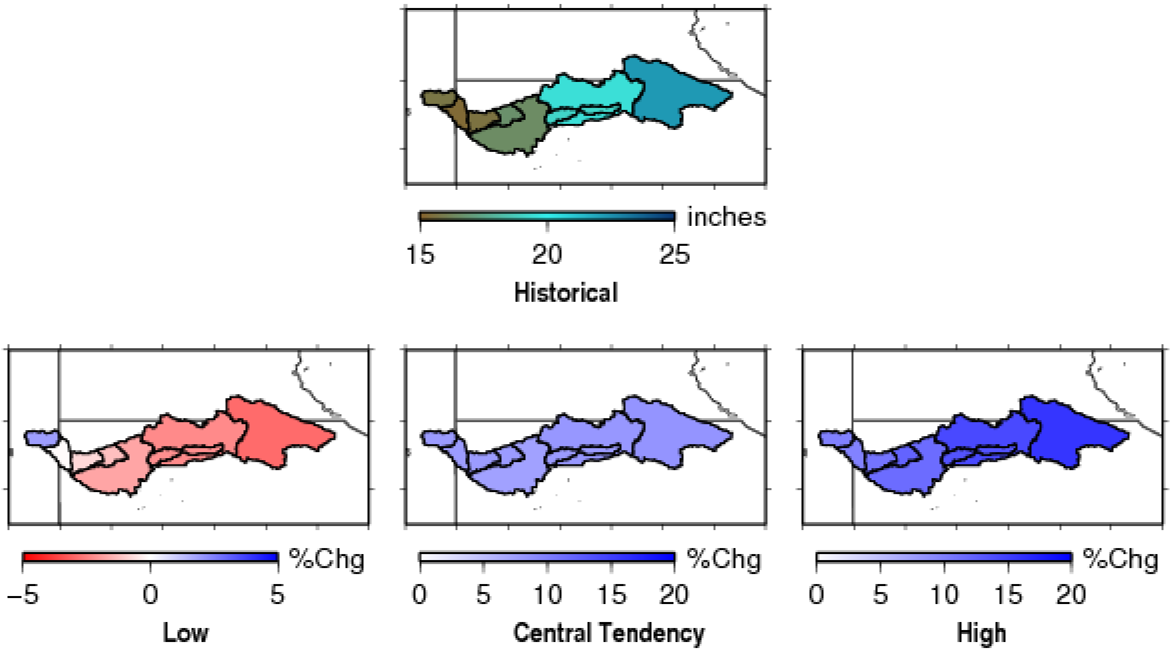


Figure 10. Historical (1960-2010) and projected changes in mean annual precipitation (inches) for three future scenarios (2050s compared with historical).

Table 6. Historical (1960-2010) and Projected Climate and Water Balance Variables Based on VIC Model Simulations for Three Future Scenarios (2050s compared with historical)

Variable	Scenario	UNW Zone 1	UNW Zone 2	UNW Zone 3	UNW Zone 4	UNW Zone 5	CENEB Zone 1	CENEB Zone 2	CENEB Zone 3	Basin
Mean Annual Precipitation (in)	Historical	15.73	15.32	15.60	16.67	16.51	19.10	19.48	22.27	19.56
	Low	16.03	15.31	15.49	16.46	16.22	18.68	19.03	21.62	19.15
	Central Tendency	16.97	16.51	16.81	17.97	17.73	20.59	21.06	24.12	21.10
	High	17.29	16.82	17.29	18.71	18.42	21.67	22.25	25.79	22.33
Mean Annual Temperature (deg F)	Historical	44.58	45.26	45.86	46.74	46.98	46.95	47.17	48.24	47.27
	Low	49.72	50.40	51.00	51.86	52.10	52.06	52.29	53.51	52.45
	Central Tendency	47.90	48.54	49.11	49.95	50.18	50.09	50.29	51.36	50.43
	High	47.00	47.69	48.28	49.13	49.43	49.47	49.70	50.89	49.82
Mean Annual Runoff (in)	Historical	0.85	0.82	0.82	1.13	0.92	0.92	1.03	1.36	1.16
	Low	0.85	0.79	0.77	1.06	0.85	0.84	0.94	1.23	1.07
	Central Tendency	0.98	0.95	0.94	1.28	1.05	1.04	1.17	1.54	1.31
	High	1.00	0.97	0.99	1.37	1.11	1.14	1.29	1.75	1.47
Mean April - September Runoff (in)	Historical	0.63	0.65	0.66	0.91	0.75	0.73	0.81	1.03	0.895
	Low	0.61	0.60	0.60	0.83	0.67	0.64	0.71	0.88	0.785
	Central Tendency	0.75	0.77	0.78	1.08	0.88	0.86	0.96	1.24	1.063
	High	0.71	0.72	0.75	1.05	0.85	0.86	0.97	1.27	1.070
Mean Annual Evapotranspiration (in)	Historical	14.75	14.40	14.70	15.42	15.48	18.09	18.31	20.34	18.06
	Low	15.04	14.42	14.64	15.29	15.28	17.78	18.00	20.06	17.86
	Central Tendency	15.75	15.43	15.79	16.55	16.56	19.45	19.72	21.95	19.43
	High	16.03	15.70	16.21	17.15	17.13	20.29	20.57	22.58	20.07

Table 7. Historical (1960-2010) and Projected Changes in Climate and Water Balance Variables Based on VIC Model Simulations for Three Future Scenarios (2050s compared with historical)

Variable	Scenario	UNW Zone 1	UNW Zone 2	UNW Zone 3	UNW Zone 4	UNW Zone 5	CENEB Zone 1	CENEB Zone 2	CENEB Zone 3	Basin
Mean Annual Precipitation (in)	Historical	15.73	15.32	15.60	16.67	16.51	19.10	19.48	22.27	19.56
	Low	1.9%	-0.1%	-0.7%	-1.2%	-1.8%	-2.2%	-2.3%	-2.9%	-2.1%
	Central Tendency	7.8%	7.8%	7.7%	7.8%	7.4%	7.8%	8.1%	8.3%	7.9%
	High	9.9%	9.8%	10.8%	12.2%	11.5%	13.5%	14.3%	15.8%	14.2%
Mean Annual Temperature (deg F)	Historical	44.58	45.26	45.86	46.74	46.98	46.95	47.17	48.24	47.27
	Low	5.14	5.14	5.14	5.13	5.12	5.11	5.12	5.26	5.19
	Central Tendency	3.32	3.28	3.24	3.21	3.21	3.14	3.12	3.12	3.16
	High	2.42	2.43	2.41	2.40	2.45	2.52	2.53	2.65	2.55
Mean Annual Runoff (in)	Historical	0.85	0.82	0.82	1.13	0.92	0.92	1.03	1.36	1.16
	Low	0.8%	-3.5%	-5.9%	-5.8%	-7.4%	-9.4%	-8.7%	-8.9%	-7.7%
	Central Tendency	16.1%	15.7%	14.3%	14.0%	13.6%	13.3%	13.7%	13.6%	13.2%
	High	18.4%	18.1%	20.6%	21.9%	20.9%	24.1%	25.2%	29.2%	26.7%
Mean April - September Runoff (in)	Historical	0.63	0.65	0.66	0.91	0.75	0.73	0.81	1.03	0.90
	Low	-3.4%	-6.8%	-9.3%	-9.1%	-10.7%	-12.6%	-12.2%	-14.3%	-12.3%
	Central Tendency	19.2%	18.8%	18.1%	18.1%	17.5%	18.2%	18.8%	20.3%	18.8%
	High	12.3%	11.4%	13.9%	15.5%	14.2%	17.8%	19.1%	23.1%	19.5%
Mean Annual Evapotranspiration (in)	Historical	14.75	14.40	14.70	15.42	15.48	18.09	18.31	20.34	18.06
	Low	2.0%	0.2%	-0.5%	-0.9%	-1.3%	-1.7%	-1.7%	-1.4%	-1.1%
	Central Tendency	6.8%	7.1%	7.4%	7.3%	7.0%	7.5%	7.7%	7.9%	7.5%
	High	8.7%	9.0%	10.2%	11.2%	10.7%	12.2%	12.4%	11.0%	11.1%

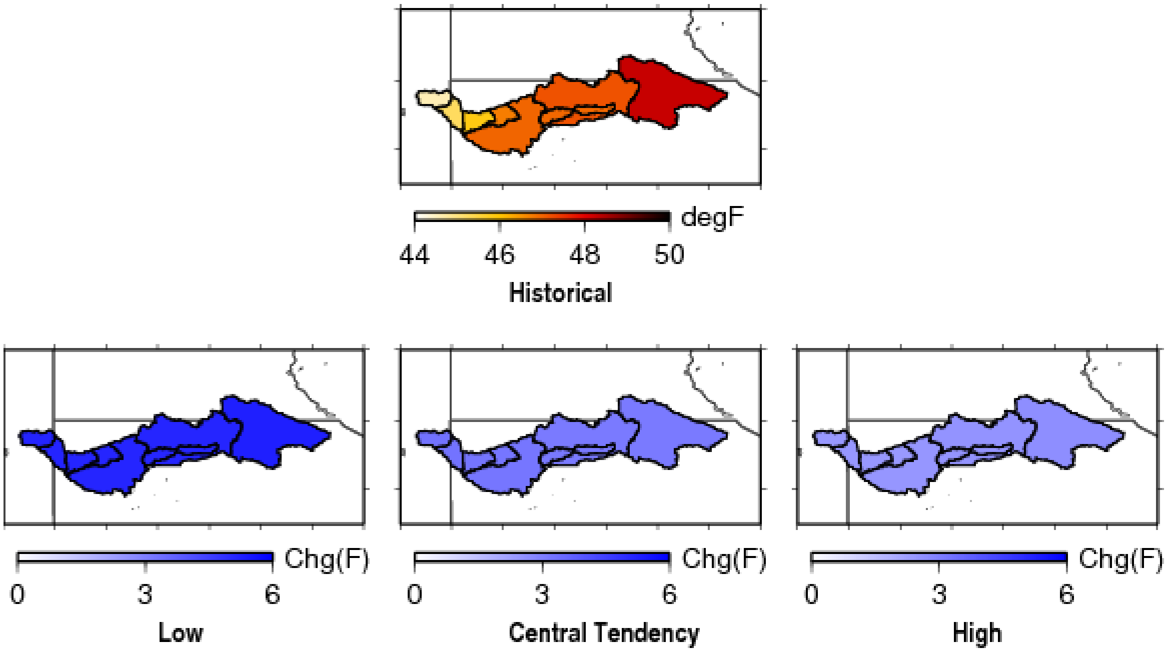


Figure 11. Historical (1960-2010) and projected changes in mean temperature (degrees F) for three future scenarios (2050s compared with historical).

The VIC model was used to evaluate potential impacts of climate change on natural surface hydrology as part of the Basin Study. Although this model was not utilized as one of the model components to quantify historical and future water supply gaps in the basin, it is a valuable tool for exploring regional surface hydrology in regions with limited measurements. Results from the model may provide additional context for the assessment of current and future surface hydrology.

Figure 12 illustrates historical and projected mean annual runoff as computed by the VIC hydrologic model. The top panel, which summarizes historical runoff by model zone, indicates the eastern part of the basin experiences higher mean annual runoff that the western part of the basin (1.5 inches compared with 1 inch). It should be noted that about 95 percent of mean annual precipitation results in evapotranspiration, leaving only about 5 percent to surface runoff. Projected changes in runoff based on the three selected climate change scenarios indicate a range of about -9 percent (Low scenario in the eastern portion of basin) to about +29 percent (High scenario in the western portion of the basin) in mean annual runoff, with an average increase of about 13 percent across the basin for the Central Tendency scenario.

About 75 percent of mean annual runoff occurs in the warm season (defined as April – September) as a result of monsoon related precipitation during that period. Projected changes in April-September runoff based on the three selected climate change scenarios indicate a range of about -14 percent (Low scenario in the eastern portion of basin) to about +23 percent (High scenario in the western portion of the basin) in mean annual runoff, with an average increase of about 19 percent across the basin for the Central Tendency scenario.

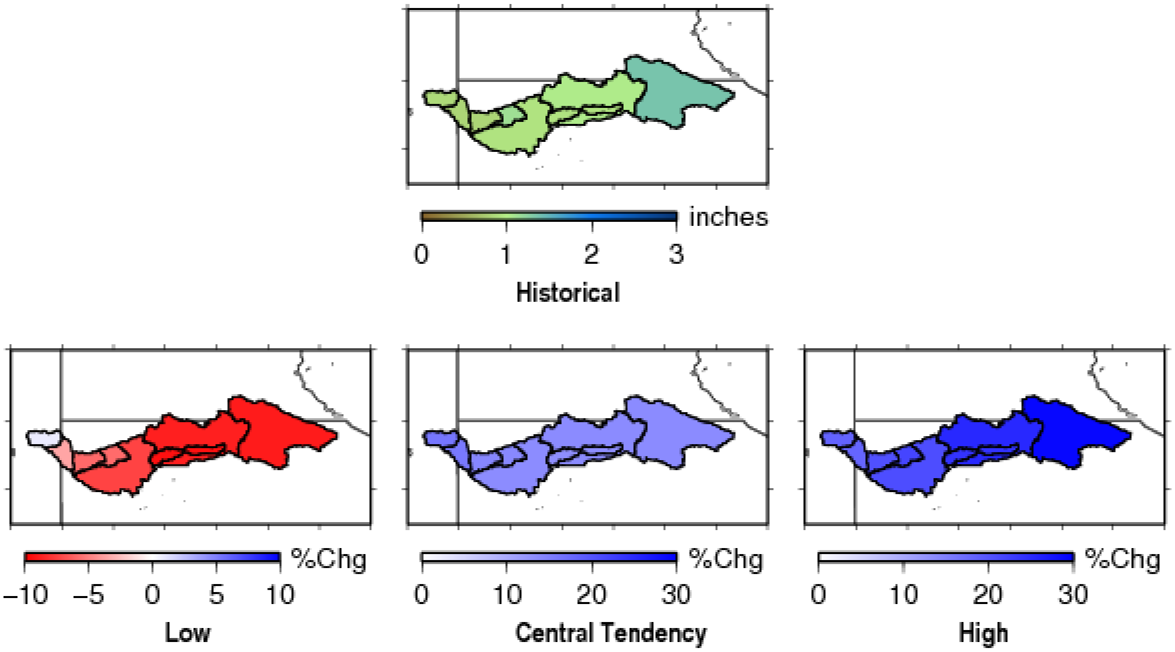


Figure 12. Historical (1960-2010) and projected changes in mean annual runoff (inches) for three future scenarios (2050s compared with historical).

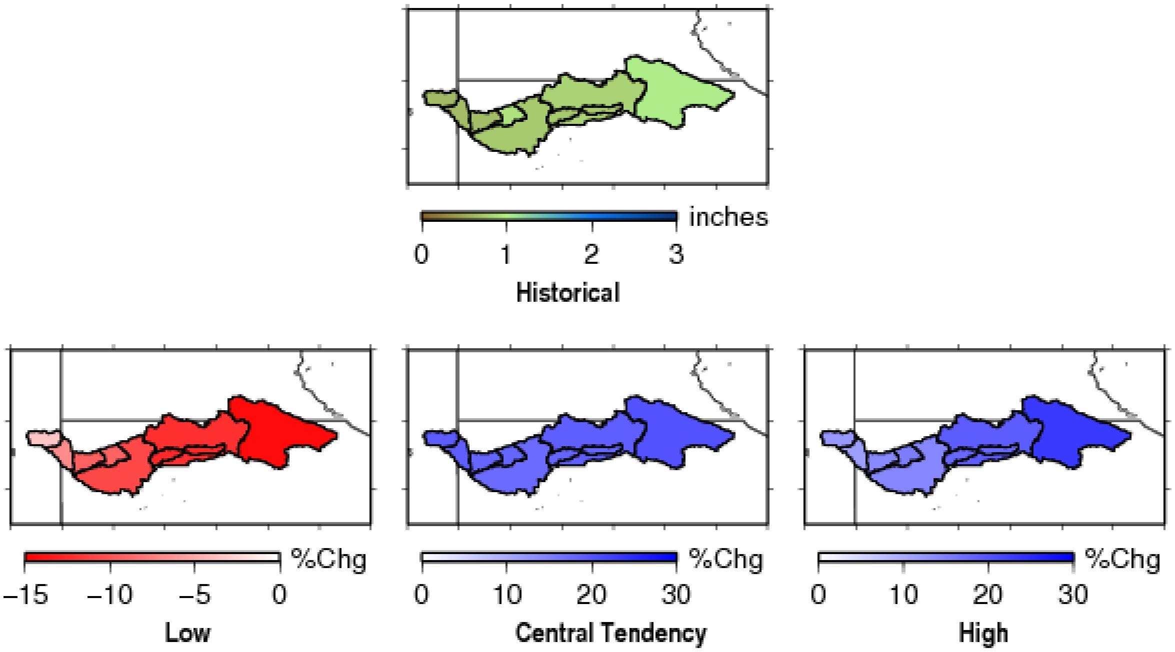


Figure 13. Historical (1960-2010) and projected changes in mean warm season (April September) runoff (inches) for three future scenarios (2050s compared with historical).

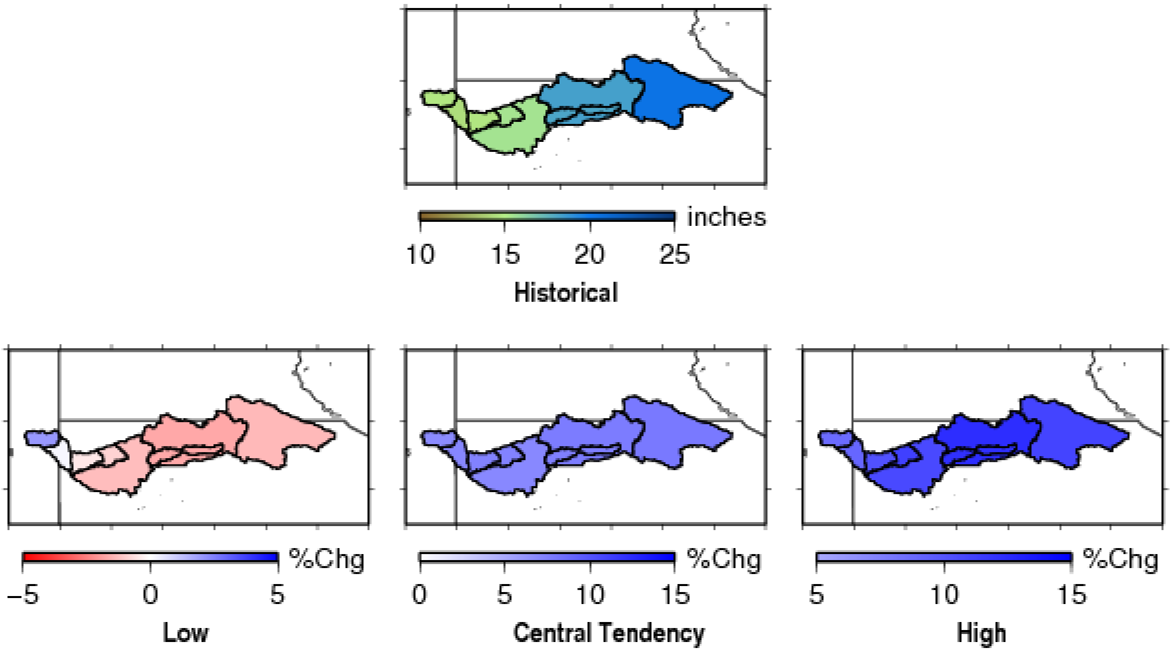


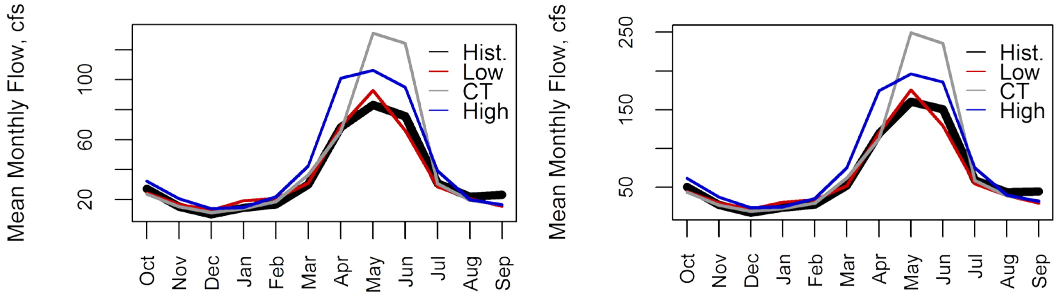
Figure 14. Historical (1960-2010) and projected changes in mean annual evapotranspiration from natural vegetation (inches) for three future scenarios (2050s compared with historical).

As discussed above, evapotranspiration consumes about 95 percent of mean annual precipitation in the basin. Historically (average over 1960-2010) evapotranspiration ranges from about 15 inches in the western part of the basin to 20 inches in the eastern part of the basin. Projected changes in evapotranspiration as computed by the VIC model range from about a 1 percent decrease (Low) to a 11 percent increase (High), both in the eastern part of the basin. The central tendency scenario indicates about a 7.5 percent increase in evapotranspiration basin wide, primarily as a result of projected increases in mean annual precipitation for the same scenario.

Results from VIC model simulations of historical (1960-2010) and projected future conditions (2030-2059) for all scenarios indicate a warmer future climate. Projected future precipitation, according to the three climate change scenarios developed, may range from a slight decrease to a more substantial increase, depending on the scenario considered and spatial location within the basin. The best available science indicates that no single climate scenario may be considered more likely than another. As such, a range of future conditions are taken through the entire modeling sequence, from surface and groundwater hydrology simulations to surface water operations simulations including facilities and operations.

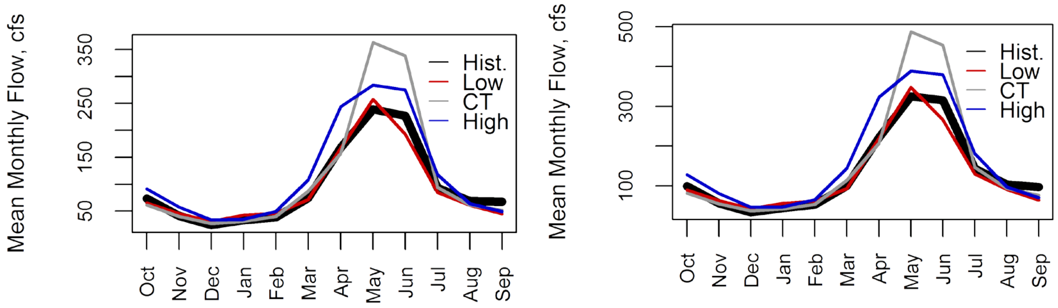
3.2.3 Projections of Unimpaired Streamflow

Evaluation of projections of unimpaired streamflow is beneficial for isolating the implications of climate change on hydrology, without the influence of changes in management. Projected changes in managed flows along with hydrology are evaluated in a separate technical report. The VIC model, along with a separate streamflow routing routine, was used to develop historical and projected natural streamflow for the chosen future time horizon at model nodes used throughout the Basin Study (refer to Table 1). Figures 15 and 16 illustrate historical and projected mean monthly hydrographs for the three climate change scenarios considered by the study. The historical hydrographs are computed over the 1960-2010 historical period, while the projected hydrographs are representative of climate over the 2030-2059 future time horizon.



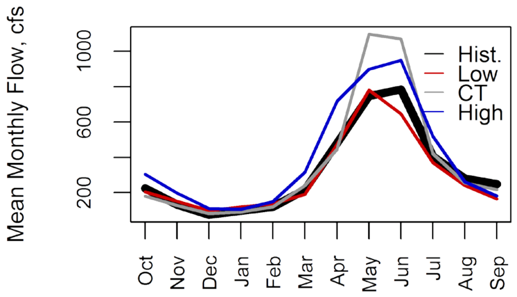
Niobrara River at Stateline (06454000)

Niobrara River at Agate (06454100)



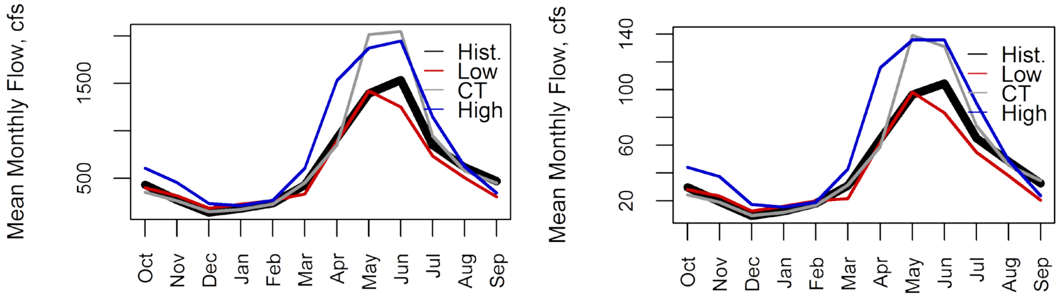
Niobrara River above Box Butte (06454500)

Niobrara River at Hay Springs (06456500)

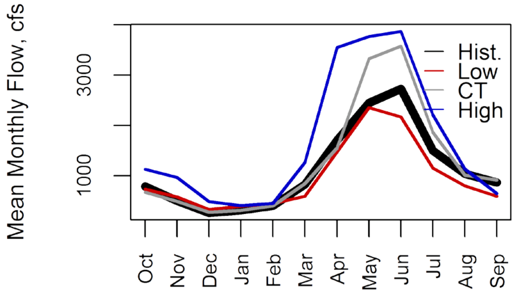


Niobrara River near Gordon (06457500)

Figure 15. Summary of projected and historical mean monthly hydrographs of natural streamflow in UNW model region.



Niobrara River near Sparks (06461500) **Snake River near Burge (06459500)**



Niobrara River near Spencer (06465000)

Figure 16. Summary of projected and historical mean monthly hydrographs of natural streamflow in CENEB model region.

Historically, unimpaired streamflow in the basin has a seasonal peak in May and June, corresponding with the seasonality of precipitation. Projected mean monthly unimpaired streamflow for the Central Tendency scenario indicates a substantial increase in seasonal peak flow for all Basin Study model nodes, on the order of 50 percent for nodes in the upper basin and on the order of 30 percent for the Niobrara River near Spencer, Nebraska. For the low flow season (generally defined as August through November), reductions in mean monthly unimpaired flow on the order of 10 to20 percent are projected for the Central Tendency scenario.

For the Low scenario (corresponding with a hot/dry projected climate), any projected changes in mean monthly unimpaired streamflow are modest. Increases in mean monthly flow are projected for November and December at most model nodes in the basin, on the order of 10 to 30 percent. The Low scenario also indicates a projected shift in seasonal peak flow by approximately one month (generally shifting to May for all sites).

For the High scenario (corresponding with less warm, along with wetter conditions), the mean annual streamflow volume increases, corresponding with projected increases in mean flows for most months of the year. Projected changes range from about 5 percent in January to 50 percent or more in fall months and in May through June.

It should be noted that historical and projected unimpaired flow are not meant to reflect actual flow measured in the Niobrara River and its tributaries. Actual flow may deviate substantially from unimpaired values, due to the effects of water deliveries, storage, and other management effects. This analysis, in conjunction with the surface water operations models used in the Basin Study, together provide a broader understanding of projected hydrologic and management changes due to changes in future climate, and by extension a broader understanding of gaps in water supply and demand.

Tables 8 and 9 summarize the data used to support Figures 15 and 16.

3.2.4 Groundwater Impacts

Groundwater supply is an important component of the overall water balance in the Niobrara River Basin. The regional agriculture industry has historically relied on groundwater supplies, in particular as a way of supplemental surface water supplies in drier years. In the Basin Study, we evaluate baseline and projected groundwater supplies in Appendix B, the groundwater modeling report. Baseline groundwater supplies are defined as a result of the Baseline No Action scenario. In the Baseline No Action scenario, historical climate (1960-2010) is used to inform a groundwater model. However, as discussed in Section 3.1, this is not a true historical simulation because current levels of agricultural development (defined by year 2010) are assumed to be unchanging into the future. This allows for the evaluation of climate change impacts alone, without the confounding factor increased groundwater development since about 1970.

Projected future groundwater supplies are evaluated using groundwater model simulations using Future No Action scenarios. These scenarios combine the same level of agricultural development assumed for the Baseline No Action scenario (defined by year 2010) and the same three future climate scenarios defined earlier in Section 3 of this technical report, namely Low, Central Tendency, and High.

The reader is referred to Appendix B, the groundwater modeling report for further analysis of climate change impacts on groundwater supplies in the basin. However, Section 4 of this report describes how the climate change scenarios defined in this technical report inform other components of analysis in the Basin Study.

Table 8. Historical (1960-2010) and projected unimpaired (natural) streamflow (cfs) based on VIC model simulations for three future scenarios (2050s compared with historical)

Variable	Scenario	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep
Niobrara River at Stateline (UNW Zone 1)	Historical	27.25	15.28	10.13	14.47	16.74	30.07	68.24	83.25	75.69	30.76	21.85	23.11
	Low	24.27	16.70	12.98	19.18	20.70	30.95	69.05	92.91	66.03	28.52	20.57	15.52
	Central Tendency	23.67	15.31	11.31	13.87	18.64	36.46	65.47	131.2	124.3	30.64	19.50	16.57
	High	32.24	20.49	13.88	14.84	21.79	42.33	101.0	106.2	94.97	39.17	19.94	16.56
Niobrara River at Agate (UNW Zone 2)	Historical	50.66	27.56	17.25	23.73	27.74	52.29	119.1	160.3	150.8	59.28	43.49	44.65
	Low	44.49	30.02	22.00	31.16	33.73	51.97	119.8	175.6	129.4	54.42	39.46	29.61
	Central Tendency	43.57	27.19	19.21	22.57	29.50	62.15	112.4	249.5	235.7	58.95	38.81	32.85
	High	61.77	37.60	23.93	24.73	35.80	75.13	174.5	196.4	185.9	75.11	39.99	31.97
Niobrara River abv Box Butte (UNW Zone 3)	Historical	73.22	41.04	24.37	33.22	38.45	74.53	167.6	238.9	226.9	93.11	68.49	67.81
	Low	64.81	45.25	31.03	43.00	46.10	71.48	166.8	257.8	192.8	84.62	60.72	44.75
	Central Tendency	61.43	39.95	27.02	31.36	40.14	87.12	156.7	363.2	338.5	93.89	61.41	51.66
	High	91.55	57.42	33.84	35.02	49.58	107.8	244.0	284.2	274.9	117.9	64.08	49.07
Niobrara River at Hay Springs (UNW Zone 4)	Historical	99.05	56.34	33.25	44.33	52.34	99.88	221.3	325.2	315.0	143.2	103.5	96.82
	Low	89.42	63.37	43.02	56.24	61.41	93.00	219.2	347.9	266.1	129.7	90.95	63.90
	Central Tendency	81.41	54.50	36.70	41.80	53.13	114.1	206.3	487.8	453.3	146.4	93.36	76.73
	High	128.3	80.79	46.56	47.00	65.50	144.0	323.0	388.3	379.7	181.4	96.70	70.55
Niobrara River near Gordon (UNW Zone 5)	Historical	223.7	131.7	74.56	97.19	120.3	217.2	480.4	747.9	783.6	405.0	279.7	248.9
	Low	203.4	151.5	98.36	119.8	137.3	189.6	471.7	780.8	645.3	369.3	240.2	164.2
	Central Tendency	180.4	128.0	81.38	91.11	119.1	240.9	445.9	1097	1070	419.3	255.1	217.0
	High	303.5	198.1	109.6	104.9	149.8	314.5	716.9	898.5	948.9	517.8	260.3	181.9
Snake River near Burge (CENEB Zone 1)	Historical	29.72	19.27	9.13	12.41	18.18	30.94	64.36	96.39	104.6	65.06	48.34	32.60
	Low	27.97	23.43	12.58	15.96	20.02	21.59	61.72	98.25	83.38	54.82	38.06	20.40
	Central Tendency	24.19	18.96	9.32	11.64	16.75	31.35	58.95	139.3	131.1	74.05	45.48	34.57
	High	44.06	37.46	17.19	15.48	18.89	42.95	115.8	135.8	135.8	90.17	49.10	23.55
Niobrara River near Sparks (CENEB Zone 2)	Historical	431.1	272.8	139.5	179.7	237.0	427.1	923.0	1394	1534	849.8	614.5	470.1
	Low	397.3	316.5	184.9	227.6	266.7	332.5	887.1	1420	1252	734.0	506.0	305.0
	Central Tendency	351.3	263.5	146.9	170.0	226.8	450.7	851.6	2015	2046	946.5	574.7	447.5
	High	606.5	453.8	233.7	211.0	268.3	604.0	1530	1872	1946	1145	623.9	345.7
Niobrara River near Spencer (CENEB Zone 3)	Historical	783.4	499.6	262.8	311.5	397.4	826.2	1702	2444	2725	1497	1040	864.1
	Low	731.4	577.8	330.2	395.3	445.9	591.1	1471	2349	2167	1150	794.6	588.0
	Central Tendency	666.7	492.0	274.3	311.9	402.0	839.4	1550	3324	3574	1856	1011	916.9
	High	1126	964.8	482.8	407.7	449.7	1260	3548	3766	3863	2203	1130	645.41

Table 9. Historical (1960-2010) and Projected Changes (Percent) in Unimpaired (Natural) Streamflow Based on VIC Model Simulations for Three Future Scenarios (2050s compared with historical)

Variable	Scenario	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep
Niobrara River at Stateline (UNW Zone 1)	Historical	27.25	15.28	10.13	14.47	16.74	30.07	68.24	83.25	75.69	30.76	21.85	23.11
	Low	-11%	9.3%	28%	33%	24%	2.9%	1.2%	12%	-13%	-7.3%	-5.9%	-33%
	Central Tendency	-13%	0.2%	12%	-4.1%	11%	21%	-4.1%	58%	64%	-0.4%	-11%	-28%
	High	18%	34%	37%	3%	30%	41%	48%	28%	25%	27%	-8.7%	-28%
Niobrara River at Agate (UNW Zone 2)	Historical	50.66	27.56	17.25	23.73	27.74	52.29	119.1	160.3	150.8	59.28	43.49	44.65
	Low	-12%	8.9%	28%	31%	22%	-0.6%	0.6%	10%	-14%	-8.2%	-9.3%	-34%
	Central Tendency	-14%	-1.4%	11%	-4.9%	6.4%	19%	-5.7%	56%	56%	-0.5%	-11%	-26%
	High	22%	36%	39%	4%	29%	44%	46%	22%	23%	27%	-8.0%	-28%
Niobrara River abv Box Butte (UNW Zone 3)	Historical	73.22	41.04	24.37	33.22	38.45	74.53	167.6	238.9	226.9	93.11	68.49	67.81
	Low	-11%	10%	27%	29%	20%	-4.1%	-0.5%	7.9%	-15%	-9.1%	-11%	-34%
	Central Tendency	-16%	-2.7%	11%	-5.6%	4.4%	17%	-6.5%	52%	49%	0.8%	-10%	-24%
	High	25%	40%	39%	5%	29%	45%	46%	19%	21%	27%	-6.4%	-28%
Niobrara River at Hay Springs (UNW Zone 4)	Historical	99.05	56.34	33.25	44.33	52.34	99.88	221.3	325.2	315.0	143.2	103.5	96.82
	Low	-10%	12%	29%	27%	17%	-6.9%	-0.9%	7.0%	-16%	-9.4%	-12%	-34%
	Central Tendency	-18%	-3.3%	10%	-5.7%	1.5%	14%	-6.8%	50%	44%	2.2%	-10%	-21%
	High	29%	43%	40%	6.0%	25%	44%	46%	19%	21%	27%	-6.6%	-27%
Niobrara River near Gordon (UNW Zone 5)	Historical	223.7	131.7	74.56	97.19	120.3	217.2	480.4	747.9	783.6	405.0	279.7	248.9
	Low	-9.1%	15%	32%	23%	14%	-13%	-1.8%	4.4%	-18%	-9%	-14%	-34%
	Central Tendency	-19%	-2.8%	9.1%	-6.2%	-0.9%	11%	-7.2%	47%	37%	3.5%	-8.8%	-13%
	High	36%	50%	47%	8.0%	25%	45%	49%	20%	21%	28%	-6.9%	-27%
Snake River near Burge (CENEB Zone 1)	Historical	29.72	19.27	9.13	12.41	18.18	30.94	64.36	96.39	104.6	65.06	48.34	32.60
	Low	-5.9%	22%	38%	29%	10%	-30%	-4.1%	1.9%	-20%	-16%	-21%	-37%
	Central Tendency	-19%	-1.6%	2.1%	-6.2%	-7.8%	1.3%	-8.4%	44%	25%	14%	-5.9%	6.1%
	High	48%	94%	88%	25%	3.9%	39%	80%	41%	30%	39%	1.6%	-28%
Niobrara River near Sparks (CENEB Zone 2)	Historical	431.1	272.8	139.5	179.7	237.0	427.1	923.0	1394	1534	849.8	614.5	470.1
	Low	-7.8%	16%	33%	27%	13%	-22%	-3.9%	1.8%	-18%	-14%	-18%	-35%
	Central Tendency	-18%	-3.4%	5.3%	-5.4%	-4.3%	5.5%	-7.7%	45%	33%	11%	-6.5%	-4.8%
	High	41%	66%	67%	17%	13%	41%	66%	34%	27%	35%	2%	-26%
Niobrara River near Spencer (CENEB Zone 3)	Historical	783.4	499.6	262.8	311.5	397.4	826.2	1702	2444	2725	1497	1040	864.1
	Low	-6.6%	16%	26%	27%	12%	-28%	-14%	-3.9%	-20%	-23%	-24%	-32%
	Central Tendency	-15%	-1.5%	4.4%	0.1%	1.1%	1.6%	-8.9%	36%	31%	24%	-2.8%	6.1%
	High	44%	93%	84%	31%	13%	52%	108%	54%	42%	47%	8.7%	-25%

4 Linkages of Climate Change Scenarios and Basin Study Models

This section describes how the historical and projected future climate change scenario data described in this technical report informs other analyses in the Basin Study. The data described here informs the study in the following ways:

1. Developing historical and projected future climate inputs for the watershed models for both UNW and CENEB portions of the study area
2. Developing projected losses due to evaporation from Box Butte and Merritt Reservoirs
3. Developing water supply inputs to the CENEB surface water operations model
4. Developing inputs to the economic benefits analysis

The modeling framework for the Basin Study consists of two modeled subregions, namely the UNW portion and the CENEB portion (see illustrations of these modeled areas in Figure 1). For each of the subregions (UNW and CENEB), a series of models have been developed to simulate the full water balance of the region, including soil water dynamics of agricultural areas, and surface and groundwater hydrology. This information is used as input to develop integrated models (one for each subregion) which simulate managed flows in the Niobrara River and major tributaries. The model component interactions are illustrated in Figure 17, which suggests a cyclical pattern without an endpoint. The following paragraph briefly describes the model interactions to provide context for how the datasets developed here fit into the overall modeling framework. The UNW and CENEB integrated models generally have the same components, although they differ somewhat with respect to the tools employed. Detailed descriptions of the modeling framework and specific components are provided in Appendix F, the integrated water management modeling report.

Climate data (historical or projected future scenarios) at select stations are used as input to the watershed model. The other input to the watershed model is available surface water supplies for irrigation. The model simulates water requirements for modeled crops and identifies on a monthly basis the amount of groundwater needed to meet total irrigation demand, the amount of applied water resulting in groundwater recharge, and surface runoff to streams. There exist unique watershed models for the UNW and CENEB subregions of the study area.

The model interactions for the UNW subregion are first described, followed by the model interactions for the CENEB subregion. The watershed model, groundwater model, and surface water operations model were linked to form the integrated model which is designed to be a dynamic representation of the total water budget for the Niobrara River (Stateline to Gordon). Each individual model is operated independently from the other models and then the integration occurs through a series of data processing and transfers. Information generated in one model can be used as input to another model. The primary information exchanges are listed below:

- Water diversions in the surface water model and well pumping in the groundwater model are taken from outputs of the watershed model.
- Recharge to the groundwater model is taken from the watershed model for deep percolation from the land, and from the surface water model for canal seepage. The stream routing in the groundwater model requires inputs from the surface water model.
- The surface water model gains runoff as calculated by the watershed model, and baseflow as calculated by the groundwater model. It can lose water to channel seepage if the river stage is higher than the water table.

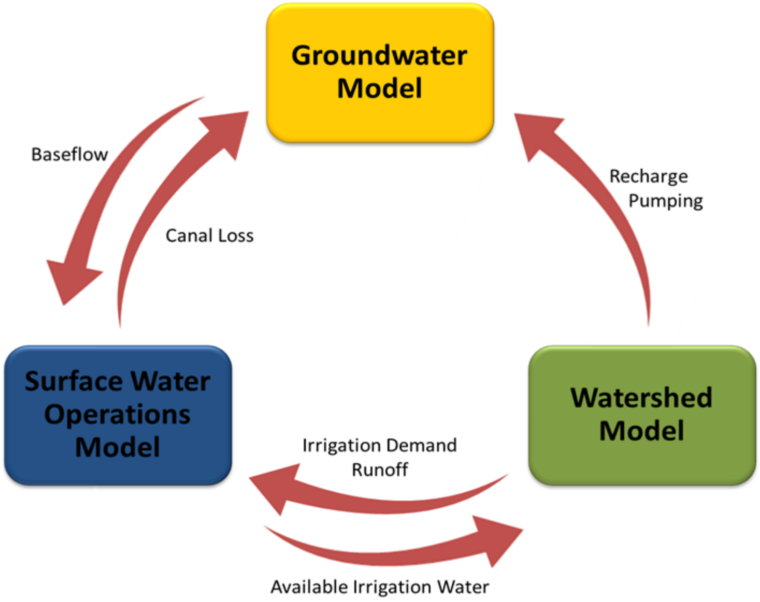


Figure 17. Model interactions for the UNW subregion of the study area. Figure developed by Nebraska Department of Natural Resources.

Because the amount of available water for the diversions may differ from initial assumptions made by the watershed model in its first iteration, a second iteration of the model is performed to incorporate the revised amount of delivered surface water to crops. Following the second iteration of the UNW watershed model, second iterations of the groundwater model and surface water operations model are also performed to achieve closure in the modeling process. Achieving closure means total streamflow in the surface water operations model differs by less than 10 percent between model iterations. It is assumed that two iterations of the model flow are sufficient to achieve closure of results. Further details of the sequence of the individual model simulations and the data transfers to achieve an integrated simulation are provided in Appendix F, the integrated model technical report.

The CENEB subregion of the study area has similar model interactions. However, a more simple representation of surface water operations comprises the CENEB surface water operations model. A simpler model is used because the alternatives considered as part of the Basin Study to reduce water supply and demand gaps are focused on the UNW subregion and it has been determined through previous studies that the CENEB subregion is hydrologically disconnected from the UNW subregion. Analysis supporting the selection of this approach is provided in Appendix B, the groundwater modeling report. In addition, due to the simple configuration of the CENEB surface water operations model, only one iteration of the models is performed.

4.1 Inputs to Watershed Models

This section describes inputs to the UNW and CENEB subregion watershed models developed by Reclamation's Technical Service Center. It should be noted that, although Reclamation provided inputs to the models, the models were implemented by DNR and its contractors. The watershed models for the UNW and CENEB subregions of the study area ingest daily precipitation, daily minimum and maximum air temperature, and daily reference evapotranspiration at select climate stations. Historical climate inputs have previously been developed by DNR and its contractors, which include data at NWS/Co-Op climate stations illustrated in Figure 18 and tabulated in Table 10 (data source: High Plains Regional Climate Center). Among those stations used for both UNW and CENEB subregions collectively, five stations have portions of the historical simulation period from 1960-2010 during which no measurements were taken (ALBI, ARNO, TRYO, WAHO, and YORK). Therefore, a filling technique was developed and implemented to fill records at these stations for the Basin Study simulations. The approach for data filling is described below.

4.1.1 Filling Years with No Measurement Data

For minimum and maximum temperature, the three stations closest to each NWS/Co-Op station with periods of no measurement are identified as anchor stations. The station with periods of no measurement may be referred to as the index station. Correlations in daily minimum and maximum temperature were computed between anchor stations and corresponding index station to confirm inclusion of three closest stations for filling of records at the index station.

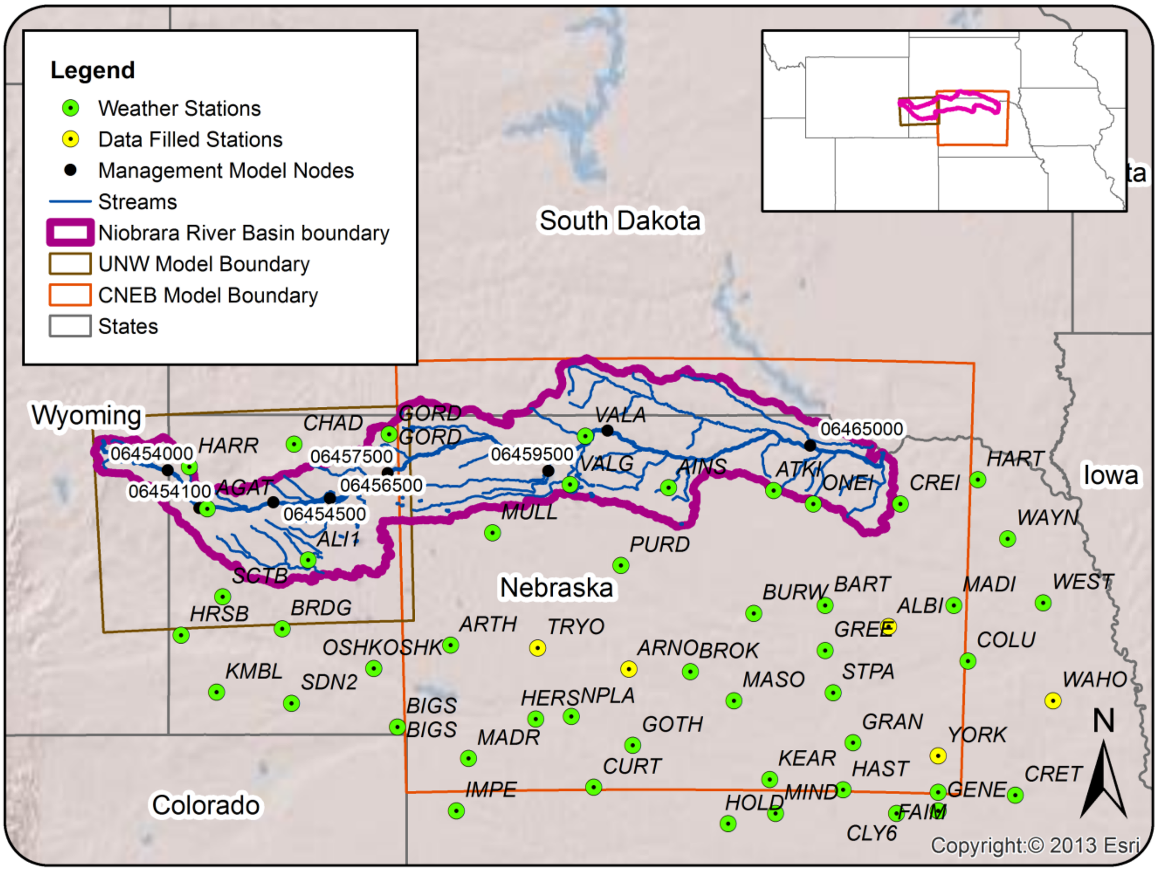


Figure 18. Summary of climate stations used by watershed models for the Niobrara River Basin Study.

Correlations exceed 90 percent for all pairs of stations evaluated. Then, for each missing Julian day at the index station, the percentile of temperature (minimum or maximum) for that Julian day at each anchor station is computed based on the distribution of temperature on that Julian day for each year of the 1960-2010 period. Then for each missing day, the median percentile of the three anchor stations is used to determine the actual missing day temperature (minimum or maximum) based on the distribution of the Julian day temperature over the 1960-2010 period at the index station.

For precipitation, a procedure similar to that described for temperature is used to fill periods of no measurement. However, due to the fact that precipitation events may be localized and not experienced in the same way at all three anchor stations, a single anchor station was used for data filling. The anchor station was selected objectively as one of the three closest stations with the highest correlation with the index station.

Table 10. Summary of NWS/Co-Op Stations Used as Input to Watershed Models (UNW and CENEB Subregions Included)

Sites highlighted in gray have portions of the historical simulation period (1960–2010) with no measurements.

Station	Code	Latitude	Longitude
AGATE_3_E	AGAT	42.42	–103.73
AINS	AINS	42.55	–99.85
ALBI	ALBI	41.68	–98.00
ALLIANCE_1_WNW	ALI1	42.10	–102.88
ARNO	ARNO	41.42	–100.18
ARTH	ARTH	41.57	–101.68
ATKI	ATKI	42.53	–98.97
BART	BART	41.82	–98.53
BIG_SPRINGS	BIGS	41.05	–102.13
BRIDGEPORT	BRDG	41.67	–103.10
BROK	BROK	41.40	–99.67
BURW	BURW	41.77	–99.13
CHADRON_1_NW	CHAD	42.82	–103.00
CLY6	CLY6	40.50	–97.93
COLU	COLU	41.47	–97.33
CREI	CREI	42.45	–97.90
CRET	CRET	40.62	–96.93
CURT	CURT	40.67	–100.48
FAIM	FAIM	40.63	–97.58
GENE	GENE	40.52	–97.58
GORDON_6_N	GORD	42.88	–102.20
GOTH	GOTH	40.93	–100.15
GRAN	GRAN	40.95	–98.30
GREE	GREE	41.53	–98.53
HARRISON	HARR	42.68	–103.88
HART	HART	42.60	–97.25
HAST	HAST	40.65	–98.38
HERS	HERS	41.10	–100.97
HOLD	HOLD	40.43	–99.35
HARRISBURG_12_WNW	HRSB	41.63	–103.95
IMPE	IMPE	40.52	–101.63
KEAR	KEAR	40.72	–99.00
KIMBALL	KMBL	41.27	–103.65
MADI	MADI	41.82	–97.45
MADR	MADR	40.85	–101.53
MASO	MASO	41.22	–99.30
MIND	MIND	40.50	–98.95
MULL	MULL	42.27	–101.33
NPLA	NPLA	41.12	–100.67
ONEI	ONEI	42.45	–98.63
OSHKOSH	OSHK	41.42	–102.33
PURD	PURD	42.07	–100.25
SCOTTSBLUFF_AP	SCTB	41.87	–103.60
SIDNEY_6_NNW	SDN2	41.20	–103.02
STPA	STPA	41.27	–98.47
TRYO	TRYO	41.55	–100.95
VALENTINE_WSO_AP	VALA	42.87	–100.55
VALG	VALG	42.57	–100.68
WAHO	WAHO	41.22	–96.62
WAYN	WAYN	42.23	–97.00
WEST	WEST	41.83	–96.70
YORK	YORK	40.87	–97.58

Notes: ALBI no measurement years are 2008–2010; ARNO no measurement years are 2008–2010; TRO no measurement years are 2008–2010; WAHO no measurement years are 2004–2010; YORK no measurement years are 2008–2010.

For reference ET, a procedure similar to that described for temperature and precipitation is used to fill periods where underlying climate data to compute ET are not available. However, due to the fact that timeseries of observed referent ET do not exist at each NWS/Co-Op station, historical simulations of a dual crop coefficient Penman Monteith ET model (further described below in Section 4.1.2) at corresponding locations were used as anchor stations and thus used for data filling. The complete datasets, resulting from the data-filling procedures described above, are used as input to the watershed models (UNW and CENEB subregions) to develop the Baseline No Action scenario for the Basin Study.

4.1.2 Deriving Future Scenario Inputs for Watershed Models (UNW and CENEB)

Precipitation and Temperature

As described previously, the watershed models use individual station data as input rather than gridded datasets, such as those used in development of climate change scenarios. Climate change scenarios were developed on a grid basis, where each grid cell is 1/8 degree square in size. In order to develop station-based future scenario inputs for the watershed models, we use the grid based historical and future scenario data to derive the future station-based data. The approach is described in detail below.

Historical and GCM projection gridded meteorological data (daily precipitation, minimum and maximum temperature) are used as the basis for deriving future scenario inputs at each NWS/Co-Op station. For each month January through December, cumulative distribution functions (CDFs) of the GCM projection data are computed over the 2030-2059 future time horizon for each selected climate change scenario (refer to Table 4). CDFs are also computed from the historical gridded data over the historical period 1970-1999. A change can be computed between the future scenario and historical period at each percentile of the CDFs. That change represents the projected climate change for that scenario for that month at each percentile. The historical NWS/Co-Op station data can then be adjusted based on the look up table of projected change at a given percentile. As a result, projected climate data are computed for each station and for each of the three climate change scenarios (Low, Central Tendency, and High). These data are used as the scenario inputs to the watershed models (UNW and CENEB subregions). This process may be qualitatively illustrated using Figure 19.

Reference Evapotranspiration

The watershed models ingest daily reference ET at NWS/Co-Op station locations (calculated using a modified Hargreaves-Samani approach; further described in Appendix E, the watershed modeling report), in addition to precipitation, and minimum and maximum air temperature. In a procedure similar to that used to develop future scenario inputs of precipitation and temperature, a mapping approach is used to adjust historical station-based reference ET for the watershed models based on projected changes in ET computed using historical and future simulations of a dual crop coefficient Penman Monteith ET model. Current and future ET estimates were developed for this study following the methods established by Reclamation's WWCRA. Brief descriptions of these methods follow and more detailed discussions are contained in Reclamation (2015).

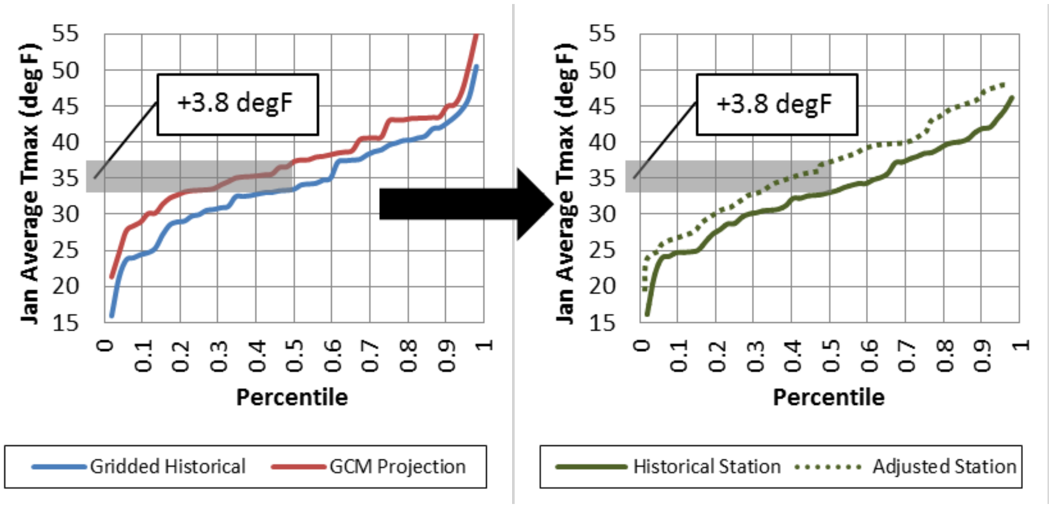


Figure 19. Example of percentile adjustments for development of station-based Future No Action maximum temperature data for input to watershed model. Fabricated data were used in development of the figure.

The ET Demands model is based on the Penman Monteith dual crop coefficient method, as described in the Food and Agriculture Organization (FAO) of the United Nations, Irrigation and Drainage Paper 56 (Allen et. al, 1998). The Environmental and Water Resources Institute of the American Society of Civil Engineers (ASCE-EWRI) has adopted the FAO-56 Penman Monteith equation as the standardized equation for calculating reference ET (ASCE-EWRI, 2005). The short grass reference crop version of the Penman Montieth equation was used to be consistent with previous Reclamation work. It should be noted that, in contrast, a tall-crop reference ET is used in the watershed models.

The ET Demands model described above was employed using historical gridded meteorological data consistent with VIC hydrologic model simulations (described earlier in this technical report) and climate change scenario development. The model was run for each grid cell data coinciding with individual NWS/Co-Op station locations. The model was employed for the same grid cells for both the Baseline No Action and Future No Action scenarios (including low, central tendency, and high). Simulated reference ET from historical and future scenario model runs were saved and used as a basis for developing future scenario reference ET for the watershed models.

Similar to the approach taken to develop scenario precipitation and temperature inputs, CDFs of reference ET were computed for each month for simulated historical and projected conditions. Changes (percent) between future and historical referent ET were computed for each percentile. The historical reference

ET at each NWS/Co-Op station was then adjusted by computed changes at each percentile to derive future reference ET at the same NWS/Co-Op stations. The adjusted precipitation, minimum and maximum air temperature, and reference ET were then used as input for Future No Action simulations of the watershed models (UNW and CENEB subregions).

4.2 Losses from Reservoir Evaporation

Net evaporation rates for Box Butte and Merritt reservoirs in the Niobrara River Basin were calculated using available data in combination with results from the Complementary Relationship Lake Evaporation (CRLE) model (Morton et al., 1985). Net evaporation rates for historical and future scenarios were developed as inputs to the UNW and CENEB surface water operations models. It should be noted that although Reclamation's Technical Service Center provided these inputs, it did not implement the integrated models.

CRLE is an open water evaporation model that accounts for water temperature, albedo, emissivity, and heat storage effects to estimate monthly evaporation. Net evaporation may be calculated as evaporation minus precipitation (evaporation – precipitation) at each timestep. This model had been previously used as part of Reclamation's WWCRA to estimate evaporative losses in 12 major reservoirs across the western US. The WWCRA Water Demands Report (Reclamation, 2015) provides a detailed description of the CRLE model and its application for the major reservoirs of the western US.

The CRLE model calculates evaporation for each reservoir based on average reservoir conditions. Average monthly historical reservoir conditions (storage volume and surface area) were calculated using historical data and assumed constant for the historical analysis period (1960-2010). Air temperature and precipitation for the VIC model grid cells that coincide with each of the two reservoirs were used as the air temperature and precipitation inputs to the model. Additional inputs, namely dewpoint depression, function parameters, and salinity were derived through various approaches described below.

As part of Reclamation's WWCRA water demands assessment (2015), monthly dewpoint depression was developed for each 8-digit Hydrologic Unit Code subbasin (HUC8 subbasin) in the western US. Dewpoint depression values for the HUC8 subbasins that encompass the two reservoirs were used as inputs to the CRLE model.

The CRLE model derives solar radiation using the approach of Thornton and Running (1999), in which a parametric equation derives solar radiation based on the difference between daily maximum and minimum temperature. Three required function parameters to compute solar radiation were calibrated at the HUC8 subbasin level as part of Reclamation's WWCRA (2015). Similar to the monthly dewpoint depression values, calibrated solar radiation function parameters at the HUC8 subbasin scale were used directly as input to the CRLE model for corresponding locations. Finally, average reservoir salinity was taken from a study by Bennett et al. (2007) in which they reported on salinity levels in various reservoirs in Nebraska. A value of 310 ppm was used for both Box Butte and Merritt Reservoirs.

It should be noted that for Box Butte Reservoir, historical net evaporation had previously been developed and used in the calibration of the UNW surface water operations model. As such, the historical net evaporation data were used for the Baseline No Action scenario. For the Future No Action scenarios (Low, Central Tendency, and High) a mapping technique, similar to that described above for development of perturbed watershed model inputs (refer to section 4.1.2), was applied to develop adjusted net evaporation at Box Butte based on computed changes between CRLE model future and historical simulations. For Merritt Reservoir, monthly pan evaporation data from 1970-2013 was available and evaluated. However, comparisons of these data with CRLE model outputs suggest that the pan evaporation data are not representative of actual reservoir evaporation. Therefore, for the purpose of the Basin Study, CRLE model outputs of net evaporation were used directly in the CENEB subregion surface water operations model for the Baseline No Action and Future No Action scenarios.

Figure 20 illustrates the distribution of Baseline No Action and Future No Action scenario (Low, Cental Tendency, and High) net evaporation at Box Butte (left) and Merritt Reservoirs (right) based on the above described assumptions and model inputs. The thick black line represents the median annual net evaporation across all simulated years, while the lower end of the box and upper end of the box represent the 25th and 75th percentile values, respectively. The lower and upper whiskers represent the 10th and 90th percentile values across all simulated years.

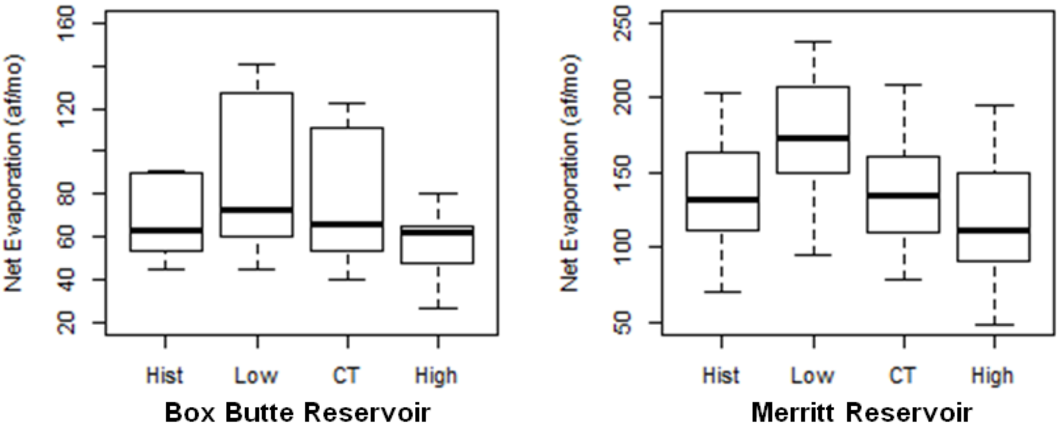


Figure 20. Distributions of historical (1960-2010) and projected net evaporation at Box Butte and Merritt Reservoirs for Low, Central Tendency, and High scenarios representing a 2030–2059 future time horizon.

According to model simulations and subsequent adjustments to Box Butte net evaporation based on observed data, Box Butte Reservoir has lower net evaporation than Merritt Reservoir, with a historical median (over 1960-2010) of about 63 inches. Merritt Reservoir has a median net evaporation of about 132 inches computed over the same years. The primary difference in net evaporation between the two reservoirs may relate to the existing historical net evaporation data for Box Butte Reservoir. Comparisons of strictly CRLE modeled net evaporation between the two reservoirs yield values much closer in magnitude.

Generally for Box Butte, the Low scenario indicates a range from a small decrease to more substantial increase in net evaporation across all scenarios for the future time horizon 2030-2059, with the median being an increase of about 15 percent. The High scenario indicates a range from a more substantial decrease in net evaporation to a modest increase in net evaporation, with the median being a decrease of about 2 percent. The Central Tendency scenario indicates a median increase of about 6 percent. For Merritt, the Low scenario indicates a median increase of about 32 percent, while the High scenario indicates a median decrease of about 15 percent and the Central Tendency indicates a median increase of about 2 percent.

Table 11. Distributions of historical (1960–2010) and projected net evaporation at Box Butte and Merritt Reservoirs for Low, Central Tendency, and High scenarios representing a 2030–2059 future time horizon

Box Butte Reservoir				
Quantile	**Hist (af/mo)**	**Low (af/mo)**	**CT (af/mo)**	**High (af/mo)**
10th	44.64	44.51	39.54	26.45
25th	53.54	60.54	53.36	47.39
50th	62.77	72.39	66.36	61.69
75th	89.79	127.7	111.2	65.30
90th	91.00	140.6	122.4	80.02
Merritt Reservoir				
Quantile	**Hist (af/mo)**	**Low (af/mo)**	**CT (af/mo)**	**High (af/mo)**
10th	70.17	94.75	78.19	48.38
25th	111.2	150.3	110.0	90.43
50th	131.7	173.8	134.9	111.7
75th	163.7	207.6	161.4	150.3
90th	202.9	237.0	208.8	194.8

4.3 Additional Inputs to CENEB Surface Water Operations Model

This technical report describes the approach for development of adjusted inputs to the CENEB surface water operations model. Appendix D, the CENEB surface water operations modeling report, describes the model in more detail and summarizes model results for the Baseline No Action and Future No Action scenarios. This technical report summarizes data development by Reclamation's Technical Service Center to support the CENEB surface water operations modeling effort. It should be noted that Reclamation's Technical Service Center assisted in development of model inputs, but did not implement the model for the Basin Study.

It should be noted that Future with Alternative scenarios (referred to as FA1 and FA2 in corresponding technical reports for the Basin Study) were assumed not to impact the CENEB subregion due to the understanding that the UNW and CENEB subregions are hydrologically disconnected. In other words, alternatives explored in the UNW subregion were assumed not to impact hydrology in the CENEB subregion.

Development of Merritt Reservoir net evaporation for the CENEB surface water operations model was described in detail in Section 4.2. Additional inputs to this model include surface runoff, groundwater baseflows, groundwater pumping, and crop water demands. As previously mentioned, surface runoff, groundwater pumping, and crop water demands result from CENEB watershed model simulations. Groundwater baseflows result from CENEB groundwater model simulations.

CENEB watershed and groundwater model simulations were available for Baseline No Action and Future No Action scenarios. Due to Basin Study time constraints, a historical simulation for each model was not performed. However, it was assumed that Baseline No Action results represent historical conditions, with the following justification. The Baseline No Action scenario is comprised of historical climate inputs and current farming and management practices. Current land use was assumed to be crop patterns and acreage from 2010. The historical condition differs in that historical annual land use would have been used. Analysis of historical crop acreage by county and crop type within the Niobrara River Basin provides justification that historical land use has not varied substantially from year to year since 1940. Table 12 summarizes mean crop acreage by county within the Niobrara River Basin, along with the standard deviation and variance. Variability around the mean acreage is small compared with the total crop acreage, which suggests little sensitivity of model results to the assumption that 2010 cropping patterns are representative of historical conditions. It should be noted that, in addition to changes in land use and water management, changes in farming practices and technology have also influenced water supply and demand; however, these practices were held constant for all model simulations.

Table 12. Summary of Historical Crop Acreage by County (statistics computed over 1940–2010)

County	Crop Acreage Annual Mean	Crop Acreage Standard Deviation	Crop Acreage Variance
Bennett	na	na	na
Boyd	328,669	535	286,529
Brown	771,749	363	131,449
Cherry	3,955,259	219	48,145
Gregory	na	na	na
Holt	1,550,257	746	556,659
Keya Paha	499,148	212	45,053
Rock	651,432	278	77,049
Sherman	366,187	386	149,233
Todd	na	na	na
Tripp	na	na	na

The CENEB surface water operations model was calibrated over the historical period to USGS measured streamflows at three locations:

- ID 06461500 Niobrara River near Sparks, Nebraska
- ID 06459500 Snake River near Burge, Nebraska
- ID 06465000 Niobrara River near Spencer, Nebraska

Reclamation’s Technical Service Center developed adjusted historical Merritt Reservoir inflows for the purpose of calibrating the CENEB surface water operations model, as well as adjusted Merritt Reservoir inflows for the Future No Action scenarios. Other model inputs were provided by DNR and its contractors.

Historical inflows to Merritt Reservoir were computed by Reclamation’s Nebraska-Kansas Area Office for the period 1967-2013. These inflows were assumed to be observed historical inflows. These inflows were compared with modeled historical inflows computed as the sum of CENEB groundwater model baseflow and CENEB watershed model surface runoff for the same period. As a way of calibrating the modeled inflows to more closely match the “observed” inflows (computed by Reclamation), modeled historical inflows were adjusted such that the mean and distribution of modeled inflows was comparable with observed inflows. The same mapping procedure described in Section 4.1.2 for development of adjusted climate scenarios was used to adjust modeled inflows at Merritt to better match observed inflows. As described in Section 4.1.2, a unique map was developed for each month, relating the CDF of modeled inflows with the CDF of observed inflows. The same monthly maps were also used to adjust Future No Action scenario inflows. Additional details regarding the approach for CENEB surface water operations model simulations and summarized results are provided in Appendix D.

4.4 Inputs to Economic Benefits Analysis

The economic benefits analysis performed as part of the Basin Study is comprised of two parts: recreation benefits and agricultural benefits at Mirage Flats Irrigation District in the UNW subregion. This section describes inputs developed by Reclamation's Technical Service Center in support of the economic benefits analysis. Details of the economic benefits analysis may be found in Appendix G, the economic benefits analysis report.

Inputs to the recreation benefits analysis include monthly average air temperature and end of month water levels at Box Butte and Merritt reservoirs, and monthly streamflow in the Niobrara Wild and Scenic River at Sparks, Nebraska. NWS/Co-Op stations that are closest to Box Butte and Merritt reservoirs were used as the basis for historical monthly average temperature data. The NWS/Co-Op station closest to Box Butte reservoir is ALLIANCE_1_WNW. The closest NWS/Co-Op station to Merritt Reservoir is VALENTINE_WSO_AP. Refer to Figure 18 and Table 9 for additional information about these stations and their geographic locations. Historical monthly average temperatures at the two stations were used for the Baseline No Action scenario. Future No Action scenario monthly average temperatures, developed for input to the UNW and CENEB watershed models, are used for the Future No Action scenarios in the recreation benefits analysis. Merritt and Box Butte reservoir elevations and monthly streamflow at Niobrara River at Sparks for the Baseline No Action and Future No Action scenarios result from the CENEB surface water operations model.

The agricultural benefits analysis at Mirage Flats Irrigation District requires monthly field deliveries, monthly pumping depths and pumping rates for each crop. These values result from the UNW watershed model. Reclamation's Technical Service Center was not directly involved in developing these values.

5 Summary

The climate change analysis report for the Niobrara River Basin Study summarizes historical and projected future climate and water supply for the Niobrara River Basin and discusses the development of climate and hydrologic inputs for various modeling components of the Basin Study. This analysis uses historical and projected future climate information consistent with Reclamation's WWCRA. It also uses simulated historical and projected future hydrology based on the VIC hydrologic model. Although hydrologic inputs to other Basin Study modeling components were primarily developed using a watershed model described in the Watershed Modeling Report, Appendix E, the simulations described in this report were used to inform those data and to provide an overall assessment of basin wide water supply and demand.

The Niobrara River Basin has a substantial moisture gradient from west to east, with the western portion being semiarid and the eastern portion being more humid. Historical trend analysis over the period 1950-2010 indicates that mean annual temperature has increased by about 0.6 degrees F, precipitation has increased about 12 percent, and mean annual runoff has increase by about 45% basin wide. These results are consistent with values reported by other studies of historical climate trends in the region.

For the 2060s future time horizon, the Central Tendency scenario projects warmer and wetter conditions on an annual basis, with greater mean annual precipitation (8 percent), temperature (3 degrees F), and runoff (13 percent). Seasonally though, projected peak streamflows are expected to increase (50 percent in the upper basin and 30 percent in the lower basin), while projected low flows are expected to decrease (by 10 to 20 percent). Additional scenarios, which span a range of projected conditions, indicate a range from slightly drier conditions with modest changes to streamflow, to more substantially wetter conditions than the Central Tendency and increased annual streamflow volumes.

6 Uncertainties

This section summarizes uncertainties associated with various aspects of the Basin Study water supply assessment, including the use of climate change scenarios, as well as surface and groundwater hydrologic models to evaluate climate change impacts. Additional discussion regarding the use of GCM climate projections and applied downscaling techniques is provided by Reclamation (2011). The nature of these uncertainties is only briefly described below.

6.1 Global Climate Projections, Modeling, and Downscaling

In the Basin Study, select GCM projections were selected that meet established criteria. This procedure is described in detail in Section 3.1. This approach has its strengths and weaknesses in the context of climate change assessment, as do all others.

The climate projections considered in this report represent a range of future climate conditions under the criteria selected for analysis. However, uncertainties associated with the select GCM projections and their assumptions of global growth and land use, are not explored in this analysis. Uncertainties associated with GCMs are further explored below.

GCMs themselves have associated uncertainty with respect to their initial conditions and representation of physical processes. GCM simulations are designed such that they develop their own long timescale climate patterns and these may differ substantially between GCM simulations. Additionally, although GCMs are continually improved to incorporate the current state of science in terms of our understanding of the climate system, they may have biases toward being too wet, too dry, too warm, or too cool. Often, a procedure to remove biases in climate projections relative to a historical baseline is performed which can affect the apparent climate change expressed by the projections (biased versus bias-corrected).

There are also uncertainties associated with the methodology used to downscale information at the scale of GCMs to the regional, or watershed, scale. As previously mentioned, the Basin Study utilizes statistically downscaled climate projections as a basis for development of future climate scenarios. By selecting single GCM projects to encompass a range of future conditions, the study does not benefit from analysis numerous future climate scenarios that may provide additional context to a climate change impacts assessment.

6.2 CMIP3 versus CMIP5 Climate Projections

The Basin Study relies on data and modeling from Reclamation's WWCRA (Reclamation, 2011). In that effort, Reclamation developed a consistent database of climate and hydrologic projections, with a focus on the 17 western United States that fall within Reclamation's management domain. These projections are based on CMIP3 GCM simulations. The next generation of projections, CMIP5 are summarized in IPCC's Fifth Assessment Report, which was completed in 2013. CMIP5 projections reflect improvements in modeling of the Earth system since the CMIP3 effort and revised scenarios of global growth and greenhouse gas emissions. Although CMIP Phase 5 provides the most recently available suite of climate projections to date, it has not been determined to be a better or more reliable source of climate projections compared to existing CMIP Phase 3 projections. Current state of practice relies on a range of climate projections for use in impacts studies.

One advantage to using CMIP3 based projections is that numerous existing studies have used CMIP3 based projections and comparisons may be more easily made between results from the Basin Study and other existing studies in the region. In addition, because CMIP3 projections have been used in numerous studies, there is a greater body of knowledge surrounding their use and application.

It should be noted that there are differences in simulated precipitation between CMIP3 based GCMS and CMIP5 based GCMs for some regions (e.g., greater warming over the Upper Columbia Basin, less precipitation over the northern Great Plains, and more precipitation over California and the Upper Colorado Basin). Projections showing wetter portions of California and the Upper Colorado are notable because they challenge the prevailing perspective of climate change impacts to the region that has been held since 2007 (informed by CMIP Phase 3 projections); namely, that these regions will become drier and result in reduced runoff. It is important to recognize that while CMIP Phase 5 offers new information, more work is required to better understand CMIP5 and its differences from CMIP3. In some regions, model resolution is likely the leading factor resulting in differences. In the North American Monsoon region, for example, the higher resolution of CMIP Phase 5 models allows these models to better capture the landward moisture transport and overland convection that results in monsoon precipitation events. These processes were not resolved in the lower resolution CMIP Phase 3 models.

6.3 Historical Meteorological Dataset

Simulations of the historical record by GCMs do not exactly match observations for many reasons. Lack of detailed representation of spatial or topographical features may play a role, as well as simplified representation of physical processes, among others. As mentioned in Section 5.1, a bias correction step is commonly used to adjust simulated GCM precipitation and temperature to better match observations, by adjusting the statistical distribution of the simulated data to better match those of the observations. The development of statistically downscaled climate projections under Reclamation's WWCRA involved bias correcting GCM simulated precipitation and temperature (daily average) to gridded observations developed by Maurer et al. (2002). The period of bias correction was generally calendar years 1950-1999. Discussion of the bias correction process is provided by Reclamation (2011).

The historical simulation period used as the basis of the Basin Study includes calendar years 1960-2010. The gridded observed historical meteorological dataset by Maurer et al. (2002) was extended by Ed Maurer from 1949-2000 to 1949-2010. Identical methodology was used to develop the extended dataset, as was used to develop the original Maurer et al. (2002) dataset. However, due to the incorporation of 10 years of additional observed station data at many of the stations, and the corresponding filtering of station data based on record length thresholds and total days of available records, the resulting station mix differs slightly between the original dataset and the extended dataset. Therefore, some inconsistency is introduced by using the original Maurer et al. (2002) dataset for bias correction of GCM simulations over the historical period, and using the extended Maurer dataset as the basis of historical simulations and climate change scenario development for the Basin Study.

Comparisons of monthly distributions of total precipitation and average daily temperature illustrate the lack of impact of the identified inconsistency on precipitation and temperature distributions by month. Figures 21 and 22 compare distributions of precipitation and temperature, respectively, using the Maurer et al. (2002) dataset over the period 1950-1999, the extended Maurer dataset over the same period (1950-1999), and the extended Maurer dataset over the period (1950-2010). The figures illustrate the similarity in their distributions by month. The similarity indicates that the use of the extended Maurer dataset for historical simulations and development of climate change scenarios for the Basin Study does not introduce a substantial bias in the results due to the inconsistency of the use of meteorological datasets.

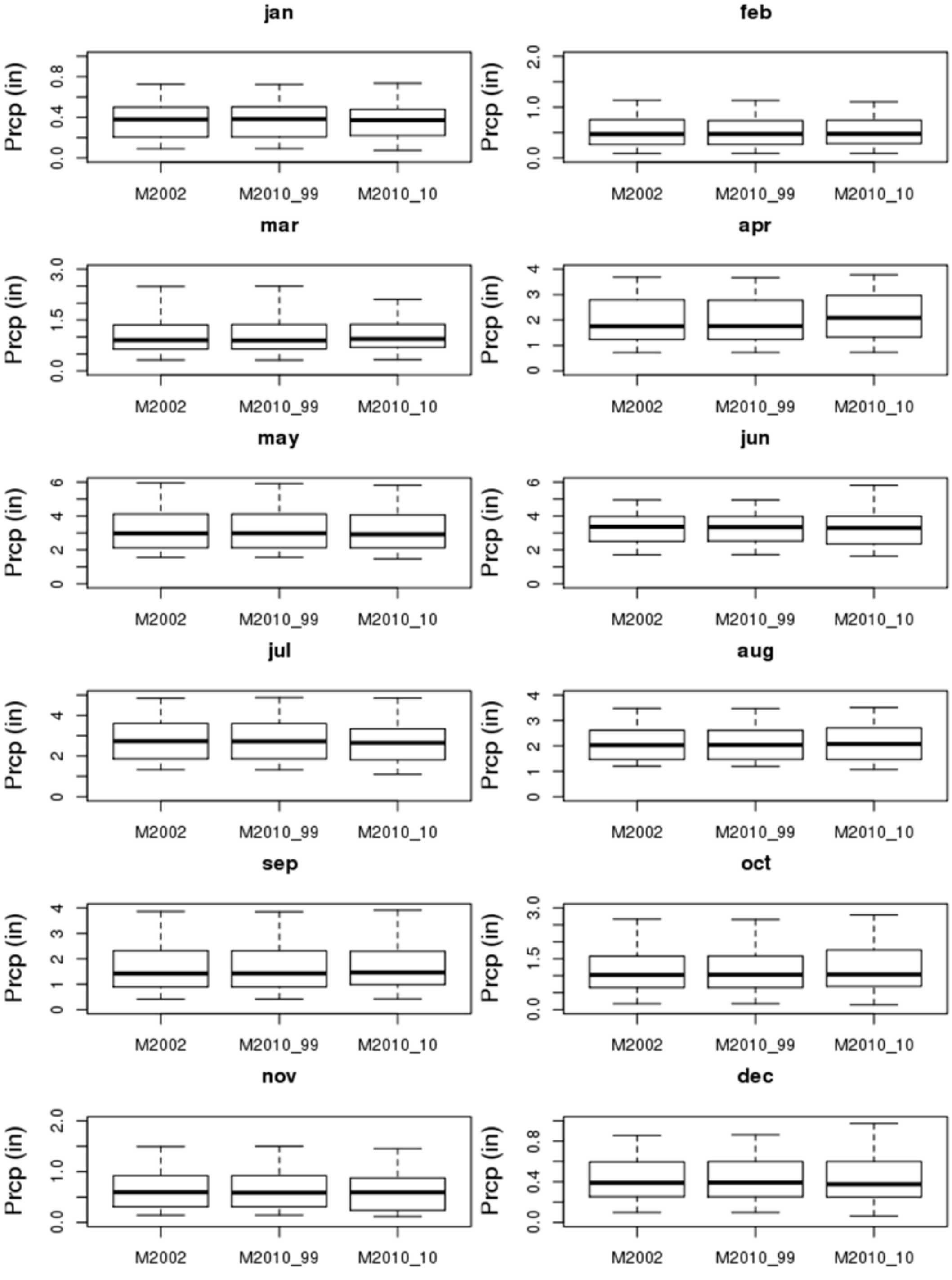


Figure 21. Summary of distributions in monthly total precipitation (in) between original Maurer et al. (2002) meteorological dataset and the extended Maurer dataset through 2010.

- **M2002 represents the Mauer et al. (2002) dataset over years 1950-1999.**
- **M2010_99 represents the extended Maurer dataset over years 1950-1999.**
- **M2020_10 represents the extended Maurer dataset over years 1950-2010.**

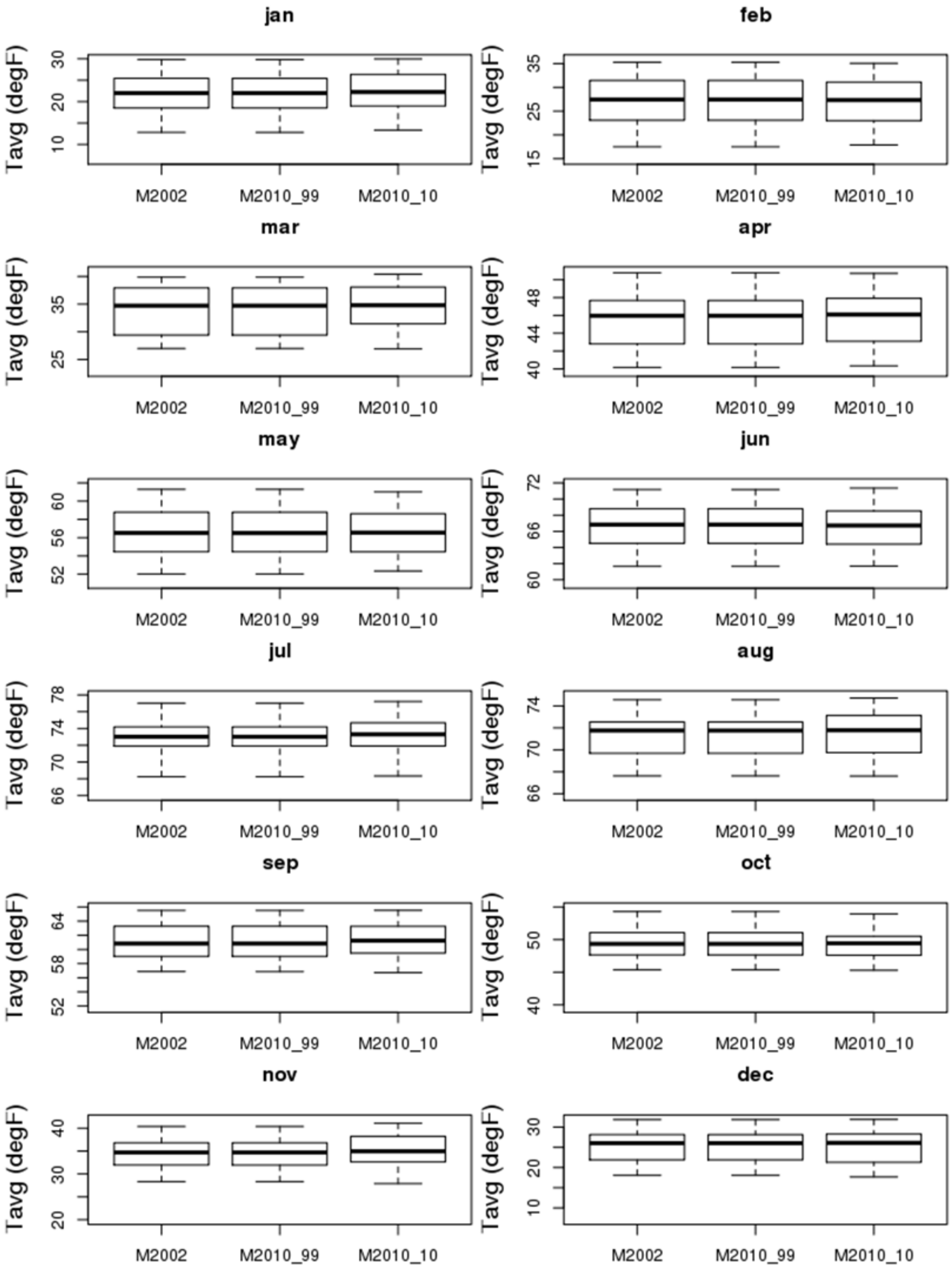


Figure 22. Summary of distributions in monthly average temperature (deg F) between original Maurer et al. (2002) meteorological dataset and the extended Maurer dataset through 2010.

- **M2002 represents the Mauer et al. (2002) dataset over years 1950-1999.**
- **M2010_99 represents the extended Maurer dataset over years 1950-1999.**
- **M2020_10 represents the extended Maurer dataset over years 1950-2010.**

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