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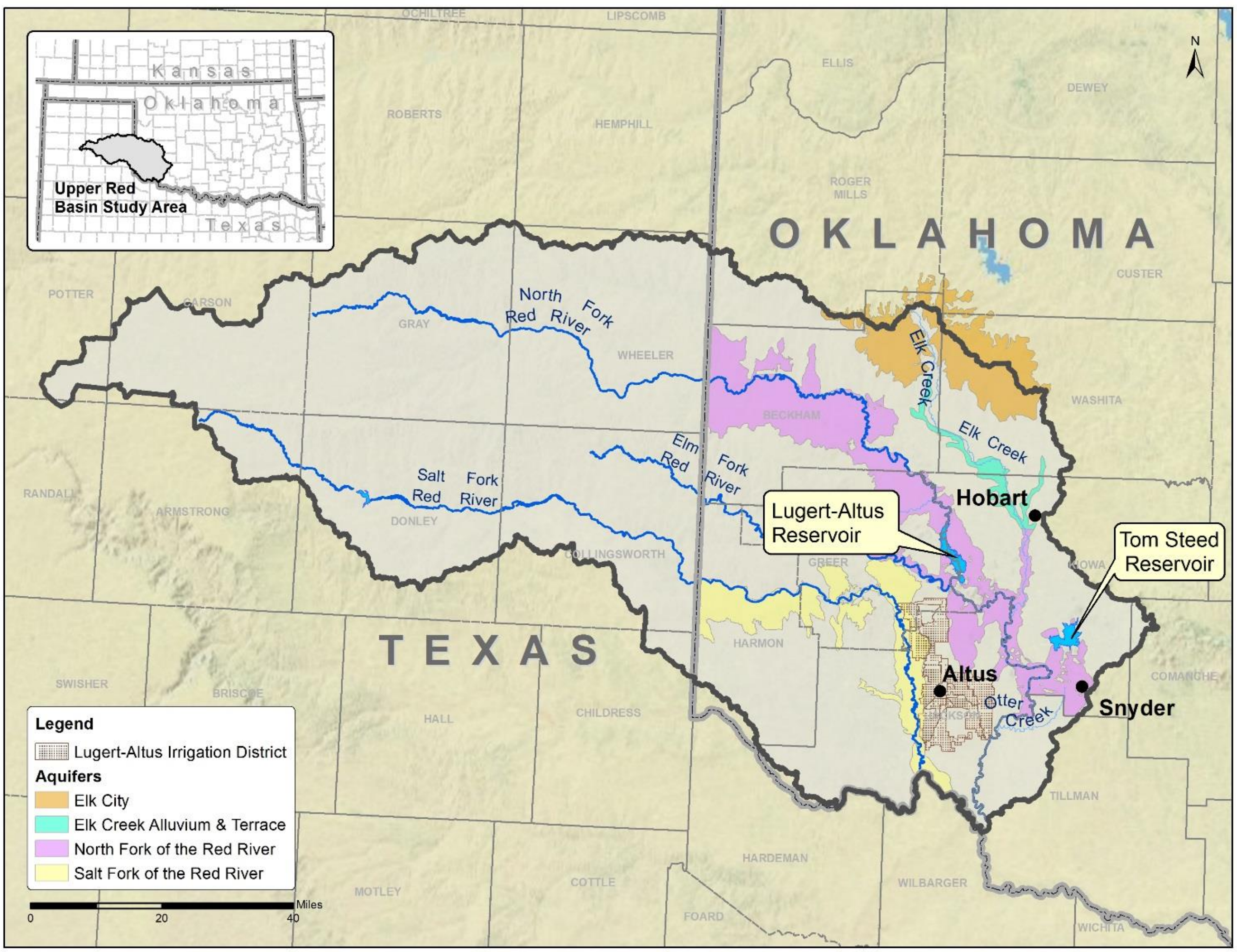
Technical Memorandum No. 86-68210-2016-05

Upper Red River Basin Study
Climate and Hydrology Projections



Department of the Interior
Bureau of Reclamation
Oklahoma-Texas Area Office

July 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

BUREAU OF RECLAMATION
Technical Service Center, Denver, Colorado

Technical Memorandum No. 86-68210-2016-05

Upper Red River Basin Study
Climate and Hydrology Projections

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Oklahoma-Texas Area Office
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Abbreviations and Acronyms

A1	CMIP3 Future Greenhouse Gas Middle Emissions Scenario Family
A1B	CMIP3 Future Greenhouse Gas Middle Emissions Scenario
A2	CMIP3 Future Greenhouse Gas High Emissions Scenario
B1	CMIP3 Future Greenhouse Gas Low Emissions Scenario
B2	CMIP3 Future Greenhouse Gas Low Emissions Scenario
BCSD	Bias Corrected and Spatially Downscaled
cfs	cubic feet per second
CMIP	Coupled Model Intercomparison Project
CMIP3	Coupled Model Intercomparison Project Phase 3
CMIP5	Coupled Model Intercomparison Project Phase 5
CT	Central Tendency
°F	degrees Fahrenheit
GCM	General Circulation or Global Climate Model
HDe	Ensemble-informed Hybrid Delta
IPCC	Intergovernmental Panel on Climate Change
LWD	Less warm-drier
LWW	Less warm-wetter
RCP	Representative Concentration Pathways
Reclamation	Bureau of Reclamation
SRES	Special Report on Emissions Scenarios
SYMAP	Synergraphic mapping system
URRBS	Upper Red River Basin Study
USGS	U.S. Geological Survey
USHCN	U.S. Historical Climatology Network
WD	Warmer-drier
WW	Warmer-wetter

1. INTRODUCTION

Climate change scenarios for the Upper Red River Basin Study (URRBS) were developed based on the World Climate Research Programme's Coupled Model Intercomparison Project Phase 5 (CMIP5) projections using the ensemble informed hybrid delta (HDe) method described in Hamlet et al., 2013. For this Study, the future period, referred to as 2060, is defined by the 30-year range, 2045-2074. The current period of record used is the 50-year period, 1950-1999. Using the weather data developed for each of the HDe based climate change scenarios, projections of hydrologic fluxes including runoff were estimated using the gridded macro-scale hydrology model VIC (Variable Infiltration Capacity; Liang et al., 1994). Routed streamflow projections for eight sites were subsequently developed from the gridded VIC runoff using the routing scheme described in Lohmann et al., 1996. Figure 1 shows the study area and surface water and groundwater sources that are being investigated as part of the URRBS. Figure 2 shows the U.S. Geological Survey (USGS) stream gage locations and major tributaries in the National Hydrography Dataset.

The region includes tributaries to the Red River, the largest being the North Fork of the Red River, the Salt Fork of the Red River, and the Elm Fork of the Red River. The basin also contains two Bureau of Reclamation (Reclamation) reservoirs, Tom Steed and Lugert-Altus Reservoirs.

This Technical Memorandum presents the climate projections developed for the URRBS. Section 2 discusses current climate conditions; Section 3 describes future climate projections for the 2060 period; Section 4 describes the development of climate change scenarios; and Sections 5 and 6 describe the VIC model and simulation results of future hydrology in the study area under three climate change scenarios that represent warmer-drier, central tendency, and less warm-drier conditions. A summary of the results is provided in Section 7.

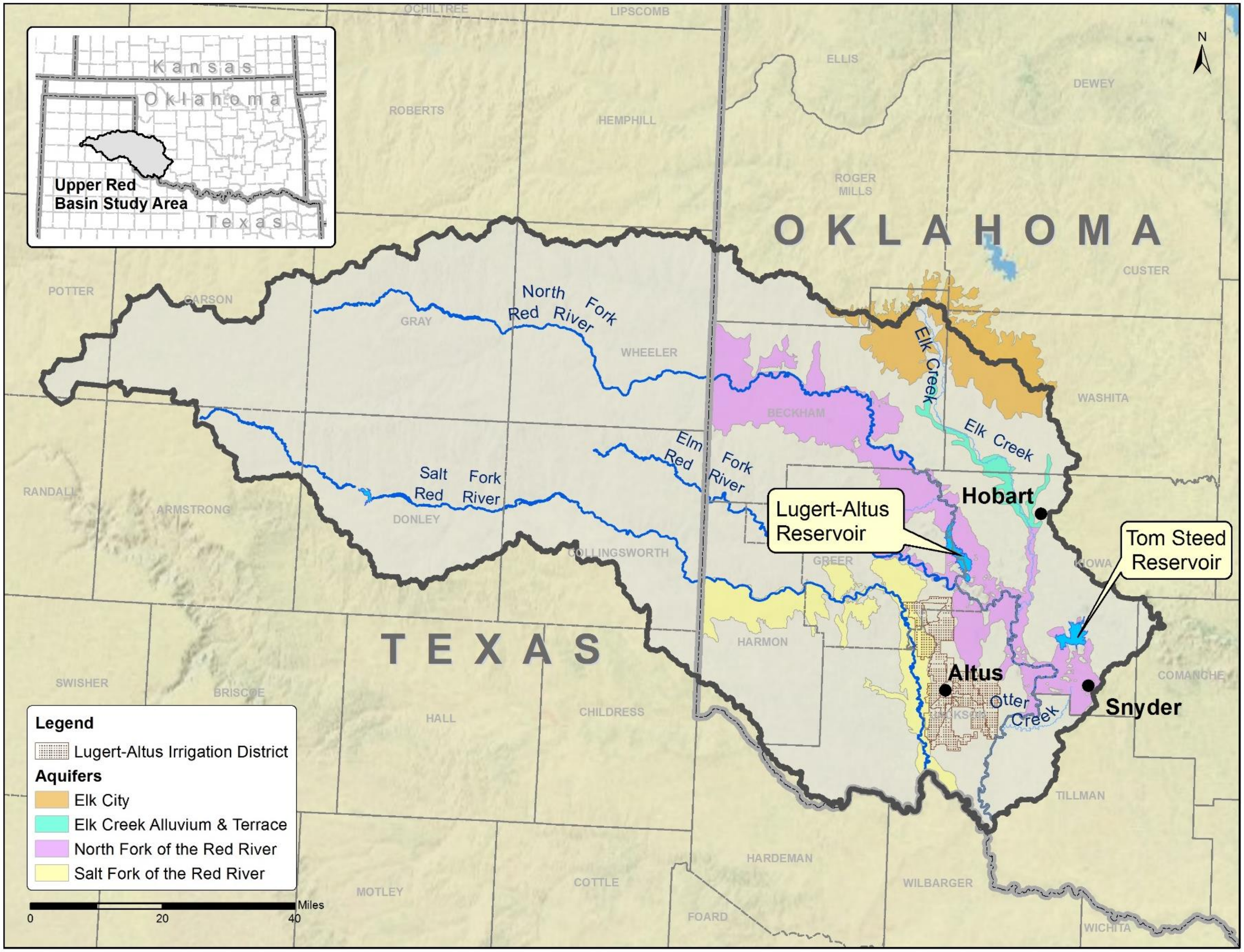


Figure 1 – Map of the Upper Red River Basin Study area.

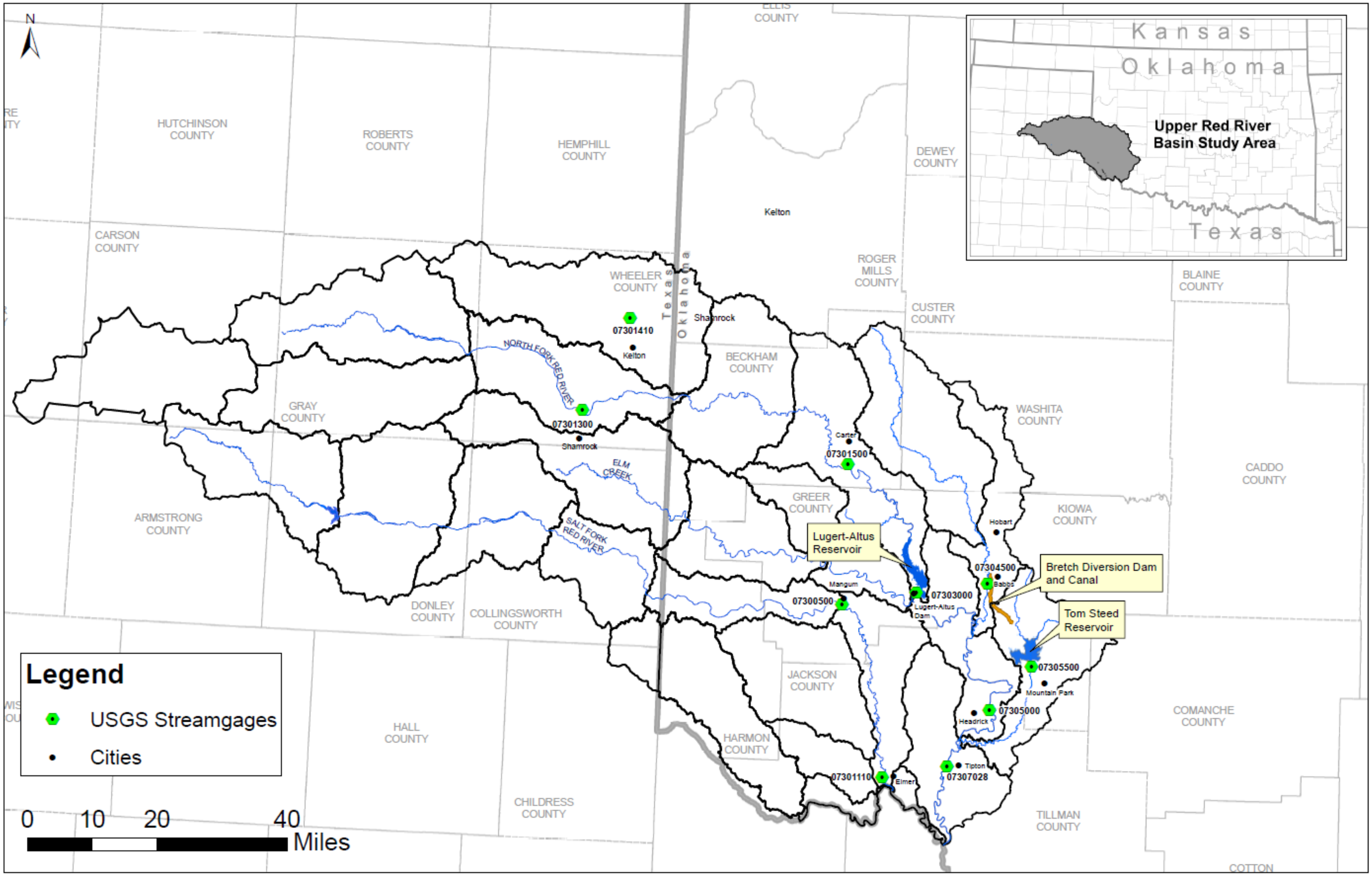


Figure 2 – Map of stream gage locations and major tributaries in the Upper Red River Basin Study area.

2. CURRENT CLIMATE CONDITIONS

Current climate conditions for the URRBS are based on gridded daily precipitation and temperature dataset developed by Maurer et al. (2002). This dataset and mean annual temperature and precipitation for the URRBS are discussed following a brief review of previous studies.

Previous Studies

The Upper Red River Basin is located in the southern portion of the Great Plains region of the U.S. The Great Plains region exhibits a continental climate characterized by extreme and variable weather and climate conditions (Rosenberg, 1987). Key weather and climate features of the southern Great Plains region and the Upper Red River Basin include: large range of daily, seasonal, and annual temperature and precipitation conditions; high solar radiation and strong winds; strong east-west gradients in annual mean precipitation and temperature; and frequent severe weather, including hurricane force winds, hail, and tornadoes (Rosenberg, 1987).

Previous analyses of current climate trends in the Great Plains region are summarized in Reclamation's 2013 literature synthesis (Reclamation, 2013). Several recent analyses of current climate data from the U.S. Historical Climatology Network (USHCN) and other historical data sources indicate a slight increase in annual precipitation over much of the region during the 20th century. While the magnitude and statistical significance of current precipitation trends vary between studies, several studies suggest a slight increase in wintertime precipitation, with more consistent precipitation trends in the southern Great Plains compared to the northern Great Plains. In addition, several studies indicate an increase in extreme precipitation events in the Great Plains during the 20th century, suggesting a warming-induced increase in thunderstorm activity (Reclamation 2013).

As summarized by Reclamation (2013), recent analyses indicate a relatively small increase in annual mean temperature over the Great Plains region during the 20th century. However, several studies cited in the literature synthesis found significant increases in seasonal mean temperature, with increases of up to 1.8 degrees Fahrenheit (°F) in spring (March-April-May) and 2.0 °F in winter (December-January-February). In contrast to precipitation trends, which are more consistent in the central Great Plains region, several studies suggest that the greatest warming occurred in the northern Great Plains region. Previous studies found an overall temperature increase of approximately 1.85 °F in the northern Great Plains and 0.63 °F in the southern Great Plains over the period 1901-2008.

Current Climate Conditions

Current climate conditions over the Basin were characterized based on the gridded daily precipitation and temperature dataset developed by Maurer et al. (2002). This dataset utilizes daily precipitation and temperature data from the National Weather Service (NWS) Cooperative Observer (Co-Op) network. The station data are processed to remove spatial and temporal inconsistencies and then interpolated to a 1/8° grid (1/8° latitude by 1/8° longitude) covering the continental United States.

The gridded daily precipitation and temperature datasets developed by Maurer et al. (2002) were previously verified by comparison to available station records, other gridded datasets, and by evaluation of hydrologic model simulations with these datasets used as meteorological inputs (Maurer et al., 2002). Results suggest that while the values at a given grid cell typically do not exactly match station records from gauges located within the cell; they do capture the daily, seasonal, and interannual variability of station records. In addition, the gridded datasets provide complete and consistent representation of climate conditions that is appropriate for analysis of spatial and temporal variability in climate conditions over large areas.

Figure 3 and 4 show the respective 1950-1999 mean annual temperature and precipitation values for each 1/8° cell in the study area. As illustrated in Figure 3 and 4, climate conditions in the Basin exhibit substantial east-west temperature and moisture gradients, with warmer and more humid conditions in the eastern portion of the Basin. Current mean annual temperature and precipitation range respectively from 56.5 °F and 19.1 inches in the western portion of the basin to 63.0 °F and 29.7 inches in the southeastern portion of the basin. The respective basin-wide temperature and precipitation current annual averages are 59.9 °F and 23.6 inches.

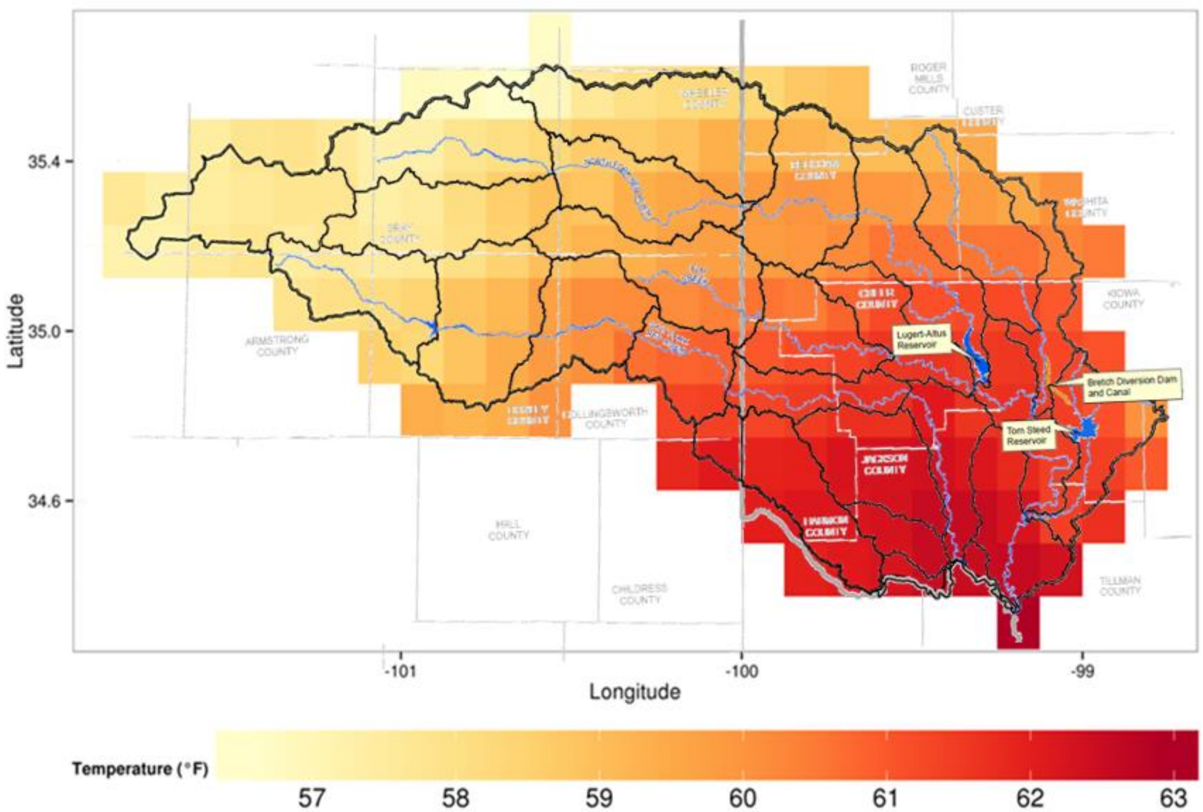


Figure 3 – Spatial distribution of mean annual temperature based on gridded dataset developed by Maurer et al. 2002 for 1950-1999. Grid cells are 1/8° resolution.

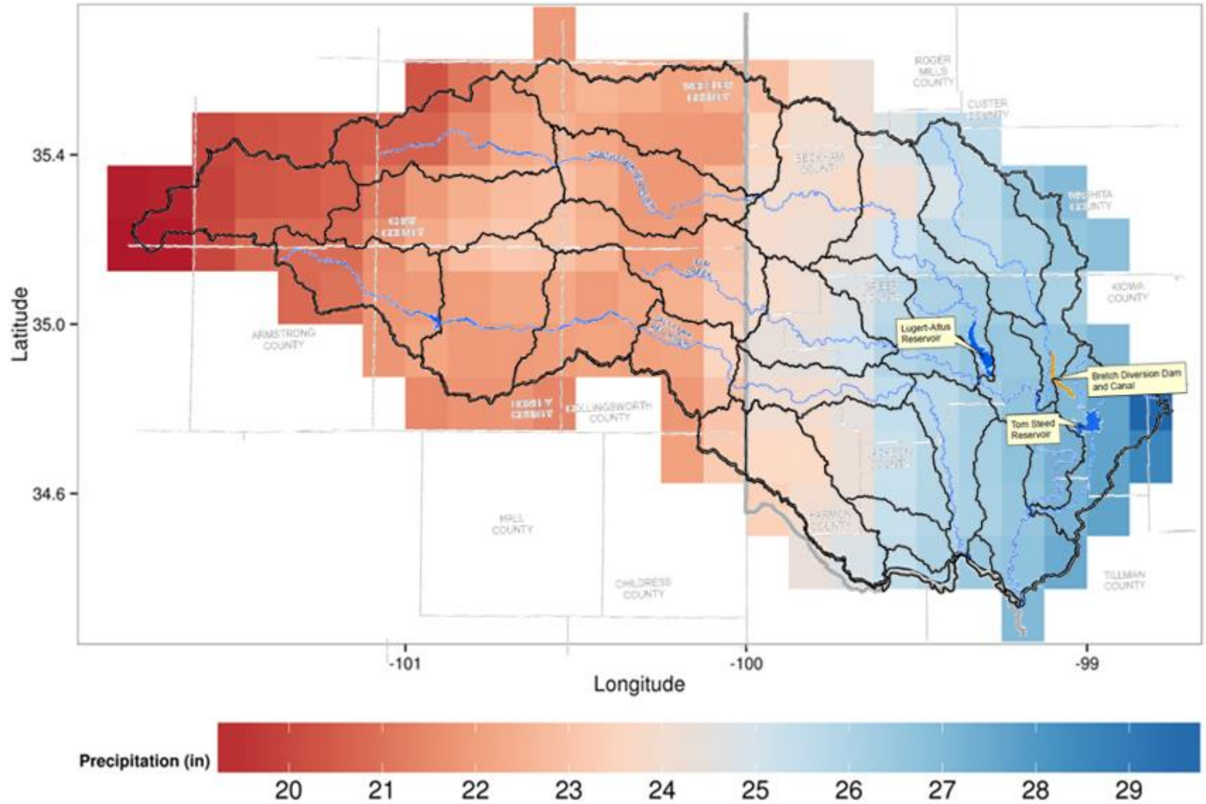


Figure 4 – Spatial distribution of mean annual precipitation based on gridded dataset developed by Maurer et al. 2002 for 1950-1999. Grid cells are 1/8° resolution.

3. CLIMATE PROJECTIONS

Climate projections for the URRBS were obtained from an archive of climate and hydrology projections developed by Reclamation in partnership with the USGS, U.S. Army Corps of Engineers, Lawrence Livermore National Laboratory, Santa Clara University, Climate Central, and Scripps Institution of Oceanography. These projections and associated documentation are available through this downscaled climate and hydrology projections website: http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/dcpInterface.html. The climate projections were statistically downscaled in space from global climate model (GCM) grid resolution to 1/8° latitude by 1/8° longitude. This archive of climate projections is based on GCM simulations compiled by the World Climate Research Programme's Coupled Model Intercomparison Project (CMIP).

Among the available climate and hydrology projections available on the above mentioned website, there are monthly bias-corrected and spatially-disaggregated (BCSD) projections of precipitation and temperature, which are utilized in the URRBS. Bias correction generally involves correcting systematic errors in GCM historical simulations based on finer scale observed data. Spatial disaggregation generally involves translating coarse scale GCM simulations to the 1/8° spatial resolution. Projections based on CMIP5 were used in the analysis of future water supply impacts in the Upper Red River Basin and are further described below. Both the CMIP Phase 3(CMIP3) and the CMIP Phase 5 (CMIP5) projections are briefly discussed below for completeness, but it should be noted that only CMIP5 projections are used in this study.

CMIP3 projections (Meehl et al., 2007) are summarized in the Fourth Assessment Report by the Intergovernmental Panel on Climate Change (IPCC), completed in 2007 (IPCC, 2007). Generally, climate projections are based on an assemblage of GCM simulations of coupled atmospheric and ocean conditions, with a variety of initial conditions of global ocean – atmosphere system and distinct "storylines" about how future demographics, technology and socioeconomic conditions might affect the emissions of greenhouse gases. There are four families of emissions scenarios (A1, A2, B1 and B2 - described in the IPCC Special Report on Emissions Scenarios,[SRES] Nakicenovic, 2000), in which the scenarios are potential futures based on assumptions of global economic activity and growth. Additionally, there are three subsets to the A1 family (A1F1, A1B, and A1T) based on their technology emphasis with regard to future energy sources with A1B having a balanced emphasis on all energy sources. Projected global warming associated with CMIP3 SRES scenarios available in a downscaled form is shown in the left panel of Figure 5.

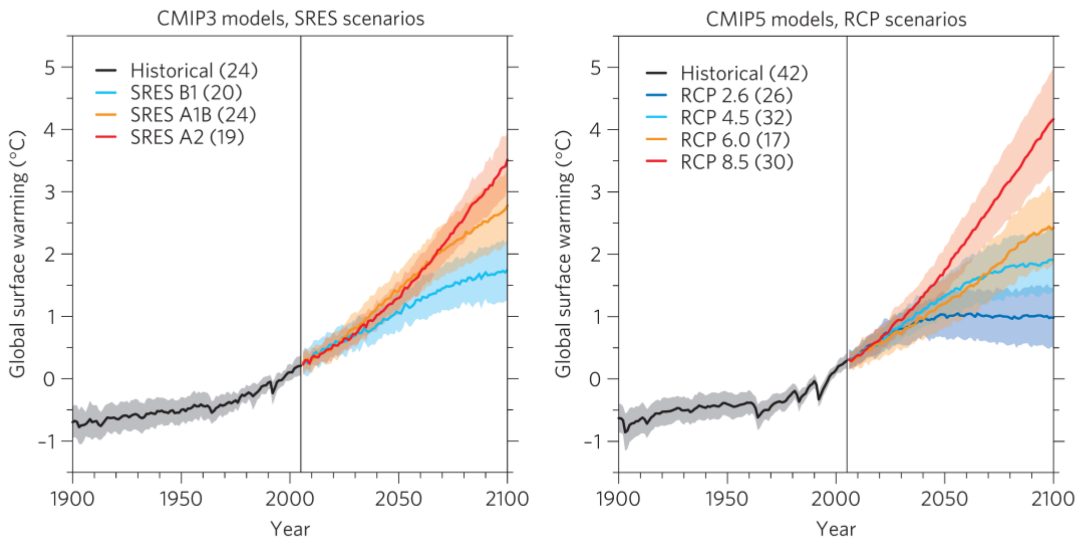


Figure 5 – Global temperature change (mean and one standard deviation as shading) relative to 1986–2005 for the SRES scenarios run by CMIP3 and the RCP scenarios run by CMIP5. The number of model projections is given in parenthesis. Source: Figure 2 from Knutti et al (2012).

CMIP5 projections are similar in concept but incorporate improvements in modeling and physical understanding of the Earth system since the CMIP3 effort. The raw CMIP5 model output has been available since early 2011 and has been increasingly used in climate change impacts studies, alongside those from CMIP3. The corresponding IPCC Fifth Assessment Report was completed in 2013. These GCMs rely on greenhouse gas storylines called Representative Concentration Pathways (RCP). Each RCP is representative of a particular amount of radiative forcing (2.6, 4.5, 6.0, and 8.5 Watts per square meter [W/m^2] respectively) occurring by the year 2100. The right panel of Figure 5 illustrates projected global warming according to the CMIP5 RCP scenarios. The figure shows that the range of emissions scenarios considered by CMIP5 result in a greater range of projected global warming than by CMIP3 emissions scenarios. The website identified above contains 112 BCSD CMIP3 monthly projections and 231 BCSD CMIP5 monthly projections of precipitation and temperature, among other available hydroclimate data products. Projections based on the four CMIP5 emissions scenarios are available via the website mentioned above and are used as a basis for URRBS climate scenarios.

The CMIP5 projections were chosen in this study because they represent improvements since the CMIP3 effort and over time have become a widely accepted and used climate resource.

4. DERIVING CLIMATE CHANGE SCENARIOS FROM CLIMATE PROJECTIONS

To meet the needs of the URRBS, three climate scenarios were developed that would be subsequently used as inputs in modeling tools to evaluate system reliability. First, a baseline climate scenario was developed to represent current climate and hydrologic conditions in the Basin. Three future climate scenarios were then developed to represent the range of projected future climate conditions in the Basin. For the baseline scenario, climate inputs consist of gridded historical observations of precipitation and temperature; for each future climate scenario, climate-related inputs were developed by perturbing baseline inputs to reflect the projected change in each input variable between the periods 1950-1999 and 2045-2074 corresponding to each of the three selected future scenarios. These future climate scenarios are derived using an ensemble informed hybrid delta (HDe) method (Hamlet et al., 2013; Reclamation, 2010), described in detail below.

The following describes the baseline scenario and development of future climate scenarios used for detailed analysis of system reliability and evaluation of alternatives.

Baseline Scenario

The climate baseline scenario is represented by the observation-based gridded historical dataset (Maurer et al, 2002) precipitation and temperature data for the period 1950-1999. The hydrology baseline scenario is subsequently produced from this climate data using the VIC hydrology model. As conceptualized in this Study, the baseline scenario is intended to reflect current climate and hydrologic conditions in the Basin.

Future Climate Scenarios

As discussed above, the URRBS utilizes climate scenarios derived using an ensemble informed hybrid delta (HDe) method based on statistically downscaled CMIP5 GCM projections. This method is described in detail below.

The HDe method for developing climate scenarios involves perturbing baseline historical climate (precipitation and temperature) by change factors computed as the change in precipitation and temperature by month between a chosen future planning horizon and a historical period (Reclamation, 2010). The URRBS utilizes an ensemble of climate projections based on CMIP5 to estimate percentile specific monthly change factors for both precipitation and temperature.

The HDe method involves defining a climate change scenario based on pooled information from a collection of climate projections. Use of a sufficiently large number of projections pooled together (i.e. projection ensemble), modulates internal climate variability inherent in each single projection which may be misinterpreted as climate change signal.

The development of HDe climate change scenarios entails two primary steps. These steps include:

1. identifying the climate projections that will inform each of the HDe climate change scenarios, and
2. generation of HDe climate change scenarios using statistical mapping of future projections onto baseline historical gridded observed data.

The first step in the development of HDe climate change scenarios involves identifying the climate projections that will inform each of the scenarios to be considered in the study. Review of climate projections over the Upper Red River Basin suggests a warmer future (no projections suggest occurrence of cooling) with a range of drier to wetter conditions, compared to history (1950-1999). As such, ensembles of climate projections that bracket the range of potential futures, from less warm to warmer and drier to wetter conditions, fall into five climate change scenarios. The five HDe scenarios as defined for this study are warmer-drier (WD), warmer-wetter (WW), central tendency (CT), less warm-drier (LWD) and less warm-wetter (LWW). As discussed later, only three of the five HDe climate change scenarios were selected by the Study collaborators for developing the hydrology projections.

For each climate change scenario, change in mean annual temperature (°F) and precipitation (percent) is calculated between the baseline period, 1950-1999, and the future time horizon (2060 defined by the 30 year range 2045-2074) for each 1/8° grid cell within the study area (see Figure 3 and 4). The Upper Red River Basin Study considers only one future time horizon, the 2060 (2045-2074). Change in mean annual temperature (°F) versus percent change in mean annual precipitation between the 2060 and reference historical period for the 231 CMIP5 projections is used to develop climate change scenarios and is shown in Figure 6. Note that, there are 231 points representing the total number of available individual GCM projections from the monthly BCSD-CMIP5 archive.

In Figure 6, the dotted black lines represents the median (50th percentile) change values while the solid red lines represents the 10th and 90th percentile change values. Climate change scenarios are developed by selecting the 10 individual climate projections that fall closest to the intersections of the 10th, 50th, and 90th percentiles of change[1]. The selected projections corresponding to each of the five climate change scenarios are shown in the figure using a range of colors (and symbols) - LWW=orange, LWD=green, WW=blue, WD=purple, CT=yellow. Using only a limited number of climate projections (specifically, 10) to inform a given climate change scenario enables each of the climate change scenarios to be distinct and representative of the defined future conditions, e.g., LWW, LWD, etc.

Once the climate projections for each of the climate change scenarios have been identified, the second component of the development of HDe scenarios involves generating perturbed historical time series informed by the 10 projections pooled together for each climate change scenario.

[1] The distance between plotted precipitation and temperature change and the 10th, 50th, and 90th percentile change values was computed using the Mahalanobis distance.

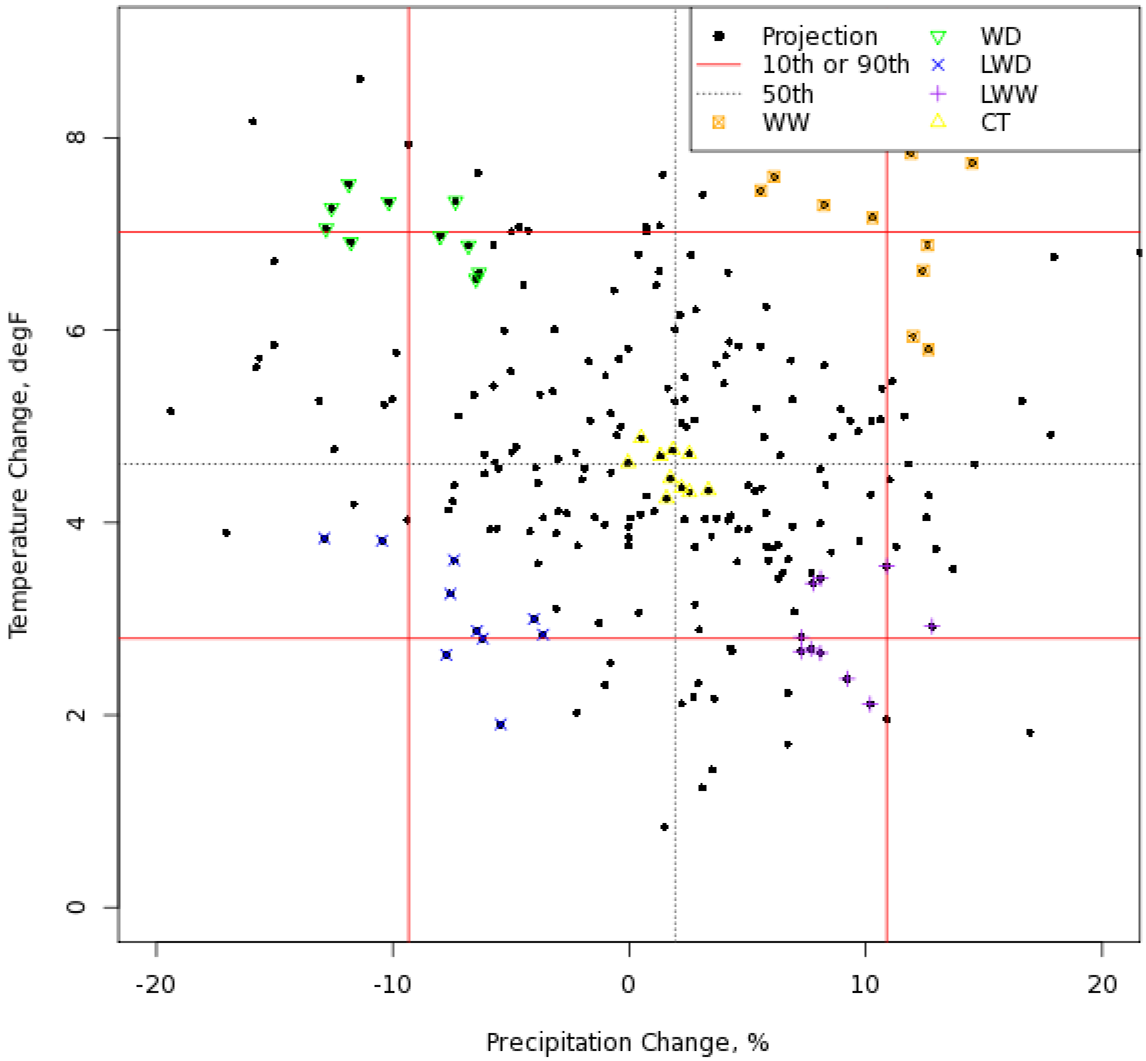


Figure 6 – Change in mean annual temperature (°F) versus percent change in mean annual precipitation between the 2060 and historical baseline period. Projected changes using statistically downscaled CMIP5 GCM simulations are illustrated.

Observed baseline gridded (Maurer et al. 2002) monthly precipitation and temperature are mapped, using a quantile mapping technique onto the bias corrected GCM data to produce a set of transformed observations reflecting the future conditions. The entire observed time series of temperature and precipitation at each 1/8° grid cell for the Basin is perturbed in this manner, resulting in a new time series that now has the statistics of the bias corrected GCM data for temperature and precipitation.

Climate change scenarios derived using HDe have a number of distinguishing features, which have their associated strengths and weaknesses. One weakness of this approach is that analysis of climate change impacts is limited to the future time horizons chosen when developing precipitation and temperature change factors. Another weakness is that the scenarios do not explicitly incorporate projected changes in drought variability or sequencing of storm events. However, one key strength of the HDe approach is that the time sequence of projected future storm events matches historical data, facilitating direct comparison between the historical data and future climate scenarios.

Table 1 summarizes projected precipitation and temperature changes using the HDe approach for 2060. The table includes CMIP5 based projections for the five climate change scenarios described above.

Table 1 – Projected change in mean annual basin wide temperature and precipitation for the climate change scenarios based on CMIP5 BCSD projections; historical period, 1950-1999; future period, 2060 (30 year range, 2045-2074).

	Basin Mean	
Historical, 1950-1999	Temperature (°F)	Precipitation (in)
Baseline	59.9	23.6
	Projected Change in Basin Mean	
Climate Change Scenarios, 2060 (2045-2074)	Temperature (°F)	Precipitation (%)
Warmer-Drier (WD)	+ 7.1	- 6.1
Warmer-Wetter (WW)	+ 7.1	+ 12.6
Central Tendency (CT)	+ 4.6	+ 4.9
Less Warm-Drier (LWD)	+ 3.1	- 4.9
Less Warm-Wetter (LWW)	+ 2.9	+ 10.6

As mentioned above, only three of the HDe-based climate change scenarios were used to develop the hydrology projections discussed in the next section. Specifically, the WD and LWW scenarios which represent two of the bounding cases of precipitation and temperature change here, and the central tendency (CT) scenario were used for further hydrologic analysis. The spatial distributions of the change from the baseline for these three scenarios are shown in Figure 7 and 8 for mean annual temperature and mean annual precipitation, respectively.

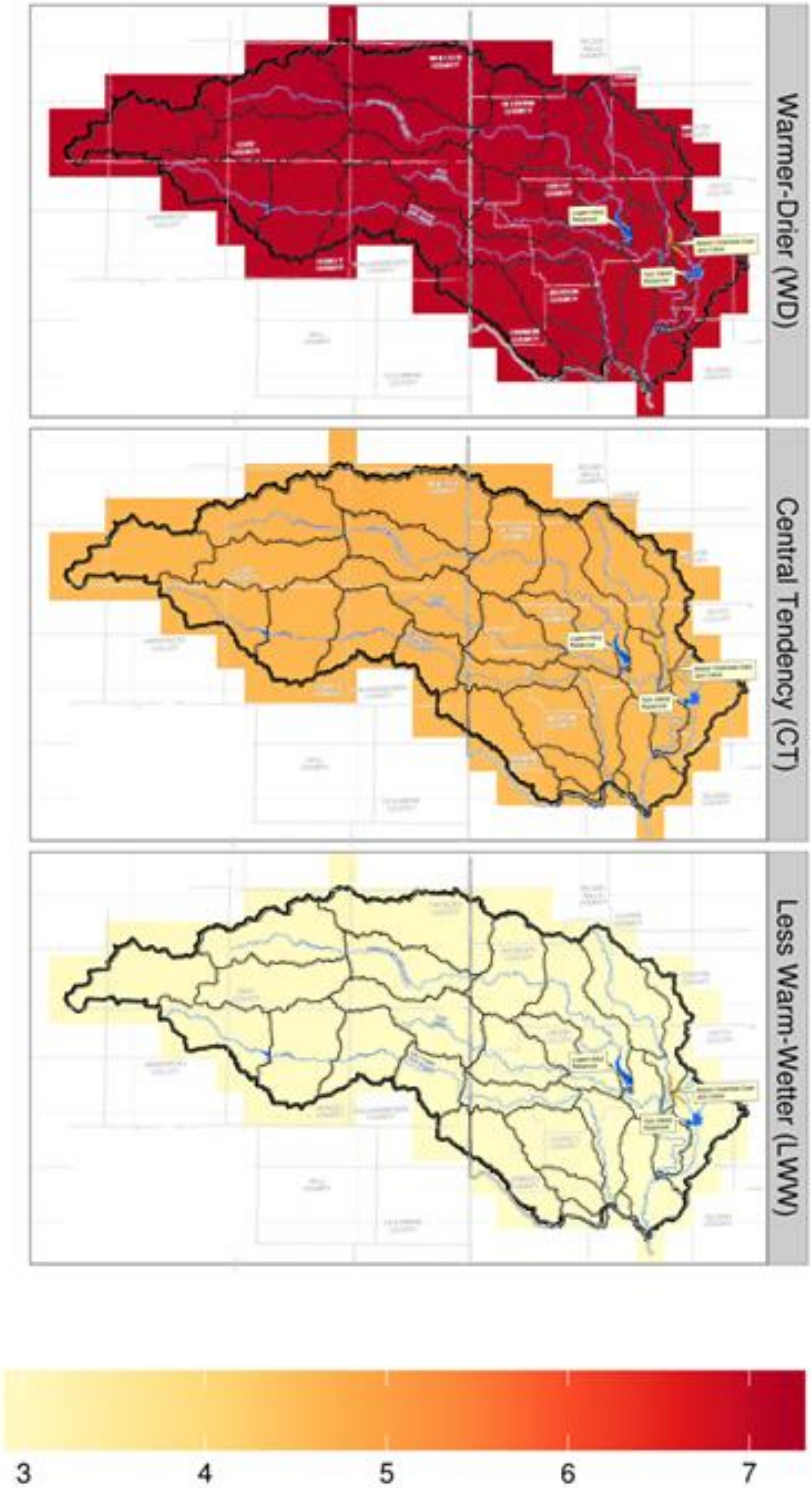


Figure 7 – Change in mean annual temperature (°F) from the baseline scenario.

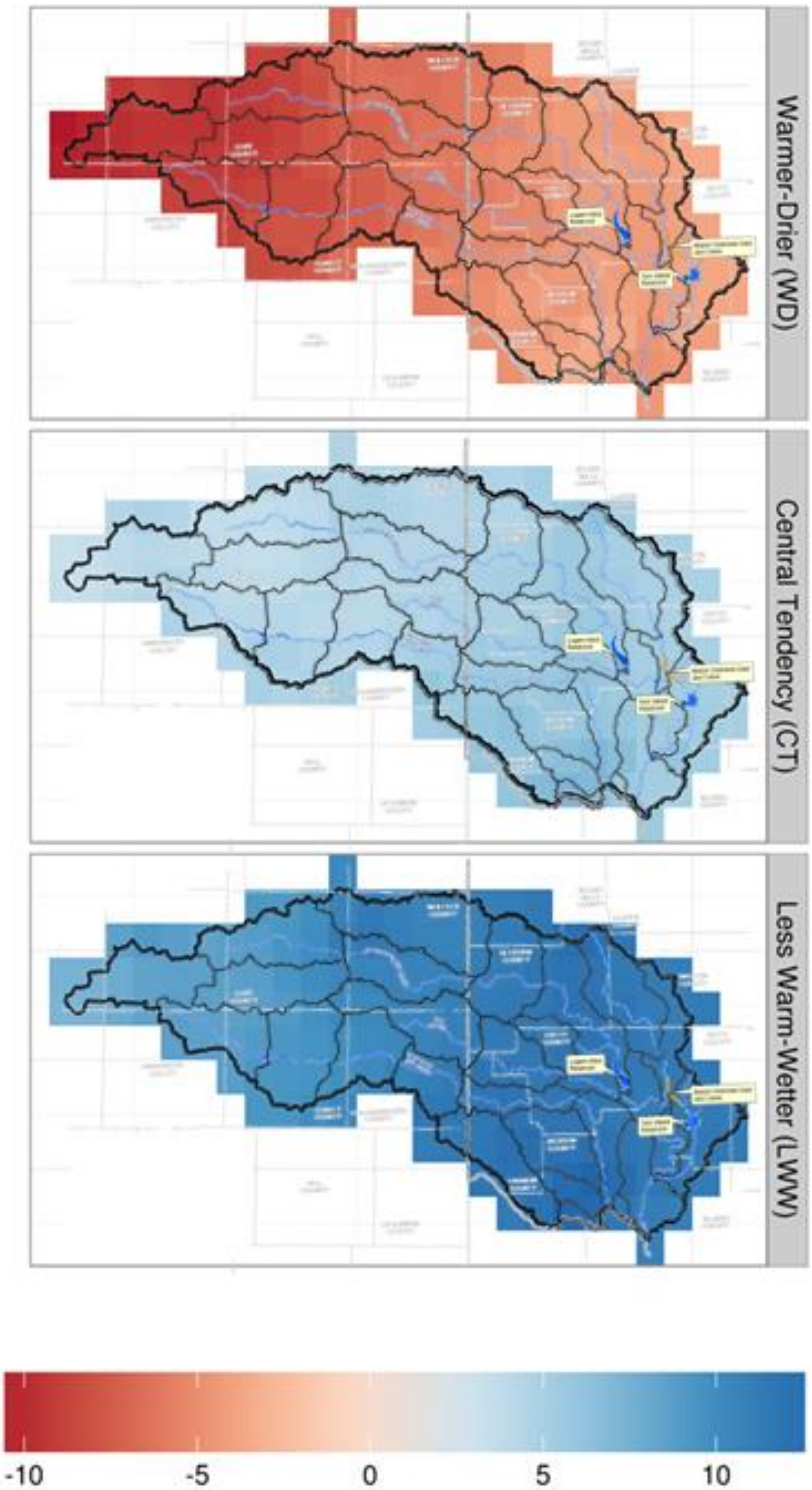


Figure 8 – Change in mean annual precipitation (percent) from the baseline scenario.

5. VIC HYDROLOGIC MODEL OVERVIEW

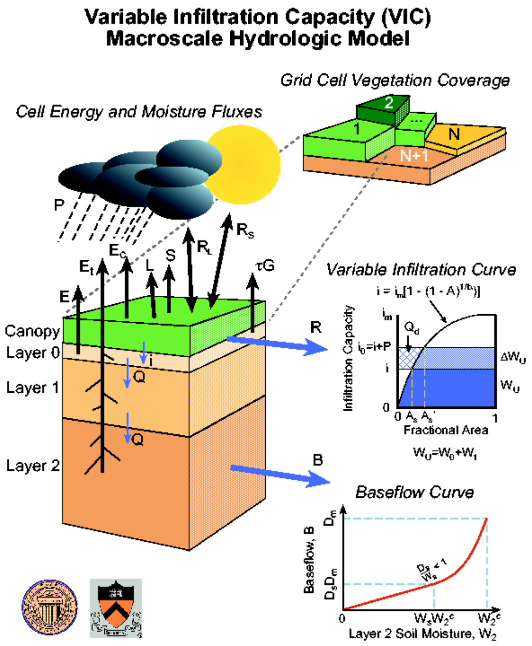
The VIC model has been widely used to evaluate hydrologic response to climate variability and change, including several analyses of large-scale watersheds in the western U.S. (e.g., Reclamation, 2011). The VIC model was selected for this basin study based on several criteria; including consideration of the physical hydrologic processes represented by the model, availability of model inputs and parameter values over the basin study area, and consistency with previous and ongoing analyses of climate change impacts by Reclamation. VIC model version 4.0.7 was used to be consistent with the version used in any calibration work used to refine model inputs.

The VIC surface water hydrologic model provides estimates of historical and projected water balance variables. The VIC model (Liang et al., 1994; Liang et al., 1996; Nijssen et al., 1997) is a grid-based hydrologic model that solves the water balance at a spatial scale of 1/8° latitude/longitude (approximately 12 kilometers on a side). An overview schematic of the VIC model is given in Figure 9.

The VIC model contains a subgrid-scale parameterization of the infiltration process, which impacts the vertical distribution of soil moisture in, typically, a three-layer model grid cell (Liang et al., 1994). The VIC model also represents subgrid-scale vegetation variability using multiple vegetation types and properties per grid cell. Potential evapotranspiration is calculated using a Penman Monteith approach (e.g., Maidment (ed.), 1993). VIC also contains a subdaily (1-hour time step) snow energy balance model, illustrated by Figure 9b. (Cherkauer and Lettenmaier, 2003; Wigmosta et al., 1994; Andreadis et al., 2009).

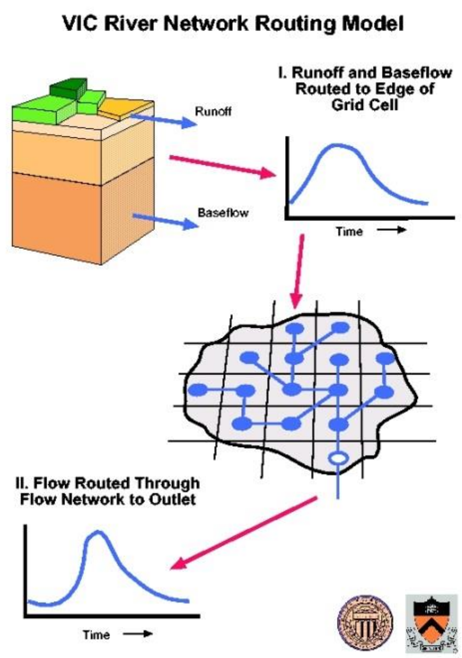
The VIC model requires gridded daily precipitation, maximum and minimum temperatures, and wind speed magnitude (at a minimum) as input to simulate gridded daily state variables such as snow water equivalent and runoff (both surface and subsurface runoff). The URRBS utilizes baseline gridded observations developed by Maurer et al. (2002) for the period January 1950 to December 1999. The dataset is primarily based on observation stations that are part of the Co-op Station Network, interpolated to a grid using the SYMAP algorithm (Shepard, 1984). The Maurer dataset only includes stations with more than 20 years of data during1949-2000. Additional model forcings that drive the water balance, such as solar (short-wave) and long-wave radiation, relative humidity, vapor pressure, and vapor pressure deficit, are calculated within the model.

The VIC outputs typically include grid cell moisture and energy states through time (i.e., soil moisture, snow water content, snowpack cold content) and water leaving the basin either as ET, baseflow, sublimation, or runoff; where the latter represents the combination of faster-response surface runoff and slower-response baseflow. Gridded surface runoff and baseflow are hydraulically routed to produce streamflow at a selected locations (e.g., stream gages), using the model presented by Lohmann et al., (1996). A schematic of the VIC routing model is shown in Figure 9c. This setup requires specifying the coordinates of each streamflow location within the basin grid, identifying tributary grid cells and flow directions through these grid cells, and ultimately the fraction-area contribution from tributary grid cells to streamflow at the location of interest. Routed streamflow using this approach represents natural streamflow, that is, streamflow that would occur in the absence of water management (diversions, return flows, and storage as examples).



a)

b)



c)

Figure 9 – Variable Infiltration Capacity Model schematics, including a) spatial discretization and overview, b) snow model algorithm, and c) routing model.

6. VIC HYDROLOGIC MODEL SIMULATIONS

The VIC model was used to generate HDe hydrology scenarios based on the baseline and associated HDe climate change scenarios. Simulated routed streamflows were developed at ten USGS stream gage locations (Figure 2, Table 2) for baseline conditions and the three HDe climate change scenarios.

Table 2 – USGS gage locations shown on the map in Figure 2.

Number	Name
07300500	Salt Fork Red River at Mangum, OK
07301110	Salt Fork Red River near Elmer, OK
07301300	North Fork Red River near Shamrock, TX
07301410	Sweetwater Creek near Kelton, TX
07301500	North Fork Red River near Carter, OK
07303000	North Fork Red River below Altus Dam near Lugert, OK
07304500	Elk Creek upstream of the Bretch Diversion Dam near Babbs, OK
07305000	North Fork Red River near Headrick, OK
07305500	West Otter Creek near Mountain Park Dam near Mountain Park, OK
07307028	North Fork Red River near Tipton, OK

Mean annual streamflow results for all gage locations are shown in Table 3. Mean annual streamflow for the wetter scenario (less warm-wetter, LWW) is greater than the baseline simulation, and is less for the dryer scenario (warmer-drier, WD). The central tendency scenario results are similar to the baseline flows and fall between the LWW and WD scenarios. These results are consistent with monthly streamflow results. The Salt Fork Red River and North Fork Red River mean monthly streamflow are shown in Figure 10, 11, and 12, ordered from upstream to downstream and plotted on the same scale to show the relative change in magnitudes. The mean monthly streamflow for three tributary streams to the North Fork Red River, Sweetwater Creek, Elk Creek, and West Otter Creek are shown in
Figure 12 and 13.

Table 3 – Mean annual streamflow in cubic feet per second (cfs) for the baseline and three HDe climate change scenario simulations for USGS gage locations shown on the map in Figure 2.

Stream Gage and Scenario	Mean Annual Flow (cfs)		
	Minimum	Average	Maximum
Salt Fork Red River at Mangum, OK			
Baseline	93	213	855
Warmer-Drier (WD)	81	186	586
Central Tendency (CT)	94	257	1,160
Less Warm-Wetter (LWW)	102	281	1,102
Salt Fork Red River near Elmer, OK			
Baseline	145	356	1,265
Warmer-Drier (WD)	128	332	948
Central Tendency (CT)	142	437	1,602
Less Warm-Wetter (LWW)	154	479	1,496
North Fork Red River near Shamrock, TX			
Baseline	88	186	726
Warmer-Drier (WD)	78	150	440
Central Tendency (CT)	85	213	715
Less Warm-Wetter (LWW)	93	237	812
Sweetwater Creek near Kelton, TX			
Baseline	13	37	165
Warmer-Drier (WD)	11	27	66
Central Tendency (CT)	13	41	133
Less Warm-Wetter (LWW)	15	51	195
North Fork Red River near Carter, OK			
Baseline	146	362	1,418
Warmer-Drier (WD)	127	295	830
Central Tendency (CT)	140	416	1,368
Less Warm-Wetter (LWW)	158	483	1,572
North Fork Red River below Altus Dam near Lugert, OK			
Baseline	158	400	1,580
Warmer-Drier (WD)	138	333	979
Central Tendency (CT)	151	464	1,594
Less Warm-Wetter (LWW)	172	537	1,766
Elk Creek upstream of the Bretch Diversion Dam near Babbs, OK			
Baseline	47	135	512
Warmer-Drier (WD)	42	134	619
Central Tendency (CT)	45	164	774
Less Warm-Wetter (LWW)	51	186	712
North Fork Red River near Headrick, OK			
Baseline	319	794	2,833
Warmer-Drier (WD)	277	712	2,293
Central Tendency (CT)	310	940	3,202
Less Warm-Wetter (LWW)	364	1,081	3,262
West Otter Creek near Mountain Park Dam near Mountain Park, OK			
Baseline	13	46	123
Warmer-Drier (WD)	11	44	215
Central Tendency (CT)	12	53	170
Less Warm Wetter (LWW)	14	63	231
North Fork Red River near Tipton, OK			
Baseline	366	934	3,073
Warmer-Drier (WD))	318	849	2,529
Central Tendency (CT)	354	1,109	3,517
Less Warm Wetter (LWW)	409	1,276	3,610

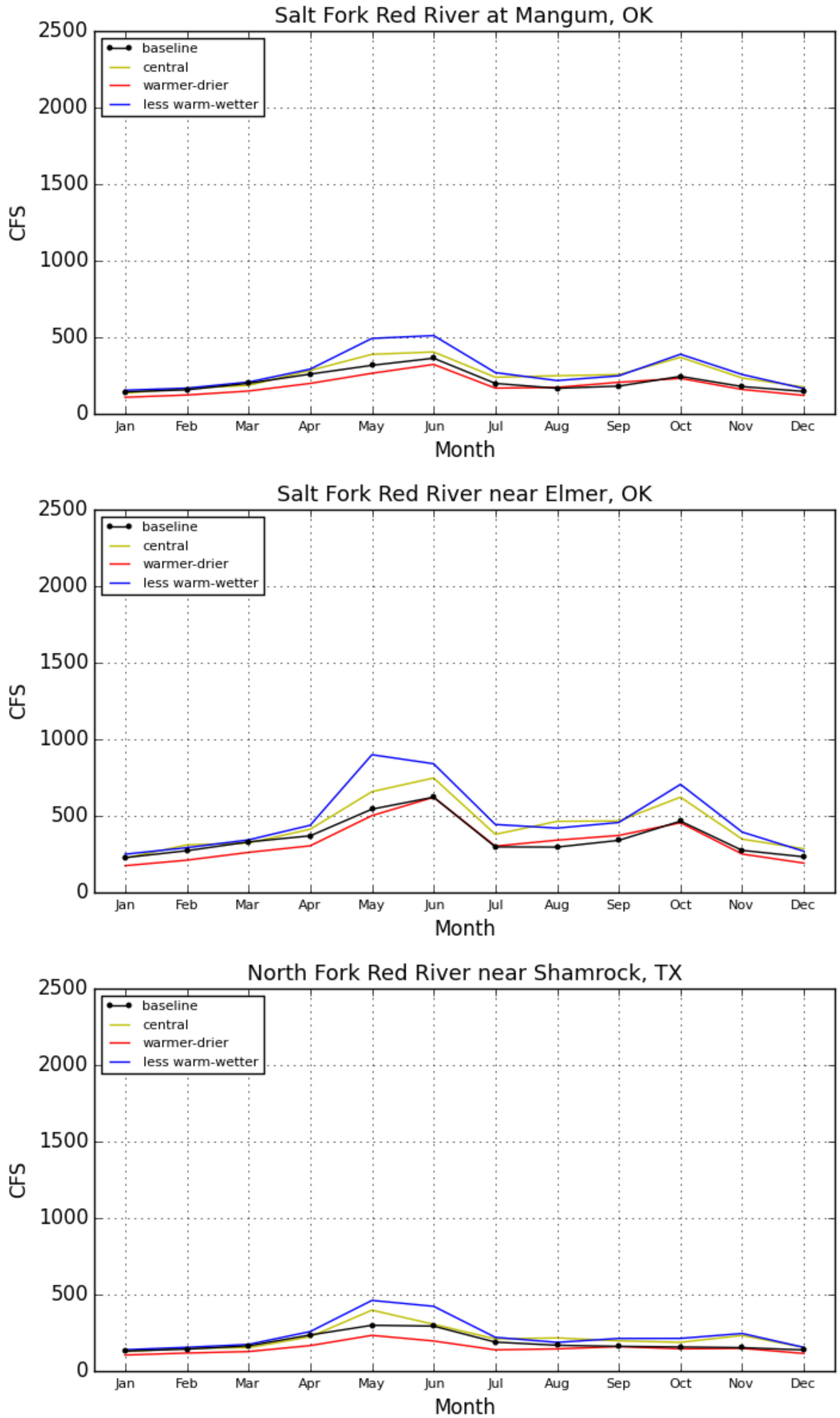


Figure 10 – Monthly averages of streamflow for the baseline and three HDe climate change scenario simulations for two sites on the Salt Fork Red River and the most upstream site on the North Fork Red River.

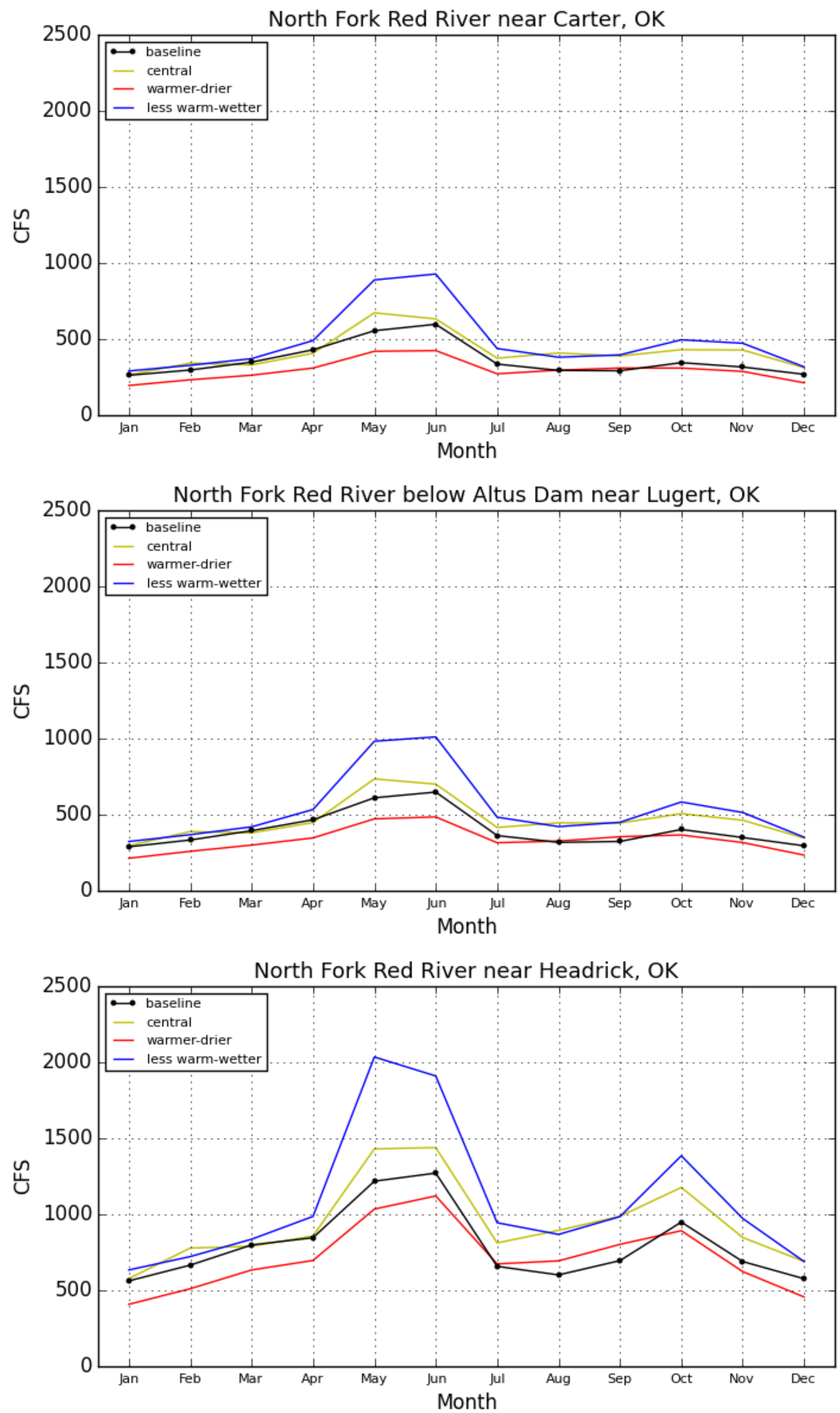


Figure 11 – Monthly averages of simulated streamflow for the baseline and three HDe climate change scenarios for three downstream sites on the North Fork Red River.

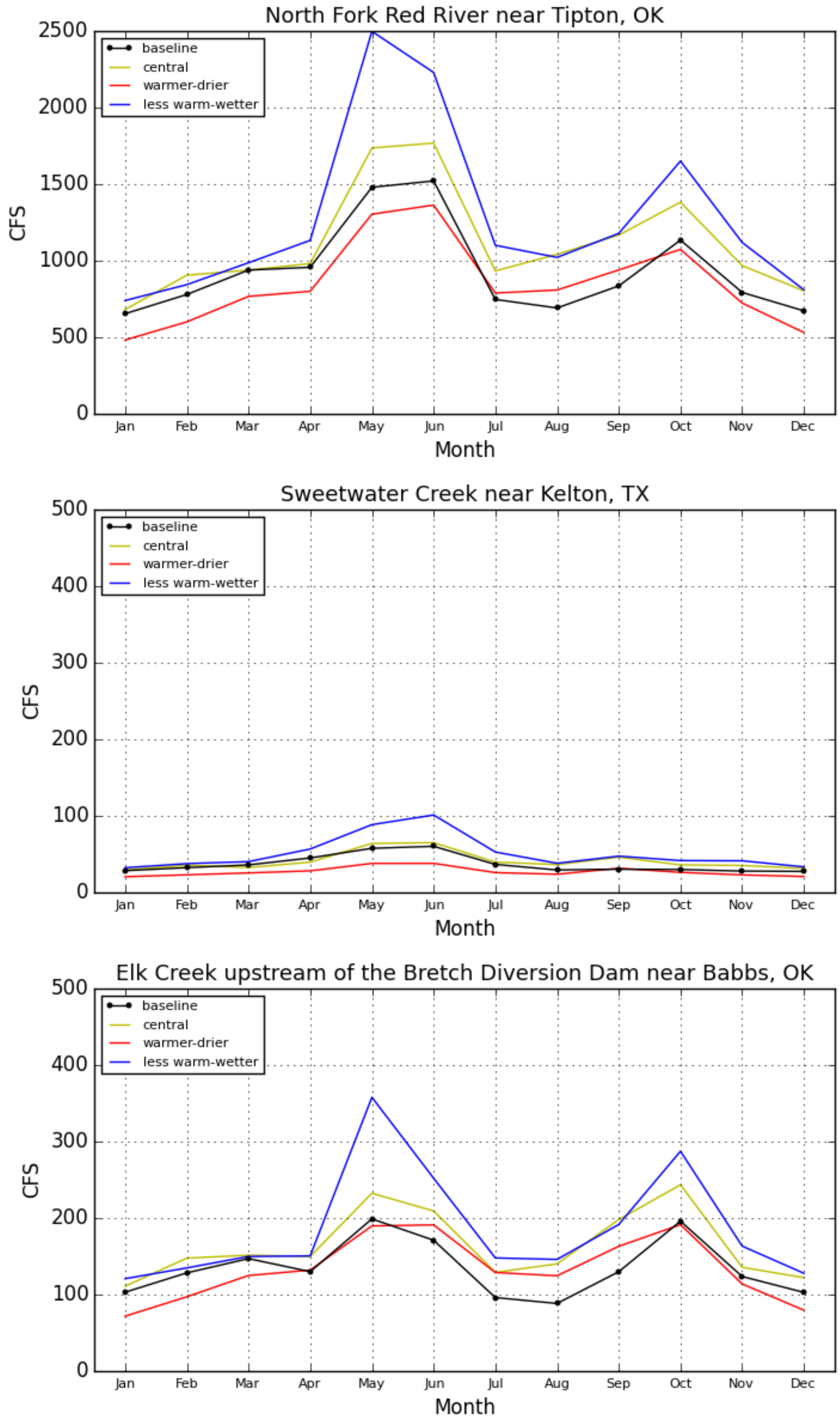


Figure 12 - Monthly averages of simulated streamflow for the baseline and three HDe climate change scenarios for the most downstream site on the North Fork Red River and the Sweetwater Creek and Elk Creek sites tributary to the North Fork Red River.

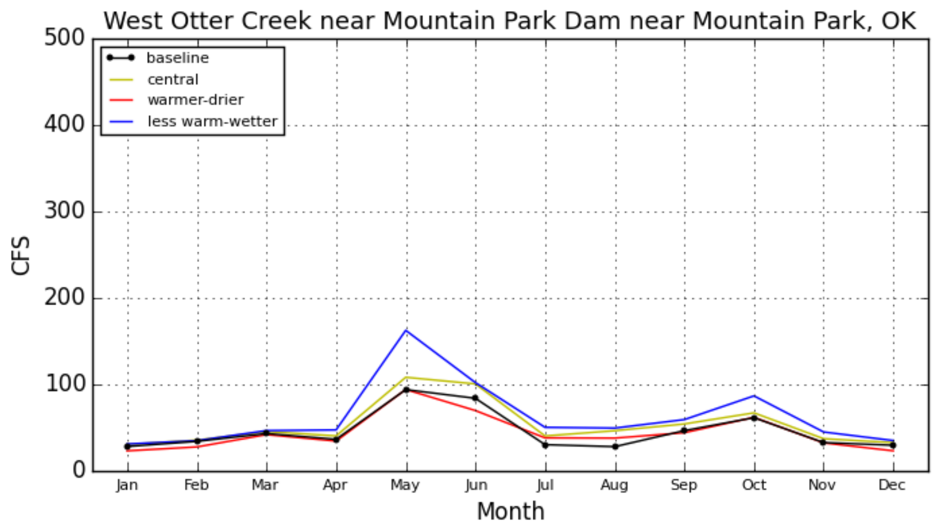


Figure 13 - Monthly averages of simulated streamflow for the baseline and three HDe climate change scenarios for the West Otter Creek site tributary to the North Fork Red River.

7. SUMMARY

Climate change scenarios for the Upper Red River Basin were developed based on CMIP5 projections using the ensemble informed hybrid delta (HDe) method.

Five climate change scenarios were derived using the future period defined by the 30-year range, 2045-2074, and the historical period of record (50 years), 1950-1999. Table 1 summarizes projected precipitation and temperature changes for these five scenarios. All five scenarios indicate warmer mean annual basin wide temperatures than the historical (1950-1999) value of 59.9 °F, ranging from an increase of 2.9 to 7.1 °F. Changes in projected mean annual basin wide precipitation range from -6.1 to +12.6 percent change from the historical value of 23.6 inches. Three scenarios representing two bounding cases (WD and LWW) of precipitation and temperature change and the central tendency (CT) were then used to develop hydrology projections.

The VIC surface water hydrologic model was subsequently used to generate three HDe hydrology scenarios based on the associated HDe climate change scenarios. Simulated routed streamflows were developed at eight USGS stream gage locations (Figure 1, Table 2) for historical baseline conditions and the three HDe climate change scenarios. Monthly streamflow results for the gage locations are shown in Figure 10-13. As expected, mean monthly streamflow for the wetter scenario (less warm-wetter, LWW) is greater than the baseline simulation, and is generally less for the dryer scenario (warmer-drier, WD). The wetter scenario generally results in greater variability and the dryer scenario in relatively lesser variability compared to the historical and central tendency results.

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