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Technical Memorandum | Final

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From:	**Ben Harding and Subhrendu Gangopadhyay (AMEC Earth & Environmental)**
Subject:	**CRWAS Phase 1 | Task 7.12 | Statistical Analysis of Climate Impacts**
Date:	**June 7, 2010**

Introduction

This Technical Memorandum summarizes information developed as part of Task 7 of the Colorado River Water Availability Study (CRWAS or Study).

The objective of Task 7 is to: *Provide agency coordination, literature review, diagnostic analysis, data preparation, and model testing to generate projections for temperature, precipitation, weighted and scaled alternate hydrology, and water use relative to potential changes in forest and climate scenarios.* Sub-task 7.12 involves conducting statistical diagnostic analyses of the ensemble of alternate hydrology and water uses.

This memorandum documents the development of estimates of values of climate-adjusted hydrology variables, the approach used to perform statistical analyses on those variables, and the results of those analyses. Subsequent sections of this technical memorandum discuss: 1) Objectives of Statistical Analyses 2) Development of Climate-Adjusted Data Sets, 3) Statistical Analysis of Climate Change Hydrology, 4) Results of Analyses, and 5) References.

Objectives of Statistical Analyses

The objective of this technical memorandum is to help stakeholders understand the estimates of future hydrologic conditions and the uncertainty in estimates of future conditions. Hydrologic conditions are characterized by three measures:

- Event magnitudes—How will projected climate conditions affect annual average values of climate-impacted variables and the intensity of drought events.
- Seasonal Pattern—How will projected climate conditions affect the seasonal distribution of hydrologic variables?

- Event frequencies—Under projected climate conditions, how frequently will annual flow and spells be expected to occur.

- Spatial Distribution—How will changes in hydrologic variables be distributed in across the study area?

The uncertainty in estimates of future climate conditions is characterized by showing the range of future conditions across five different climate projections for magnitudes, seasonal patterns and event frequencies.

This task memorandum focuses on hydrologic variables*;* other task memoranda will address the effect that climate-impacted streamflows have on legal and physical water availability at key points of diversion in the Colorado River within Colorado, and the effect that climate impacted streamflows will have on the legal availability of water to the State of Colorado according to the terms of the Colorado River Compact.

Development of Climate-Adjusted Data Sets

CRWAS used a method of *differences* to develop a set of *climate-adjusted* conditions for crop irrigation requirement (CIR), and natural flow that represent the conditions during the study period (1950 – 2005) as if projected changes in climate had been fully developed by the start of the study period. Data sets representing climate-adjusted weather, climate-adjusted CIR, and climate-adjusted hydrology were developed as part of Task 7.

The difference method applies the *change* in conditions (weather or hydrology) due to projected climate conditions to an accepted set of baseline data (observed weather data or historical natural flow data). The difference method has three principal advantages: 1) it reduces the unavoidable bias in modeled climate and hydrologic conditions, 2) it normalizes projected changes to accepted weather and flow data, so stakeholders do not need to adapt to a new “baseline” condition and 3) it does not rely on climate models to represent the year-to-year variability of weather and flows[1].

Observed Weather

CRWAS hydrology modeling uses weather data that have been disaggregated to a regular grid. The data set used in CRWAS, originally developed by Maurer, et al. (2002) and later extended by Andrew Wood, is a model-derived dataset of daily maximum and minimum temperature, precipitation depth and wind for the conterminous United States and portions of Canada and Mexico spanning from 1950-2005. The grid geometry of this data set is identical to the climate projections used to quantify projected climate conditions.

The availability of the Maurer, et al. gridded weather to serve as the basis for the CRWAS hydrology modeling was the limiting factor in determining that the CRWAS observed hydrology period would run from 1950 through 2005.

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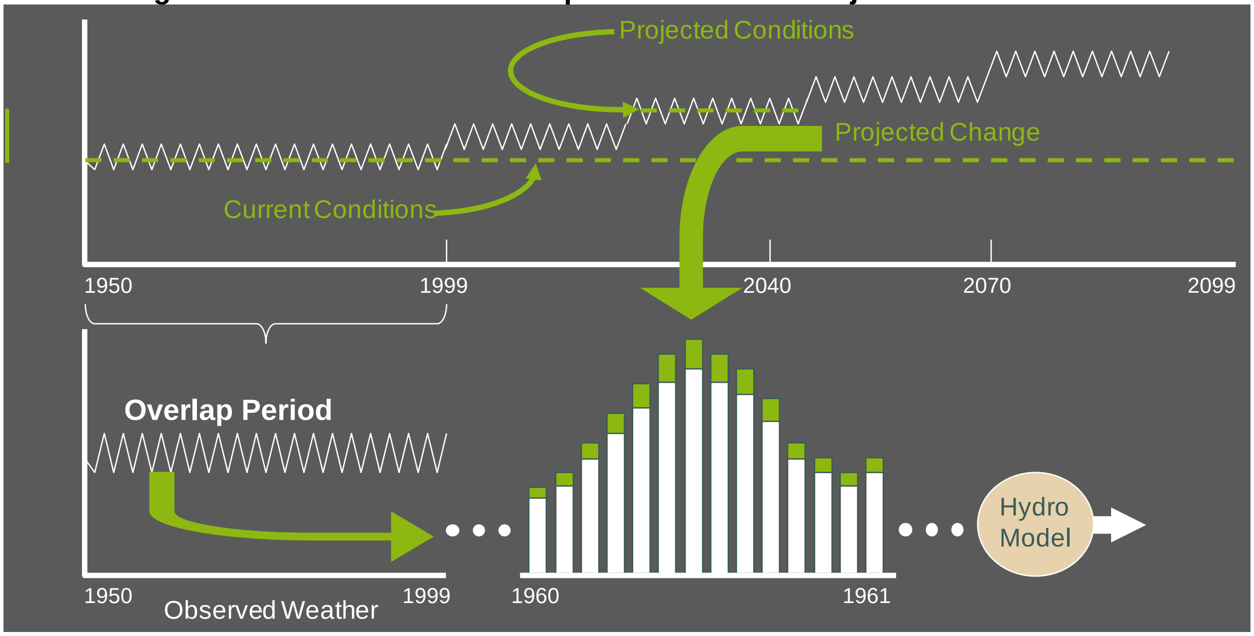
[1] There is evidence in the literature that at least in some situations some global climate models have low skill in simulating the year-to-year variability of precipitation.

Applying Climate Adjustments

The first step, common to developing both climate-adjusted CIR and climate-adjusted natural flows, is generating a time series of weather that represents the climate-adjusted condition—the observed weather adjusted to represent the projected change in temperature and precipitation[2]. The development of the climate-adjusted weather is illustrated in Figure 1.

Figure 1 – Illustration of Development of Climate-Adjusted Weather



A climate projection is the output of one run of a global climate model (GCM) with a given set of initial and boundary conditions. In Figure 1 the climate projection is illustrated in the upper half of the figure. Each projection consists of an overlap period and a projection period. In Figure 1 the overlap period runs from 1950 through 1999 and the projection period runs from 2000 through 2099. Projected climate change at a particular point in the future is determined by comparing the average condition during all or part of the overlap period with the average future condition. In CRWAS, the change in temperature for the period 2040 was characterized by calculating the monthly average temperature for the period 2025 – 2054 (projected conditions in Figure 1) and for each month of the year subtracting the corresponding average value for the period 1970-1999 (current conditions in Figure 1). The same approach is used with precipitation except a ratio rather than a difference is used. This yields the projected change shown in Figure 1, which is expressed as a monthly pattern of change.

The projected change is then applied to each month in the historical weather. For temperature the change is additive, for precipitation it is a scaling factor. Figure 2 is a flow chart of this process.

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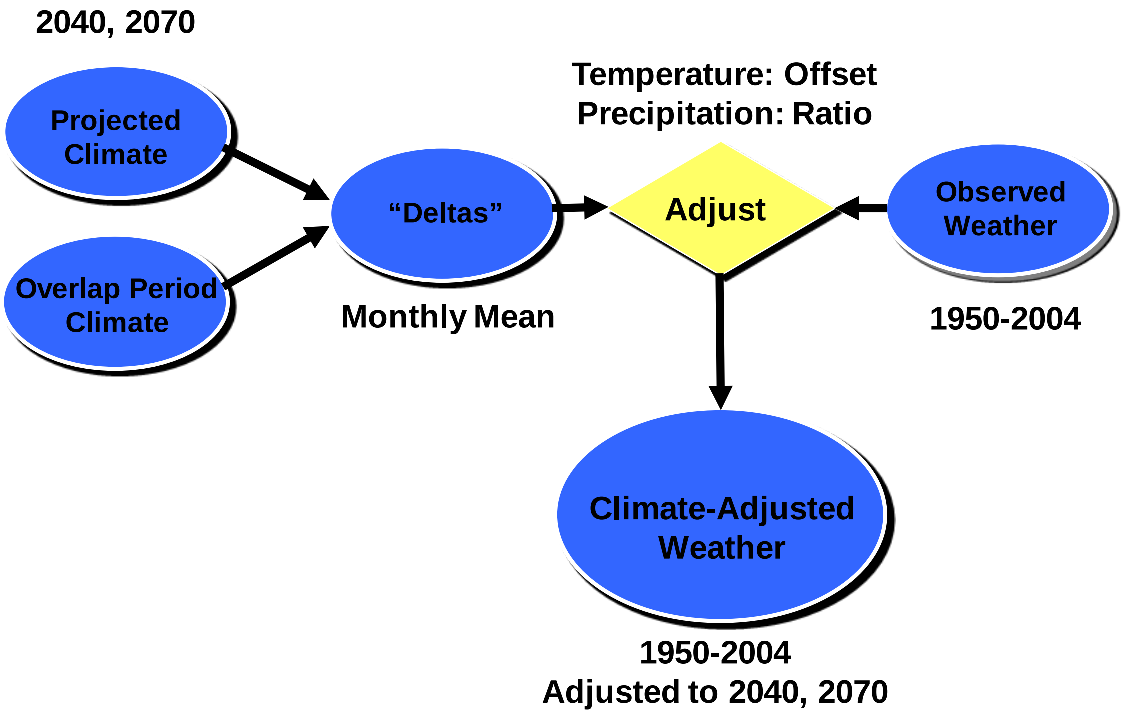
[2] No down-scaled data for winds are available, so wind was not adjusted in the CRWAS climate-adjusted weather data set.

Figure 2. Method for Developing Climate-Adjusted Weather



For the gridded data used in the CRWAS hydrology modeling this process is repeated for each grid cell, and for each month of the year. Because the hydrology modeling (VIC) uses daily data, each day of the month is adjusted by the same offset (for temperature) and the same ratio (for precipitation). This process is straightforward because the grid geometry for the observed weather and the climate projections are identical.

The consumptive use analyses for the Study basins superimposes historical or projected mean monthly temperature and total monthly precipitation for each of the 54 climate stations in the Study area on current irrigated acreage and crop types to estimate crop irrigation requirements (CIR). Climate adjustments for each of the ten climate projections were developed by adjusting the data at each weather station location by the projected change for the grid cell in which the weather station is located. Projected change in temperature was provided as net monthly increases to historical temperature, in degrees Celsius, for the Study period 1950 through 2005. Projected change in precipitation was provided as a scale factor of historical precipitation for the Study period 1950 through 2005.

Historical temperature and precipitation StateCU input files were developed as part of the CDSS. The CDSS Data Management Interface, TSTool, includes the capabilities to perform addition and scaling operations, and was used to create new mean monthly temperature and total monthly precipitation input files for each of the ten climate projections. The data-centered "command" approach allowed instructions to be created that directed TSTool to perform the analysis for one climate projection; then the commands were duplicated for the other nine projections.

Trend analyses were performed to better understand the spatial aspect of temperature and precipitation changes associated with the climate projections.

Climate-Adjusted Crop Irrigation Requirement

StateCU Consumptive Use Methodology

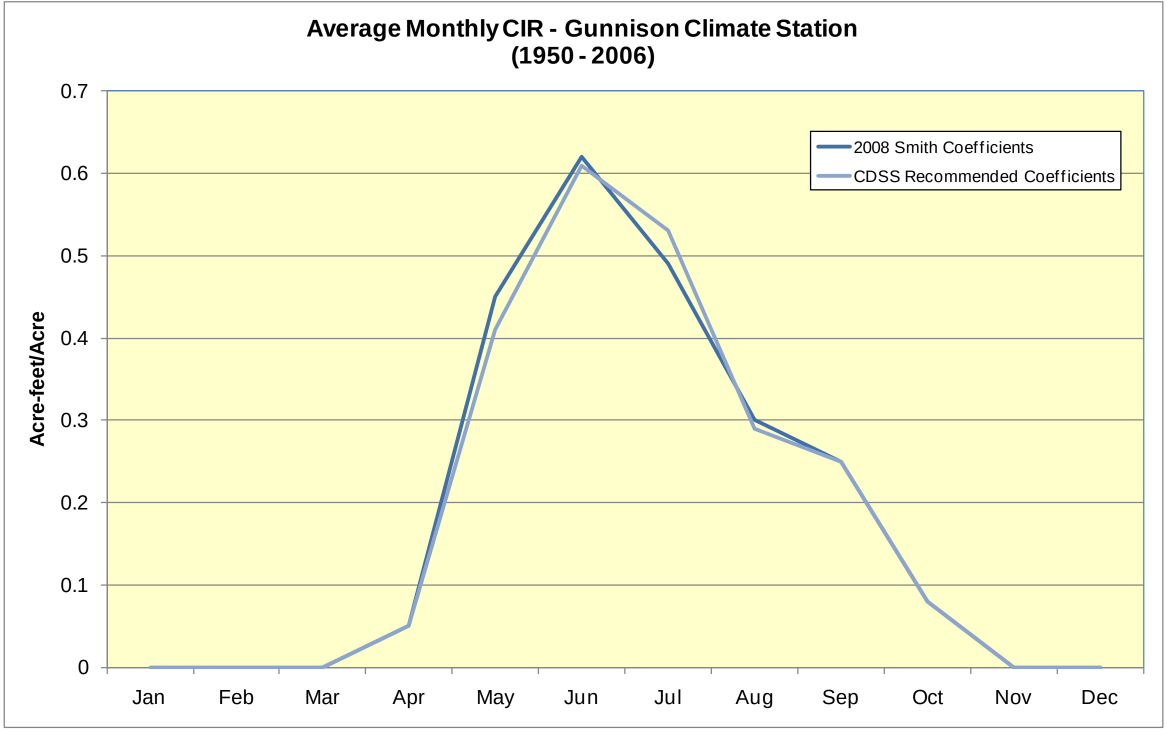
The consumptive use analyses for the Study basins superimpose historical or projected mean monthly temperature and total monthly precipitation on current irrigated acreage and crop types to estimate crop irrigation requirements (CIR). Climate data required for a detailed daily method, such as Penman-Monteith, is not available in the Study basins. Therefore, CDSS has adopted a monthly Blaney-Criddle approach using StateCU, incorporating locally calibrated crop coefficients where available.

Crop irrigation requirement is estimated in CDSS first by using the Blaney-Criddle approach to determine potential crop evapotranspiration (ET). Potential crop ET, also called potential crop consumptive use, is an estimate of the maximum amount of water a crop could consume if given a full water supply. Crop irrigation requirement is the potential crop ET less the amount of precipitation effective in meeting a portion of the potential crop ET. CDSS has selected the SCS Effective Rainfall method outlined in SCS Technical Release 21 (TR-21). Crop irrigation requirement is an estimate of the maximum amount of water a crop could consume if given a full irrigation supply.

For irrigated pasture grass above 6,500 feet elevation, the originally Blaney-Criddle method is used with calibrated crop coefficients recommended in a comprehensive study of high-elevation lysimeter data sponsored by Denver Water, “Evapotranspiration and Agronomic Responses in Formerly Irrigated Meadows, South Park, Colorado.” The basin-specific Historic Crop Consumptive Use Analysis reports detail the CDSS investigation that resulted in selection of the coefficients. Nearly 50 percent of the irrigated acreage in the Study basins is pasture grass grown above 6,500 feet elevation.

After the CDSS investigation, a study sponsored by the Upper Gunnison Water Conservancy District was published by Dr. Dan Smith that presented calibrated coefficients based on a more recent lysimeter study near Gunnison, Colorado. As part of CRWAS, the results were reviewed, and the Smith calibrated crop coefficients were compared to the coefficients used in the CDSS modeling effort. Figure 3 shows the comparison of crop irrigation water requirement using the CDSS-adopted high-altitude coefficients compared to the coefficients recently developed by Smith. As shown, the differences are minor, resulting in an average annual difference in crop irrigation requirement of less than 1 percent using historical temperature and precipitation at the Gunnison climate station, which allowed the continued use of CDSS-adopted high-altitude crop coefficients.

Figure 3 – CIR Using CDSS Coefficients and 2008 Smith Coefficients



For irrigated pasture grass grown below 6,500 feet elevation, and for other crops grown in the Study basins, the modified Blaney-Criddle method is used with crop coefficients recommended by TR-21. Because locally calibrated crop coefficients are not available, an elevation adjustment of 10 percent upward for each 1,000 meters above sea level is applied to potential consumptive, as recommended in the ASCE Manuals and Reports on Engineering Practice No. 70, Evapotranspiration and Irrigation Water Requirements (1990) and used by the State Engineer's Office.

In addition to crop coefficients, growing season "triggers" are defined in TR-21. For most perennial crops, including grass pasture, the growing season start and end dates are based on mean monthly temperature. This is ideal for the CRWAS analysis, as it allows growing seasons to vary with alternate projected monthly temperature.

For the perennial crop alfalfa, the beginning of growing season is defined by mean monthly temperature; however the end of growing season trigger is when the minimum daily temperature reaches 28 degrees Fahrenheit. The down-scale process to minimum daily temperature, and therefore killing frost dates, is much more involved than the downscaling to average monthly temperature. Therefore, an analysis was performed to determine an appropriate mean monthly temperature for alfalfa that can be used to represent, on average, the killing frost date.

The procedure resulted in the recommendation to end alfalfa growing season when the mean daily temperature (based on interpolation of mean monthly temperatures) drops below 54 degrees Fahrenheit. This provides the ability for the alfalfa growing season to vary with alternate projected monthly temperature, and is important since alfalfa makes up approximately 13 percent of the irrigated acreage in the Study basins.

StateCU Inputs

Current estimates of irrigated acreage in the Study basins, by crop type, are used in the CRWAS estimates of crop irrigation requirements under alternate projected climate conditions, as shown in Table 1. For CDSS, irrigated acreage is assigned to a water supply ditch, and the analysis is performed on a ditch-wide basis. Ditch structures are paired with the 54 climate stations used in CDSS based on proximity. As discussed previously, there are over 1,200 ditch structures represented in the CDSS analyses of crop irrigation requirements.

Table 1 – Current Irrigated Acreage by Crop Type (acres)

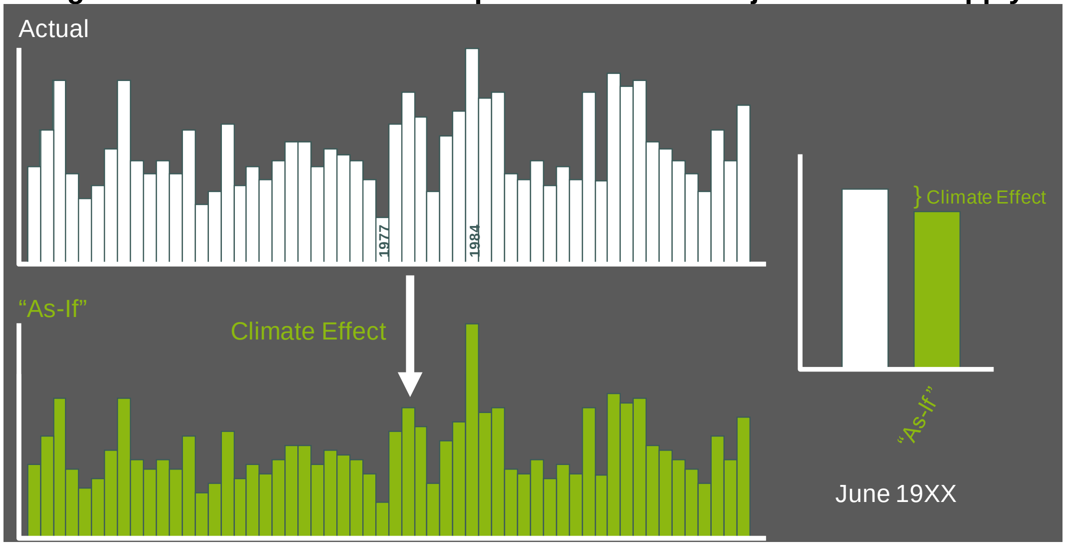
Crop Type	Yampa	White	Upper Colorado	Gunnison	San Juan / Dolores	Total
Alfalfa	3,547	3,134	37,965	30,232	26,646	101,524
Grass Pasture<6,500 ft	27,136	16,350	99,097	70,662	55,707	268,952
Orchard and Grapes^1)	3	0	3,435	6,045	894	10,377
Grains/Vegetables^2)	400	68	11,831	19,045	4,603	35,947
Corn	0	327	14,847	23,291	1,477	39,942
Grass Pasture>6,500 ft	74,539	6,993	103,672	122,677	134,735	442,616
Basin Totals	105,625	26,872	270,847	271,952	224,062	899,358

1) Orchard and grapes combined for this summary only, CIR is calculated separately for each crop.
2) Spring grains, dry beans, and vegetables are combined for this summary only; CIR is calculated separately for each crop.

Climate-Adjusted Natural Flows

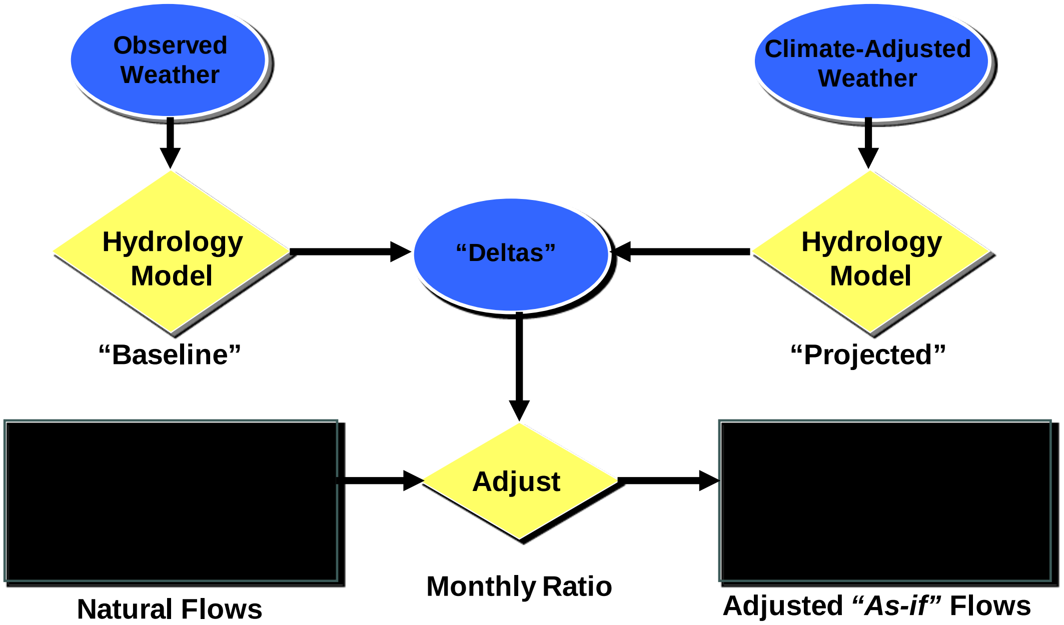
Development of climate-adjusted natural flows uses three primary data sets: historical weather, historical natural flows and projected climate conditions. Development of climate-adjusted natural flows proceeds in two principal steps. First, climate-adjusted weather is developed as described above. The observed weather and the climate-adjusted weather are then used to force a hydrology model in “with” and “without” cases and the changes between the modeled flows from those two cases represent the change in streamflow attributable to the projected change in climate conditions. These changes are applied to the historical water supply condition to produce a *climate-adjusted* water supply condition. This is the water supply condition as if the projected climate conditions had been fully developed at the start of the specified study period. The development of the climate-adjusted hydrology is illustrated in Figure 4.

Figure 4 – Illustration of development of climate-adjusted water supply



The method illustrated in Figure 4 shows the adjustment of a time-series record. For each month of the record the ratio is calculated between the two modeled values of streamflow, one based on observed weather and one based on climate-adjusted weather, and then the historical streamflow for that month is adjusted by that ratio. Figure 5 is a flow chart of this process.

Figure 5 – Method for developing "as-if" hydrology



The results of this process are traces of climate-adjusted streamflow for 227 locations required by StateMod to model water availability within Colorado, and for 29 points required by CRSS to model water availability in the Colorado River Basin. Each climate-adjusted data set consists of a 56-year trace of monthly flows. For each location there will be eleven flow traces of climate-adjusted flows: one historical trace, five climate-adjusted traces for the 2040 time frame and five climate-adjusted traces for the 2070 time frame.

Hydrology Modeling

The climate effect on streamflows is estimated using hydrology modeling. A hydrology model (VIC) takes as input weather conditions and returns as output estimates of streamflow. It simulates the significant hydrologic processes that affect the water balance and the physical processes that affect the transport of water and thus affect the timing of flows. Two principal categories of hydrology modeling (statistical models and process models) have been applied to climate change research, and within these two primary modeling categories there are a large number of individual models. The suitability of hydrology models for application to climate change impact studies varies based on both practical and scientific considerations. In addition, there are different choices of how hydrology modeling is used to represent the impacts of climate change.

Statistical hydrology models are based on deriving a functional relationship between streamflow and the climate variables – precipitation, temperature, etc—several of which are typically developed for selected seasons (i.e., monthly or for a set of months, e.g., Dec-Jan-Feb, etc.) In climate change studies, like CRWAS, use of statistical models requires the assumption that the relationships on which the model is based will hold under the climate change scenarios. However, under climate change a seasonal shift is expected in the annual streamflow hydrographs with, for example, warmer temperatures bringing earlier spring runoff (Hayhoe et al., 2004; Barnett et al., 2005; Maurer, 2007). Thus, statistical models are expected to have only a limited application in analyzing streamflows under climate change. CRWAS employed a physical process-based hydrology model, the Variable Infiltration Capacity (VIC) macro-scale hydrology model.

The VIC model is a physically distributed (gridded) macro-scale (regional-scale) hydrology model that consists of a variable-layer soil-vegetation-atmosphere transfer (SVAT) scheme used in general and regional circulation and weather prediction models. The VIC model has two main components – (i) a component to model land-surface (e.g., snow dynamics) and, (ii) a sub-surface modeling component (e.g., infiltration). These two components work in a manner with feedbacks controlling coupled land-surface and sub-surface processes such as infiltration and evapotranspiration.

Evapotranspiration (ET) is the most significant water loss process in the hydrologic water balance. As such, the reliability of a hydrology model is directly related to the accuracy and reliability of the representation of ET. In the mountainous terrain of the significant water-producing areas of the Colorado River basin, physically-based ET models, as used in VIC, are preferred for hydrology modeling over temperature-based ET models that require local calibration.

Snow accumulation and snow melt are also important processes in simulating the seasonal pattern of streamflow. Because all of the available projections of future climate show that temperature will increase, changes in the pattern of snow accumulation and melt will result. A more physically-based snow model, of the sort used in VIC, provides more confidence that simulations involving changes in temperature will result in realistic changes in snow accumulation and snow melt.

The land-surface component in the VIC model has detailed underlying physical process models, but the sub-surface component is more conceptual. So in terms of calibration, the focus was to calibrate the VIC sub-surface model. A third component is the routing model that transports simulated flows in VIC grid cells to the outlets of the individual sub-basins of the Colorado River. Parameters from the routing model were also not changed from the initial calibrated model as these parameters were determined using a physical basis.

The sub-surface model consists of five parameters that control – (i) shape of the variable infiltration curve (b_infilt), i.e. the partition of surface runoff versus soil infiltration; (ii) maximum velocity of baseflow in the lowest soil layer in a model grid cell (Dsmax); (iii) soil depth for each of the three model soil layers; and two parameters that define the onset of nonlinear baseflow dynamics in the lowest soil layer – (iv) Ws, fraction of maximum soil moisture where nonlinear baseflow occurs and (v) Ds, fraction of the Dsmax parameter at which nonlinear baseflow occurs.

A preliminary calibrated model for the Colorado River Basin was obtained from Niklas Christensen. This calibrated model provided excellent fit of simulated and observed streamflows for gage locations covering large basin areas, for example the Colorado River at the Lees Ferry gage. This is expected because of the focus of the studies for which the calibrated model had been developed. Further calibration was performed to estimate effective sub-surface model parameters to improve fit at some smaller basins using the automated optimal parameter estimation algorithm MOCOM (Yapao, et al., 1998). The five sub-surface parameters described above were optimized using the MOCOM code for a subset of sub-basins and were used to derive a composite soil file consisting of a combination of cells from the initial calibrated model and the cells with optimized soil parameters. This resultant soil file was used in carrying out the VIC model runs. No change was made to the land-surface parameters from the initial calibrated model though sensitivity analysis was carried out to test the performance with respect to simulating snow dynamics (snow water equivalent).

Re-sequencing Climate-adjusted Natural Flows

The climate-adjusted natural flows were re-sequenced into ensembles of 100 56-year traces. Because the climate-adjusted natural flows are associated with an historical year, a 56-year trace of climate-adjusted natural flows can be re-sequenced into a 100-trace ensemble using the same re-sequencing approach and the same year sequences described in the CRWAS Technical Memorandum for Tasks 6.1-6.3 (see box, below). One set of climate-adjusted flows resulted for each of the five climate projections associated with each of the two time frames, 2040 and 2070, so a total of ten ensembles of climate-adjusted natural flows were developed.

Where to find more detailed information:

Details on the choice of the Non-Homogeneous Markov Chain Model for re-sequencing environmental variables are provided in the CRWAS Technical Memorandum *Task 6.1 – Literature Review and Method Evaluation, Task 6.2 – Analyses of Tree-Ring Data, and Task 6.3 – Recommendation for Extending Historical Hydrology*. Additional details on the Non-Homogeneous Markov Chain Model are provided in CRWAS Technical Memorandum *Task 6.4 – Methods for Alternate Hydrology and Water Use*. Results of statistical analysis of the extended historical hydrology are provided in CRWAS Technical Memorandum *Task 6.7 Summarize Alternate Historical Hydrology.*

Statistical Analysis of Climate Change Hydrology

Three separate statistical analyses were conducted on climate-adjusted environmental variables.

- Low-flow Intensity-duration. Intensity-duration analysis provides a comparison of low-flow intensity for different durations. Mean flow values are calculated for the full 56-year period and for low flows at durations of two years, five years, and ten years. The four values are calculated for a given location for all five climate projections. Separate analyses are done for both time frames.

- Seasonal conditions. The seasonal distribution of climate-adjusted conditions is calculated for natural flow data (a monthly hydrograph) and for temperature, precipitation and CIR.

- Frequency analyses. Frequency analyses were applied only to natural flow data. The frequency analyses were the same as were applied to the extended historical hydrology and described in CRWAS Technical Memorandum Task 6.7 – *Summarize Alternate Historical Hydrology*. These analyses were applied to each of the five ensembles of alternate climate change hydrology for each time frame and a set of box-whisker charts were developed for each site, showing the five statistics (annual mean flows, longest surplus spell length, longest drought spell length, maximum surplus volume, and maximum drought volume) for each of the five alternate streamflow data sets, for the composite population consisting of the combined data from all five alternate streamflow data sets, and, for reference, for the extended historical hydrology.

Where to find more detailed information:

More detail on the statistical analyses described in this section can be found in CRWAS Technical Memorandum Task 6.7 – *Summarize Alternate Historical Hydrology*, available at http://cwcb.state.co.us/.

Nature of Data

Climate-adjusted data were developed as described above for the following hydrologic and water supply variables:

- Temperature
- Precipitation
- Crop Irrigation Requirement (CIR)
- Naturalized flow

Each climate-adjusted dataset consisted of a 56-year time series of monthly values for each of the ten climate projections. In addition, an ensemble of 100 re-sequenced traces of the climate-adjusted historical data for natural flows was analyzed to evaluate the frequency of annual flows, droughts and wet spells.

Statistical Analyses

Low-flow Intensity-duration analysis was applied to streamflow data to illustrate the impact of projected climate on mean flows and on the intensity of low flows at specified durations. Comparison of these values across the projections illustrates the uncertainty inherent in the climate projections (projection-to-projection variability).

Mean flow values are calculated for the full 56 years and for low flows at durations of two years, five years and ten years. The intensity values for the four durations are calculated for a given location for all five climate projections and plotted in low-flow comparison charts.

The low-flow comparison charts illustrate the effect of projected future climate conditions on statistics of low flows but not on wet spells. The modeling methods used to quantify water availability will quantify the impact of both drought and wet spells on the physical and legal availability of water. Phase 2 of CRWAS will address potential projects that can put water from wet spells to use to support new beneficial consumptive or non-consumptive use.

Average monthly values (e.g. an average monthly hydrograph or hyetograph) are calculated for all four hydrologic variables and are used to illustrate the impact of projected climate on the seasonal pattern of those variables. Comparison of these values across the projections illustrates the uncertainty inherent in the climate projections (projection-to-projection variability).

For each month of the year, the mean value of a hydrologic variable is calculated over the 56 values for that month contained in the trace. The twelve average monthly values are calculated for a given location/variable for all five climate projections.

Boxplots for statistics of annual flows, surplus spells and drought spells were developed for natural flow as described in CRWAS Technical Memorandum *Task 6.7 Summarize Alternate Historical Hydrology.* The boxplots illustrate the impact of projected climate on the frequency distribution of annual and spell statistics Comparison of the boxplots across the projections illustrates the uncertainty inherent in the climate projections (projection-to-projection variability). In addition, a boxplot is provided for the comprehensive population encompassing all five ensembles of climate-impacted flow from a particular time frame. The calculation of spell length and magnitude are based on the mean within a particular climate-impacted trace and not on the mean of the historical period.

Maps were developed to illustrate the spatial pattern of change in temperature, precipitation and CIR. Changes in precipitation were mapped separately for summer (April through October) and winter (November through March) precipitation.

Where to find more detailed information:

Details on the approach used to perform statistical diagnostic analyses on the ensemble of extended historical hydrology and the results of those analyses and an explanation of boxplots are provided in the CRWAS Technical Memorandum *Task 6.7 – Summarize Alternate Historical Hydrology* available at http://cwcb.state.co.us/.

Results of Analyses

This section provides descriptions of primary CRWAS findings associated with the following list of quantitative parameters. In addition to the list below, the last part of this section provides a description of general qualitative Study findings.

- Temperature
- Precipitation
- Crop Irrigation Requirement
- Climate-Adjusted Natural Streamflow

Presentation of Findings

The primary chart types used to present quantitative Study findings are referred to herein as “Band Charts” (monthly hydrograph charts) and “Low-Flow Comparison Charts”, for which sample figures and descriptions are included below.

Each of the five projections of future climate for a particular time period (2040 or 2070) represents alternative possible futures with respect to mean climate conditions. The band charts and the low-flow comparison charts in the following sections show the range of those possible futures with respect to historical conditions that were experienced in the 56 years from 1950 through 2005.

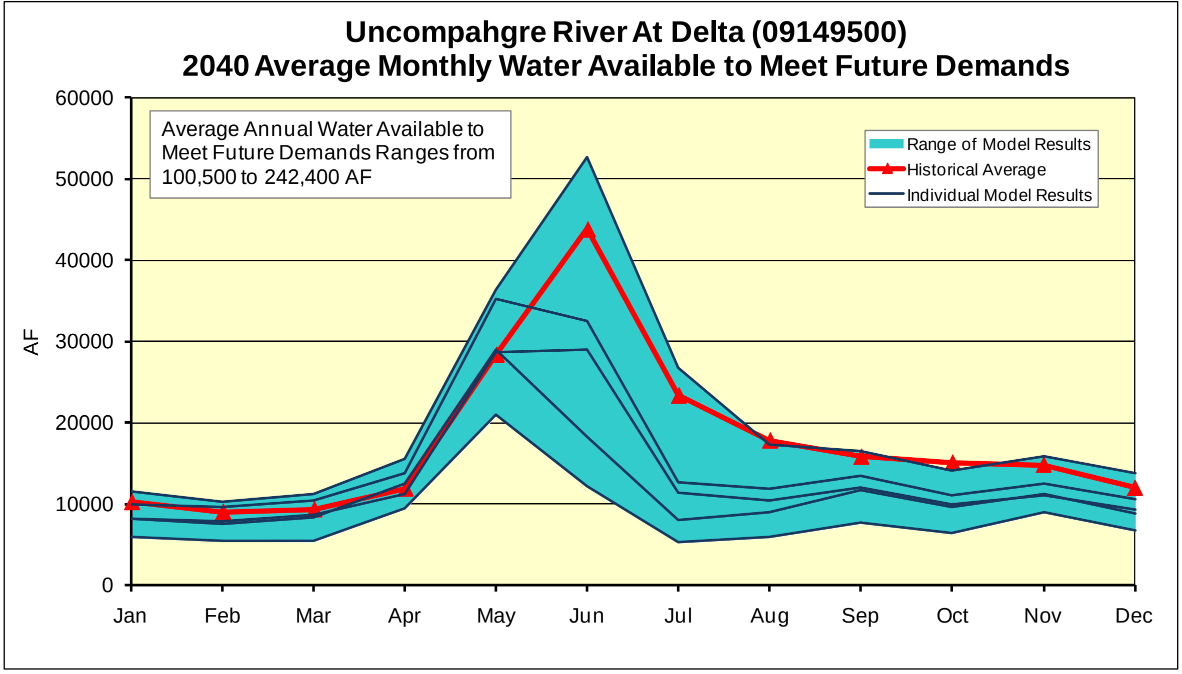
Comparisons are sometimes made in the text between historical average values and values estimated by averaging the five climate projections. When the five climate projections are averaged together for comparison, they are referred to as the five climate projections’ “combined average”. For instance, if historical climate-based average annual values are compared to the average of the five climate projections average annual values, the reference will read “historical average annual values are greater than the five climate projections’ combined average.”

Band Charts

Figure 6 illustrates graphically the effect of projected future climate on the average monthly distribution of flows. This monthly hydrograph chart (band chart) shows several pieces of information. The red line connecting filled triangles represents the average monthly hydrograph from the historical record during the Study period. The estimated average monthly hydrographs for the five different projections of future climate are represented by the thin dark blue lines. The filled band shows at a glance the overall range of the projected future average monthly hydrographs. This chart can help understand how runoff and low flows may shift during the year, and illustrates the uncertainty inherent in the climate projections (projection-to-projection variability).

Each of the five projections of future climate for a particular time period (2040 or 2070) represents alternative possible futures with respect to mean climate conditions. The band charts show historical average monthly values (in CRWAS, the Study period lasted 56 years, so the historical monthly averages for that duration are shown), and the average monthly value for each of the five climate projections. The wide cyan band encompasses the range of the alternative possible future values, calculated from the five climate projections.

Figure 6 – Example Presentation of Findings (Band Chart)

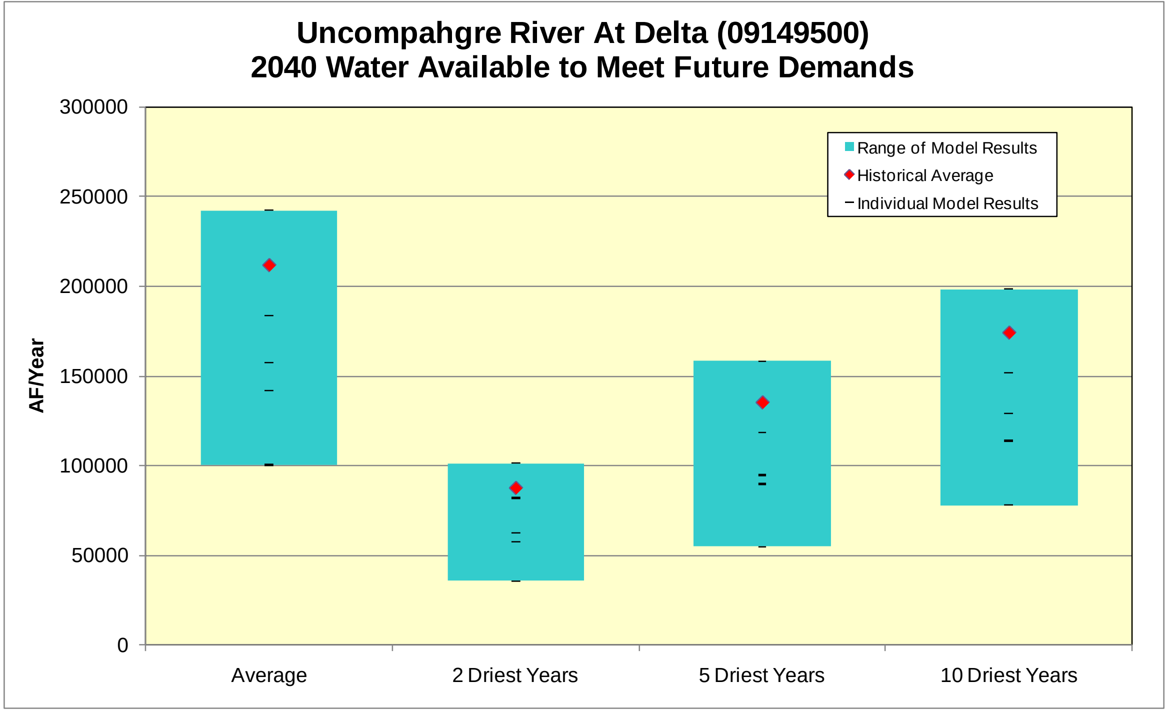


Low-Flow Comparison Charts

Figure 7 illustrates the effect of projected future climate conditions on mean flows and on low-flow events. From left to right, the chart represents four statistics of annual flow: average annual flow over the 56-year study period, the lowest consecutive 2-year average flow in the 56-year study period, the lowest consecutive 5-year average flow in the 56-year study period, and the lowest consecutive 10-year average flow in the 56-year study period.

For each statistic several pieces of information are shown. The red filled diamond represents the value of the statistic from the historical record during the Study period. The estimated values of the statistics for the five different projections of future climate are represented by dashes. The wide cyan-colored bars show the overall range of the projected future values of the statistic.

Figure 7 – Example Presentation of Findings (Low-Flow Comparison Chart)



Temperature

Temperatures based on projected climate changes were compared to historical temperatures at the 54 climate stations used in the consumptive use analyses. These 54 climate stations are located throughout the Study basins, as shown in Figure 8, and represent areas of agricultural production. Figure 8 shows the increase in average annual temperature for the 2040 climate projections compared to historical average annual temperature, based on the 54 climate stations shown in the figure over the 1950 through 2005 study period.

Figure 8 – 2040 Projected Average Annual Temperature Increase from Historical (deg F)

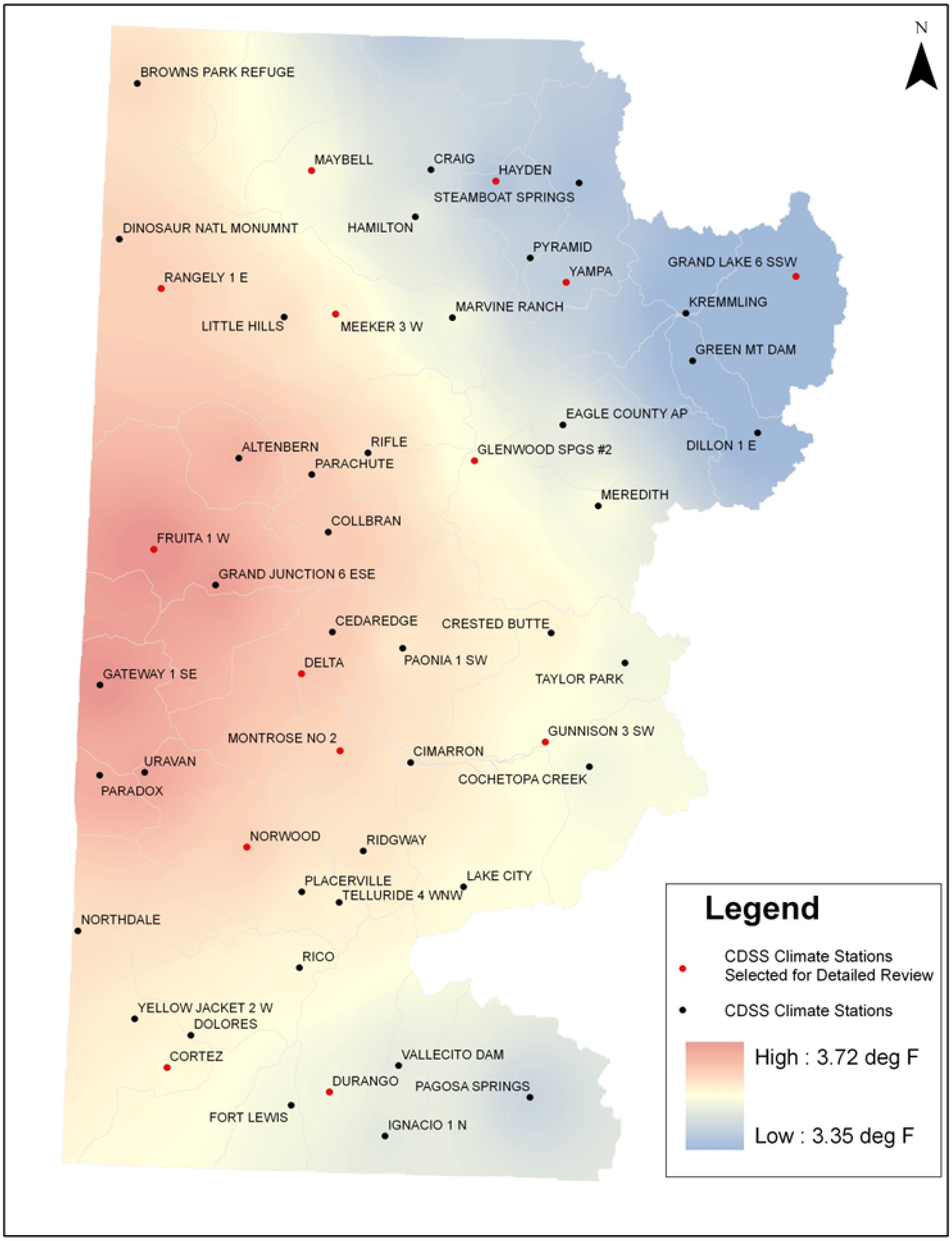


Table 2 presents the range of average annual temperature increases from historical values for the 2040 climate projections at selected climate stations. Temperature increases are based on the 1950 through 2005 study period. Also presented is the average of the five 2040 climate projections compared to historical values. The climate stations presented in the table were selected to represent lower, middle, and higher elevations in each of the Study basins. The table includes the elevation and elevation designation, plus the location as generally in the northern or southern part of the State.

Table 2 – 2040 Average Annual Projected Temperature Compared to Historical Temperature

Climate Station	Elevation	Elevation Designation	Location	Increased Temperatures Degrees Fahrenheit		
				Lowest Projection	Highest Projection	Average of Projections
Fruita 1W	4480	Lower	North	2.0	5.4	3.7
Glenwood	5880	Mid	North	1.8	4.6	3.5
Grand Lake	8288	Higher	North	1.6	5.0	3.3
Rangely 1E	5290	Lower	North	1.9	5.3	3.6
Meeker 3W	6180	Mid	North	1.9	5.3	3.6
Maybell	5908	Lower	North	1.8	5.2	3.5
Hayden	6440	Mid	North	1.7	5.1	3.4
Yampa	7890	Higher	North	1.8	5.2	3.5
Delta 3E	5010	Lower	South	1.9	5.3	3.7
Montrose No 2	5785	Mid	South	1.8	5.3	3.6
Gunnison 3SW	7640	Higher	South	1.7	5.2	3.5
Cortez	6153	Lower	South	1.9	5.4	3.6
Durango	6592	Mid	South	1.8	5.3	3.5
Norwood	7020	Higher	South	1.9	5.3	3.6

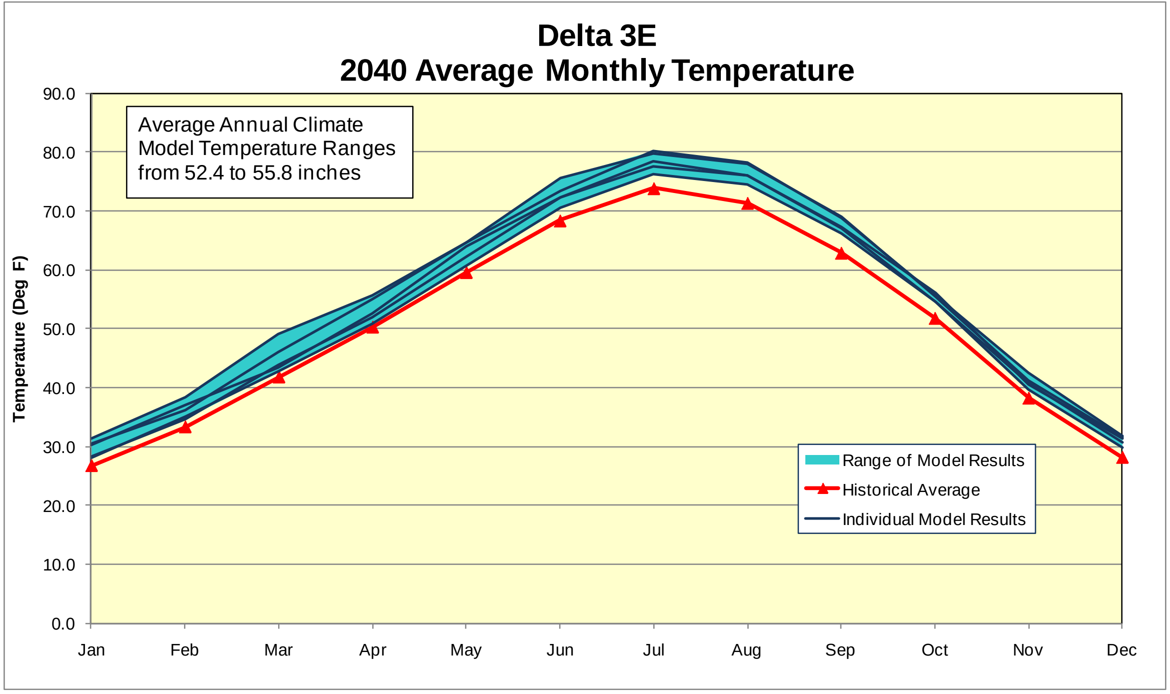
The basin-wide increase for the five climate change projections' combined average is 3.6 degrees Fahrenheit. As shown, the 14 stations show combined average increases ranging from 3.3 to 3.7 degrees Fahrenheit. The lowest increase in average annual projected temperature is 1.6 degrees Fahrenheit in Grand Lake and the greatest increase in average annual projected temperature is 5.4 degrees Fahrenheit in both Fruita and Cortez. The following general trends can be observed from Table 2 and Figure 8:

- Each of the five climate projections shows average annual temperature increasing over historical values.
- The increase in temperature is greater at lower elevations.
- The increase in temperature is less than the basin-wide average at the higher elevation stations of Grand Lake, Yampa, and Hayden.

Figure 9 shows the average monthly temperature for each 2040 climate projection compared to the historical average monthly temperature at the Delta climate station over the 1950 through 2005 study period. Similar graphs are included in Appendix A of the CRWAS Phase I Report for each selected climate station for both 2040 and 2070 projections. As with Figure 9, similar figures in the CRWAS Phase I Report Appendix A generally show that temperature increases are similar for each month.

Taken as a whole, the temperature graphs for the 2040 time frame show that the temperature increases each month and that there is not a wide range of average temperatures between the five climate projections.

Figure 9 – Delta 2040 Average Monthly Temperature Comparison



Precipitation

Climate projected precipitation was compared to historical precipitation at the 54 climate stations used in the consumptive use analyses. Winter months (November through March) and the months of April through October show different trends, therefore are discussed separately. Table 3 presents the range of average winter (November through March) precipitation variation from historical values for the combined 2040 climate projections at selected climate stations over the 1950 through 2005 study period. Also presented is the combined average of the five 2040 climate projections compared to historical values. The climate stations represent lower, mid, and higher elevations in each of the Study basins. The table includes the elevation and elevation designation, plus the location as generally in the northern or southern part of the State.

Table 3 – 2040 Average Winter (Nov through Mar) Projected Precipitation Compared to Historical Precipitation

Climate Station	Elevation	Elevation Designation	Location	Percent of Historical * Lowest Projection	Percent of Historical * Highest Projection	Percent of Historical * Average of Projections
Fruita 1W	4480	Lower	North	96%	112%	106%
Glenwood Springs 2	5880	Mid	North	104%	115%	109%
Grand Lake 6SSW	8288	Higher	North	109%	122%	113%
Rangely 1E	5290	Lower	North	103%	115%	109%
Meeker 3W	6180	Mid	North	103%	116%	109%
Maybell	5908	Lower	North	104%	118%	110%
Hayden	6440	Mid	North	107%	121%	112%
Yampa	7890	Higher	North	107%	121%	111%
Delta 3E	5010	Lower	South	99%	112%	107%
Montrose No 2	5785	Mid	South	98%	114%	108%
Gunnison 3SW	7640	Higher	South	101%	116%	109%
Cortez	6153	Lower	South	87%	115%	107%
Durango	6592	Mid	South	92%	116%	108%
Norwood	7020	Higher	South	95%	113%	107%

*Less than 100% difference indicates less annual projected rainfall than historical.

Figure 10 shows the combined average increase in precipitation during the winter months of November through March for the 2040 climate projections as a percentage of historical average winter precipitation over the 1950 through 2005 study period, based on the 54 climate stations used in the CDSS modeling. The basin-wide combined average precipitation for the five projections in winter months is 109 percent of historical average. Winter precipitation change from historical varies by location. The following general trends can be observed:

- Combined average winter precipitation for the five 2040 climate projections increases from historical values basin-wide, ranging from 106 to 113 percent of historical winter precipitation.
- The projections show winter precipitation both increasing and decreasing throughout the State for individual climate projections.
- Each of the five projections show increases in winter precipitation at the northern most climate stations in the Yampa and White basins.
- Each of the five projections shows an annual increase at the highest elevation climate stations, including Yampa, Grand Lake and Gunnison.
- The stations with the least combined average increase in precipitation are at the lower elevations and in the southwest portion of the State.
- Coupled with the increase in temperature during the winter months, the projections indicate a shift from snow to rain in the early and late winter months.

Figure 10 – 2040 Percent of Historical Winter (November - March) Precipitation

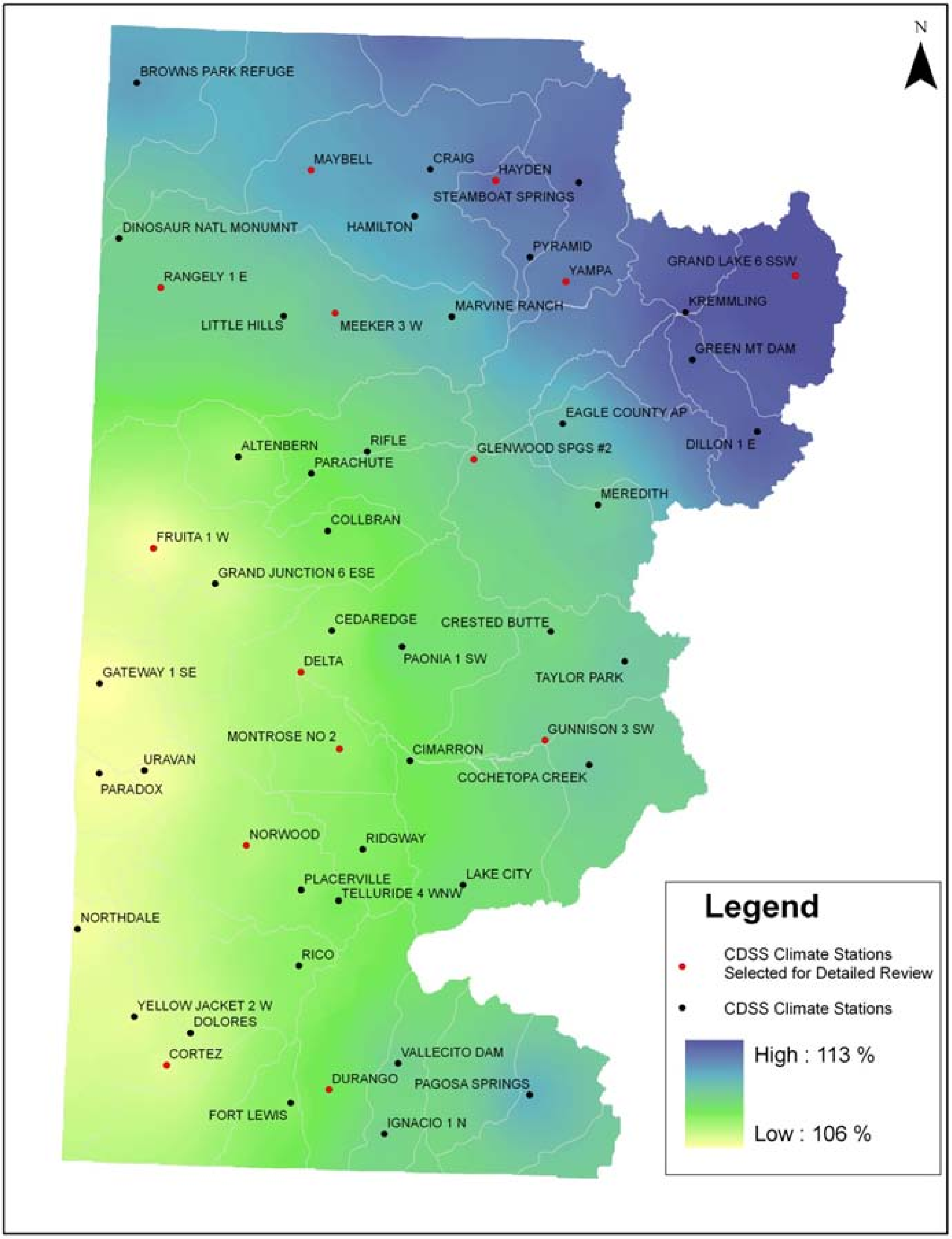


Table 4 presents the range of average April through October precipitation variation from historical values for the combined 2040 climate projections at selected climate stations over the 1950 through 2005 study period. Also presented is the combined average of the five 2040 climate projections compared to historical values. The climate stations represent lower, mid, and higher elevations in each of the Study basins. The table includes the elevation and elevation designation, plus the location as generally in the northern or southern part of the State.

Table 4 – 2040 Average Apr through Oct Projected Precipitation Compared to Historical Precipitation

Climate Station	Elevation	Elevation Designation	Location	Percent of Historical * Lowest Projection	Percent of Historical * Highest Projection	Percent of Historical * Average of Projections
Fruita 1W	4480	Lower	North	81%	102%	91%
Glenwood Springs 2	5880	Mid	North	82%	107%	93%
Grand Lake 6SSW	8288	Higher	North	82%	104%	92%
Rangely 1E	5290	Lower	North	82%	104%	94%
Meeker 3W	6180	Mid	North	82%	105%	94%
Maybell	5908	Lower	North	83%	106%	95%
Hayden	6440	Mid	North	81%	107%	95%
Yampa	7890	Higher	North	81%	107%	95%
Delta 3E	5010	Lower	South	82%	104%	92%
Montrose No 2	5785	Mid	South	82%	104%	91%
Gunnison 3SW	7640	Higher	South	82%	106%	90%
Cortez	6153	Lower	South	79%	102%	90%
Durango	6592	Mid	South	80%	103%	91%
Norwood	7020	Higher	South	82%	104%	92%

Figure 11 shows the combined average decrease in precipitation during the months of April through October for the 2040 climate projections as a percentage of historical average precipitation over the 1950 through 2005 study period, based on the 54 climate stations used in the CDSS modeling. The basin-wide combined average precipitation for the five projections during the months of April through October is 93 percent of historical average. The following April through October precipitation trends can be observed:

- Combined average April through October precipitation for the five 2040 climate projections decreases from historical basin-wide, ranging from 90 to 96 percent of historical April through October precipitation.
- The projections show April through October precipitation both increasing and decreasing throughout the State for individual climate projections.
- April through October precipitation decreases more in the southwestern corner of the State, and decreases less at higher elevations.

Figure 11 – 2040 Percent of Historical Winter (November - March) Precipitation

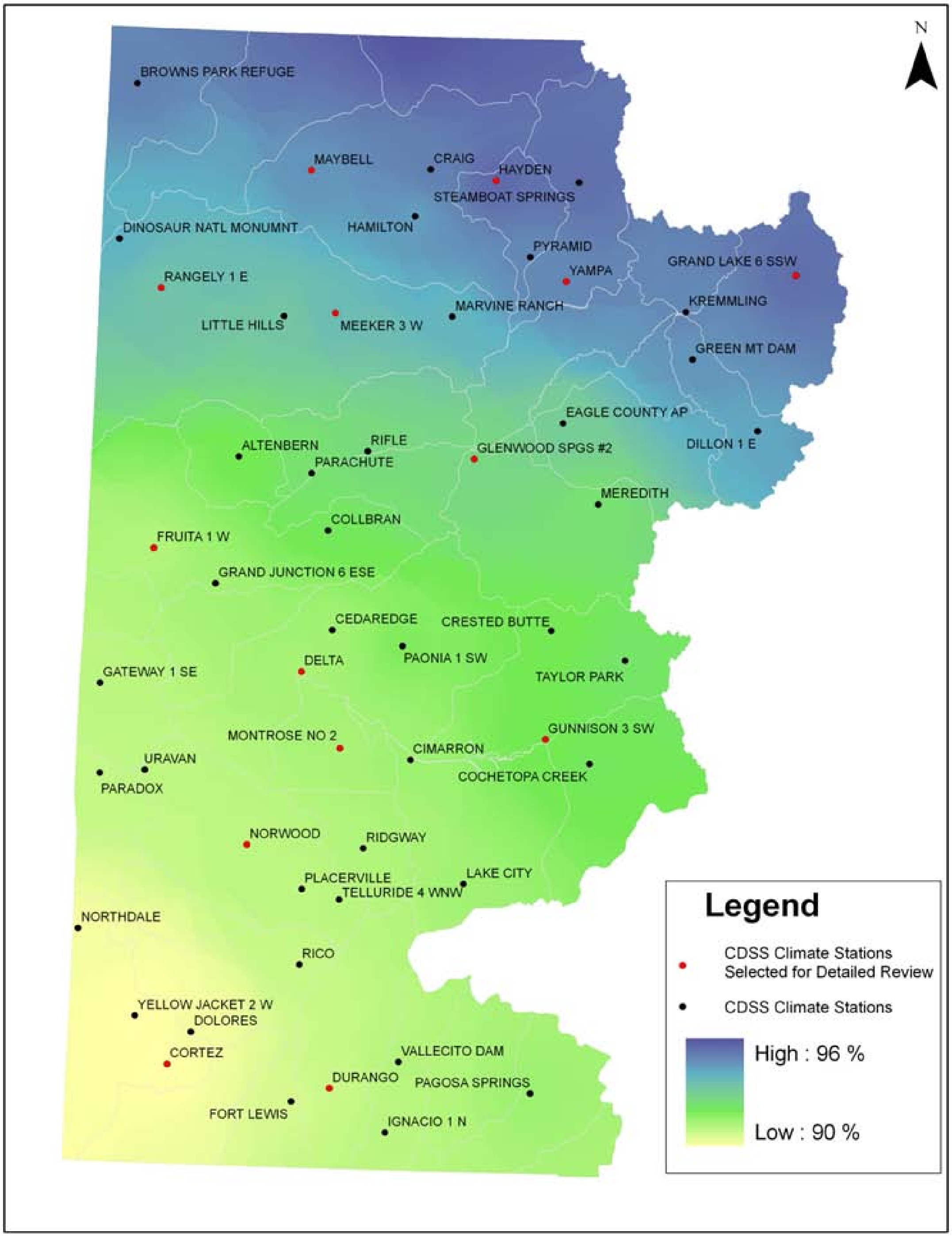
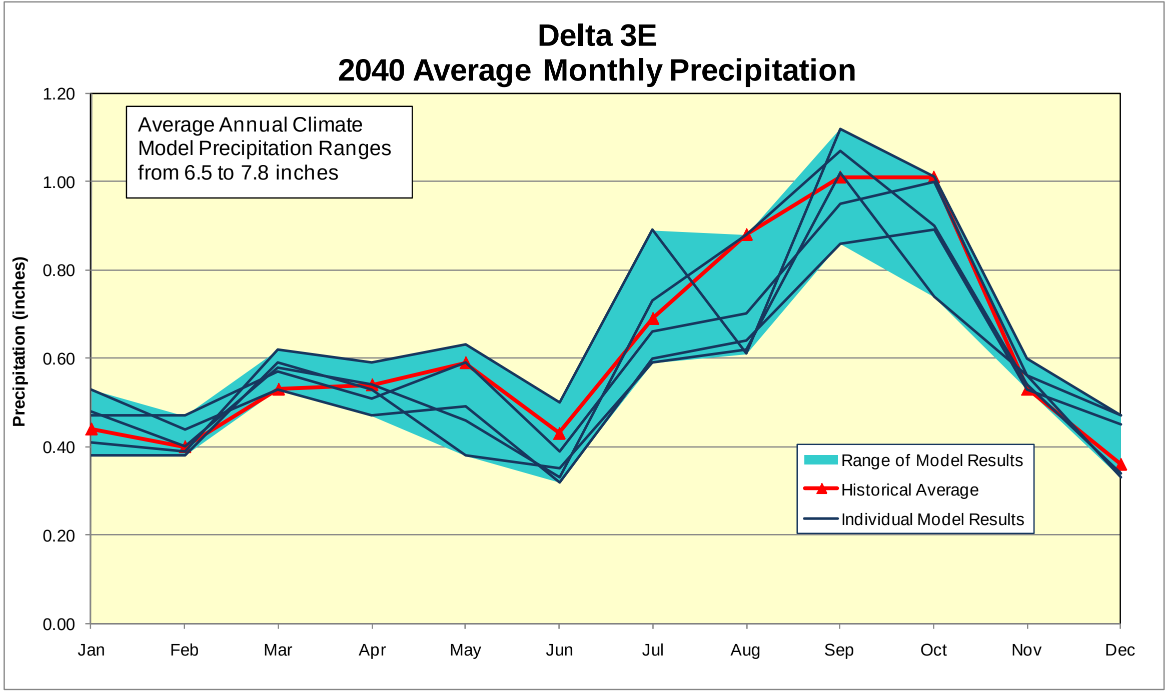


Figure 12 shows the average monthly precipitation for each 2040 climate projection compared to the historical average monthly precipitation for the 1950 through 2005 study period at the Delta climate station. Similar graphs are included in Appendix B of the CRWAS Phase I Report for each selected climate station for both 2040 and 2070 projections. As with Figure 12, figures in Appendix B of the CRWAS Phase I Report generally show the following:

- Each of the climate projections show precipitation generally greater than historical averages during the winter months from November through March throughout the Study basins. However, it is only slightly higher in the winter months for the lowest elevation station at Fruita, and for the southern-most stations including the Cortez, Norwood, and Durango.

- Most of the climate projections show precipitation less than historical averages during the irrigation season, from May through October, with the exception of July. Average projected precipitation in July is about the same as historical average July precipitation throughout the Colorado basins.

Figure 12 – Delta 2040 Average Monthly Precipitation Comparison



Climate model experts recognize that there is more uncertainty in the global climate models' ability to predict summer precipitation than winter precipitation. According to the CWCB-sponsored report "Climate Change in Colorado, a Synthesis to Support Water Resources Management and Adaptation, "the scale of global climate models limits their ability to accurately predict the local thunderstorms that dominate rainfall during the summer months in the Study basins." In addition, the report indicates that larger scale systems such as the monsoon-based conditions that strongly influence the southern areas of the State are not well simulated by climate models. Until more detailed global climate models are created that better represent "regional" weather processes that affect temperature and precipitation of the Colorado River basin, the scientific information used in this Study is currently the best available for a study of this nature.

Where to find more detailed information:

Climate Change in Colorado, a Synthesis to Support Water Resources Management and Adaptation available at http://wwa.colorado.edu/.

Irrigation Water Requirement

Crop irrigation requirements were estimated using the monthly Blaney-Criddle methods in StateCU, as discussed above. The Blaney-Criddle method relies on mean monthly temperature to both define the growing season, and in the monthly equation, to determine potential crop consumptive use. Therefore, as temperature increases, potential crop consumptive use increases.

Crop irrigation water requirement is determined by subtracting the amount of monthly precipitation estimated to be effective in directly meeting crop demands from potential crop consumptive use. Therefore, as irrigation season precipitation decreases, crop irrigation requirement increases.

Table 5 presents the combined average annual grass pasture crop irrigation requirement variations from historical for the 2040 climate projection scenarios at the selected climate stations based on the 1950 through 2005 study period. Also shown is the average change in the start and end of the growing season for grass pasture compared to historical seasons.

Table 5 – 2040 Average Annual Grass Pasture CIR and Growing Season Length Compared to Historical

Climate Station	% Difference CIR	Increase In CIR (inches)	Earlier Start of Growing Season (days)	Later End to Growing Season (days)	Increase to Growing Season (days)
Fruita 1W	21%	6.4	11	7	18
Glenwood Springs	25%	5.8	11	8	19
Grand Lake 6SSW	16%	3.7	9	9	18
Rangely 1E	22%	6.0	9	7	16
Meeker 3W	28%	5.5	10	8	18
Maybell	26%	5.2	9	7	16
Hayden	25%	4.8	8	7	15
Yampa	13%	3.3	9	8	17
Delta 3E	21%	6.4	11	7	18
Montrose No 2	23%	6.4	12	8	20
Gunnison 3SW	13%	3.5	9	7	16
Cortez	24%	6.2	14	8	22
Durango	10%	2.8	13	8	21
Norwood	10%	2.7	9	8	16
Average	**20%**	**4.9**	**10.5**	**7.6**	**18.1**

As shown in Table 5, crop irrigation requirement based on the 2040 climate projection scenarios increased by 20 percent throughout the Colorado River basins, resulting in an average annual increase in crop irrigation requirement ranging from 2.7 to 6.4 inches per year. The following general trends can be observed:

- Increases in crop irrigation requirement throughout the Colorado River basins are primarily due to higher temperature, which increases: 1) the number of days in the growing season for perennial crops such as grass pasture, alfalfa, and orchards and 2) the crop demand for irrigation water. In addition, precipitation is less during the growing season, decreasing the amount of crop demand satisfied from effective precipitation; thereby increasing the crop demand for irrigation water.

- The increase in crop irrigation requirement is greater at lower elevation stations including Fruita, Delta, Montrose, and Cortez.

Figure 13 shows the average monthly grass pasture CIR at the Delta climate station for each of the 2040 climate projections compared to the historical average monthly CIR for the 1950 through 2005 study period. Similar graphs are included in Appendix C of the CRWAS Phase I Report for each selected climate station for both 2040 and 2070 projections. As with Figure 13, the figures shown in Appendix C of the CRWAS Phase I Report generally show that peak CIR continues to be in the same month as occurred historically (July in most locations throughout the Study basins) except as noted below.

Figure 13 – Delta 2040 Average Monthly CIR Comparison

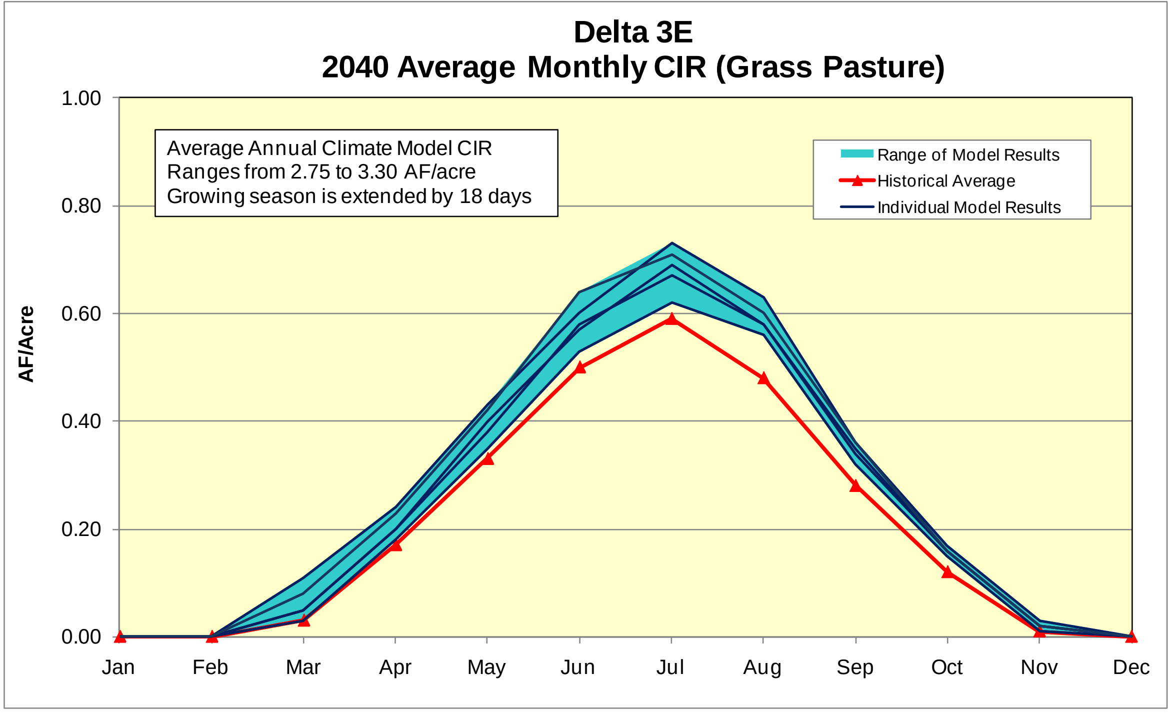


Figure 14 shows the average monthly grass pasture CIR at the Gunnison climate station for each of the 2040 climate projects compared to the historical average monthly CIR for the 1950 through 2005 study period. Similar to the Gunnison climate stations, the figures for the higher elevation stations including Grand Lake, Yampa, Durango, and Norwood, included in Appendix C of the CRWAS Phase I Report, show both the peak historical and climate projected CIR in June.

Figure 14 – Gunnison 2040 Average Monthly CIR Comparison

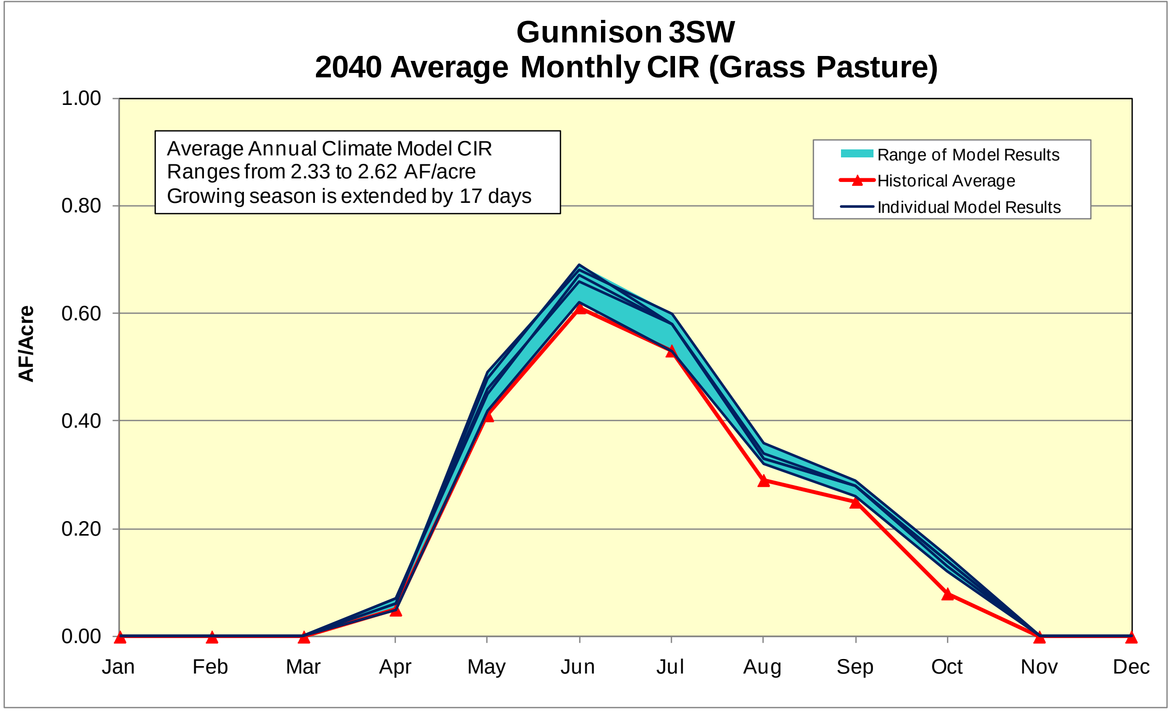
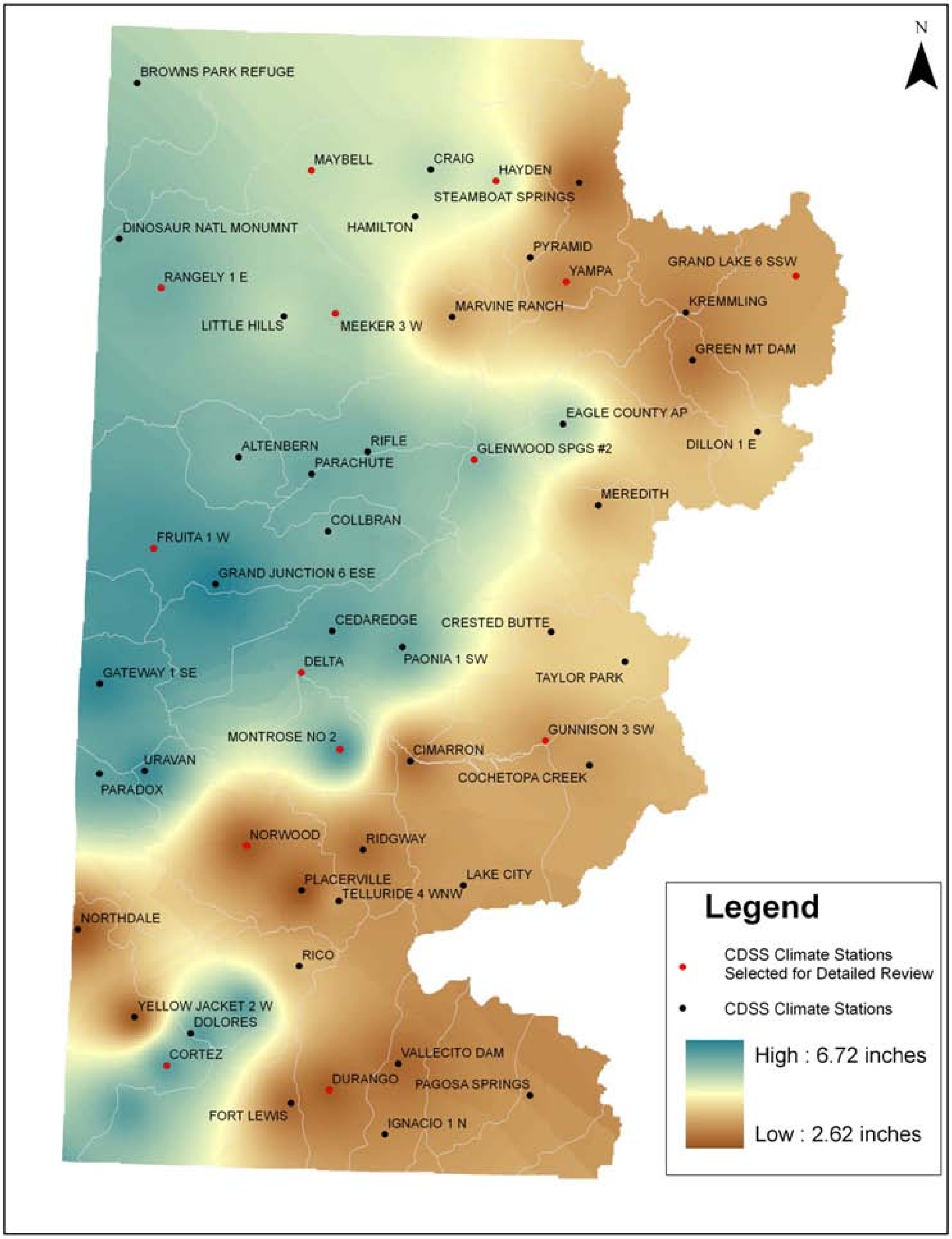


Figure 15 spatially shows the increase in combined average annual CIR for the 2040 climate projections compared to historical average CIR, based on the 54 climate stations used in the CDSS modeling over the 1950 through 2005 study period. This spatial representation further highlights the greater increase in annual CIR at lower compared to higher elevations.

Figure 15 – 2040 Increase in Grass Pasture CIR from Historical CIR (inches)



The increase in CIR directly impacts irrigation diversion demands represented in the water resources planning models. The results here have been summarized based on grass pasture, which represents about 80 percent of the irrigated acreage in the basin. Other perennial crops grown in the Study basins, including alfalfa and orchard, account for an additional 12 percent of the total irrigated acreage and show similar increases in growing season and CIR. The annual crops grown in the basin, mostly corn, small grains, and dry beans, show an increase in CIR; however growing season, based on maximum days to harvest, does not increase.

Crop Irrigation Requirements for Study Basins

Table 6 shows average annual CIR for current irrigated acreage and crop types over the 1950 through 2005 study period, by study basin, based on historical climate conditions and 2040 projected climate. As shown, there is a 17 percent increase in CIR basin-wide. The White River basin experiences the largest increase in CIR from historical, since most of the basin irrigated acreage is at lower elevations and lower elevations experience a greater increase in temperature. Conversely, the Yampa Basin experiences the smallest increase in CIR from historical conditions due to a combination of acreage at higher elevations where there is less temperature increase, plus a smaller decrease in irrigation season precipitation compared to other study basins.

Table 6 – 2040 Average Annual Study Basin CIR Compared to Historical Conditions (AF)

Study Basin	Historical Period	Minimum Projection	Maximum Projection	Average of Projections	% Increase From Historical
Yampa River	214,271	225,440	263,438	245,964	15%
White River	45,937	50,123	62,182	56,713	23%
Upper Colorado River	577,043	618,704	736,863	686,314	19%
Gunnison River	618,070	660,364	768,486	724,335	17%
San Juan/Dolores Rivers	554,821	591,795	685,620	647,506	17%
Total	**2,010,142**	**2,146,426**	**2,516,589**	**2,360,832**	**17%**

Climate-Adjusted Natural Streamflow

Low-flow comparison charts and monthly hydrograph charts (band charts) for natural flow for the Uncompahgre River at Delta are provided below in Figures 16 and 17. General descriptions for the components of the low-flow comparison charts and monthly hydrograph charts (band charts) are provided on pages 14 and 15. Similar graphs are included in Appendix D of the CRWAS Phase I Report for each selected flow station for both 2040 and 2070 projections and corresponding charts for all natural flow sites are provided in the electronic data.

The following general observations can be drawn from those results:

- At virtually all flow stations the range of projected average annual flow includes the historical average flow.
- At virtually all flow stations the ranges of projected average annual low flows at all durations include the historical average annual low flows for the same durations.
- The projected average flows and low flows at all durations tend toward higher values in the Yampa basin and at some high-elevation locations, and tend toward lower values in the southwestern basins and some lower-elevation basins.
- The range of projected flows tends to be wider in the more southwestern basins.
- At virtually all sites there is a tendency toward earlier streamflow.
- At virtually all sites the range of flow magnitudes tends to be greater in the summer months.

Figure 16 – 2040 Climate Impacts on Flows

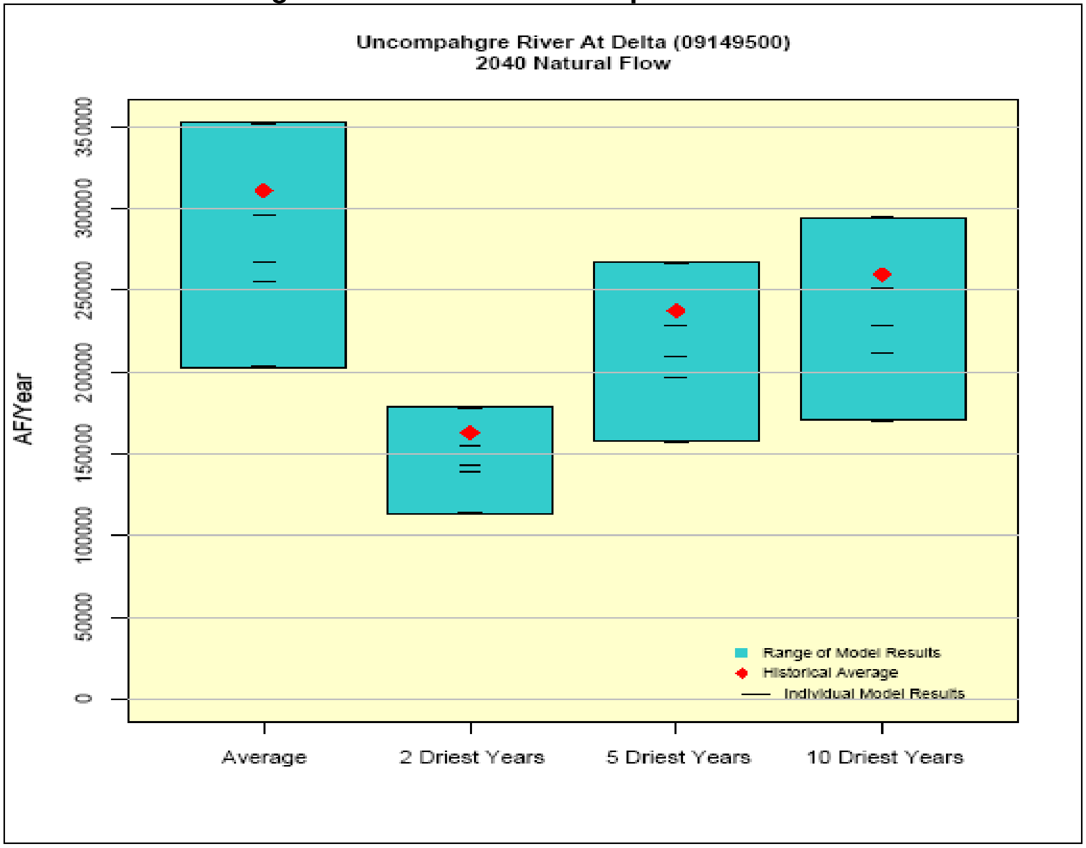
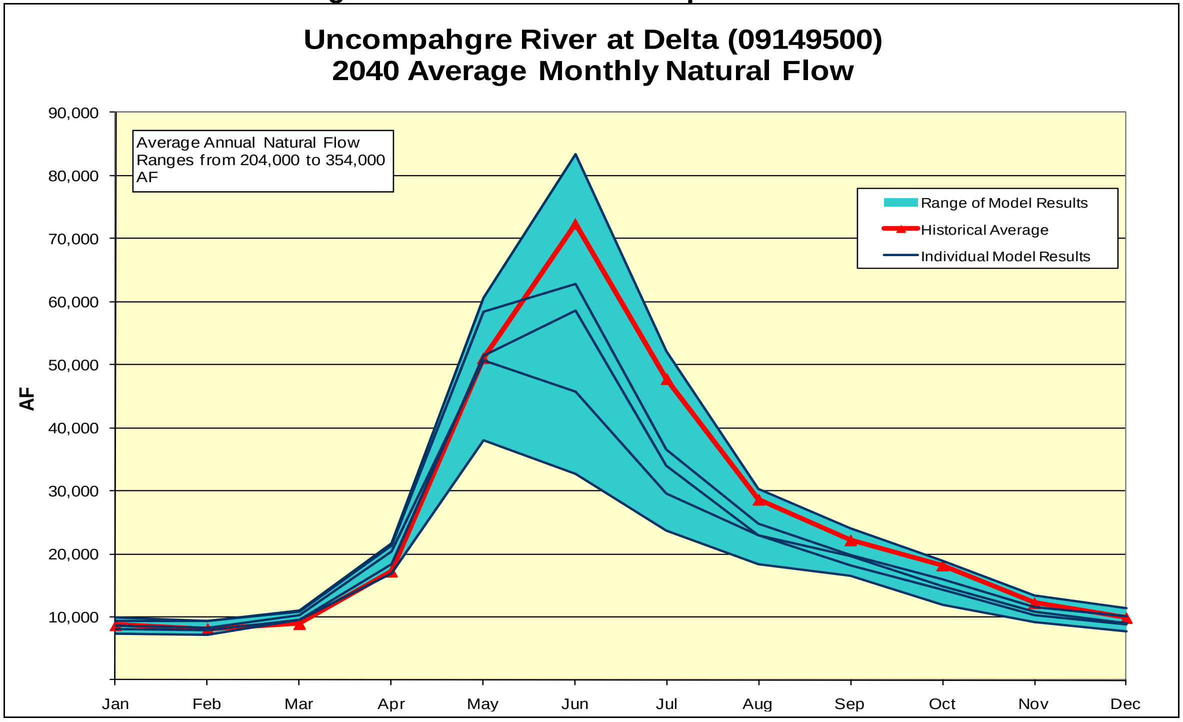


Figure 17 – 2040 Climate Impact on Flows



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