APPENDIX D: CLIMATE CHANGE AND HYDROLOGY ANALYSIS

Rising temperatures, increased evaporation rates, and an acceleration of the hydrological cycle is increasing the intensity of heavy precipitation and the duration and severity of droughts in many places around the world (IPCC, 2012). These and other changes that have been attributed to human-induced climate change are projected to continue over the remainder of this century and beyond.

In the United States, both flooding and short-term droughts are expected to intensify in the future (Georgakakos et al., 2014), raising concerns regarding their impacts on water supply for cities such as Austin, Texas that are located in drought-prone regions. The southern Great Plains are expected to see longer dry spells and more intense long-term droughts, even in areas where average precipitation is not expected to change significantly (Walsh et al., 2014). These impacts are expected to affect water supply and demand, leading the Third US National Climate Assessment (NCA3) to conclude that, “in most U.S. regions, water resources managers and planners will encounter new risks, vulnerabilities, and opportunities that may not be properly managed within existing practices” (Georgakakos et al., 2014).

Across Texas, average temperatures are increasing, the risks of extreme temperatures are changing, and precipitation patterns are shifting, with heavy precipitation becoming more frequent in many locations. As climate changes, the past can no longer serve as a reliable guide to the future. Instead, climate projections are needed to assess the potential impacts of human-induced change on our communities and our natural resources. This appendix documents the development, evaluation, and application of a new approach to generating streamflow projections for individual river gauges under future climate conditions for Austin’s Integrated Water Resource Plan. This appendix describes the methodology and summarizes the results of an analysis of the potential impacts of climate change on Austin’s future water supply that combines observations and existing models and methods with the development of new statistical models and analysis techniques.

D.1 Study Area and Data Overview

D.1.1 Study Area

Long-term daily streamflow data for 43 gauges in the Colorado River Basin study area was obtained from the United Stated Geological Survey (USGS) website. Gauge locations relative to the study region are shown in **Figure D-1**. The gauge locations represent a wide range of watershed scales with upstream contributing drainage areas of approximately 120 to nearly 31,000 square miles.

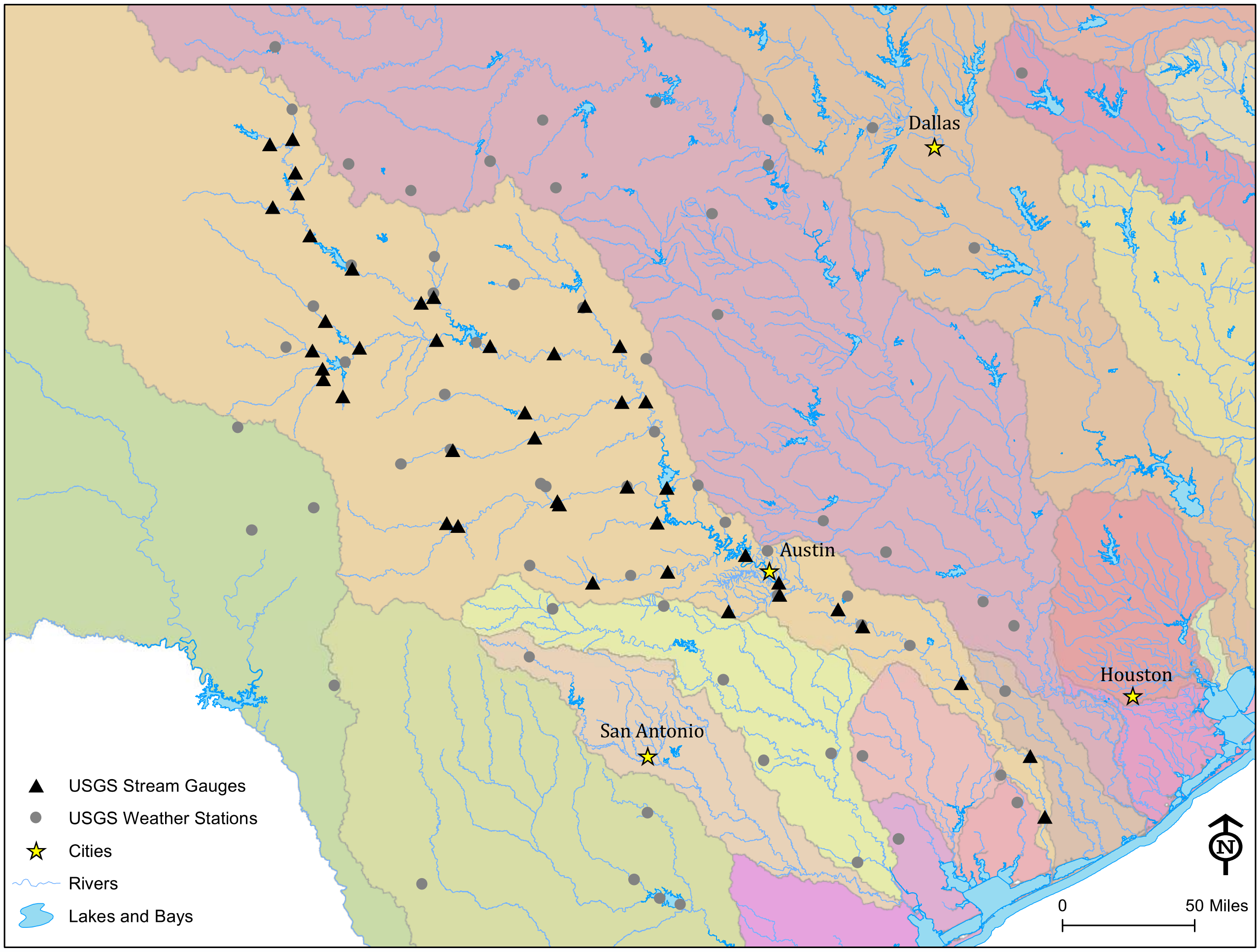

Figure D-1. Locations of streamflow gauges (black triangles) and weather stations (gray circles) used in this analysis.

Gauge names, identification numbers, and locations presented in the figure are listed in **Table D-1**. Water availability model (WAM) properties such as control point ID, drainage area, and closest weather station are also presented in the table.

Table D-1. WAM primary control point identification numbers, drainage area, USGS identification numbers, locations, latitude and longitude of the gauges used, and corresponding weather stations.

WAM CP ID	WAM Drainage Area (mi^2)	USGS ID	Gauge Name	Lat	Lon	Weather Station
A30000	1,074	08119500	Colorado River at Hwy 350 near Ira	-101.054	32.538	USC00418433
A20000	193	08120500	Deep Creek near Dunn	-100.908	32.574	USC00418433
A10000	1,575	08121000	Colorado River at Colorado City	-100.879	32.393	USC00418433
B40000	176	08123600	Champion Creek Reservoir	-100.858	32.281	USC00418433
B30000	1,974	08123800	Beals Creek near Westbrook	-101.014	32.199	USC00418433
B20000	4,559	08123850	Colorado River above Silver	-100.762	32.054	USC00418433
B10000	5,046	08124000	Colorado River at Robert Lee	-100.481	31.885	USC00417743

WAM CP ID	WAM Drainage Area (mi^2)	USGS ID	Gauge Name	Lat	Lon	Weather Station
D40000	6,090	08126380	Colorado River near Ballinger	-100.026	31.715	USC00417743
D30000	464	08127000	Elm Creek at Ballinger	-99.948	31.749	USC00410493
C30000	258	08128000	South Concho River at Chrisoval	-100.502	31.187	USC00418449
C60000	1,613	08128400	Middle Concho River above Tankersley	-100.711	31.427	USC00418449
C50000	340	08129300	Spring Creek above Tankersley	-100.640	31.330	USC00418449
C40000	164	08130500	Dove Creek at Knickerbocker	-100.631	31.274	USC00418449
C70000	1,202	08134000	North Concho River near Carlsbad	-100.637	31.593	USC00410493
C20000	4,139	08136000	Concho River at San Angelo	-100.411	31.455	USC00410493
C10000	5,185	08136500	Concho River at Paint Rock	-99.920	31.516	USC00410493
D20000	12,548	08136700	Colorado River near Stacy	-99.574	31.494	USC00412741
D10000	13,788	08138000	Colorado River at Winchell	-99.162	31.468	USC00411875
F30000	1,654	08143500	Pecan Bayou at Brownwood	-98.974	31.732	USC00411875
F20000	2,074	08143600	Pecan Bayou near Mullin	-98.741	31.517	USC00411138
E40000	1,137	08144500	San Saba River at Menard	-99.786	30.919	USC00415650
E30000	1,636	08144600	San Saba River near Brady	-99.269	31.004	USC00415650
E20000	589	08145000	Brady Creek at Brady	-99.335	31.138	USC00415650
E10000	3,048	08146000	San Saba River at San Saba	-98.719	31.213	USC00411138
F10000	19,830	08147000	Colorado River near San Saba	-98.564	31.218	USC00411875
G50000	897	08148500	North Llano River near Junction	-99.806	30.517	USC00418449
G40000	1,859	08150000	Llano River near Junction	-99.735	30.504	USC00418449
G30000	3,251	08150700	Llano River near Mason	-99.109	30.661	USC00415650
G20000	215	08150800	Beaver Creek near Mason	-99.096	30.644	USC00415650
G10000	4,201	08151500	Llano River at Llano	-98.670	30.751	USC00415650
I40000	20,521	08148000	Lake Buchanan near Burnet	-98.418	30.751	USC00411250
I30000	346	08152000	Sandy Creek near Kingsland	-98.472	30.558	USC00411250
H20000	370	08152900	Pedernales River near Fredericksburg	-98.870	30.220	USC00414782
H10000	901	08153500	Pedernales River near Johnson City	-98.399	30.292	USC00410832
I20000	27,357	08154500	Lake Travis near Austin	-97.907	30.392	USC00411250
I10000	27,611	08158000	Colorado River at Austin	-97.694	30.245	USC00418415
J50000	124	08158700	Onion Creek near Driftwood	-98.008	30.083	USC00415193
J40000	324	08159000	Onion Creek at US Hwy 183, Austin	-97.689	30.178	USC00418415
J30000	28,580	08159200	Colorado River at Bastrop	-97.319	30.105	USC00415193
J20000	29,062	08159500	Colorado River at Smithville	-97.162	30.013	USC00418415
J10000	30,244	08161000	Colorado River at Columbus	-96.537	29.706	USC00418415
K20000	30,601	08162000	Colorado River at Wharton	-96.104	29.309	USC00411048
K10000	30,862	08162500	Colorado River near Bay City	-96.012	28.974	USC00411048

D.1.2 Data Overview

Given the long time horizon of the data, the high population density of the region, and the abundance of reservoirs throughout these watersheds, it is clear that these flows have been modified through the years via impoundment, withdrawals, and other human activities. For that reason, daily streamflow data were developed to replicate naturalized streamflow on a monthly volumetric basis. A naturalized streamflow dataset is maintained by the Texas Commission on Environmental Quality as a part of the statewide Water Availability Modeling System. Naturailzed streamflow is derived from adjustments to gauged streamflow to reverse all human activities that are represented in the WAM simulation, such as diversion from the river. WAM naturalized streamflow is an estimate of the flow which would have occurred each month in the absence of diversions, discharges, or storage reservoirs for water supply and flood control purposes.

Sythnetic daily naturalized discharge data were calculated directly from the monthly naturalized streamflow time series at each WAM primary control point using a linear spline that was fit to match the variation in monthly flows (Wurbs and Hoffpauir, 2015). The area under the linear spline was divided by the number of days per month to produce daily naturalized flows. The method of calculating daily naturalized flows using a linear spline is included as an algorithm within the daily simulation model of the Water Rights Analysis Package (WRAP). WRAP is the modeling software within the TCEQ WAM System (Wurbs, 2005).

Weather stations reflecting characteristics of daily maximum and minimum temperature and 24-hour cumulative precipitation encompassing the time period of the gauge data from 1950 to 2015 were identified for each gauge. The identification numbers of the stations and their geographic locations are listed in **Table D-1** and shown on the map in **Figure D-1**. Observations for each station were obtained from the National Climatic Data Center Cooperative Observer Network Summary of the Day, and then quality-controlled for anomalous data points. Data points were removed if nighttime minimum temperature was greater than daily maximum temperature, values were greater or less than state-wide daily records, non-zero identical values to within a tenth of a degree Celsius or a millimeter were repeated over five or more consecutive days, or outliers were not validated by neighboring stations.

Next, a set of more than 120 secondary climate indicators to be used as predictors in the correlation analysis was dervied as described in Gelca et al. (2015). These indicators represent a broad range of permutations of temperature and precipitation over time scales ranging from 1 day to 2 years. Quantifying both long-term averages as well as the frequency of extreme conditions, the indicators are intended to capture changes in mean and extreme temperature and precipitation of relevance to water availability. Some examples of the indicators used are one-week average precipitation, number of dry days in the previous two weeks, or the three-month average temperature.

D.2 Future Climate Uncertainty

Future climate projections are uncertain for four main reasons:

1. **Natural variability**, which causes temperature, precipitation, and other aspects of climate to vary from year to year and even decade to decade;
2. **Scientific uncertainty**, as it is still uncertain exactly how much the Earth will warm in response to human emissions and global climate models cannot perfectly represent every aspect of Earth's climate;
3. **Scenario or human uncertainty**, as future climate change will occur largely in response to emissions from human activities that have not yet occurred; and
4. **Local uncertainty**, which results from the many factors that interact to determine how the climate of one specific location, such as Austin, will respond to global-scale change over the coming century.

D.2.1 Natural Variability

To address the first source of uncertainty, natural variability, the climate projections summarized here are averaged over 30-year time scales: historical (1971-2000), near-term (2011-2040), mid-century (2041-2070) and end-of-century (2071-2100). In other words, the number of days per year over 100ºF were first calculated for each year from 1960 to 2100, and were then averaged over the 30 years corresponding to each historical or future time period. Natural variability is an important source of uncertainty over shorter time scales. Averaged over longer time scales of multiple decades, the contribution of natural variability to overall uncertainty becomes virtually negligible.

D.2.2 Scientific Uncertainty

To address the second source of uncertainty, scientific uncertainty, future projections were based on simulations from 20 global climate models from the Coupled Model Intercomparison Project phase 5 (CCSM4, CNRM-CM5, CSIRO-Mk3.6.0, MPI-ESM-LR, HadGEM2-CC, INMCM4, IPSL-CM5A-LR, MIROC5 and MRI-CGCM3; Taylor et al. 2012). Differences between the models represent the limitations of scientific ability to simulate the climate system. Scientific uncertainty is an important source of uncertainty in determining the magnitude and sometimes even the direction of projected changes in average precipitation, as well as dry days and extreme precipitation.

D.2.3 Human Activities

To address the third source of uncertainty, that of human activities and heat-trapping gas emissions, future projections use two very different scenarios, the Intergovernmental Panel on Climate Change lower Representative Concentration Pathway (RCP) 4.5 scenario where global carbon emissions peak and then decline by end of century, and the higher RCP 8.5 scenario where continued dependence on fossil fuels means that carbon emissions continue to grow throughout the century (Moss et al. 2010; see Figure 3). Scenario labels (4.5 and 8.5) refer to the projected change in radiative forcing in units of watts per square meter. Radiative forcing is a measure of the magnitude of the human influence on the naturally-occurring greenhouse effect described previously. Scenario uncertainty is an important source of uncertainty in temperature-related projections, particularly over the second half of the century as the scenarios diverge (see Error! Reference source not found.). The higher emission scenario was selected for use in Water Forward (Scenario B and Scenario D hydrology) because it represents the current trajectory of carbon emissions and results in a distinctly different outcome of future hydrologic conditions when compared to the historical observations of basin hydrology.

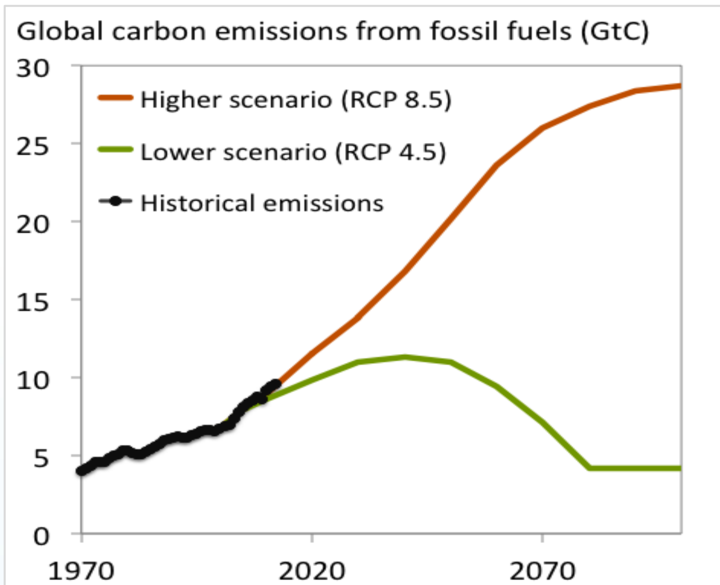

Figure D-2. Historical carbon emissions (black) continue to increase. Data: CDIAC, IIASA

D.2.4 Local Changes

Finally, to address the fourth source of uncertainty, that of local change, global climate model simulations for daily maximum and minimum temperature and 24-hour cumulative precipitation were downscaled to each long-term weather station using the Asynchronous Regional Regression Model as described in Stoner et al. (2012). From these daily simulations from 1950 to 2100, a set of more than 120 secondary climate indicators were calculated to be used as predictors for future streamflow. Quadrangle scale monthly precipitation and monthly potential evaporation were created from the precipitation and temperature outputs of the global climate models (see **Appendix E** for more detail on quadrangles and evaporation). Potential evaporation was developed using the Hargreaves equation (Kra, 2013) and converted to lake evaporation using regional pan-to-lake coefficients

D.3 Historical Climate Data Analysis

D.3.1 Developing Climate Indicators

Streamflow gauges used for this analysis were all located within the Colorado River Basin and share the same broad topographical characteristics. As such, it would be reasonable to expect them to be affected by similar climatic indicators. At the same time, however, the gauges are located on rivers and creeks with very different watershed characteristics: from deep rivers with high flow volumes year-round to intermittent creeks. For that reason, each gauge was considered separately when deriving a statistical regression model for the flow at each, based on the hypothesis that the resulting predictors should represent a combination of common factors, reflecting their co-location and shared geography, as well as unique indicators that influence the physical processes of flow generation at each gauge.

To determine which of the 120 climate indicators from the relevant weather stations have the greatest explanatory power as predictors in the statistical regression model for each gauge, the Spearman rank coefficient was used to calculate the relationship between water flow at each gauge and the climate indicators from each of the weather stations in this geographic region. The analysis was not limited to only the station closest to each gauge, as weather affecting upstream conditions can play an important role downstream. Spearman rank coefficient is an effective method for quantifying both linear and nonlinear correlations, previously shown to reproduce the results of both Pearson correlation and Mann-Kendall τ for water data in Texas (Gelca et al., 2015). Correlations with p-values < 0.1 were considered significant.

The results of this analysis for all gauges are summarized in Figure 4, which groups climate indicators with the strongest correlation to streamflow in all gauges combined into three categories. The first consists of "primary" indicators that are selected as predictors for nearly every gauge. These consist of precipitation and dry days over time scales ranging from 1 to 6 months. The second consists of "secondary" indicators that are selected as predictors for most but not all gauges. These include precipitation over both shorter (1 week) and much longer (12 month) time horizons, as well as extreme heat days. Finally, the third category consists of indicators that tend to modify streamflow in more shallow or intermittent rivers: precipitation over shorter time frames and more extreme heat.

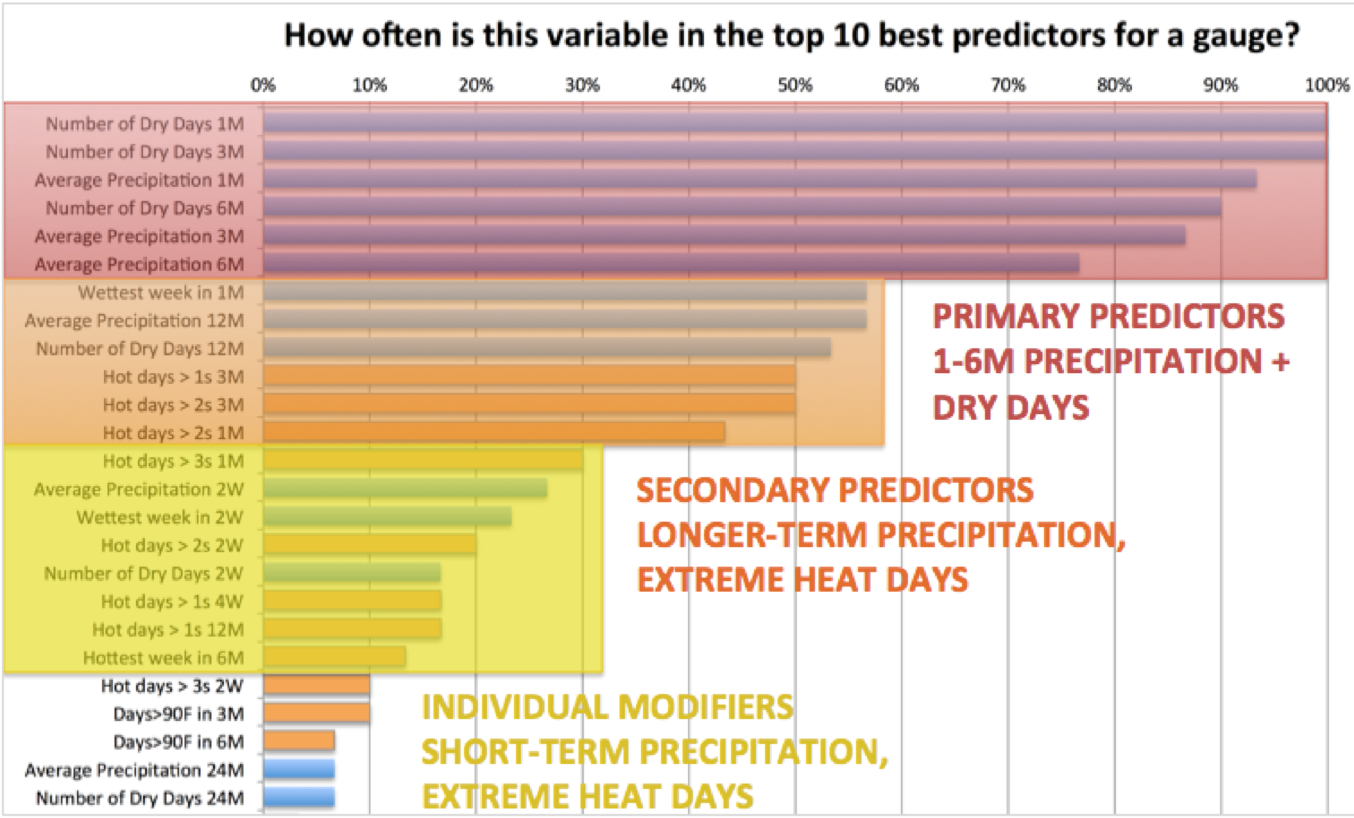

Figure D-3. Climate indicators with the strongest correlation to streamflow in all gauges combined, including primary predictors that are significant at 75 to 100% of the gauges (red); secondary predictors significant at 40-60% of the gauges (orange); and individual modifiers significant at 10-30% of the gauges (yellow).

Although the top predictors varied from one river and gauge to the next, in general the climate indicators showing the strongest correlations with streamflow were the 1-6 month average precipitation and number of dry days, as well as hot days, as measured by calculating the number of days over periods ranging from 1-3 months with maximum temperature 1, 2, and 3 standard deviations above the mean. The most important predictors for gauges located on a deep river with high flow volume are all precipitation-related indicators (Colorado River at Austin and at San Saba). The Colorado River flows towards the Gulf of Mexico, and as a result, drainage area increases in the direction of increasing average precipitation. The stream gauges representing deeper rivers therefore have increasing average precipitation in addition the lagged contribution of flows from previous precipitation events over upstream intermittent shallow rivers. The natural flow characteristics of deeper rivers in the Colorado River Basin are also influenced by baseflow created by shallow sub-surface discharge from alluvial formations. For spring-fed and more shallow rivers such as Llano and San Saba, longer-term precipitation indicators play a role and there is some influence from hot days. The Llano River in particular receives perineal spring flow discharge from its upper-most tributaries. These spring discharges are naturally more responsive to long-term precipitation accumulations. Finally, for very shallow and intermittent creeks, both precipitation and hot temperatures are important, indicating that direct runoff from storm events and intervening periods of evaporation plays an important role in the streamflow.

D.3.2 Selecting Significant Climate Indicators for Each Gauge

The correlation analysis was a necessary step to identify unique predictors to the regression model. However, it is insufficient, as it identifies a large number of predictors that are highly correlated with each other in both space and time. For each gauge, this analysis identified significant correlations with anywhere from 10 to over 60 climate indicators at each of the weather stations, with average correlation coefficients around 0.3. To reduce the pool of predictors to only those that are unique and relatively independent of each other, the second step was to select from significant predictors those to be used as input to the regression model. This was accomplished by grouping the predictors by variable (temperature and precipitation) and by time frame: from 1 to 3 days, from 1 to 4 weeks, from 3 to 6 months, and from 12 to 24 months. For each streamflow gauge we selected a total of fourteen variables most highly correlated with streamflow: two variables were selected from each predictor grouping, one representing extremes and one representing average conditions. For the time period 1 to 3 days, no "average" indicator was used, since by definition this time frame will only capture extremes. We then iterated through statistical models with all possible combinations of variables (including leaving variables out), using the least absolute shrinkage and selection operator regression analysis method to select and regularize variable selection and thereby measure the relative quality of the statistical models that could be built using these variables and to identify the model that explained the majority of the variance.

These regression models were then validated on observed data by dividing the historical data in odd and even years, using one set of the data to build the regression model, and the other for cross-validation, then switching. Modeled data for even (then odd) years obtained by training a regression model on odd (then even) years, then driving that model with observed climate indicators for even years. For the deeper, high-flow gauges of the Colorado River (**Figure D-4** a, b), modeled streamflow data (red line) show a higher density in the middle of the distribution and a lower density for low and high stream flow values compared with the observed streamflow data (black line). This bias is reduced but still visible for the year-round spring-fed rivers (c, d), while for the creeks and intermittent rivers (e, f) there is little difference between modeled and observed.

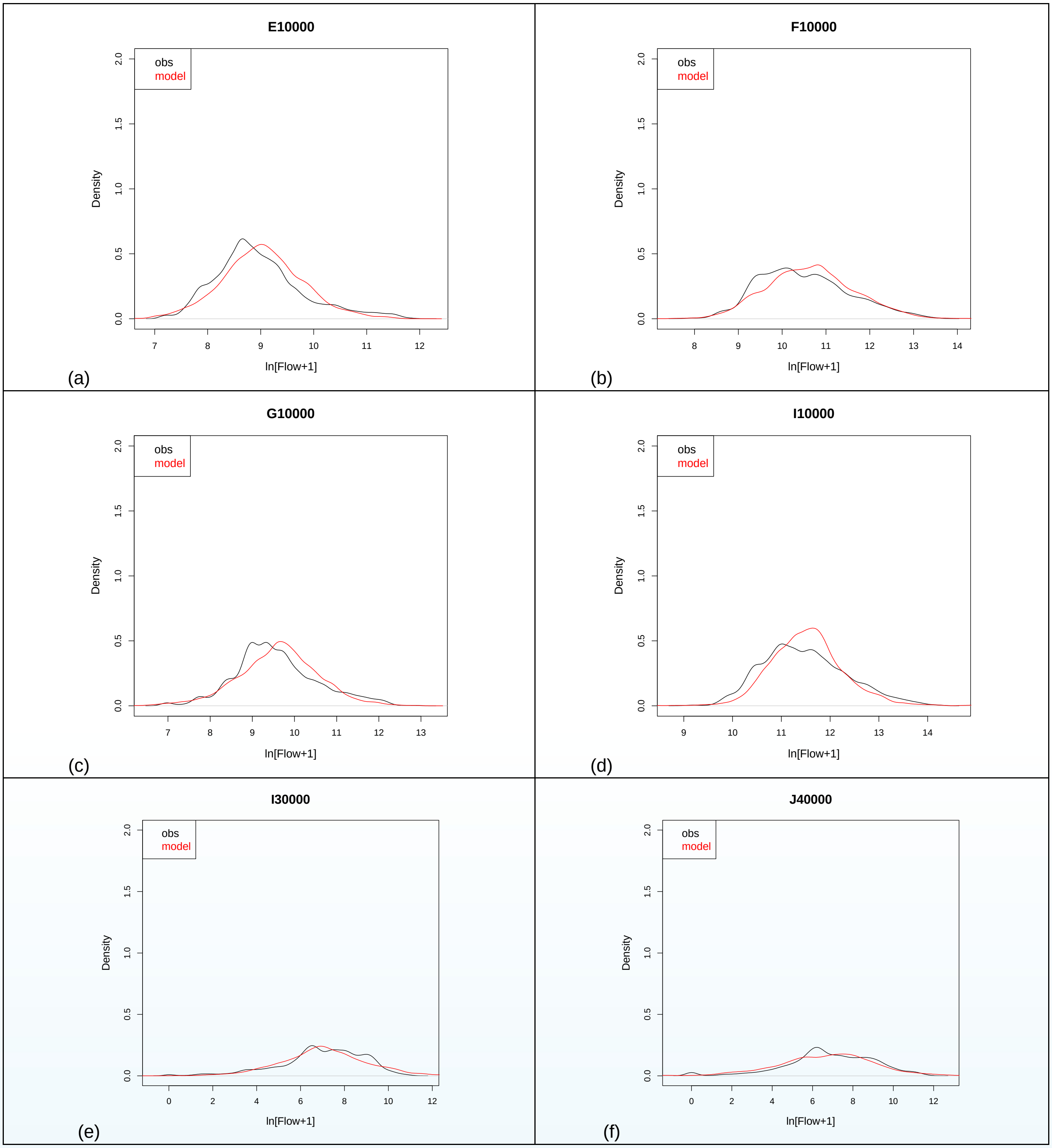

Figure D-4. Cross-validation of streamflow regression models on observed data. Comparisons shown for full data record from 1950 to 2014; plots for data beginning in 1981 and 1998 are virtually identical (not shown). Observational records were divided into odd and even years; the model was trained on each and validated on the other; results show combination of both validation exercises. Observations are indicated by the black lines and model predictions by the red lines.

D.4 Future Streamflow Projections

Once the streamflow regression models were developed and evaluated, they were then driven using climate indicators derived from historical global climate model simulations, statistically downscaled each weather station and the resulting streamflow was downscaled using the same empirical quantile regression method described in Stoner et al. (2012) and compared to observations. Despite the range in historical simulations, largely reflecting the range of natural variability in the historical period, downscaled simulation-based streamflow climatologies strongly resemble observationally-based climatologies.

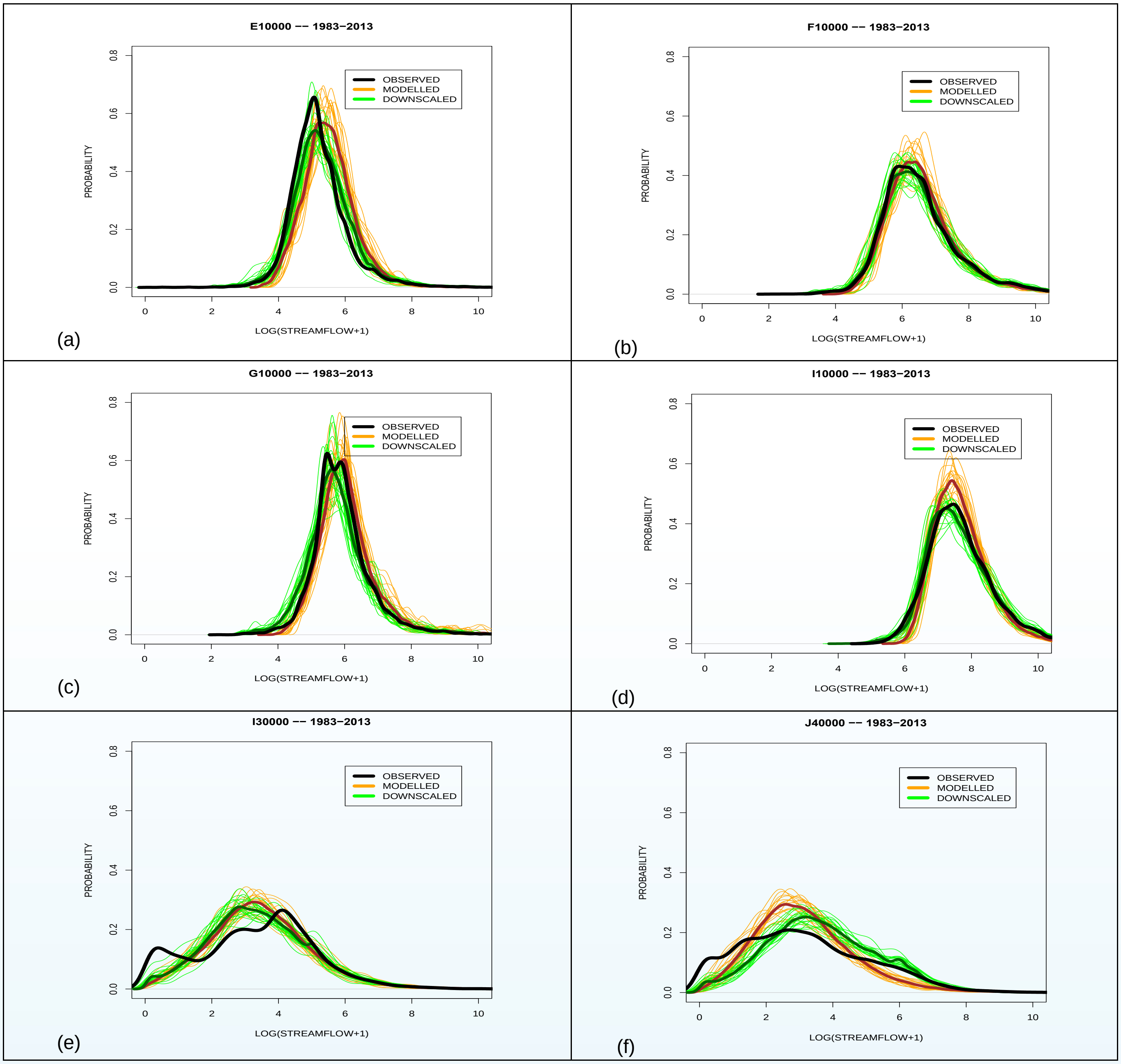

Figure D-5. Figure 5. Comparison of historical model-simulated streamflow (orange lines) with downscaled streamflow (green lines) and observed streamflow (black lines) from 1983 to 2013.

The last step in generating daily streamflow projections is to use projected future climate indicators to drive the streamflow regression models, to quantify potential future changes in streamflow under a changing climate. **Figure D-6** compares the distribution of observed (black lines), historical model-simulated (blue) and future model-simulated (orange) streamflow for two representative gauges. The distributions shift to the left, indicating a trend towards overall lower streamflow, and also become more skewed to the left, indicating more frequent low-flow days. This result is consistent with projections of little change in average and seasonal annual precipitation under both higher and lower future scenarios (Walsh et al. 2014), but increased risk of summer drought (Ryu & Hayhoe, 2017), more frequent extreme heat and higher evaporation rates, and the tendency of long-term (6 to 12 month precipitation) to be a primary driver of median flow volume.

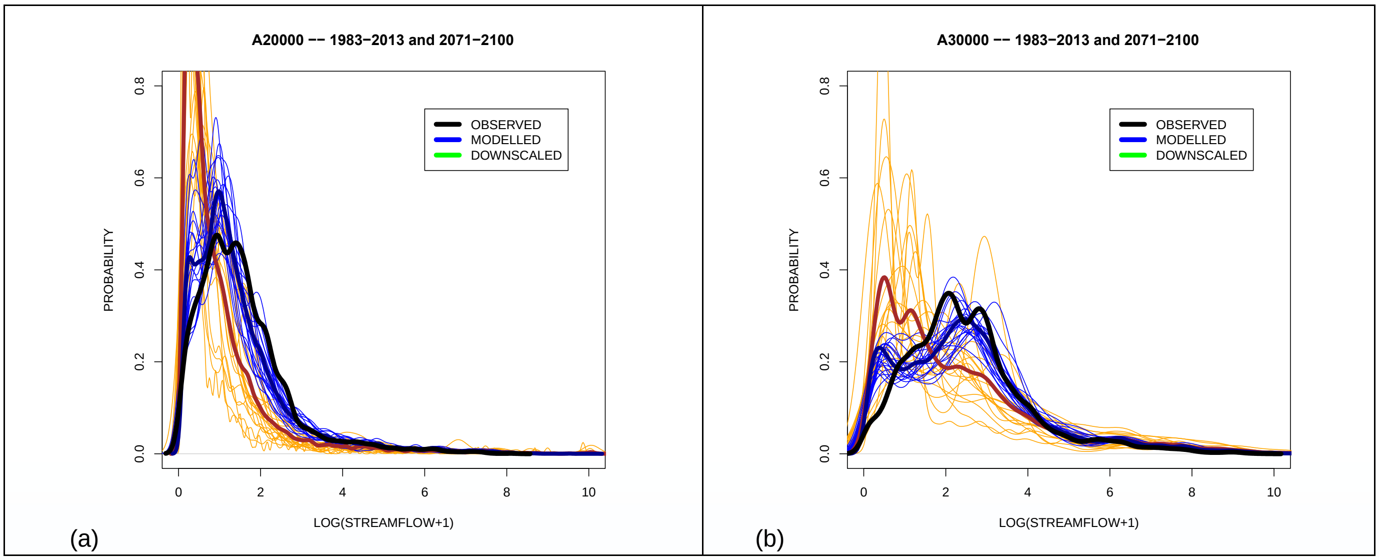

Figure D-6. Comparison of historical downscaled model-simulated streamflow (blue lines) with future streamflow (orange lines) and observed streamflow (black lines) from 1983 to 2013 and 2071-2100 under a higher future scenario.

Finally, in terms of future changes in high and low flow extremes, **Figure D-7** summarizes projected changes in mean winter and summer streamflow as well as consecutive 7-day low flows, and the 5th percentiles of the distribution (which corresponds to streamflow on approximately the 18 driest days of the year, whether consecutive or not).

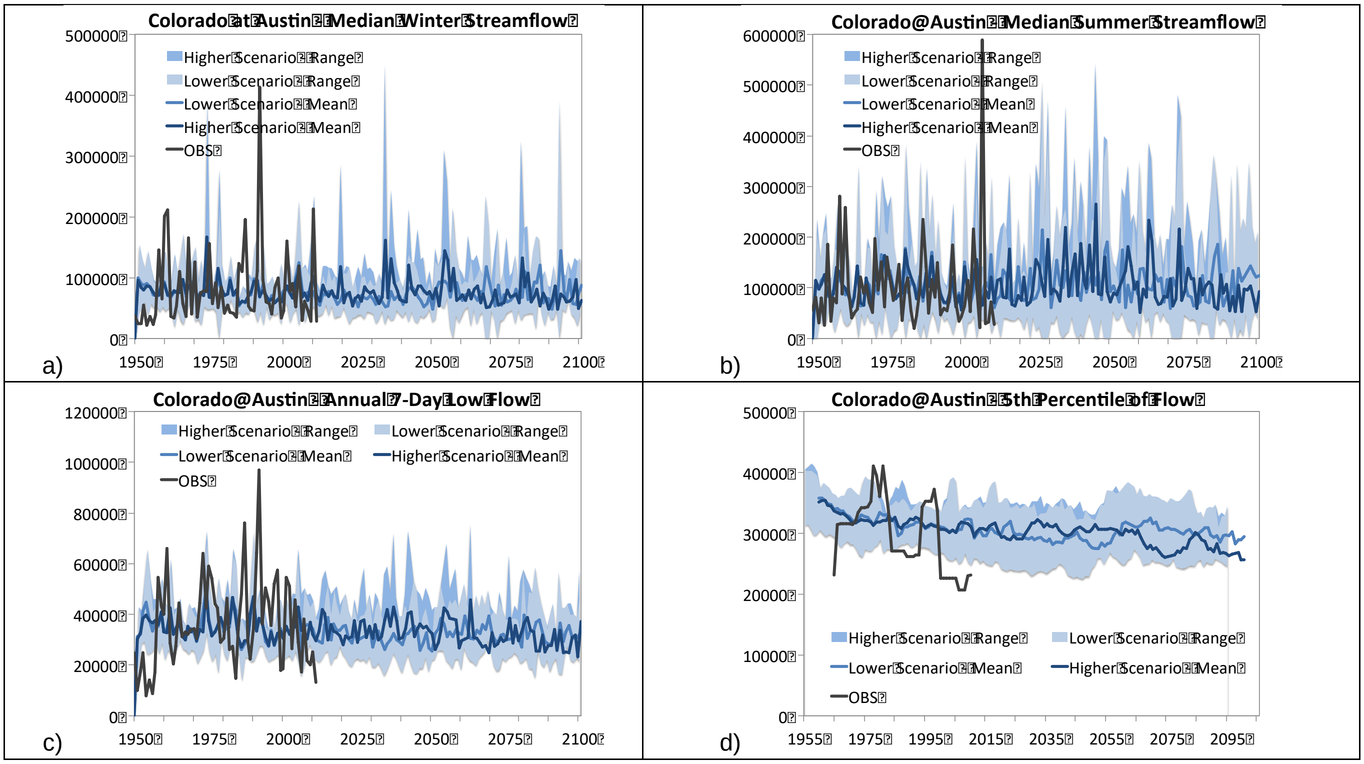

Figure D-7**. Simulated historical and projected future change in (a) winter and (b) summer streamflow as well as for (c) the annual seven-day lowest flow amounts and (d) the 5th percentile of streamflow for the Colorado River gauge at Austin. The black line indicates observations, the shaded area the range of historical and future climate model projections and the colored lines, the multi-model mean.**

D.5 Climate Change Adjustments to Historical Hydrology

The TCEQ WAM is a surface water availability computer simulation modeling system covering every river basin in Texas, and was created pursuant to Article VII of the 1997 Senate Bill 1, which required the development of new water availability models (WAMs) for the state's river basins. The WAM uses naturalized streamflow, net lake evaporation minus precipitation (net evap-precip), and a water management scenario as its three main inputs. The WAM simulates surface water availability to basin water rights under the specified water management scenario. Outputs include water diversions, reservoir storage content, and remaining streamflow after accounting for the water management activities. The WAM consists of basin-specific input files, supporting geographic information, and a generalized simulation model known as the Water Rights Analysis Package (WRAP).

TCEQ uses the WAM system to evaluate water right applications for water availability under new permits or permit amendments and to assess potential impacts to existing water rights. The Texas Water Development Board (TWDB) and the Regional Water Planning Groups modify the WAMs to estimate surface water supply for the entire state using a 50-year planning horizon. The WAM system is also used by river authorities, other state agencies, and individual water right holders to assess water availability from the river, reservoir operations, and environmental flow conditions.

The City of Austin is using the Colorado River Basin WAM in the development of its Integrated Water Resources Plan (IWRP) as a part of the Water Forward planning process. The Colorado WAM serves as a key modeling tool to assess baseline future needs and the performance of portfolios of options to address those needs. The IWRP is examining water available to the City of Austin and the lower Colorado River Basin for the worst drought conditions experienced since the construction of the Highland Lakes (period of record), drought conditions that are worse than observed in the period of record, and drought conditions that are reflective of future climate change. Creation of WAM hydrologic data which are reflective of future climate change conditions is addressed in this report.

This section of the appendix describes development of hydrologic input data sets to the Colorado WAM, both naturalized flow and net evap-precip, reflective of future climate change conditions developed as part of the climate change analysis discussed previously. The City's IWRP identifies four key periods of time for needs assessment: 2020, 2040, 2070, and 2115. Demand projections were created for these four planning horizons and the WAM's demand scenario is adjusted accordingly. Hydrologic inputs from the existing period of record are used for modeling the 2020 demand period. The remaining three time periods are the focus for developing hydrologic inputs reflective of future climate change to coincide with the future demand projections in the WAM. Because the output of the global climate model simulations ends with 2100, the hydrologic inputs for the WAM will be reflective of climate change conditions up to 2100 and assumed to reasonably approximate 2115 conditions.

D.5.1 Hydrologic Data WAM Inputs Description

Two pairs of data sets are used in development of climate change adjusted hydrology which are ultimately used as WAM simulation inputs. The first pair consist of the known historical naturalized streamflows and net evap-precip for the period from January 1940 through December 2013 and were obtained from the Colorado WAM simulation. Total monthly naturalized streamflows, naturalized surface streamflows plus the contribution of springflow discharge, were used for all WAM control point locations in the development of relationships between climate indicators and naturalized flow discussed in the Historical Analysis section of this report. Historical monthly net evap-precip were obtained directly from the WAM input files for all reservoir locations. The second pair of data sets include monthly naturalized streamflow obtained from aggregation of daily future model-simulated streamflow and future model-simulated net evap-precip. The process of calculating net evap-precip from quadrangles of monthly precipitation and lake evaporation for WAM reservoir locations in the Colorado River Basin is described by Pauls et al. (2013). The second pair of data sets consist of 20 separate time series from 1950 through 2100 corresponding to each GCM used for each carbon emission scenario.

The hydrololgy for the historical period of record is assumed to reflect a stationary hydrologic condition. Stationary processes have the same statitstical properties over time. Statistical measures, such as the mean and standard deviation, in the early portion of the dataset are equivalent or very similar to statistical measures calculated in the mid or latter portions of the dataset. Stationary hydrologic conditions across the entire simulation period are important for water availability modeling. A static set of demand assumptions are simulated over a long simulation period. If the hydrologic processes that generate wet or dry conditions are changing during the simulation, the water availability measures from one portion of the simulation are not comparable to the measures in other portions of the simulation.

The hydrologic inputs derived from the downscaled local weather of the 20 global climate models have changing statistical properities from 1952 through 2100 as the atmosphere warms in response to the carbon emission scenario. While the long-term mean flow across all hydrologic inputs derived from 20 global climate models is stable for the location shown in **Figure D-8**, this is not the case for all locations in the basin. Additonally, statistical measures other than the long-term mean are changing in the flows shown in **Figure D-8**. To address changing hydrologic conditions over time from the global climate model derived hydrology, and to build a hydrologic input dataset for the WAM that reflects the same underlying hydrologic processes for the entire WAM simulation period, an *ensemble* and adjustment approach was adopted. An ensemble is collection of all results from multiple models for a particular period of time. The ensemble of all 20 global climate model derived hydrolgies are grouped together for periods of time, centered around the future planning horizons. It is assumed that the groupings centered around the future planning horizons are narrow enough to have similar hydrologic statistical properties from the start to end dates of the ensembles. The ensembles are then used to adjust the historical period of record to reflect a consistentent set of future hydrologic statistical properties. The adjustment process is described further in **Section D.5.2**.

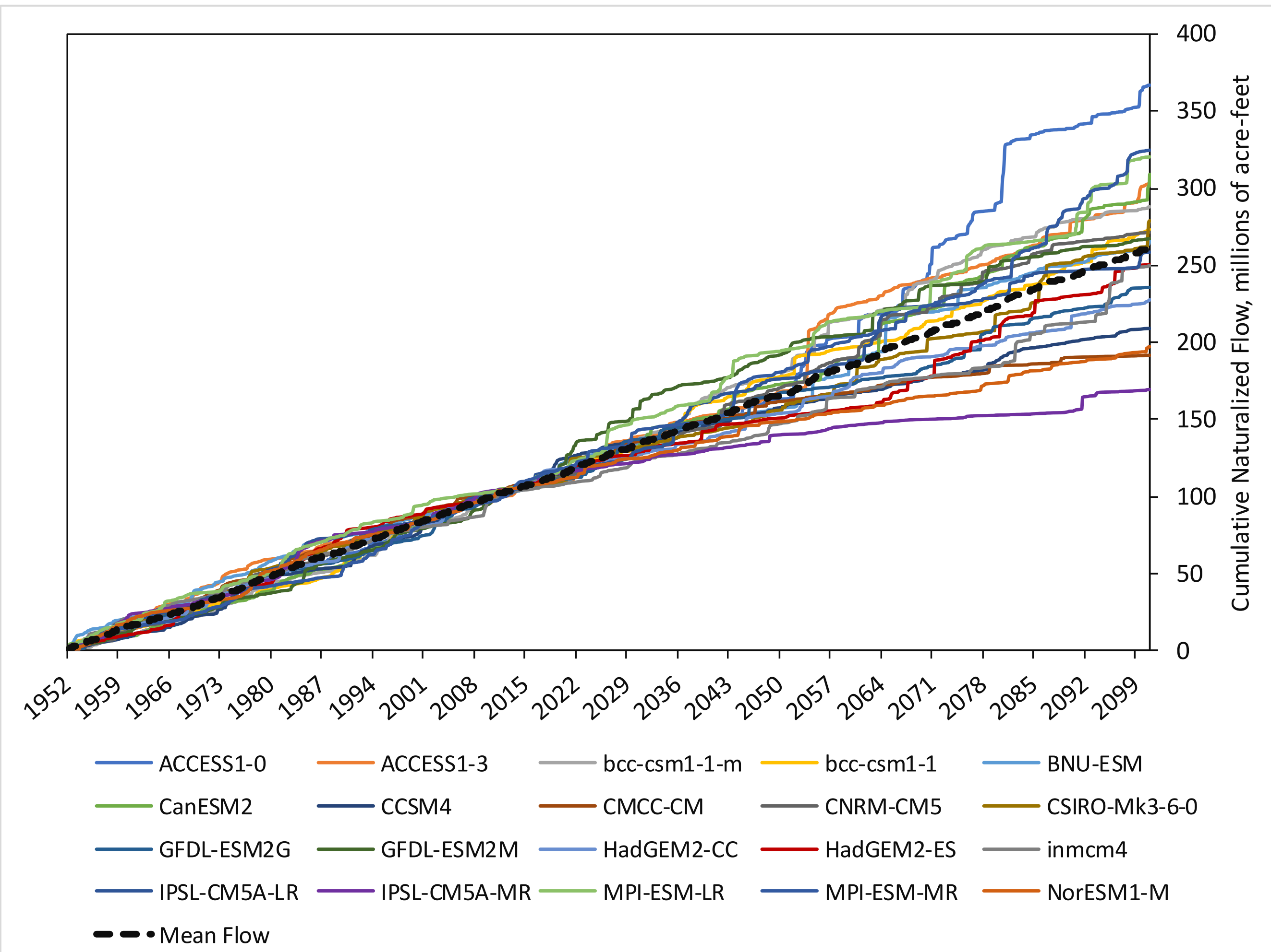

Figure D-8. Cummulative naturalized flow for the Colorado River at Austin

Ensembles of monthly naturalized streamflows, precipitation, and evaporation were created by grouping the results derived from all 20 global climate models. The ensembles were created from 21-year spans of time centered around years 2040 and 2070. Since data from the global climate models were only available through 2100, a third ensemble was created from the last 21 years of the results from 2080 through 2100. The ensembles of global climate models' derived hydrology are as follows: 2030 through 2050 (21 years centered on 2040), 2060 through 2080 (21 years centered around 2070), and 2080 through 2100 (the last 21 years of global climate model results). Each ensemble contains hydrology derived from all 20 climate models, which creates 5,040 monthly samples of projected future hydrologic conditions at each gaging station and considers a narrow enough time window that the data can be considered statistically stationary. The ensembles were centered around the demand projection years 2040, 2070, and 2115. The exception is the third ensemble, which was created from the last 21 years of global climate model results. However, it is assumed to approximate hydrologic conditions matching with the 2115 demand projection.

D.5.2 Hydrologic Adjustment Methodology

Hydrology inputs covering a 77-year period of record are required for the WAM simulations. The hydrology inputs are expected to represent the full range of hydrologic variability, including flooding, average conditions, and droughts. The historical 1940-2016 naturalized streamflows and corresponding net evaporation-precipitation data sets meet such criteria. In order to generate a 77-year sequence of hydrologic conditions that reflect future climate change conditions, the historical hydrologic record was adjusted using the three ensembles of hydrology previously described. The adjusted historical hydrologic record results in three new sequences of 77 years (one for each planning horizon—2040, 2070, and 2115), each corresponding to the same 77 years of historical hydrology, but now reflecting the climate change variability of the ensembles.

The statistical characteristics of the ensembles of future hydrology were mapped onto the existing historical period of record at each gaging location in the basin using a methodology known as *quantile mapping*. The statistical properties of the ensemble, such as the mean and variability, are transferred to the adjusted WAM hydrology, evaporation, and precipitation. Only the sequencing of dry and wet periods of the historical WAM hydrology is retained. In essence, the range of values from the ensemble are adopted, with sequencing according to the pattern of flows from the historical record. Quantile mapping has been applied similarly in other long-term future water planning studies (Wood et al., 2002; Salathe et al., 2007; CH2M Hill, 2008; Hamlet et al., 2009; Bureau of Reclamation, 2010; California Dept. of Water Resources, 2013).

The methodology of quantile mapping is as follows. The naturalized streamflows in the historical record and the selected ensemble are sorted in ascending order on a month-by-month basis at each control point. For example, in the case of the historical record there are 77 monthly streamflow values for January. Correspondingly, there are 420 monthly streamflow values for January from the selected ensemble obtained from 21 years of data and 20 global climate models. The sorted values are assigned cumulative probabilities. Returning to the historical period of record time series, the probability of each month of flow is determined from the ranking. The corresponding flow of the same probability for the same month in the ensemble is selected. The selected flow value from the ensemble replaces the flow in the historical period of record. The process repeats each month until a new, climate-adjusted, time series of flows is created for the period of record, January 1940 through December 2016. The process also repeats at each naturalized flow control point and at each quadrangle of precipitation and evaporation.

The quantile mapping process is shown in **Figure D-9** for January streamflows at an example control point. Step 1 refers to selecting the probability of a flow event of 24,000 acre-feet. Next, in Step 2, the streamflow from the ensemble is selected with the same probability. Finally, in Step 3, the streamflow from the ensemble is used to replace the historical flow event. In this example, a flow event of 24,000 acre-feet in the historical period of record is replaced with a monthly flow of 6,500 acre-feet.

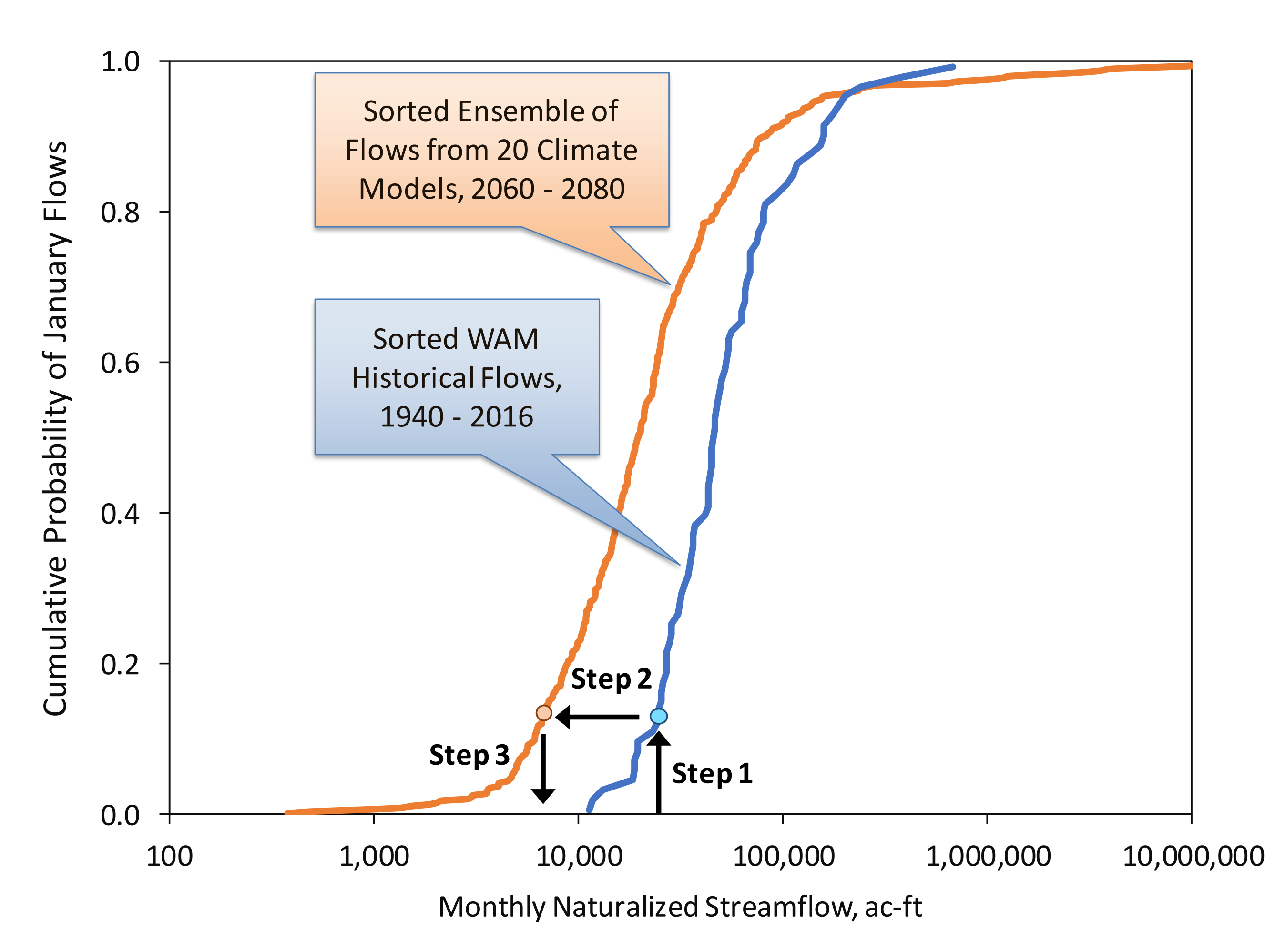

Figure D-9. Example of Quantile Mapping Methodology

The process shown in **Figure D-9** repeats at each control point with a different set of sorted flows and probabilities for each month in the 77-year period of record**Figure D-9** is fairly characteristic of the climate change effects at each gauge, particularly with the ensembles for 2060-2080 and 2080-2100. Most of the ensemble streamflows have a lower magnitude for the same probability compared to the historical period of record. However, the effects of amplifying the hydrologic cycle due to a warming climate create higher streamflow magnitudes at the upper end of the flow regime. As seen in **Figure D-9**, flow magnitudes are higher than the historical period of record for probabilities in excess of 95%.

Figure D-10 shows an example of implementing the steps exemplified in **Figure D-9** across the historical period of record. Most of the streamflows in the adjusted data set are lower in magnitude compared to the historical period of record. A high flow event is shown in the figure that is greater in magnitude from the ensemble relative to the historical period of record. The final hydrologic input data set for the WAM includes the adjustment results at all control points and all quadrangles.

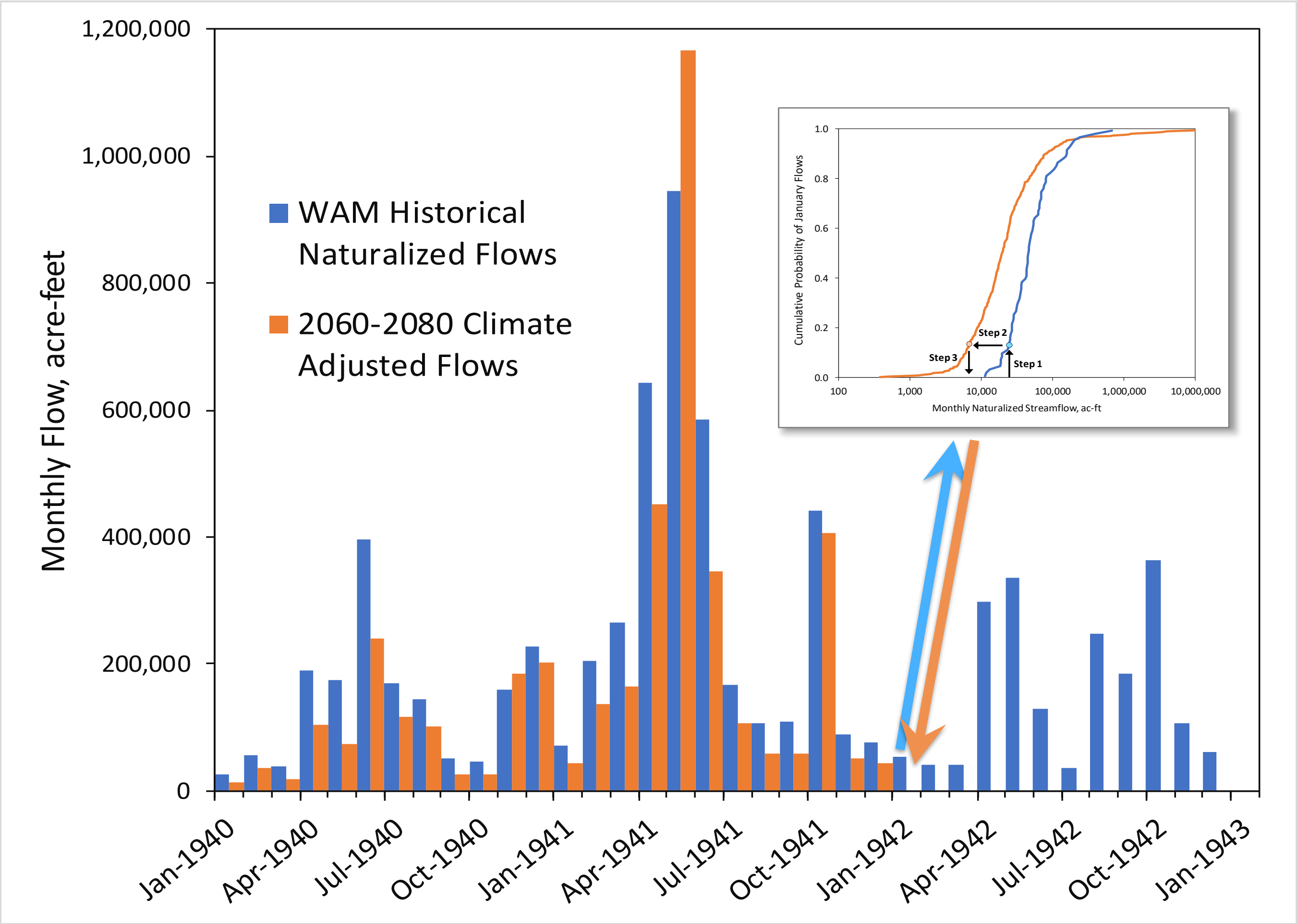

Figure D-10. Example of Adjusted Naturalized Streamflows for the Historical Period of Record

D.6 Results Of Hydrologic Adjustment

The selected carbon emission scenario, RCP 8.5, results in a warming global climate through the end of the 21st century. Downscaled weather for the Colorado River Basin derived from the 20 global climate models results in typically drier conditions that are occasionally interrupted by greater rainfall intensity and higher streamflow events when compared to the historical period of record for 1940-2016. In other words, drought conditions are likely to occur with greater frequency, but major flood events can be expected as flow variability increases across the lower Colorado River Basin.

Figure D-11 and **Figure** D-12 show the annual lower basin naturalized flows for control point I10000, the Colorado River at Austin. Lower basin naturalized flows are extracted from the WAM after all water rights in the upper basin priority cutoff areas have been simulated. The lower basin naturalized flows are the remaining naturalized flows available to water rights downstream of the priority cutoff areas. **Figure D-11** shows the historical period of record data for 1940-2016. **Figure D-12** shows the same period of record but with adjustment using the 2080-2100 ensemble data. Both figures show an average annual flow of approximately 1.2 million acre-feet. However, the effects of adjustment for end-of-century climate conditions result in more years of lower flows with a smaller number of years of substantially higher annual flows.

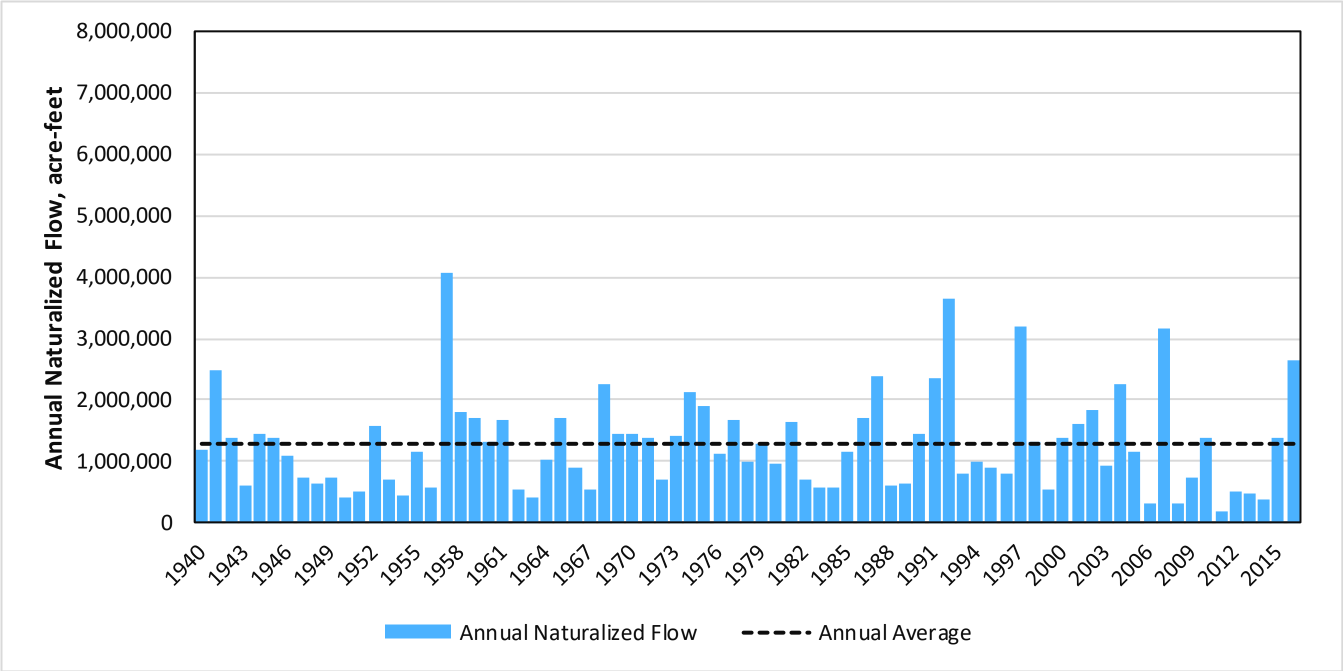

Figure D-11. Historical Annual Lower Basin Naturalized Flows, Colorado River at Austin

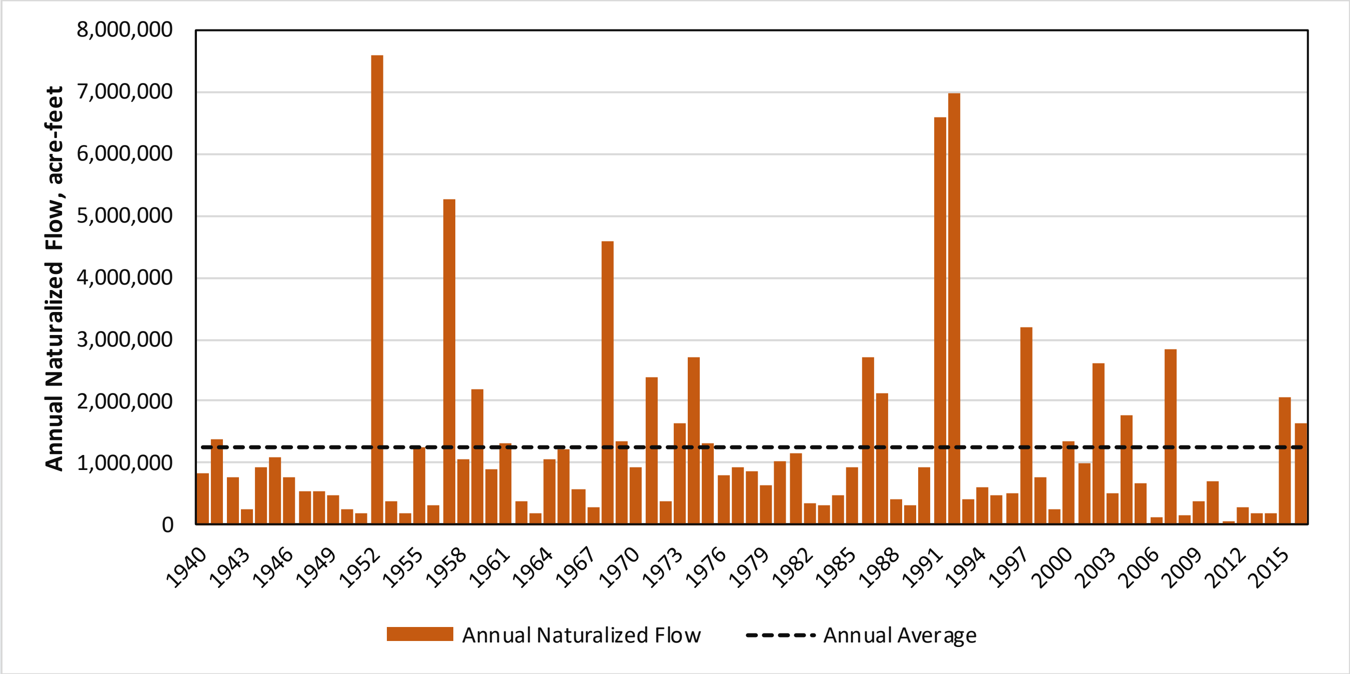

Figure D-12. Adjusted Annual Lower Basin Naturalized Flows, Colorado River at Austin

Annual lower basin naturalized flows for the Colorado River at Austin are statistically summarized in box-plot form in **Figure D-13**. The flows are summarized for the 1940-2016 period of record for the historical condition and for the three ensemble periods. The X mark in each box indicates the magnitude of the annual average. The line through the middle of each box indicates the magnitude of the annual median. The lower and upper bounds of the box indicate the magnitude of the 1st and 3rd quartiles, or the 25th and

75th percentiles. The whiskers indicate the minimum and maximum values of annual flow that are within 1.5 times the interquartile range below and above the 1st and 3rd quartiles. Outlier values are designated as annual flows less than or greater than the ends of the whisker lines. Outlier values are shown as small circles. The statistical summary shown in **Figure D-13** shows an overall lower flow trend across the ensembles, as the whiskers, median, and 1st and 3rd quartiles fall in magnitude as the ensemble adjustments reach the end of the century. The annual naturalized flow magnitude does not show a consistent trend over time. The increasing magnitude of high flow events, as represented by the outlier dots, tends to offset the annual volume reduction in the other years of the period of record.

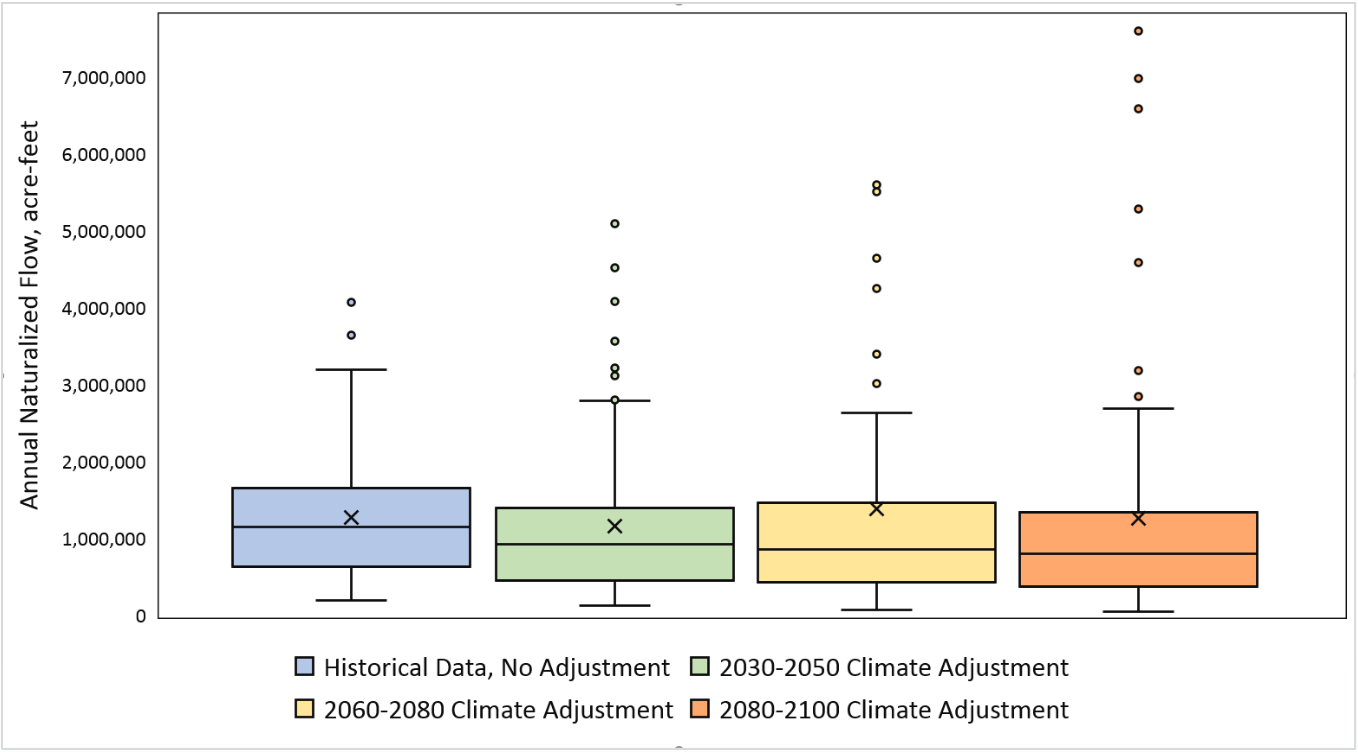

Figure D-13. Box Plots of Annual Lower Basin Naturalized Flows, Colorado River at Austin

Net evaporation-precipitation depth at Lake Travis is statistically summarized in the box plots shown in **Figure D-14**. Increasing temperature toward the end of the century increases the evaporation rate in each of the three ensemble adjustments. The average, medians, and 1st and 3rd quartiles rise in each adjustment compared to the earlier period and compared to the historical data. The trend is similar throughout the basin over time.

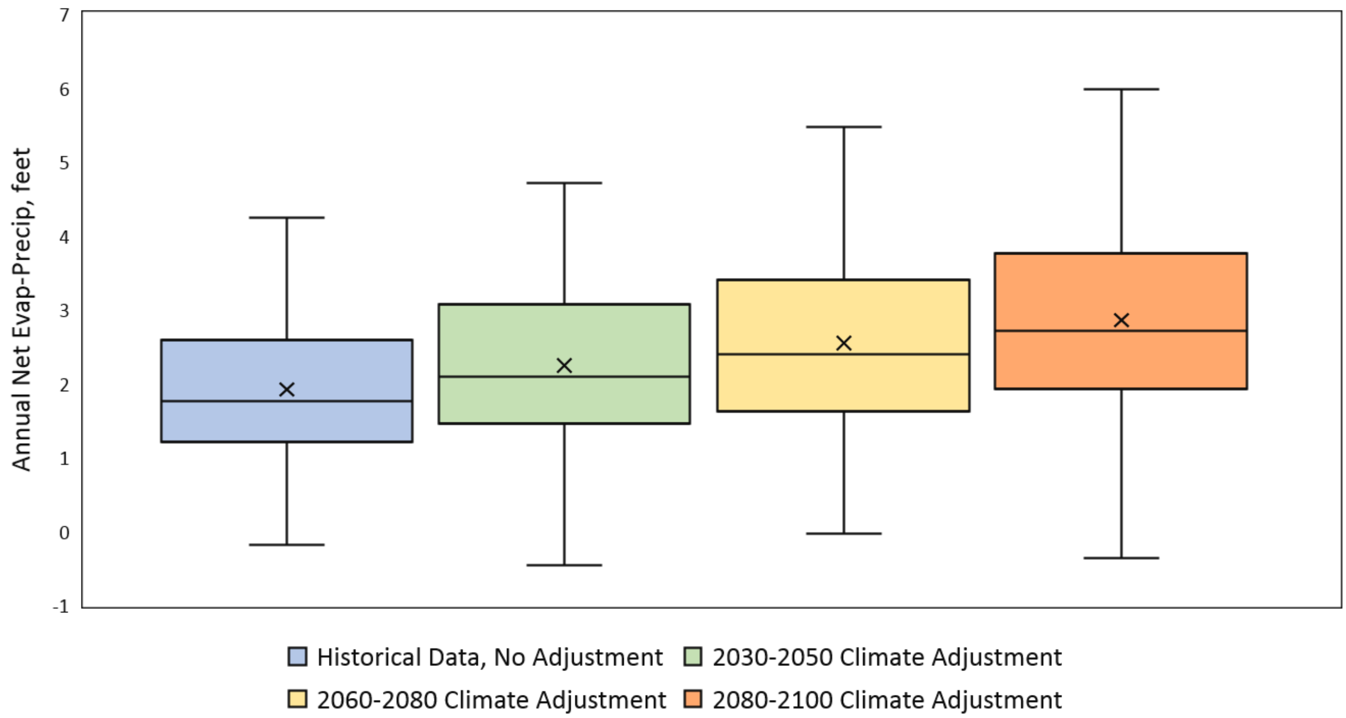

Figure D-14. Box Plots of Annual Lower Basin Naturalized Flows, Colorado River at Austin

D.7 Conclusions on Climate Change Anlaysis and Climate-Adjusted Hydrology Analysis

Climate in Texas is already changing. Observed changes are consistent with larger-scale trends observed across the U.S. and the world. In the future, climate is expected to continue to change as a result of human emissions of carbon dioxide and other heat-trapping gases including increases in annual and seasonal average temperatures, more frequent high temperature extremes, little change in annual average precipitation, more frequent extreme precipitation, a slight increase in the number of dry days per year, and more frequent drought conditions in summer due to hotter weather as well as decreases in summer precipitation.

This analysis developed statistical regression models based on temperature- and precipitation-related climate variables, and demonstrated their abilities to reproduce the climatology of observed streamflow at individual gauges when driven by both historical observations independent of those used to train the model, as well as when driven by high-resolution climate projections obtained by statistical downscaling of GCM simulations.

This approach was applied using a dataset composed of 43 long-term streamflow gauges and nearby weather stations in relevant river basins upstream and downstream to the city of Austin, Texas. In contrast to many other Texas cities that rely on groundwater, Austin depends on surface water for its water supply. Future projections suggest that, consistent with precipitation projections for the region, no significant change in long-term annual average streamflow is expected for deep rivers with high flow volumes that primarily respond to precipitation. However, occrences of drought and flooding will be different as the pattern of precipitation changes, leading to longer durations of dry conditions broken by intermittent extreme flow events. For shallower rivers, however, the impact of temperature on evaporation rates is expected to increase the risk of low flow events.

These projections were used to develop a comprehensive dataset of daily naturalized streamflow inputs. The daily streamflows were aggregated to monthly naturalized flows and used to adjust the existing inputs of the TCEQ WAM for the Colorado River Basin, a computer based-simulation used by the Texas Commission on Environmental Quality and used by various agencies and stakeholders including the City of Austin to estimate the amount of water that would be in a river or stream under a specified set of conditions. Projections of monthly quadrangle precipitation and evaporation were used to adjust the existing Colorado WAM net evaporation-precipitation inputs. The Colorado WAM hydrologic record, as adjusted for projections of conditions in 2040, 2070, and 2100, give the City of Austin the ability to compare water availability with future demands with a stationary climate (existing hydrologic record) versus hydrology affected by climate change.

D.8 Referenecs

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APPENDIX E: EXTENDED HYDROLOGY ANALYSIS AND WATER AVAILABILITY MODELING

Development of Austin's Integrated Water Resources Plan for the Water Forward planning process required, among many other considerations, a framework for assessing water availability to the City. Water availability models (WAMs) are computer simulations that quantify the amount of water from river and reservoir sources that can be diverted under a specified set of streamflow conditions and a specific water management scenario, which allows comparison of water availability to the City under different portfolios. The Texas Commission on Environmental Quality (TCEQ) WAM for the Colorado River Basin (Colorado WAM) is a widely used computer model for assessing Colorado River water availability for all water rights holders in the basin, including the City of Austin. The City of Austin currently derives its water supply largely from the Colorado River through City-owned water rights and contracts with the Lower Colorado River Authority (LCRA). The City is one of many entities with water rights and reservoirs in the basin, so the Colorado WAM was selected for use in the Water Forward planning process to assess water availability to the City under different scenarios within the context of water rights allocation.

This report documents the steps taken to develop key WAM inputs: hydrology, water demands, and water management scenarios. **Appendix D** covers climate-adjusted hydrology, while this appendix focuses on development of extended hydrology and droughts worse than the drought of record inputs to the WAM and the actual modeling. To develop hydrology inputs for the WAM, naturalized streamflow, evaporation, and precipitation were modeled according to the known historical period of record. The hydrologic inputs were also adjusted in some scenarios to account for future climate change conditions (see **Appendix D** for more detail on climate change modeling). Additional hydrology inputs including severe drought conditions worse than the historical drought of record were developed by extending hydrologic inputs over a very long-period simulation (10,000 years), which is the focus of this appendix. Candidate droughts were selected from the extended period of simulation to represent potential scenarios for droughts worse than the drought of record. To determine water demands for input to the WAM, basin-wide demands, including those for the City of Austin, were developed for four planning horizons: 2020, 2040, 2070, and 2115. Demands for 2040, 2070, and 2115 were adjusted in some scenarios to account for potentially hotter and drier conditions under climate change scenarios.

As mentioned above, another key WAM input is water management scenarios. For Water Forward, this involved using the Colorado WAM in an iterative process to test various combinations of demand management and water supply options to develop groupings of demand management and supply options, known as portfolios. The demand management and water supply options evaluated in portfolios in Water Forward were modeled across the four planning horizons according to their projected implementation yield. Water availability results were summarized from the WAM outputs and used to score the performance of the various portfolios. The water supply scoring was one criteria that was used to evaluate and score portfolios to ultimately arrive at a recommended set of strategies for the Water Forward Integrated Water Resources Plan.

Figure E-1 summarizes the work described in this report. Water demand projections, both climate-adjusted and non-climate adjusted, for four planning horizons were paired with four hydrologic conditions, with the exception of the 2020 demand projection (climate-change-adjusted hydrology was not considered for the 2020 demand projection). The four hydrologic conditions are (A) a repeat of the historical hydrology, (B) historical hydrology adjusted to consider possible future climate change, (C) stochastically-selected droughts worse than the drought of record under historical hydrologic conditions, and (D) stochastically-selected droughts worse than the drought of record adjusted to consider possible future climate change. In total, water availability results were obtained for 14 combinations of the demand projections paired with the array of hydrologic conditions.

Demand Projection Planning Horizons
2020
2040
2070
2115

X

	Historical Hydrology, No Adjustment	Hydrology Adjusted to Consider Possible Future **Climate Change**
Simulate Drought of Record **(Period of Record)**	**Scenario A** Historical Hydrology (77 Years, 1940-2016)	**Scenario B** Hydrology Adjusted for Future Climate Change (77 Years)
Simulate Droughts Worse than the Drought of Record **(Extended Period)**	**Scenario C** Stochastically Sampled Historical Hydrology (10,000 years)	**Scenario D** Stochastically Sampled Hydrology Adjusted for Future Climate Change (10,000 years)

Figure E-1. Conceptual Roadmap for Water Availability Modeling

E.1 Water Availability Models (WAMs)

The TCEQ Water Availability Model is a publicly available computer modeling system for simulating surface water availability. The WAM system covers every river basin in Texas, including the Colorado River Basin. It was created pursuant to Article VII of the 1997 Senate Bill 1, which required the development of new WAMs for the State's river basins. The WAM system is comprised of two components: a generalized computer modeling software known as the Water Rights Analysis Package (WRAP) and a set of basin-specific input files and supporting geographic information system (GIS) coverages. The basin-specific input files and GIS coverages were initially developed in the late 1990s and are updated regularly by TCEQ to reflect new conditions.

The WAM uses naturalized streamflow, net lake evaporation minus precipitation, and a water management scenario as its three main inputs. Naturalized streamflows can be thought of as an estimate of what the natural flow in river would have been if no permitted water rights were using that water. These monthly naturalized streamflows are calculated from historical streamflow gaging records by reversing the historical water diversions, changes in reservoir storages, and return flows for all state-granted water rights. The naturalized streamflows represent the total surface water production of the basin in the absence of state-granted water rights. In addition to naturalized streamflows, the WAM uses monthly net lake evaporation minus precipitation as an input for reservoir water balance calculations. Monthly lake evaporation and precipitation data are calculated over quadrangles that cover 1° longitude by 1° latitude as shown in **Figure E-2**.

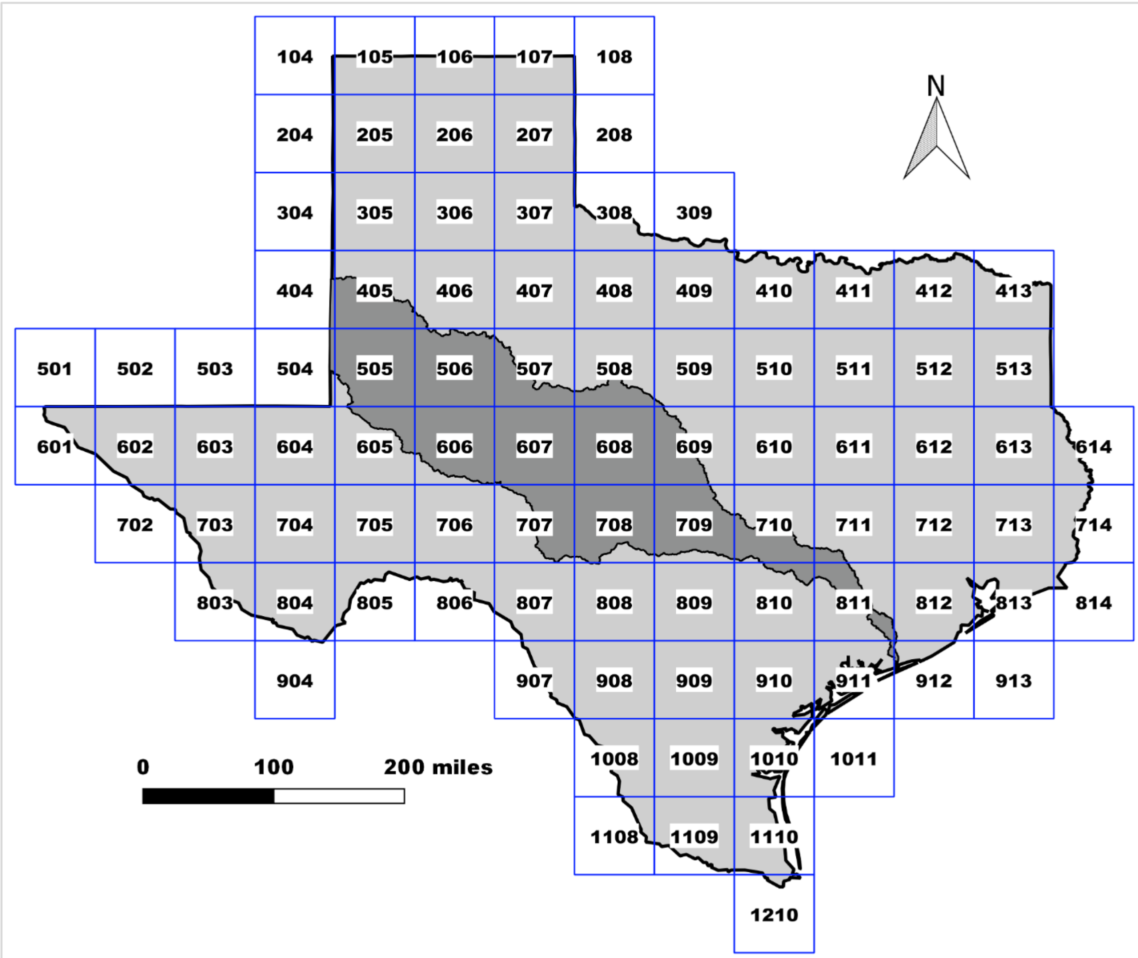

Figure E-2. TWDB Quadrangle Coverage

The WAM simulates surface water availability to basin water rights under the user-specified water management scenario. TCEQ maintains two sets of water management scenarios for every river basin in the WAM system. The full authorization scenario, used for water rights permitting, is more theoretical and assumes all state-granted water rights are utilized to the full extent of their permitted rights, including full reservoir conservation storage. The current conditions scenario assumes that all state-granted water rights are utilized according to recent water-use reporting levels, including return-flow discharge volumes, and that reservoir storage reflects recent sedimentation conditions. Water management scenarios other than those TCEQ maintains can be developed by the user, as in the case of Water Forward.

Simulation outputs include numerous variables such as monthly water diversions, reservoir storage content, and remaining streamflow after accounting for water management activities. As mentioned, TCEQ uses the outputs of the WAM system to evaluate water right applications for water availability under new permits or permit amendments and to assess potential impacts to existing water rights. Other state agencies, planners, and permit holders use the WAM as well. The Texas Water Development Board (TWDB) and the Texas Regional Water Planning Groups modify the WAMs to estimate surface water supply for the State Water Planning process, which spans a 50-year planning horizon. The WAM system is also used by river authorities and individual water right holders to assess water availability from the river, reservoir operations, and environmental flow conditions for various planning or permitting purposes.

E.1.1.1 Colorado River Basin WAM

The Colorado River Basin contains approximately 31,000 square miles of contributing drainage area. The basin extends for over 1,000 river miles, from southeast New Mexico, to across Texas, to where it discharges into the Gulf of Mexico at Matagorda Bay. A map of the Colorado River Basin is shown in **Figure E-3.** Climatic conditions range from arid desert in west Texas to humid subtropical near the eastern gulf coast. Major tributaries within the basin and upstream of the city of Austin include Pecan Bayou and the Concho, San Saba, and Pedernales Rivers. Minor tributaries downstream of the city of Austin include Onion, Willbarger, Cedar, and Cummins Creeks.

The TCEQ Colorado River Basin WAM covers the entire portion of the river basin inside Texas, from the border of southeast New Mexico downstream to Matagorda Bay. The TCEQ input files for this WAM include the Brazos-Colorado Coastal Basin. However, the coastal basin is not used in the modeling described in this report. The Colorado WAM as used in this report refers only to the portion of the TCEQ input files relevant to the Colorado River Basin. There are over 2,000 water rights and over 500 major and minor reservoirs represented within the Colorado WAM.

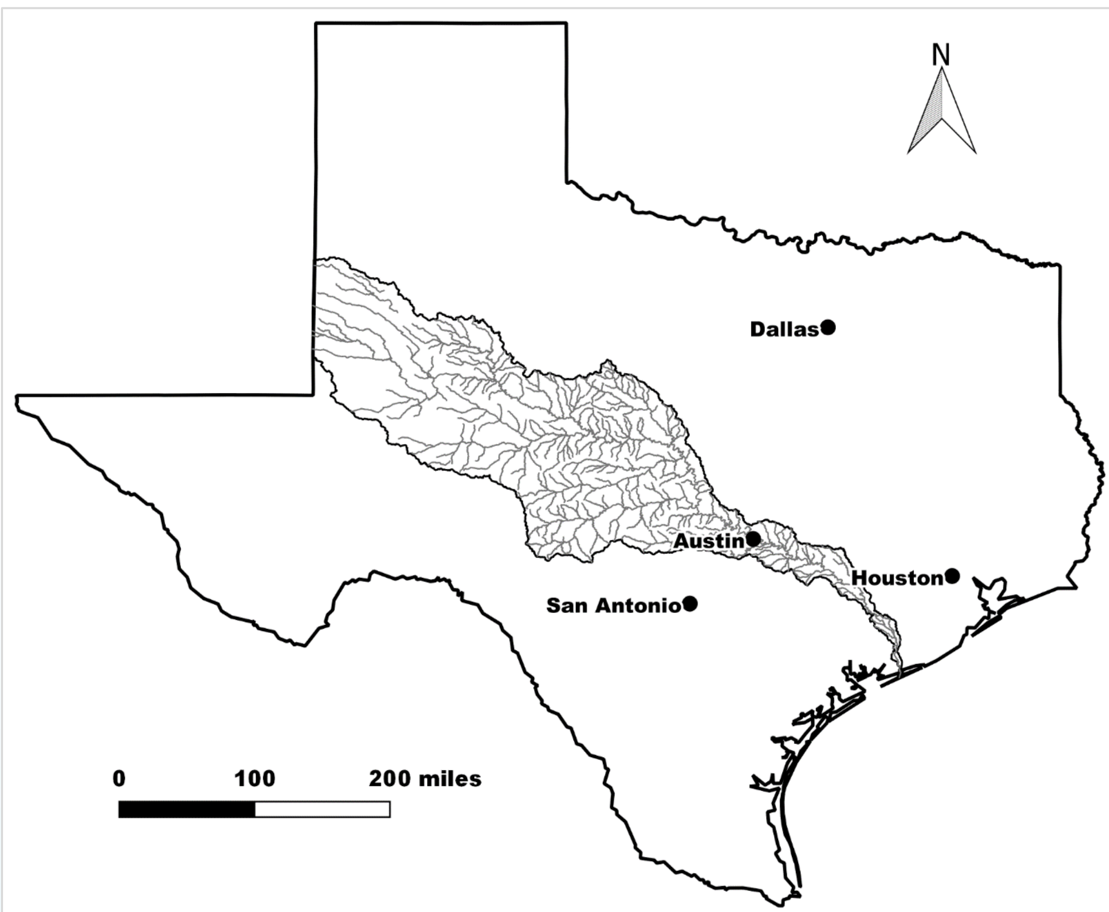

Figure E-3. Colorado River Basin

Physical locations in the river basin network, such as USGS stream gauges, water right diversion points, or reservoirs, are represented with control points. Locations in the river basin network are designated as either primary or secondary control points. Primary control points are typically located at USGS stream gauges or major reservoirs and are associated with naturalized flow inputs. The Colorado WAM uses a monthly naturalized hydrology period of record from January 1940 through December 2016 for the entire river basin The 43 primary control points where naturalized flows are input in the Colorado WAM are listed in **Table E-1** and illustrated in **Figure E-4**.. Secondary control points do not have naturalized flows provided as input. Secondary control points are assigned naturalized flows from nearby primary control points during the simulation. A variety of methods are available in WRAP for distributing naturalized flows from primary to secondary control points, though the drainage area ratio is the generally accepted transfer method in the TCEQ WAMs. There are over 2,100 secondary control points in the Colorado WAM.

Table E-1. Primary Control Points in the Colorado WAM

WAM CP ID	Drainage Area, sq. miles	River Miles to Bay	USGS Gauge No.	USGS Gauge Name
A30000	1,074	868	08119500	Colorado River at Hwy 350 near Ira
A20000	193	858	08120500	Deep Creek near Dunn
A10000	1,575	828	08121000	Colorado River at Colorado City
B40000	176	825	08123600	Champion Creek Reservoir
B30000	1,974	807	08123800	Beals Creek near Westbrook
B20000	4,559	787	08123850	Colorado River above Silver
B10000	5,046	758	08124000	Colorado River at Robert Lee
D40000	6,090	709	08126380	Colorado River near Ballinger
D30000	464	706	08127000	Elm Creek at Ballinger
C30000	258	763	08128000	South Concho River at Chrisoval
C60000	1,613	763	08128400	Middle Concho River above Tankersley
C50000	340	756	08129300	Spring Creek above Tankersley
C40000	164	760	08130500	Dove Creek at Knickerbocker
C70000	1,202	758	08134000	North Concho River near Carlsbad
C20000	4,139	734	08136000	Concho River at San Angelo
C10000	5,185	693	08136500	Concho River at Paint Rock
D20000	12,548	646	08136700	Colorado River near Stacy
D10000	13,788	598	08138000	Colorado River at Winchell
F30000	1,654	595	08143500	Pecan Bayou at Brownwood
F20000	2,074	562	08143600	Pecan Bayou near Mullin
E40000	1,137	632	08144500	San Saba River at Menard
E30000	1,636	584	08144600	San Saba River near Brady
E20000	589	594	08145000	Brady Creek at Brady
E10000	3,048	529	08146000	San Saba River at San Saba
F10000	19,830	506	08147000	Colorado River near San Saba
G50000	897	550	08148500	North Llano River near Junction
G40000	1,859	541	08150000	Llano River near Junction
G30000	3,251	489	08150700	Llano River near Mason
G20000	215	484	08150800	Beaver Creek near Mason
G10000	4,201	444	08151500	Llano River at Llano
I40000	20,521	458	08148000	Lake Buchanan near Burnet
I30000	346	428	08152000	Sandy Creek near Kingsland
H20000	370	471	08152900	Pedernales River near Fredericksburg

WAM CP ID	Drainage Area, sq. miles	River Miles to Bay	USGS Gauge No.	USGS Gauge Name
H10000	901	432	08153500	Pedernales River near Johnson City
I20000	27,357	368	08154500	Lake Travis near Austin
I10000	27,611	311	08158000	Colorado River at Austin
J50000	124	335	08158700	Onion Creek near Driftwood
J40000	324	309	08159000	Onion Creek at US Hwy 183, Austin
J30000	28,580	249	08159200	Colorado River at Bastrop
J20000	29,062	229	08159500	Colorado River at Smithville
J10000	30,244	138	08161000	Colorado River at Columbus
K20000	30,601	65	08162000	Colorado River at Wharton
K10000	30,862	30	08162500	Colorado River near Bay City

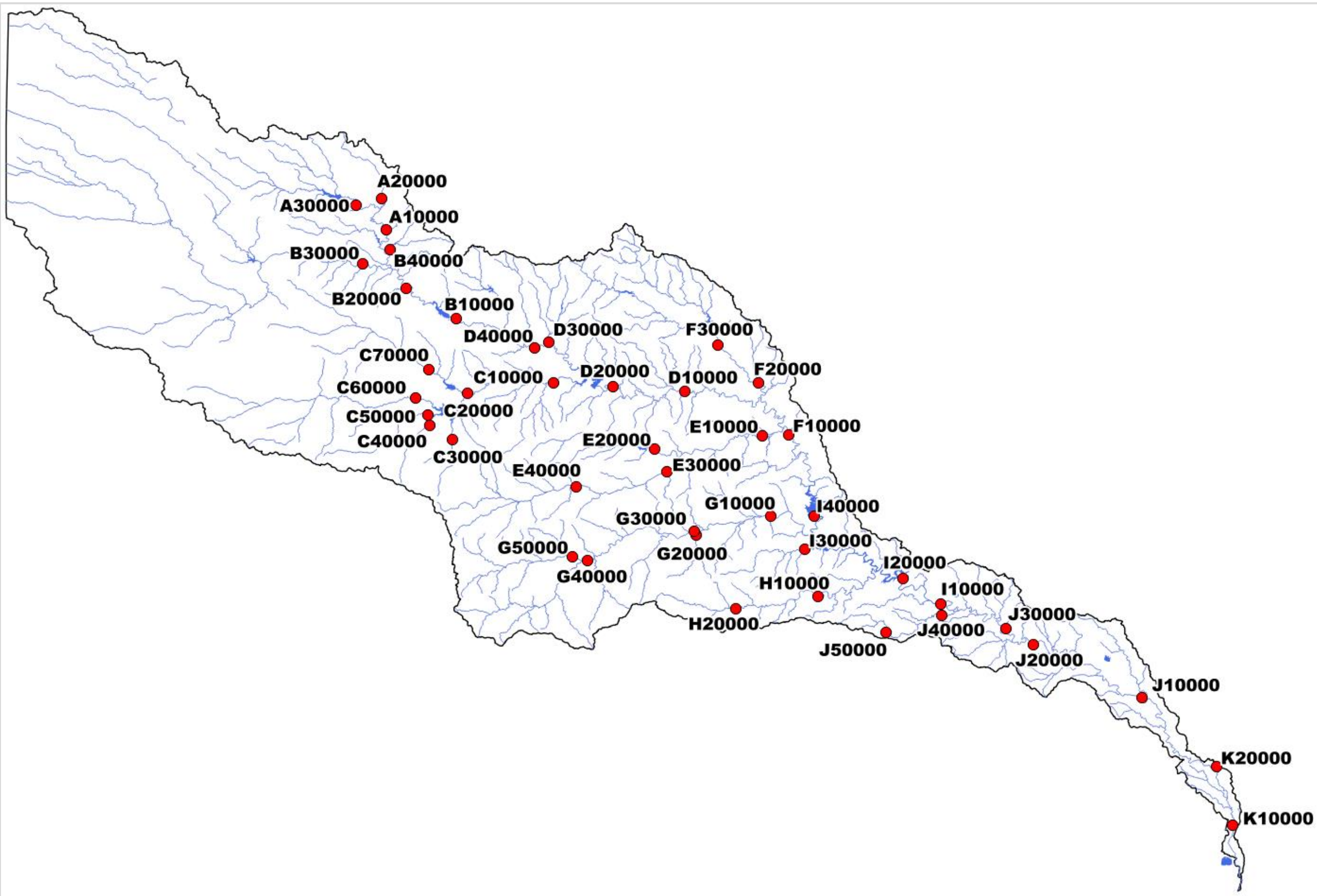

Figure E-4. Primary Control Points in the Colorado WAM

Control points are also used for the input of net evaporation-precipitation depths at major reservoirs or other pertinent locations in the basin. There are 47 control points in the Colorado WAM that receive input net evaporation-precipitation depths. Like secondary control points that are assigned naturalized flow based on primary control points, net evaporation-precipitation can be distributed to any control point not included in the input file. The net evaporation-precipitation depths are developed from monthly lake evaporation and precipitation quadrangle data maintained by TWDB. The quadrangles are shown in

Figure E-2. Information regarding the calculation of net evaporation-precipitation depths for reservoirs in the Colorado WAM using the TWDB quadrangles can be found in Pauls et al. (2013). A summary of the connectivity of primary control points in the Colorado WAM is shown in **Figure E-5**.

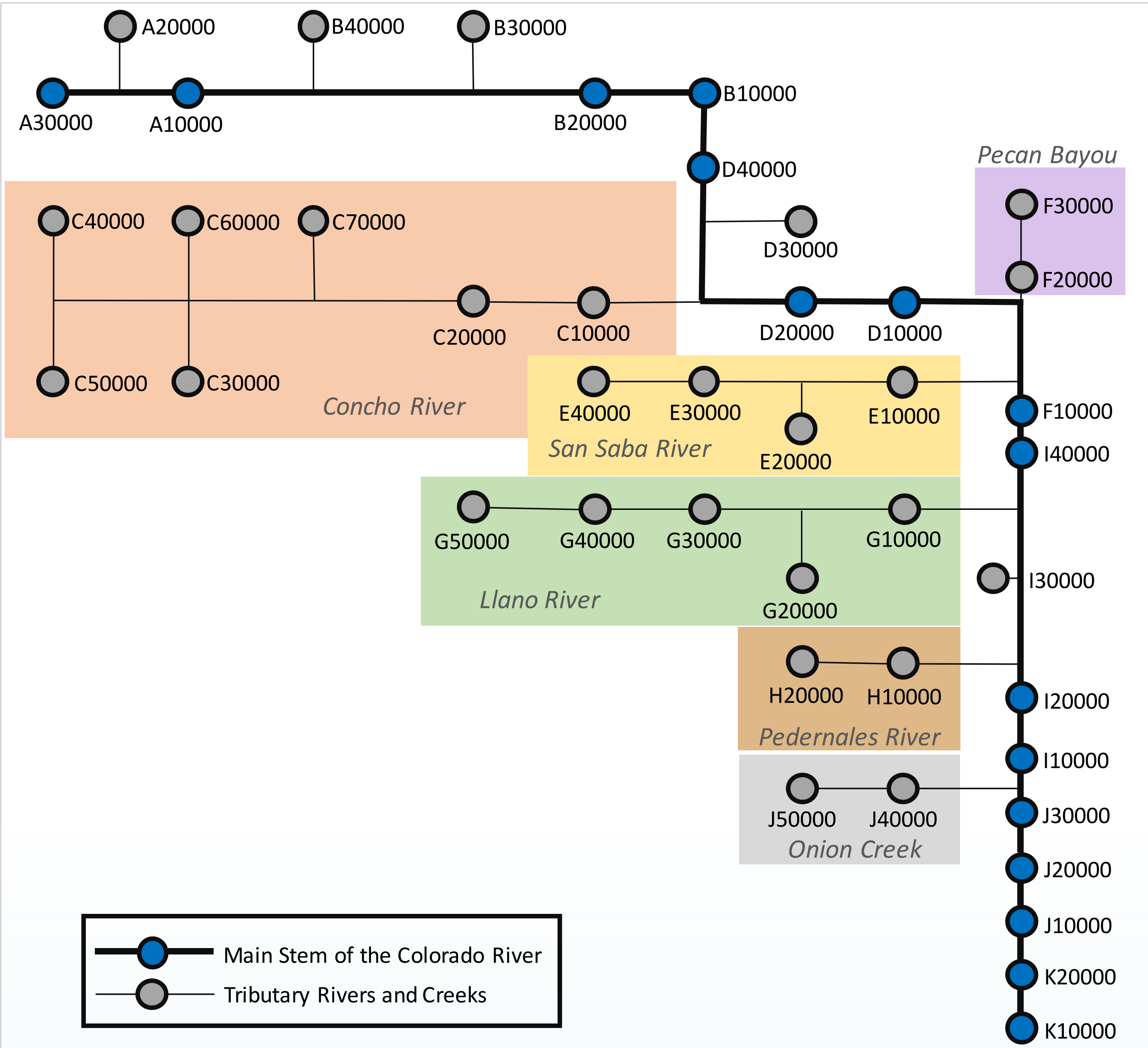

Figure E-5. Connectivity of Primary Control Points in the Colorado WAM

E.1.2 Variants of the Colorado WAM

As mentioned previously, the WAM system is a publicly available computer modeling system and is used by entities other than TCEQ. Other state agencies, river authorities, local governments, or private water right holders use the WAM system and often modify the input water management scenario for specific planning or permitting applications. Modifications are typically made to the input water management scenario to reflect future water demands, explore alternative water right and reservoir system operations, or estimate the size of potential projects to fulfill unmet demands. Modification can also be made to the input hydrology datasets to extend the period of record or to reflect alternative conditions such as those projected with future climate change.

The Lower Colorado Regional Water Planning Area (Region K) is one of 16 regional planning groups supported by TWDB and generally covers the Colorado River Basin that drains into the Highland Lakes and downstream to Matagorda Bay. Each planning group develops a 50-year regional water plan, updated on a 5-year cycle, for submittal to the TWDB. The State Water Plan is developed from the regional water plans. In developing the regional water plans, the planning groups utilize the TCEQ WAM for their respective river basin. Modifications typically include adjustments for surface water demands and return-flow discharges each decade over the 50-year planning horizon, adjustments for future reservoir sedimentation, and extensions to the hydrologic period of record.

Region K employs a major modification to the water rights allocation system in the TCEQ WAM. Instead of all state-granted water rights being simulated with their actual priority dates, water rights at and upstream of lakes O.H. Ivie and Brownwood are modified so that their priority dates are senior to all other water rights downstream. The modification is formally known as the Region K Cutoff Model since it forms a water right seniority disconnect, or *cutoff*, between the upper and lower portion of the Colorado Basin. All water rights included in the upper basin cutoff areas maintain their relative priority dates to each other, and similarly all water rights included in the lower basin area maintain their relative priority dates to each other. The cutoff assumption is intended to reflect current and historical basin operations that have not included priority calls by lower basin senior water rights for the passage of streamflows from the upper basin.

The Lower Colorado River Authority (LCRA) modifies the TCEQ WAM in preparation of amendments to its Water Management Plan (WMP) and for calculation of the combined firm yield of its water supply reservoirs, lakes Buchanan and Travis. A complete description of the modifications for the WMP and combined firm yield models can be found in the Appendix A Technical Papers of the LCRA WMP.[1] Major modifications for the WMP include the Region K priority date cutoff assumption plus additional priority date cutoffs for all water rights not associated with LCRA or LCRA customers, portions of reservoir releases that are not diverted downstream, and reduced streamflow availability for run-of-river water rights downstream of Austin to represent historical baseflow conditions. Water rights associated with LCRA and LCRA customers are assigned near-term future demands. All other water rights in the basin are simulated with their fully authorized water right demands.

The LCRA combined firm yield model utilizes the Region K priority date cutoff assumption for upper basin water rights, though it does not include the additional cutoff assumption for lower basin water rights not associated with LCRA or LCRA customers. Reduced water availability for lower basin baseflow conditions is not considered in the combined firm yield model. All water rights in the basin are simulated with their fully authorized water right demands. Elements of the LCRA WMP are not included, such as storable inflow and stored water allocations for WMP environmental flow maintenance and the availability of interruptible stored water for downstream agricultural purposes.

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[1] https://www.lcra.org/water/water-supply/water-management-plan-for-lower-colorado-river-basin/Pages/default.aspx

E.1.3 Baseline Assumptions of the Water Forward WAM

The City of Austin used the Colorado River Basin WAM in the development of its Integrated Water Resources Plan (IWRP) as a part of the Water Forward planning process, and plans to use it to inform the implementation process. The Colorado WAM serves as a key modeling tool to assess baseline future needs and the performance of portfolios of options to address those needs. For the Water Forward IWRP process, the WAM was used to evaluate water available to the City of Austin and the lower Colorado River Basin for the four scenarios (A, B, C, D) illustrated in **Figure E-1**.

Modeling modifications to create the Water Forward WAM mirror those contained in the Region K Cutoff Model and the LCRA WMP WAM. As in the Region K Cutoff Model, priority dates of upper basin water rights at and upstream of lakes O.H. Ivie and Brownwood are made senior to all water rights in the basin. A second seniority cutoff is utilized for lower basin water rights not associated with LCRA or LCRA customers. Water rights in both cutoff assumptions maintain their relative priority dates. In addition, water rights other than LCRA and LCRA customers in both cutoff assumptions are simulated with their fully authorized water right demands. The cutoff and full authorization assumptions provide both a historical operational component (priority cutoff assumptions) and a conservatively high level of streamflow consumption outside of the planning area for Water Forward (full authorization assumption).

The Water Forward WAM incorporates additional operational assumptions contained in the LCRA WMP WAM. Streamflow availability for major run-of-river water rights downstream of the Highland Lakes is limited to estimates of historical baseflow conditions and return-flow discharges. Portions of reservoir releases not diverted by downstream water rights are represented. However, LCRA's Arbuckle Reservoir, located near Lane City, is simulated with the ability to store the undiverted releases according to its water rights. Water rights associated with LCRA and LCRA customers are simulated with future demands that follow and extrapolate Region K demand trends. Future City of Austin demands are set according to the City's disaggregated demand model (see Appendix A for more detail on the disaggregated demand model).

Additional information regarding the modeling modifications for the Water Forward WAM is described in the remainder of this report. The modifications include those associated with the development of future hydrologic conditions associated with climate change trends, simulation of droughts worse than the drought of record, and representations of portfolios of demand management and water supply options.

A conceptual roadmap for the work described in this report was presented in **Figure E-1**. City of Austin demands and regional demands in the lower Colorado Basin in the Water Forward WAM were projected and simulated for four planning horizons: 2020, 2040, 2070, and 2115. The 2020 demand set is paired with the historical period of record hydrology as well as an extended hydrologic set constructed from the period of record. The extended hydrologic sets are used for testing water availability under droughts worse than the drought of record. Demand sets for 2040, 2070, and 2115 are paired with all four hydrologic categories shown in **Figure E-1** to simulate water availability under drought of record, droughts worse than the drought of record, and conditions reflective of the historical climate and future climate change trends.

E.2 Extended Hydrologic Data

The historical hydrologic period of record for the Colorado WAM is January 1940 through December 2016. The record contains 77 years, or 924 monthly samples, of naturalized streamflow and net evaporation-precipitation. Within the historical period of record are two major drought periods known as the droughts of the 1950s and 2010s. The drought during the 2010s represents the worst drought from a reservoir water supply perspective and, for the purposes of Water Forward planning, is referred to as the “drought of record” (DOR) because it sets the minimum firm water supply from the Highland Lakes’ supply reservoirs, lakes Buchanan and Travis. The drought of the 2010s began in October 2007 and was significantly alleviated, though not completely ended from a reservoir firm water supply perspective, by major rainfall events in the spring of 2016.

A risk factor and source of uncertainty for characterizing water availability to the city of Austin are droughts worse than the drought of record (DWDR). DWDR events are, by definition, droughts that have not yet occurred, and hence are not yet part of the period of record. However, with such a relatively short historical period of record, conservative water supply planning processes should consider the possibility of DWDR events occurring, especially over the 100-year planning horizon of the Water Forward process and against the backdrop of climate change.

The methodology used in Water Forward to create a long sequence of plausible hydrology for modeling DWDR events involves stochastically resequencing the 1940-2016 period of record. The methodology is formally known as Markov Chain Monte Carlo (MCMC) sampling (Brooks et al., 2011). Whole years of hydrology from the period of record are randomly selected and connected back-to-back to build a long sequence of flows. Random sampling of calendar-year sequences of streamflows is conditioned by the observed transition frequencies, such as transitioning from wet to dry years or dry to average years. Modeling the annual flows with a Markov chain ensures the long sequence of randomly sampled calendar-year streamflows matches the same transition frequencies in the period of record and has the same long-term statistical properties of the period of record.

A long sequence of extended synthetic hydrology that preserves the statistical characteristics of the observed period of record is useful for analyses of river and reservoir water availability (Wurbs, 1991). A long sequence of synthetic hydrology allows for the random occurrence of conditions that are both wetter and drier on a short-term basis than contained in the period of record. Multi-year droughts in the extended hydrology can be worse than the drought of the 2010s. For example, the drought of the 2010s is punctuated by high flow events in early 2012 and mid-2015. If random sampling replaced the hydrology of 2012 or 2015 with a drier year in the extended hydrology, then the new drought sequence could be worse than the observed drought of the 2010s.

The hydrology inputs used for Water Forward cover 10,000 years of simulation. The length of this simulation is arbitrary, but it is intended to be long enough for random chance to produce a large number of candidate droughts that are worse than those contained in the period of record. The WAM allows for a maximum of 10,000 years of hydrologic record in a single simulation. Thus, the maximum length was selected even though a shorter extension may be sufficient to produce a large number of candidate droughts. A large number of candidate events is desirable for exploring a range of potential water availability sequences during DWDR conditions. Shiau and Shen (2001) likewise used a 10,000-year sequence of synthetic streamflows for drought recurrence analysis.

These candidate droughts are further ranked by the degree to which they are worse than the drought of the 2010s. Criteria for selecting the ranked candidate droughts for water availability calculations are used to narrow the range of DWDR events for consideration. Further discussion about ranking and selecting candidate droughts is provided in Section 4 of this report. Creating plausible candidate DWDRs in the extended hydrology and ranking their severity allows Water Forward to test water availability in a mathematically sound manner under DWDR conditions.

E.2.1 Transition Frequencies

Creation of an extended synthetic hydrologic record can be accomplished by randomly selecting years from the historical period of record. Serial correlation between calendar-year annual naturalized flow volumes is nearly zero, indicating calendar-year annual flow volumes are likely independent. However, the historical record may reflect persistence of low or moderately low annual naturalized flow volumes, particularly in drought events. Persistence between states of naturalized flows can be quantified by the probability for a year of higher flows to be followed by a year of average flows or a year of lower flows to be followed by another low year of flows, for example. A Markov chain is a type of stochastic modeling process that assigns the probability of an event based on the state of the prior event (Maidment, 1993). In the case of annual naturalized flows, a Markov chain model assigns the probability for a designated state of flow to be followed by the same or different states of flow.

Transition probabilities from the present state to the future state are fundamental to Markov processes. A transition matrix was created that assigns a probability to switch to any possible state in the system based on the prior state. The dependency of the future state based only on the prior state is known as a first-order Markov process. Stochastic streamflow generation is commonly performed as a first-order Markov process (Maidment, 1993; Yeh, 1985).

In the case of annual naturalized flows for the Colorado Basin, a transition matrix was created to designate the probabilities of switching between low, average, and high naturalized streamflow years. Naturalized streamflows at control point I20000, the location of Lake Travis in the WAM, were used for creating the transition matrix. Low, medium, and high flow years were defined by ranking all 77 years in the period of record in ascending order. The lowest one-third of annual flows were classified as low flow. The highest one-third of annual flows were classified as high flow. The remaining one-third of annual flows were classified as medium flows. The historical frequency of switching between low, medium, and high flow years was used as estimates of probability for the transition matrix.

Table E-2 gives the transition matrix calculated for states of lower basin naturalized streamflows at the location of Lake Travis in terms of the number of years and the frequency as a percentage of 76 years of transition. There are only 76 possible transition states in 77 years of record. The transition matrix shown in **Table E-2** corresponds to lower basin naturalized streamflows in the historical period of record. The same process of calculating transition matrices was repeated for the adjusted naturalized streamflow data sets using the quantile mapping methodology described in Section 2 of this report. The transition matrix for naturalized streamflows adjusted for the 2080-2100 ensemble is given in **Table E-3**.

Table E-2. Transition Matrix for 1940-2016 Historical Lower Basin Naturalized Streamflows

		Annual Transition State, Number of Years and Frequency		
		Low	Medium	High
Prior Annual State	Low	11 (42.3%)	10 (38.5%)	5 (19.2%)
	Medium	4 (26.9%)	4 (26.9%)	12 (46.2%)
	High	8 (33.3%)	8 (33.3%)	8 (33.3%)

Table E-3. Transition Matrix for POR Lower Basin Naturalized Streamflows Adj. with 2080-2100 Ensemble

		Annual Transition State, Number of Years and Frequency		
		Low	Medium	High
Prior Annual State	Low	9 (34.6%)	7 (26.9%)	10 (38.5%)
	Medium	9 (36.0%)	6 (24.0%)	10 (40.0%)
	High	8 (32.0%)	11 (44.0%)	6 (24.0%)

E.2.2 Random Sampling of Flow States and Years

Stochastic sampling can proceed with the transition matrices defined for the historical period of record and the three adjusted periods of record for climate change conditions. Stochastic sampling involves the use of a (pseudo) random number generator and forms the basis of the Monte Carlo portion of the MCMC methodology. Combined linear congruential generators (L'Ecuyer, 1988) were used to provide the necessary sets of random numbers for each sampling. Two streams of random numbers were used for two samplings as discussed below.

Two samplings were performed. First, the sequence of low, medium, and high states was generated using the transition matrices for the relevant hydrologic dataset. The first 1,000 samples were discarded to allow for a "warm-up" period and the calculation of the distribution of states. Since the low, medium, and high states were created from evenly breaking the ranked years into one-third groupings, the algorithm checks the long-term distribution between low, medium, and high states before selecting a transition state. Transitioning to a new state was allowed based on the probability of maintaining the long-term even distribution of states and the probabilities represented in the transition matrix. The Metropolis algorithm (Kuczera and Parent, 1998) was adapted and used to accept or reject a transition to a different state and to maintain a long-term even distribution between low, medium, and high flows as calculated from the preceding 500 states. Period of record monthly serial correlation was maintained in the extended period from the selection of whole calendar years of hydrologic records with the exception of maintaining serial correlation between December and January.

After the first sampling to establish the sequence of low, medium, and high flow states, a second sampling was conducted to select a year from the 1940-2016 period of record that corresponds to the low, medium, and high states. Sampling of years from the period of record for a given state was random. However, an algorithm was created to ensure that each year from the period of record was selected approximately the same number of times as any other year, i.e., the years of the period of record were evenly sampled. Even sampling of years from the period of record ensures that the long-term annual average naturalized flow of the period of record is the same as calculated for the extended period of record.

E.2.3 Building the Extended Hydrologic Dataset

The extended hydrologic datasets were built after selection of low, medium, and high naturalized flow states and selection of a corresponding year from the period of record. Using the selected year from the period of record, a program was written to select the entire set of naturalized flows from all primary control points and all net evaporation-precipitation control points from the WAM input files. The whole years of input records were added in sequential order to the new extended hydrologic input files. The new extended hydrologic input files span 10,000 years, or 120,000 months of hydrology.

Figure E-6 shows an overview of the steps used in this work to build an extended stochastic hydrologic input dataset using the MCMC methodology. Annual naturalized flow volume was used as a basis for state classification, transition probability based on the prior annual state, and selection of a long sequence of states and years for the period of record. The steps shown in **Figure E-6** were applied to the historical hydrology and the three sets of hydrology, which were adjusted with the ensembles reflecting future climate conditions. Thus, the steps in **Figure E-6** were applied four times total. The final hydrologic input files for the Water Forward WAM consist of 77 years of period of record hydrology, either historical or adjusted for future climate conditions, plus an additional 9,923 years of extended hydrology stochastically sampled from the period of record. The total length of the input hydrologic datasets is 10,000 years.

High, Upper 1/3
Medium, Middle 1/3
Low, Lower 1/3

Step #1 Classify each year in period of record based on annual flow volumes

1940	1950	1960	1970	1980	1990	2000	2010
1941	1951	1961	1971	1981	1991	2001	2011
1942	1952	1962	1972	1982	1992	2002	2012
1943	1953	1963	1973	1983	1993	2003	2013
1944	1954	1964	1974	1984	1994	2004	2014
1945	1955	1965	1975	1985	1995	2005	2015
1946	1956	1966	1976	1986	1996	2006	2016
1947	1957	1967	1977	1987	1997	2007	
1948	1958	1968	1978	1988	1998	2008	
1949	1959	1969	1979	1989	1999	2009	

Step #2 Calculate transition probability between states based on the observed transitions

		Annual Transition State		
		Low	Med	High
Prior Annual State	Low	42.3%	38.5%	19.2%
	Med	26.9%	26.9%	46.2%
	High	33.3%	33.3%	33.3%

Step #3 Select sequence of states	**Step #4** Select specific year
High	2007
Med	1985
Med	1966
Low	2012
Low	1947
Med	1995
Low	2006
Low	1972
Low	1993
High	1957
High	1965
Med	2000
Med	1994
Low	2011
Med	1978
High	1951
High	1989

Step #5 Build extended WAM hydrology input files according to the sequence of selected years

Figure E-6. Steps for Building Extended WAM Hydrology Input with MCMC

E.3 Droughts Identification and Selection

The preceding section of this report describes the methodology to extend the Colorado WAM period of record beyond the 77-year historical period of record covering January 1940 through December 2016. Two major drought sequences are contained within the period of record and are conventionally known as the droughts of the 1950's and 2010's. Previously, the 1950's drought was known as the drought of record (DOR) and represented the worst water availability conditions in the lower Colorado River Basin. However, the drought of the 2010s is considered to be the new DOR for Water Forward Planning purposes. Extension of the historical record was selected as the methodology to assess drought conditions that may exceed the DOR.

It is expected that additional major drought sequences will occur within the 100-year planning horizon of Water Forward. One or more of the expected future droughts may produce worse river and reservoir water availability conditions than experienced in either of the droughts of the 1950s or 2010s. Such future drought conditions are designated as droughts worse than the drought of record (DWDR) because the conditions are not yet part of the historical record. It is essential for a long-term water resources plan to anticipate the likelihood of DWDR events occurring within the planning horizon.

The extended hydrology datasets representative of the historical record and those adjusted for future climate change conditions are utilized for detection and characterization of DWDR events. The goal of the work described in this section is to rank major drought events and select a group of candidate or design droughts that can be considered as possible DWDR events relative to the 2010's DOR. Techniques to identify drought sequences and to estimate the return period of major droughts are utilized. Based on estimated return periods, a group of candidate droughts within a range of probability of occurrence in 100 years is proposed for evaluation with the Water Forward portfolios of options.

E.3.1 Definition of Drought

Droughts are prolonged periods of conditions that are lower than normal. Droughts can be defined for many different hydrologic conditions or their associated impacts (Maidment, 1993; Heim, 2002). Meteorological droughts involve the prolonged absence or diminished abundance of precipitation over a given area. Meteorological droughts lead to additional types of drought conditions. Agricultural droughts may be characterized by lower than necessary soil moisture or water availability for crops or livestock. Hydrologic droughts may be characterized by deficits in streamflow or reservoir storage necessary for support of aquatic life or water supply for human activity. Socioeconomic droughts may be characterized by the loss of economic activity as a result of meteorological, agricultural, hydrological, or other deficient physical conditions.

There exists a long history of and abundant methods for characterizing droughts (Heim, 2002; Ward, 2013). In this work, drought detection and characterization are focused on the effects to streamflow in the Colorado River. Thus, the term drought is used synonymously with hydrologic drought and specifically with the characterization of below normal streamflow conditions. Hydrological droughts can be characterized by duration, magnitude or greatest measurement of deficiency, severity or cumulative deficiency, and frequency of occurrence. Both the duration and severity of the streamflow deficits are considered in this work because both variables impact the water supply to the city of Austin during multi-year droughts, either from direct diversion of available streamflow or from reservoir storage. Frequency of occurrence is derived from analysis of duration and severity.

E.3.2 Standardized Runoff Index

The standardized precipitation index (SPI) was developed by McKee et al. (1993) as a drought characterization tool. The SPI has since gained wide use for communication of precipitation departure from average conditions. The National Climatic Data Center (NCDC) publishes updated SPI coverages for the United States for precipitation aggregation periods of 1 to 24 months to evaluate short- and long-term drought conditions. The SPI is also one of the constituent drought indices incorporated into the U.S. Drought Monitor.

The standardized runoff index (SRI) is calculated in exactly the same manner as the SPI (Shukla and Wood, 2008). Whereas the SPI is calculated using precipitation values, the SRI is calculated using streamflow values. The SPI or SRI are calculated in the following manner. The streamflow values are aggregated over a user-defined accumulation period. Each value in the dataset represents the total flow in the user-defined preceding number of time intervals, which in this case are months. The accumulated flows are fit to a probability distribution to establish a relationship of cumulative probability to accumulated flow. The cumulative probabilities, which have a value range between 0 and 1, are transformed to standard normal (Gaussian) deviates, also known as the Z-scores. The Z-scores are the value of the SRI and have a mean of zero and a standard deviation of 1. The SRI values indicate how many standard deviations the data are away from the mean. Half of the SRI values exceed zero, indicating that the accumulated flows exceed the long-term average. Correspondingly, half of the SRI values are less than zero, indicating accumulated flows are below the long-term average.

The SPI/SRI methodology was selected for this work for several reasons. The methodology has widespread acceptance and is relatively easy to calculate. The user-selected averaging period allows the SRI to be adjusted to reflect an accumulation period that may be relevant to a particular measure of drought conditions. In this work, an 18-month accumulation period of lower basin naturalized flows was found to produce an SRI that best approximates the duration of the drought of the 2010s. The SRI values are standardized and can be compared to differing climatic conditions. This property of the SRI allows it to be compared between historical naturalized flows or the adjusted hydrologic datasets derived from adjustment for future climate conditions.

Drought events are identified from the SRI whenever the value is negative, i.e., the accumulated streamflow value is less than the long-term average. Drought duration can be calculated by counting the number of consecutive SRI values that are either below zero or below a threshold that indicates a qualifying dry state. For this work, a month in which the SRI was less than -0.1 is counted towards the drought category in order to avoid prematurely detecting only slightly below average streamflow conditions. Once a drought duration is established for consecutive months of SRI below the threshold, the drought severity is calculated by summing all of the negative values of the SRI. The drought severity is a unitless number that can be compared between historical- or climate-adjusted naturalized flow datasets.

The monthly lower basin naturalized flows at the location of Lake Travis in the WAM are shown in **Figure E-7** for the period of January 2000 through December 2016. The flows in **Figure E-7** correspond to the historical naturalized flows without adjustment for future climate conditions. From the perspective of the SRI, the drought of the 2010s begins after the high flow event in 2010. Drought relief is provided between high flow events in mid-2015 and mid-2016.

It should be noted that the SRI's streamflow-based calculation of drought starting and ending dates may be different than drought starting and ending dates obtained from a traditional reservoir firm yield analysis. The SRI is an indicator of above or below average streamflow conditions and is independent of factors affecting reservoir water supply. Both the SRI and the traditional firm yield analysis will identify the same general periods of low streamflows. However, drought starting and ending dates identified with a firm yield analysis will reflect a combination of streamflow conditions, reservoir specific storage capacity, and basin-wide water rights utilization assumptions.

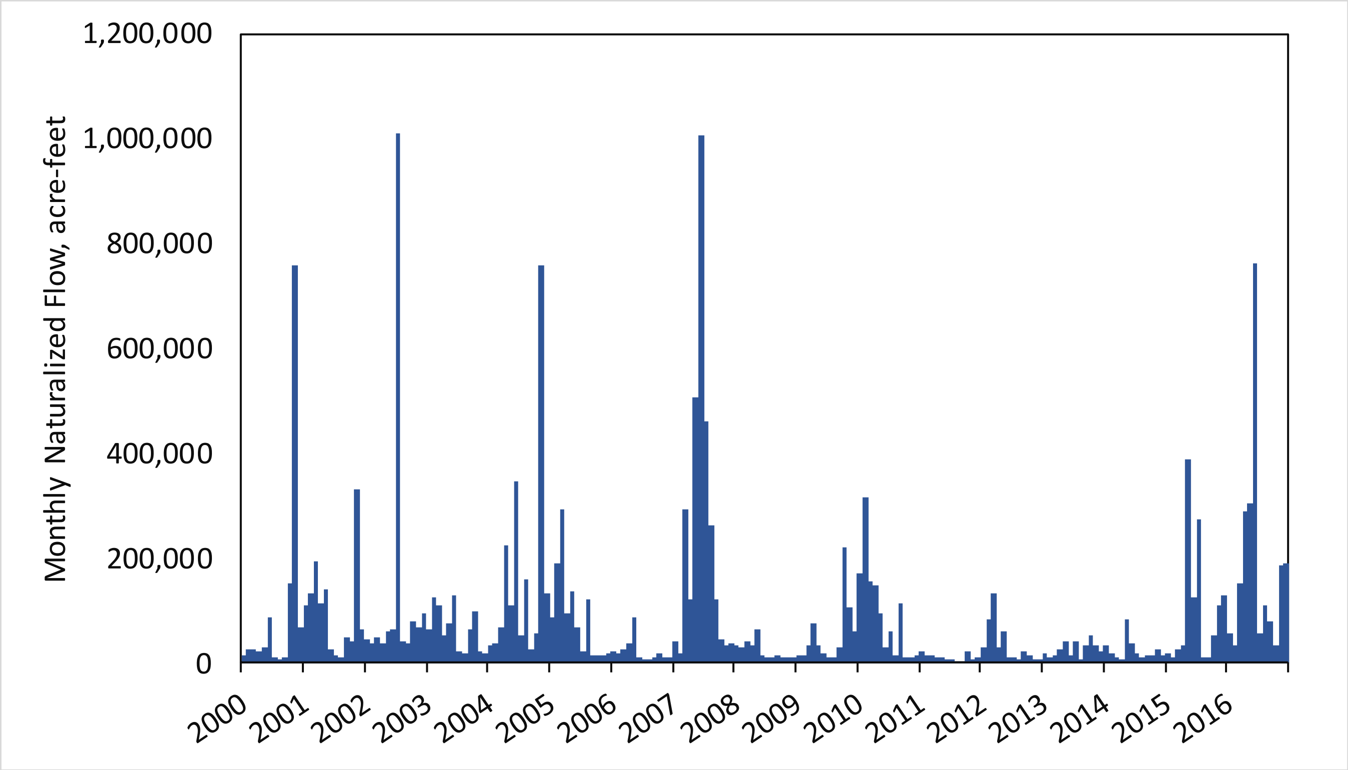

Figure E-7. Lower Basin Monthly Naturalized Flow at Lake Travis

An 18-month accumulation period was applied to the monthly naturalized flows and is shown in **Figure E-8**. The accumulation period was iteratively changed based on the outcome of the SRI calculation. The 18-month accumulation period was found to create SRI values that best reflected multi-year river and reservoir water availability in the lower Colorado Basin during drought conditions before and after the elevated flows in late 2009 through mid-2010. Each monthly value in **Figure E-8** represents the total flow in the preceding year-and-a-half period. The monthly accumulation values for the entire 10,000-year extended dataset were found to fit best to a 3-parameter gamma probability distribution to produce cumulative probability values uniformly distributed between 0 and 1.

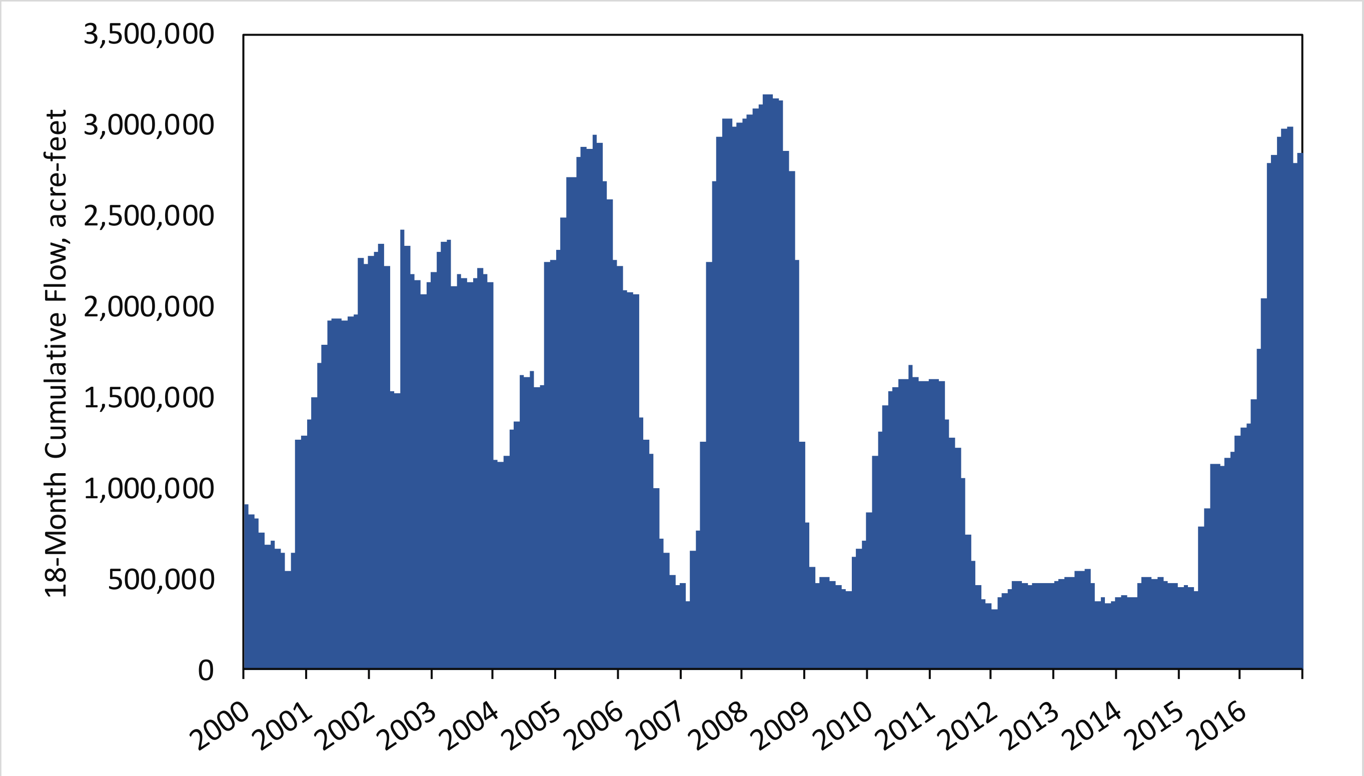

Figure E-8. Monthly Lower Basin Naturalized Flow at Lake Travis with an 18-Month Accumulation Period

The cumulative probabilities were transformed to standard normal Z-scores to create the SRI. The SRI values for the 2000-2016 example period are shown in **Figure E-9**, with the drought of the 2010s indicated. As seen in **Figure E-9**, the elevated flow period in late 2009 through mid-2010 created a short period of positive SRI values. This alleviated naturalized flow drought conditions that began to form in 2008. Based on negative SRI values, the 2010s' drought had a duration of 59 months, from April 2011 through February 2016. Individual months of low naturalized flows began prior to April 2011. However, an 18-month accumulation period is being applied, and the elevated flows of late 2009 through mid-2010 were not offset until 2011. The minimum SRI value during the drought is -2.5 in January 2012 and is indicative of extreme drought conditions in the preceding 18 months. The drought severity, as measured by the sum of the absolute values of SRI during the drought period, is 93.

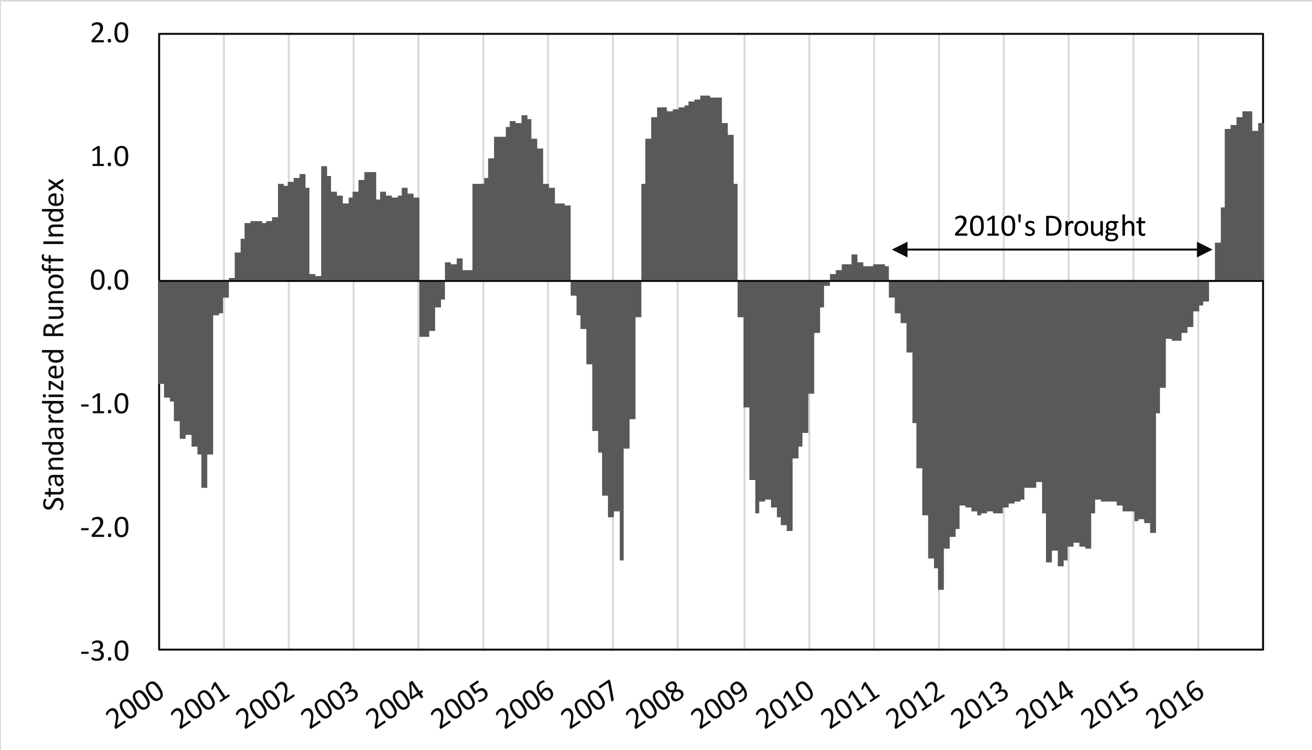

Figure E-9. Monthly SRI Values

E.3.3 Drought Return Period

The extended hydrologic dataset covers 10,000 years of monthly values of naturalized flow and net evaporation-precipitation. Extended hydrologic datasets were created for conditions reflecting the historical observation, as well as for the three ensemble periods reflecting modeled future climate conditions. The first 77 years of each extended dataset correspond to the historical period of record. The remaining 9,923 years of monthly values are derived from resampling the first 77 years. An SRI time series was created for each extended naturalized flow time series at Lake Travis, as described above.

Droughts are identified in SRI time series when the value falls below zero. A threshold of -0.1 was applied to avoid detecting conditions that may not be meaningfully below the average of zero. Consecutive months of negative SRI values are counted as contiguous drought events. The drought event durations can be calculated as the number of consecutive months of SRI values below the threshold. Likewise, the severity of drought events can be calculated as the absolute value of the sum of SRI values during the event duration.

Figure E-10 and **Figure** E-11 show the distribution of SRI-derived durations and severities of selected drought events for the extended naturalized flows at Lake Travis for the historical hydrologic conditions. The distributions shown in the figures were limited to drought events with at least 12 months of duration. In total, 1,365 drought events were identified. An additional 1,769 events have durations of 1 to 11 months but were excluded for their low duration and severity values and lower relevancy to multi-year river and reservoir water availability.

Recall that half of the SRI values are greater than zero and the other half are less than zero, indicating accumulated flow conditions above or below the long-term mean. There are 120,000 monthly values of

SRI, one for each month in the extended naturalized flow. The identified 1,365 drought events under historical hydrologic conditions have an average duration of 33.7 months. Therefore, approximately 46,000 of the 120,000 months are part of the identified droughts. The remaining 74,000 months have SRI values above zero or are part of periods with minor or short-term below average flows. The average interarrival time between the 1,365 identified droughts is 87.9 months, or 7.3 years, and will be used to calculate return period, as discussed below.

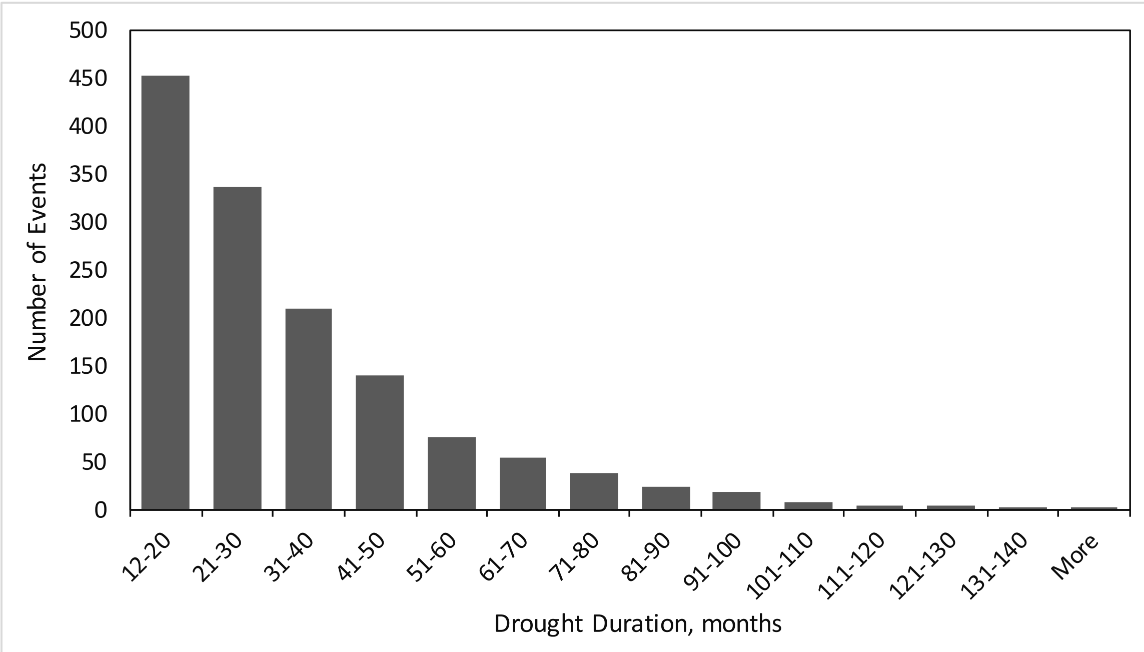

Figure E-10. Distribution of Drought Duration

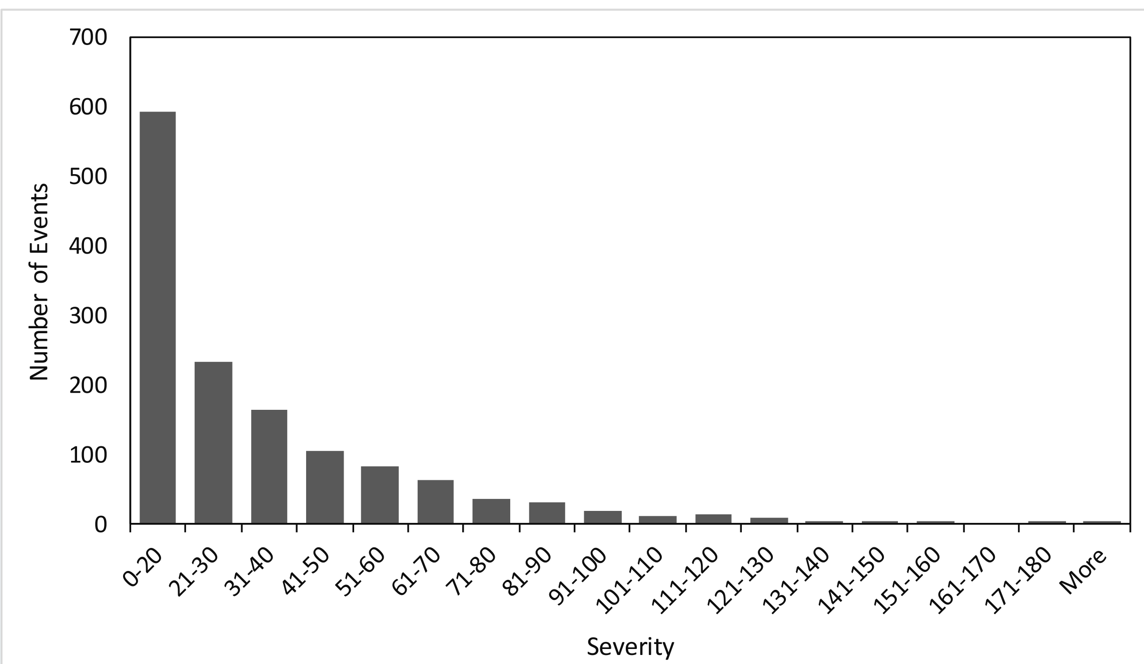

Figure E-11. Distribution of Drought Severity

Duration and severity are two common measures to characterize drought events. A large amount of research exists on the relationship of either duration or severity for characterizing drought event probabilities (Shiau, 2006). However, duration and severity are related measures. Consideration of the two measures jointly provides more information about the probability of droughts occurring than consideration of a single measure alone. A scatter plot of drought severity and duration is shown in **Figure E-12** to illustrate the close relationship between the two measures. The linear correlation of the measures shown in the figure is 0.93.

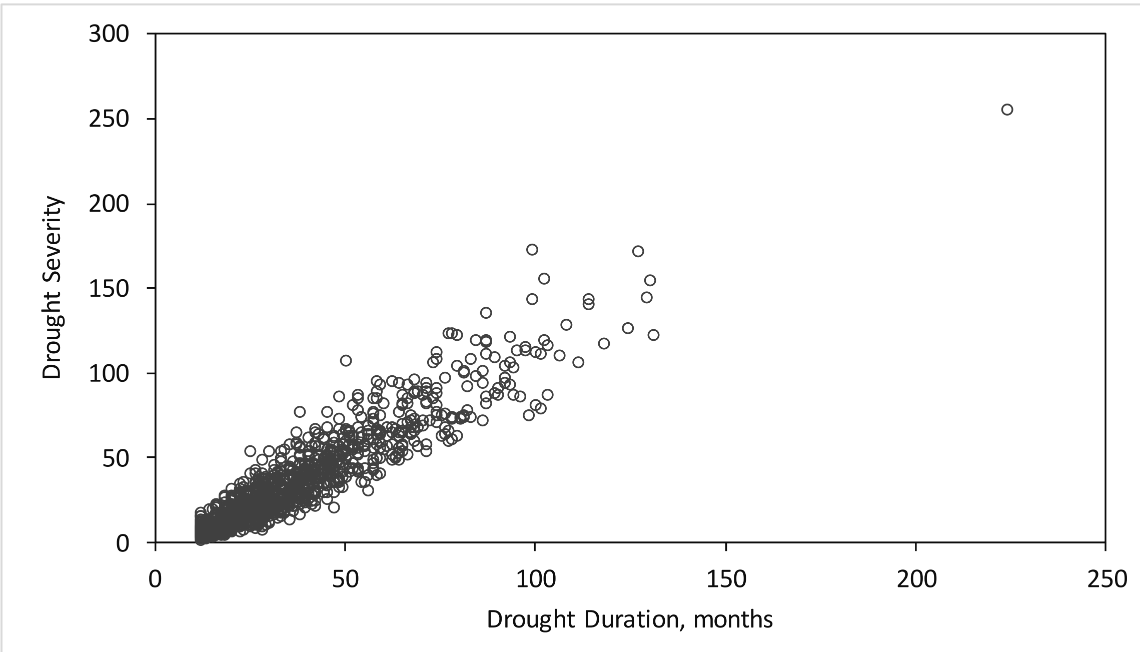

Figure E-12. Drought Severity versus Duration

To estimate the joint probability of drought duration and severity, the probabilities of the two individual variables are first estimated. Probability distributions are fit to both the duration and severity distributions shown in **Figure E-10** and **Figure** E-11. The probability distributions may be the same, but that is not required. For the examples shown in **Figure E-10** and **Figure** E-11, the best fits were found to be the Weibull and Inverse Gaussians distributions, respectively.

With duration and severity fit to probability distributions, the joint probability of the two variables can be assessed with a function known as a *copula* (Genest and Favre, 2007). Copulas are functions that relate the dependence between two or more variables without requiring the individual variables to be derived from the same probability distributions. A copula from the Archimedean family was fit to relate the joint probability of duration and severity.

Drought event return period can be estimated using the univariate distributions for duration and severity and the joint distribution of the two variables (Shiau, 2006). The return period of drought events in the historical extended datasets, in which duration and severity both exceed certain thresholds, is mapped to contour plots shown in **Figure E-13**. The same return period contour map for drought events in the extended dataset as adjusted for the year 2100 climate change ensemble is shown in **Figure E-14**. The 2010s' drought event is plotted with a black square. The 1950s' drought event is plotted with a black triangle. Drought events that exceed the return period of the 2010s' drought but have a return period of less than 450 years are plotted with red circles. The meaning of the red circles is explained in the next section. All other drought events are plotted with gray circles. The gray circles in the bottom left of the plots have return periods equal to the average interarrival time between droughts, which equal 7.3 and 6.5 years for **Figure E-13** and **Figure** E-14, respectively.

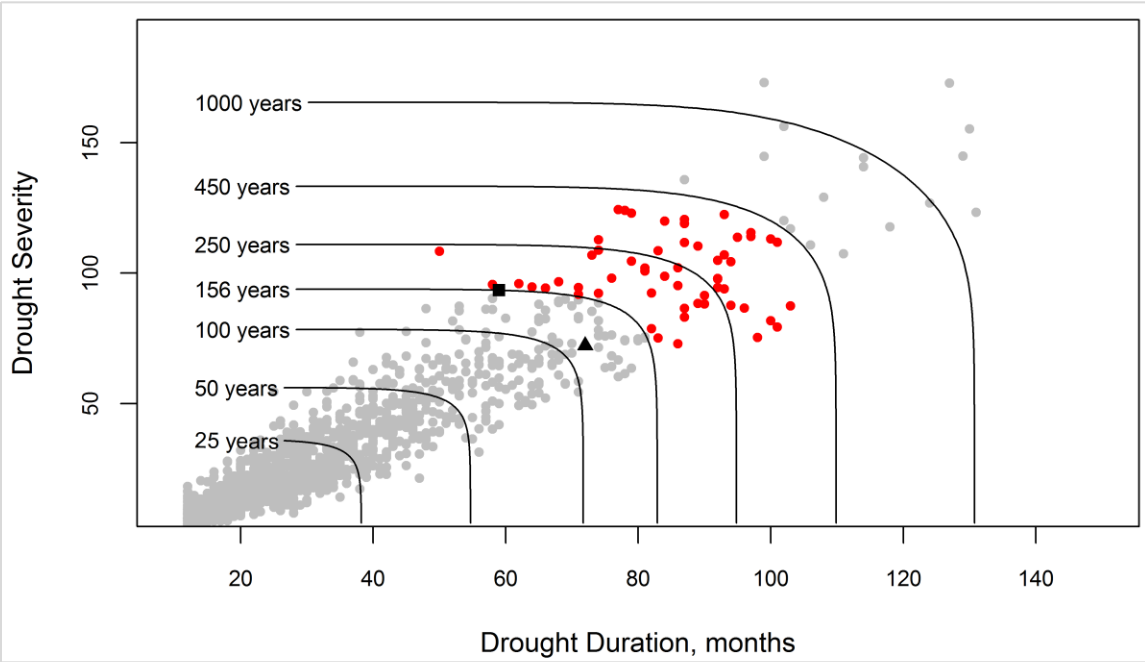

Figure E-13. Joint Drought Duration and Severity Return Period, Historical Extended Hydrology

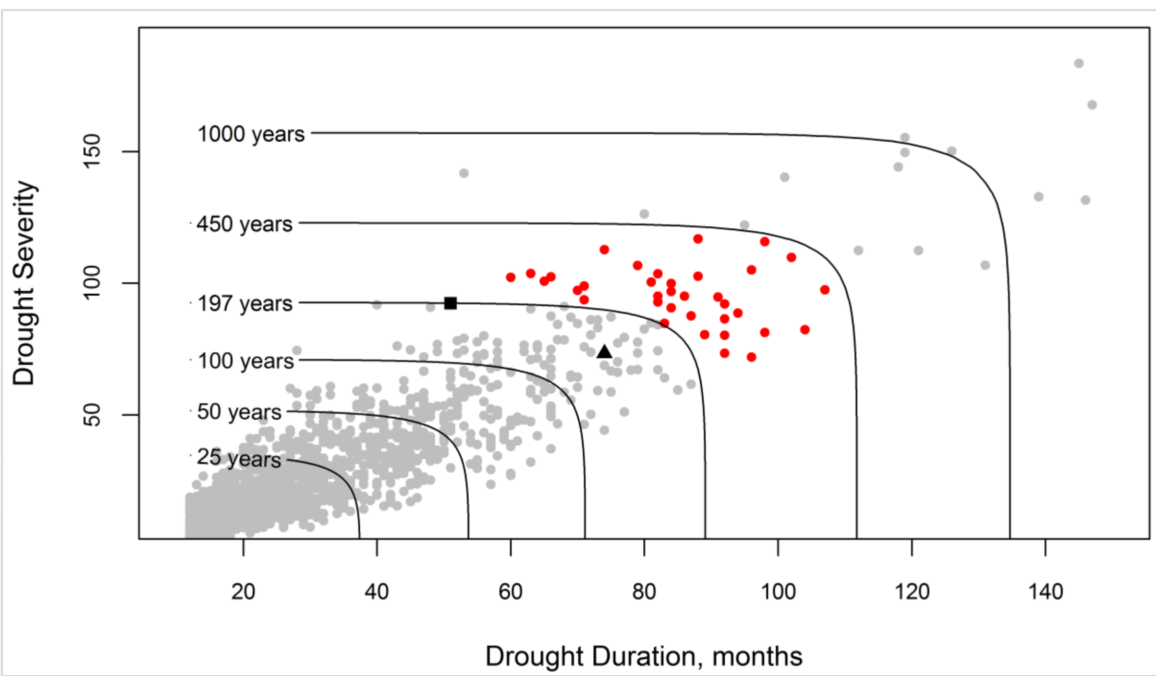

Figure E-14. Joint Drought Duration and Severity Return Period, Extended Hydrology with 2080-2100 Climate Change Ensemble Adjustment

E.3.4 Candidate Droughts

The two major droughts in the historical record are the droughts of the 1950s and 2010s, with the latter representing the DOR. As shown in **Figure E-13** and **Figure** E-14, the DOR status is confirmed by the higher return period for the 2010s' drought. The extended hydrologic datasets contain a large number of drought events with varying return periods representing frequent short-term drought events to infrequent and extreme droughts. The number of droughts to be considered as potential DWDR events was narrowed based on return period and the corresponding risk of occurrence.

Return period does not indicate that a given event has 100% certainty of occurring in a given interval of time. For example, an event assigned a 100-year return period has a probability of 1 in 100 in any given year. Over the course of 100 years, an event with a 100-year return period can be expected to occur at least once, with a probability of approximately 63%. Over the course of a theoretically very long observational period, an event with a 100-year return period would tend to occur on average every 100 years.

The associated probability or risk of at least one event occurring in a given number of years of observation for a given or greater return period is calculated by subtracting the probability of non-occurrence from 1. The following equation provides a calculation for the occurrence risk:

$$Occurrence\ Risk = 1 - \left(1 - \frac{1}{T}\right)^{N}$$

where *T* is the return period expressed in years and *N* is the number of year of observation. The equation is presented graphically in **Figure E-15** for various return periods and observation years.

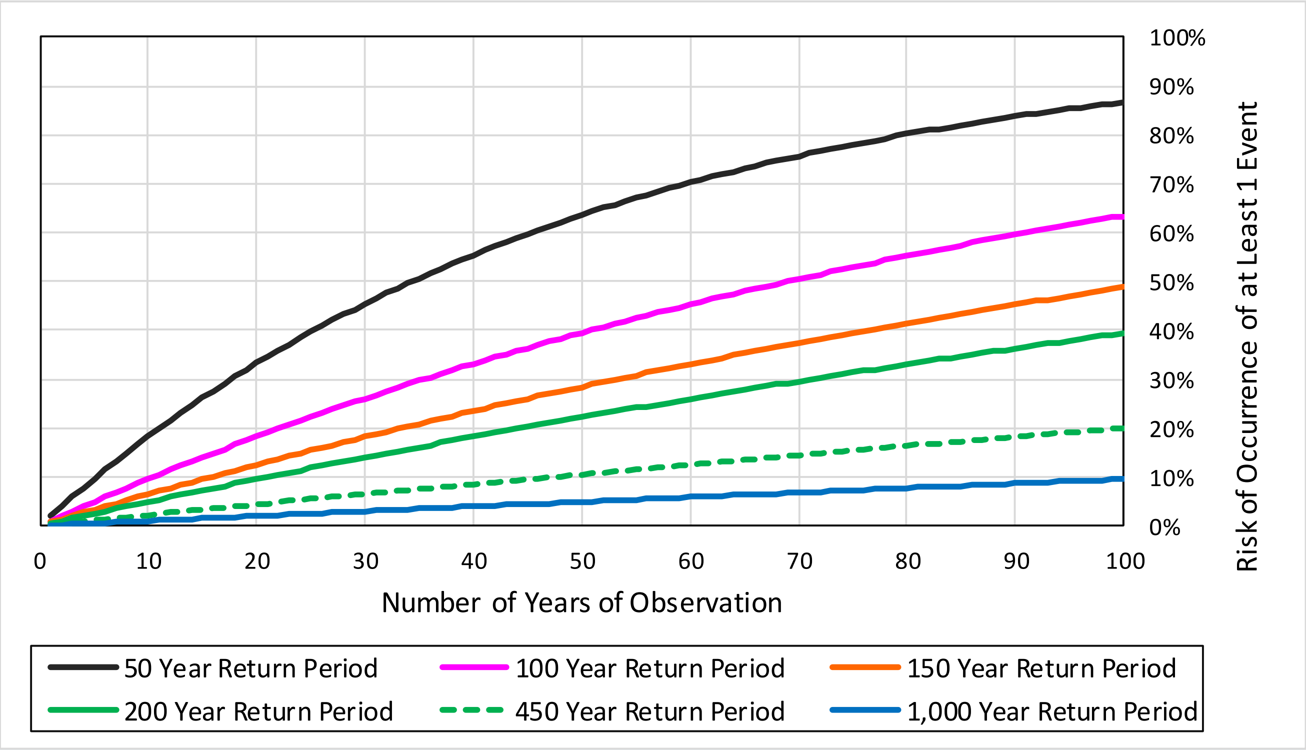

Figure E-15. Risk of Occurrence versus Years of Observation

Selection of candidate DWDR events for evaluating water availability was based on risk of occurrence. Selecting all drought events in the extended hydrologic dataset would include events with a very low risk of occurrence in the 100-year planning horizon. Conversely, selecting drought events only slightly worse than the DOR would not provide an adequate level of assurance that the recommended strategies in the Water Forward plan could perform as necessary during DWDR conditions. Based on judgement and conservative planning, the candidate DWDR events were selected that had up to a 20% risk of occurrence within the 100-year planning horizon. This is equivalent to approximately at 450-year return interval.

Candidate DWDR events are plotted with red circles in **Figure E-13** and **Figure** E-14. The candidate events have a return period greater than the drought of the 2010s and less than 450 years. The candidate droughts represent a range of durations and severities that is important for performance evaluation of the water management strategies. For the historical extended hydrologic dataset, there are 56 candidate droughts. Under the future climate change conditions represented in **Figure Figure** E-14, the DOR increased in estimated return period. This reduced the number of candidate droughts to 35.

The use of a return period methodology that incorporates two variables, duration and severity, provides a greater diversity of candidate droughts. In both **Figure E-13** and **Figure** E-14, it can be seen that the 2010s' DOR has a shorter duration than most droughts of a similar or greater return period. The 2010s' drought severity is high for droughts of similar duration. By incorporating both duration and severity, candidate DWDR events can be selected that have lower severity but greater duration than the 2010s' DOR. This provides a greater breadth of planning information than if candidate droughts had been selected based on either duration or severity as the only selection criterion.

Tables M-4 and **M-5** provide a selection of drought events from the historical and future climate change adjusted extended datasets. The ending year and month in the dataset are indicated in the two leftmost columns. The years in the extended dataset begin with zero. However, the first 77 years of the dataset correspond to 1940 through 2016. Therefore, the drought of the 1950s has an ending year of 12, which corresponds to 1952, and the drought of the 2010s has an ending year of 75 or 76, which corresponds to 2015 or 2016. Extended hydrology beyond 1940-2016 are indicated by simulation years 77 through 9,999.

The bottom two rows of each table contain information for the droughts of the 1950s and 2010s. The remaining rows of each table are a small selection of DWDR events in the extended hydrology. The DWDR events in both tables have equivalent risks of occurrence in 100 years. The far right column of each table indicates if the DWDR was designated as a candidate DWDR event for evaluation in Water Forward.

The drought severity measure is a summation of all SRI values during the drought duration. Severity is a standardized measure and is comparable across climatic conditions. The drought events in **Table E-4** and **Table** E-5 have a similar range of severity. However, the average annual naturalized flow volume is significantly different between the historical and climate change adjusted datasets. For example, the naturalized flow during the drought of the 2010s under the future climate change condition is only 43% of the historical annual average.

Table E-4. Selected Drought Events, Historical Extended Hydrology

End Year	End Month	Duration, Months	Severity, Unitless	Annual Average Nat. Flow, ac-ft/yr	Return Period, Years	Risk of at Least 1 Occurrence in 100 Years	Candidate DWDR, Yes/No
6472	5	131	123	630,000	1,207	8%	No
1021	12	99	145	580,000	716	13%	No
761	2	102	120	600,000	471	19%	No
1976	10	100	113	590,000	403	22%	Yes
2911	4	84	120	540,000	346	25%	Yes
8594	7	92	105	595,000	292	29%	Yes
577	11	94	88	630,000	260	32%	Yes
593	1	50	108	430,000	233	35%	Yes
76	2	59	93	595,000	156	47%	No
12	8	72	72	605,000	114	59%	No

Table E-5. Selected Drought Events, Extended Hydrology w/ 2080-2100 Climate Change Ensemble Adj.

End Year	End Month	Duration, Months	Severity, Unitless	Annual Average Nat. Flow, ac-ft/yr	Return Period, Years	Risk of at Least 1 Occurrence in 100 Years	Candidate DWDR, Yes/No
1522	6	139	133	260,000	1,213	8%	No
3455	3	53	142	110,000	708	13%	No
4737	12	95	122	210,000	468	19%	No
1716	7	107	98	235,000	409	22%	Yes
422	12	96	105	225,000	343	25%	Yes
3555	2	88	103	250,000	296	29%	Yes
7439	8	66	102	130,000	265	32%	Yes
2178	3	70	97	185,000	233	35%	Yes
75	6	51	92	255,000	197	40%	No
12	8	74	73	245,000	141	51%	No

E.3.5 Uncertainty

The goal of the work described in this section is to select a group of candidate or design droughts based on a relative ranking. The candidate droughts can be considered as possible DWDR events relative to the 2010s' DOR. Techniques to identify drought sequences and to estimate the return period of major droughts are utilized. Based on estimated return periods, a group of candidate droughts within a range of probability of occurrence in 100 years is proposed for evaluation with the Water Forward portfolios of options.

The methodology applied requires fitting of probability distributions calculations of the SRI, probability of duration and severity, and a copula model for the joint probability of duration and severity. As such, the methodology is sensitive to the goodness-of-fit of the distributions. Many probability distributions and copula were tested at each step of the methodology, and the best fits were chosen. Creating the extended hydrology sequences also required calculation of transition probabilities between states of high, medium, and low annual flows. Therefore, there is inherent uncertainty because of the necessary model-upon-model approach to arrive at drought return period.

The historical record, 77 years, is relatively short for characterization of the return period of major multi-year droughts such as the droughts of the 1950s and 2010s. The short length of the historical record and the uncertainty described above should be considered with respect to the estimated drought return periods of those specific droughts. Additional years of hydrologic observation will improve drought return period estimation. However, the goal of the work was not to accurately estimate the drought return periods of those two events. Instead, the goal was to select candidate drought events that are worse than the 2010s' DOR. To this end, the methodology was successful, and groups of DWDR events were selected for the historical hydrologic condition and the climate change adjusted hydrology datasets.

E.4 Water Management Scenario Modeling Assumptions

The TCEQ WAM System is introduced and described in Section 1 of this report. The WAM system is comprised of two components: generalized computer modeling software known as the WRAP and a set of basin specific input files and supporting GIS coverages. The WAM uses naturalized streamflow, net lake evaporation minus precipitation, and a water management scenario as its three main inputs for every river basin. The WAM simulates surface water availability to basin water rights under the specified water management scenario through a repeat of the input hydrologic conditions. TCEQ, other state agencies, planners, and permit holders use the WAM for a variety of applications ranging from permitting to short-term and long-term planning.

Sections 2, 3, and 4 of this report focus on modeling assumptions for the hydrologic inputs of the Water Forward WAM. Climate change adjustments, extension of the hydrologic period of simulation, and drought analysis are addressed. This section of the report focuses on the WAM modeling assumptions for water management scenarios. The assumptions cover basin-wide water management as well as those specific to the City of Austin and the Water Forward planning process.

E.4.1 Baseline Assumptions of the Water Forward WAM

Modified versions of the TCEQ WAM are created to suit specific permitting and planning applications. Modifications to the Colorado WAM used by Region K and LCRA, as well as the baseline modifications for the Water Forward WAM, are described in Section 1 of this report. The baseline modification for the Water Forward WAM mirror those contained in the Region K Cutoff Model and the LCRA WMP WAM.

The Water Forward WAM baseline assumptions include the following:

- Austin and other lower basin firm customers demand projections for 2020, 2040, 2070, and 2115.
- Weather-variable lower basin agricultural demands for 2020, 2040, 2070, and 2115.
- Demand increases of 2%, 4%, and 6% for firm customers as estimates of future climate change impact on demand in 2040, 2070, and 2115 for hydrologic scenarios modelled with climate change.
- Demand increases for lower basin agricultural demand for future climate change in 2040, 2070, and 2115 calculated with weather variable-demand equations that consider precipitation and evaporation.
- Interruptible stored water availability for lower basin agriculture maintained according to the 2015 LCRA WMP through 2040 with conversion to lower basin supplies only between 2040 and 2070.
- Conservation capacity for lakes Buchanan and Travis adjusted for future sedimentation estimates through 2100.

- 2015 LCRA WMP instream flow targets and bay and estuary inflow targets, including lake-level triggering levels, are maintained through 2115, but with proportional adjustment of the lake-level triggering levels to account for future sedimentation of lakes Buchanan and Travis.
- Firm and interruptible demands downstream of the Longhorn Dam are provided run-of-river availability according to estimates of reliable baseflow supplies.
- The amended LCRA Garwood water right is utilized for delivery of run-of-river water to LCRA customers after first meeting agricultural irrigation demands.
- LCRA Arbuckle off-channel reservoir operational and providing for agricultural and firm demands, and Matagorda Bay threshold needs in all time horizons.
- Drought contingency curtailment of firm customer demands at 900,000 acre-feet or less of combined storage in lakes Buchanan and Travis.
- Pro-rata curtailment of firm customer demands begins at 600,000 acre-feet of combined storage with a second level of increased pro-rata curtailment at 450,000 acre-feet.
- City of Austin municipal demand curtailment is implemented according to levels in the city's drought contingency plan according to the following combined storage schedule:
    - Full to 1.4M acre-feet: Conservation Stage.
    - 1.39M to 900k acre-feet: Stage 1.
    - 899k to 600k acre-feet: Stage 2.
    - 599k to 450k acre-feet: Stage 3.
    - 449k or less: Stage 4 (trigger level assumed; actual implementation at the discretion of city management).
- Upper basin water rights, defined as all water rights upstream of lakes O.H. Ivie and Brownwood, are assigned a senior priority to all downstream water rights (priority "cutoff" assumption) while maintaining their relative upper basin priority order; the priority cutoff is consistent with Region K and LCRA planning assumptions.
- Other lower basin water rights, defined as all water rights not included the upper basin priority cutoff and not associated with LCRA or LCRA customers, are assigned a priority senior to all water rights associated with LCRA or LCRA customers but junior to all upper basin water rights. This second-tier priority cutoff is consistent with LCRA WMP modeling.
- All water rights not associated with LCRA or LCRA customers are modeled with demands according to the fully authorized water rights.
- Additional operational modeling assumptions for lakes Buchanan and Travis, such as "ordered but not diverted" deliveries of stored water, as contained in 2015 LCRA WMP Appendix A.

Demand projections for the City of Austin, other lower basin firm customers served by LCRA, and lower basin agricultural are presented in **Table E-6**. The City of Austin municipal demands shown in the table are for the baseline condition that does not include the advanced additional demand management, conservation, and non-potable reuse options considered in the Water Forward portfolios. City of Austin municipal demands were developed by the City's detailed disaggregated demand model (see **Appendix C**) for an average use case rather than a hot-dry use case. The disaggregated demand model was also used to estimate return flow discharge to the Colorado River after accounting for direct reuse needs.

Table E-6. Lower Colorado River Basin Demand Projections

		Non-Climate Adjusted Demands				Climate Adjusted Demands		
	DEMAND CATEGORY All Demands in units of acre-feet per year	**Year 2020**	**Year 2040**	**Year 2070**	**Year 2115**	**Year 2040**	**Year 2070**	**Year 2115**
[1]	**Firm Demands**					***2.0%***	***4.0%***	***6.0%***
[2]	City of Austin Municipal Baseline Demand (Avg Year)	153,853	207,453	296,992	467,392	211,602	308,872	495,436
[3]	City of Austin Municipal Direct Reuse (Avg Year)	3,816	3,816	3,816	3,816	3,816	3,816	3,816
[4]	City of Austin Parks and LBL Evap	1,415	1,415	1,415	1,415	1,443	1,472	1,500
[5]	**City of Austin Baseline, Rows 2+3+4**	**159,084**	**212,684**	**302,223**	**472,623**	**216,862**	**314,159**	**500,752**
[6]	Fayette County (Downstream of lakes)	20,000	20,000	20,000	20,000	20,000	20,000	20,000
[7]	Sim Gideon / Lost Pines Demand	0	0	0	0	0	0	0
[8]	Llano County (Near/upstream of lakes)	5,500	11,300	20,000	20,000	11,300	20,000	20,000
[9]	**LCRA - Power Plant Demand**	**25,500**	**31,300**	**40,000**	**40,000**	**31,300**	**40,000**	**40,000**
[10]	Fayette County	9,000	9,000	9,000	9,000	9,000	9,000	9,000
[11]	Travis County	9,000	9,500	9,500	9,500	9,500	9,500	9,500
[12]	**City of Austin - Power Plant Demand**	18,000	18,500	18,500	18,500	18,500	18,500	18,500
[13]	Municipal Firm Contract Demand	65,684	97,170	143,046	169,000	99,113	148,768	179,140
[14]	LCRA New Contracts (2016 Region K Table 5-19)	2,877	19,154	33,654	45,000	19,537	35,000	47,700
[15]	Domestic lakeside use	5,000	5,000	5,000	5,000	5,000	5,000	5,000
[16]	LCRA Firm Irrigation	4,800	7,400	10,000	10,000	7,548	10,000	10,000
[17]	BRA - HB 1437 Demand	6,386	25,000	25,000	25,000	25,000	25,000	25,000
[18]	Manufacturing and Mining Demand	16,253	18,277	20,300	24,000	18,642	21,112	25,440
[19]	Other (Conveyance and Emergency Release)	5,000	5,000	5,000	5,000	5,000	5,000	5,000
[20]	**Other Firm Demands**	**106,000**	**177,000**	**242,000**	**283,000**	**179,840**	**249,880**	**297,280**
[21]	**Total Firm Demand, Rows 5+9+12+20**	**308,584**	**439,484**	**602,723**	**814,123**	**446,502**	**622,540**	**856,532**
[22]	STPNOC ROR + LCRA Backup (Rolling Average)	102,000	102,000	102,000	102,000	102,000	102,000	102,000
[23]	Corpus Christi Garwood Water Rights	35,000	35,000	35,000	35,000	35,000	35,000	35,000
	Interruptible Agricultural Demand							
[24]	Garwood Demand (Dry - 90th Percentile)	89,700	85,300	79,200	69,300	90,369	86,546	77,258
[25]	Gulf Coast Demand (Dry - 90th Percentile)	147,400	113,400	103,900	88,600	136,928	127,371	111,875
[26]	Lakeside Demand (Dry - 90th Percentile)	135,500	128,100	119,300	106,700	137,464	131,580	121,074
[27]	Pierce Ranch Demand (Dry - 90th Percentile)	27,000	25,600	24,100	22,300	26,091	25,608	24,390
[28]	**Total Interruptible Agricultural Demand, Rows 24+25+26+27**	**399,600**	**352,400**	**326,500**	**286,900**	**390,852**	**371,106**	**334,597**

Firm customer demands, excluding the City of Austin municipal demands, were developed from information in the 2016 Region K Water Plan. Region K uses a 50-year planning horizon that currently extends through 2070. Demands beyond 2070 were extrapolated from the trend. Region K planning assumptions use demands for hot-dry conditions as could be expected during severe drought. Some firm customer demands have contractual limits and are represented in the table with a capped constant demand over time. The power generation demand in Bastrop County, Row 7 in the table, are almost entirely supplied from groundwater and thus are not represented as having a demand on the river and reservoir system.

Lower basin agricultural demand projections were taken from a technical paper contained in the 2015 WMP. The demands were provided in the technical paper on a decadal basis through 2060. The demand trend of the 2040-2060 decadal projections were extended to estimate agricultural demands for the 2070 and 2115 planning years. Seasonal weather variability of agricultural demands was developed from regression equations provided by LCRA to account for precipitation and evaporation conditions over the agricultural divisions.

The Water Forward planning horizon extends through 2115. Changes to demand projections, especially beyond the Region K planning horizon of 2070, can be expected as new information regarding population projections and per capita water use is developed. Regular updates in the Water Forward planning process will take new information into consideration, and the demands as presented in Table 5.1 will be adjusted accordingly. In addition to demand updates, the LCRA WMP will be updated over time to account for new demand projections and new hydrologic data. Interruptible stored water availability under updated WMPs will be incorporated into the modeling for Water Forward. The LCRA WMP also includes water for instream and bay and estuary inflow needs according to operational levels in lakes Buchanan and Travis. Updates to the Water Forward WAM will reflect changes in the WMP.

E.4.2 Source Assumptions for Water Supply Strategies

Demand management and water supply options to meet future City of Austin municipal needs were grouped into portfolios. Within the context of the Water Forward WAM, the portfolios were evaluated for their water supply benefits, particularly during periods of extreme drought. Definitions of water supply needs were developed for periods of extreme low storage conditions in lakes Buchanan and Travis and for long-term needs above the 1999 water supply contract between the City and LCRA. The 1999 Contract provides water from Colorado River sources to the City of Austin for municipal purposes up to an amount of 325,000 acre-feet per year.

Water conservation and demand management strategies are described in IWRP, Chapter 7. Water supply strategies are described in IWRP, Chapter 8. The definitions of Types 1, 2, and 3 water supply needs are described further in **Appendix F**. For reference, the definitions of Types 1, 2, and 3 water supply needs are given below:

Type 1—Water need in an amount equal to the estimated savings from the City's Stage 4 Drought Contingency Plan (DCP) implementation.

Type 2—Fifty percent of the amount of water the City expects to receive from LCRA supply when combined storage in lakes Buchanan and Travis is extremely low; for modeling purposes, this is assumed to be

450,000 acre-feet. Type 2 needs are calculated each month during the simulation and only when the City's existing run-of-river rights cannot fulfill the monthly municipal demand during extreme low lake levels.

Type 3—Amount of water above Austin's current LCRA contract for municipal supply of 325,000 acre-feet per year.

Water conservation and demand management strategies were indirectly modeled in the Water Forward WAM. For example, a portfolio's water conservation and demand management strategies were applied toward reducing the total demand from the disaggregated demand model to calculate an adjusted total demand for physical water diversion. The total demands were distributed to each stage in the City's DCP plan. The DCP varying demands to be met from river and reservoir supplies were used as inputs for the Water Forward WAM.

Water supply strategies are explicitly modeled in the Water Forward WAM. Based on the water source and intended water supply need to be addressed, the water supply strategies were entered as WRAP input record modeling code in the Water Forward WAM. Approximations were necessary since not all aspects of daily operation for water supply strategies can be represented in a monthly water availability model. The water supply strategies were modeled for conjunctive use with the City's existing run-of-river water rights and LCRA stored water supplies under the 1999 Contract. Water supply strategies were generally modeled as secondary sources to maximize utilization of the City's existing water rights and LCRA stored water supply.

E.4.2.1 Sources of Water Supply for Aquifer Storage and Recovery (ASR) and Off-Channel Reservoir (OCR)

Five authorizations contained in the City of Austin's water rights were considered as sources for the water supply strategies. The five authorizations were assumed to be applicable in a multi-use and system operations manner consistent with the principle of fully utilizing the City's water rights to meet demands under the 1999 Contract (see **Section 2.1** of the full plan report for more detail). It is acknowledged that the multi-use and system operations assumptions will require amendments to the City's water rights and cannot presently be implemented as modeled. The Water Forward Plan has a 100-year planning horizon, and it is expected that, if the recommended water supply strategies are pursued, water right amendments will be required over time.

The five authorizations used as sources for the water supply strategies are the following:

- 250,000 acre-feet per year for municipal use with a 1913 priority.
- 21,403 acre-feet per year for municipal use with a 1914 priority.
- 24,000 acre-feet per year for industrial cooling with a 1914 priority.
- 20,300 acre-feet per year for municipal use with a 1945 priority.
- 16,156 acre-feet per year for industrial cooling with a 1945 priority.

In total, the five authorizations provide 331,859 acre-feet per year of run-of-river water, although seldom, if ever, is there sufficient Colorado River streamflow across an entire year to divert the entire amount. Run-of-river diversions are subject to the prior appropriation system and hydrologic conditions, the latter of which is highly variable and frequently results in uneven distribution during the year. The five authorizations were modeled as first being utilized for their intended purposes. For example, the three municipal authorizations were modeled as first providing water for municipal demands. Unutilized portions of the authorizations on an annual basis were made available to water supply strategies.

Two water supply strategies that make use of unutilized portions of the five authorizations are aquifer storage and recover (ASR) and an off-channel reservoir (OCR). Since both strategies derive water from the City's existing water rights, water supplies from ASR and OCR are only applied to meeting Type 1 and Type 2 needs. Demands in excess of 325,000 acre-feet per year are considered Type 3 needs and are beyond the scope of the 1999 Contract. Alternate sources of water not derived from the City's water rights are used for meeting Type 3 needs.

Water to be stored in the ASR facility is modeled as being diverted at Lake Austin from existing water treatment plant infrastructure. In any month, if there is vacant storage capacity in the ASR and if there are unused portions of any of the five authorizations, then run-of-river water is diverted for injection into the ASR. If vacant storage capacity still exists after use of the five authorizations, and if there is remaining injection rate capacity, unused amounts of the 1999 Contract for stored water are diverted. If a portfolio has a Type 3 need, then there is no unused amount under the 1999 Contract, as an assumption. Stored water under the 1999 Contract is only modeled for ASR injection if combined storage in lakes Buchanan and Travis is 1.4M acre-feet or greater to minimize any impacts to lake levels.

Water to be stored in the OCR facility is modeled as being diverted into the river reach downstream of Longhorn Dam and upstream of discharge points of any Austin wastewater treatment plant. No diversion point presently exists for the five authorizations in this reach. The location is for modeling purposes only. Diversion from the Colorado River with the five authorizations for storage in the OCR is modeled with the junior-most priority in the basin. Because the OCR could have a high pumping rate, all LCRA WMP instream flow conditions and bay and estuary inflows are checked prior to diversion. Senate Bill 3 environmental instream flow standards at the Bastrop stream gauge are also modeled. The location, junior priority, and multiple environmental flow considerations are intended to provide a conservative estimate of water availability and to avoid impacts to all existing needs for streamflow.

E.4.2.2 Source of Water Supply for Indirect and Direct Potable Reuse

Indirect potable reuse (IPR) is modeled as a strategy for meeting needs under extremely low combined storage levels. If combined storage is below 450,000 acre-feet, a fraction of Austin's return flow is modeled as discharged into Lady Bird Lake for indirect reuse purposes. Although IPR was modeled as coming online if combined storage is below 450,000 AF, in actual operation Austin Water would plan to utilize this strategy only if combined storage is below 400,000 AF. Diversion from Lady Bird Lake occurs in an amount equivalent to the return flow discharge. IPR is only utilized to meet Type 1 and Type 2 needs.

Direct potable reuse (DPR) is modeled as a supply source derived from the City's wastewater treatment plant's effluent stream prior to discharge to the Colorado River as return flow. A fraction of the effluent stream is modeled as directly recycled to the water treatment plant facilities. DPR is utilized to meet Type 1 and Type 2 needs during extremely low lake-level conditions. It is also utilized to meet Type 3 needs for portfolio scenarios with demands in excess of the 1999 Contract.

E.4.2.3 Source of Water Supply for Other Strategies

The portfolio scenarios may contain three additional water supply strategies not derived from the Colorado River Basin. All three strategies are modeled with alternative water sources provided in the model but unrelated to naturalized inflows or return flows. Brackish groundwater desalination, seawater desalination, and imported groundwater are modeled as strategies to meet Types 1, 2, and 3 needs. Seawater desalination and imported groundwater were not modeled together based on the portfolio compositions.

E.4.3 Order of Water Supply Strategy Utilization

Under the 1999 Contract, the City's municipal run-of-river water rights are utilized to meet municipal demands as streamflow is available. The demands are input to the model with adjustments for conservation and demand management strategies included in the respective portfolios. The monthly demands are lowered from Conservation Stage down to Stage 4 as combined storage in lakes Buchanan and Travis decrease. Any unmet monthly municipal demand is met from either the portfolio's water supply strategies or LCRA sources. When in Conservation Stage, the overall municipal demand that is eligible to be met from LCRA sources cannot exceed 325,000 acre-feet per year (1999 LCRA contract amount).

The order in which the City's municipal demands are met under the 1999 contract, from Conservation Stage to Stage 4, is as follows:

1. Austin's municipal run-of-river water rights.
2. If the City's river demands are lowered to Stage 4, then portfolio water supply strategies are used to satisfy the Type 1 need, which is calculated in the model as the difference between Stage 3 and Stage 4 demands. Type 1 needs are met from water supply strategies in the following order:
    a. Aquifer storage and recovery.
    b. Off-channel reservoir.
    c. Brackish groundwater desalination.
    d. Direct potable reuse.
    e. Seawater desalination or imported groundwater.
    f. Indirect potable reuse.
3. If the City's run-of-river water rights have not fully satisfied the monthly municipal demand, and Stage 4 demands are in effect, the Type 2 need is calculated. Water supply strategies are used to meet the Type 2 need in the following order:
    a. Aquifer storage and Recovery.
    b. Off-channel reservoir.
    c. Brackish groundwater desalination.
    d. Direct potable reuse.

e. Seawater desalination or imported groundwater.

f. Indirect potable reuse.

4. The remaining unmet monthly municipal demand is met from LCRA sources. If Stage 4 demands are not in effect, Steps 2 and 3 above are skipped.

Storage content in the ASR and OCR facilities is derived from the City's five water right authorizations. The ASR facility is not modeled as diverting water for injection during times when Stage 3 or Stage 4 demands are in effect. The OCR is modeled with the ability to divert and store water at any time that streamflow is available and there is vacant storage capacity in the reservoir. However, there may be little to no available water for many months during extreme drought conditions. The ASR and OCR can be viewed as finite resources during extreme drought and utilized in a manner to extend their storage content to the greatest degree. Though the ASR and OCR are listed as the first two options for meeting Type 1 and Type 2 needs, the model attempts to reserve their utilization if the other four water supply strategies are included in the portfolio and if the four strategies have remaining monthly yield to divert.

Water Forward has a 100-year planning horizon. Firm demands for municipal, industrial, and manufacturing customers are projected to grow to a level that reaches the full LCRA system yield during this horizon. Agricultural demands are also projected to be present over the planning horizon, but with lower demands over time. Climate change conditions are also modeled, which adds to water availability scarcity, especially in 2070 and 2115, through the effects of reduced streamflow during drought and higher evaporation levels. There are periods during extreme droughts in which the combined storage of lakes Buchanan and Travis are simulated as empty. The Water Forward WAM includes existing triggering levels for firm customer voluntary and mandatory curtailment levels, as well as assumptions for the degree of potential mandatory curtailment under never before seen storage conditions.

When the combined storage of lakes Buchanan and Travis is simulated as empty, no water is available in the model to meet the demands under the 1999 Contract as listed in Step 4 above. During such months, the model simulates a diversion from an alternative source. The alternative source diversion is recorded in the model output and represents a potential regional supply shortage. These potential shortages appear in the simulations for 2070 and 2115.

When demands exceed the 1999 Contract, new sources of water supply must be used. The City's water right authorizations cannot provide for Type 3 needs by definition. DCP Stage demand reductions are also applied to Type 3 needs. The order in which the City's Type 3 municipal needs, from Conservation Stage to Stage 4, are met in the model is as follows:

1. New contract supply from LCRA.

2. Direct potable reuse.

3. Brackish groundwater desalination.

4. Seawater desalination or imported groundwater.

E.5 Shortage Metrics

Water availability models, such as the Water Forward WAM, simulate a water management scenario through a repeat of a hydrologic sequence. With most simulations, reproduction of the historical past performance of the water management scenario is not of interest. Development of water availability simulations is generally motivated by estimating or predicting how the water management scenario will behave under future conditions. Future conditions may involve near-term or long-term demands as well as future hydrologic conditions. Time series of water availability can be generated from simulation outputs once the appropriate future demand and hydrologic conditions of interest are assembled. The time series may be directly analyzed and/or summary measures may be generated to describe performance in terms of meeting or failing to meet certain criteria.

The preceding sections of this work introduce the Water Forward WAM and describe the methodologies to develop hydrologic and water management scenario inputs. The hydrologic inputs include consideration of future climate change conditions and identification and selection of candidate droughts. The water management scenario inputs include future basin-wide demands and demands for the City of Austin. The water management scenario also includes options that make up the Water Forward portfolios of future water supply options. The work described in this section brings together the hydrologic and water management scenario inputs for summarization in the form of shortage metrics developed from the simulation outputs.

E.5.1 Reliability, Resilience, and Vulnerability

Hashimoto *et al.* (1982) introduced the concepts of reliability, resilience, and vulnerability – collectively known as RRV – as measures for evaluating satisfactory performance of a water resources system. Measuring the performance of a water resources system is important during droughts or periods of high demands. Since the introduction of RRV, the concepts have been widely applied in water resources evaluations. Defining satisfactory and unsatisfactory states of performance is central to the definitions of reliability, resilience, and vulnerability. For this work, a *satisfactory state* is a period in which water supply is able to fully meet demands above DCP Stage 4. An *unsatisfactory state* is therefore a period of water shortage. The period used for this work is a month. Satisfactory months, unsatisfactory months, and monthly shortage volumes are conceptually illustrated in **Figure E-16**.

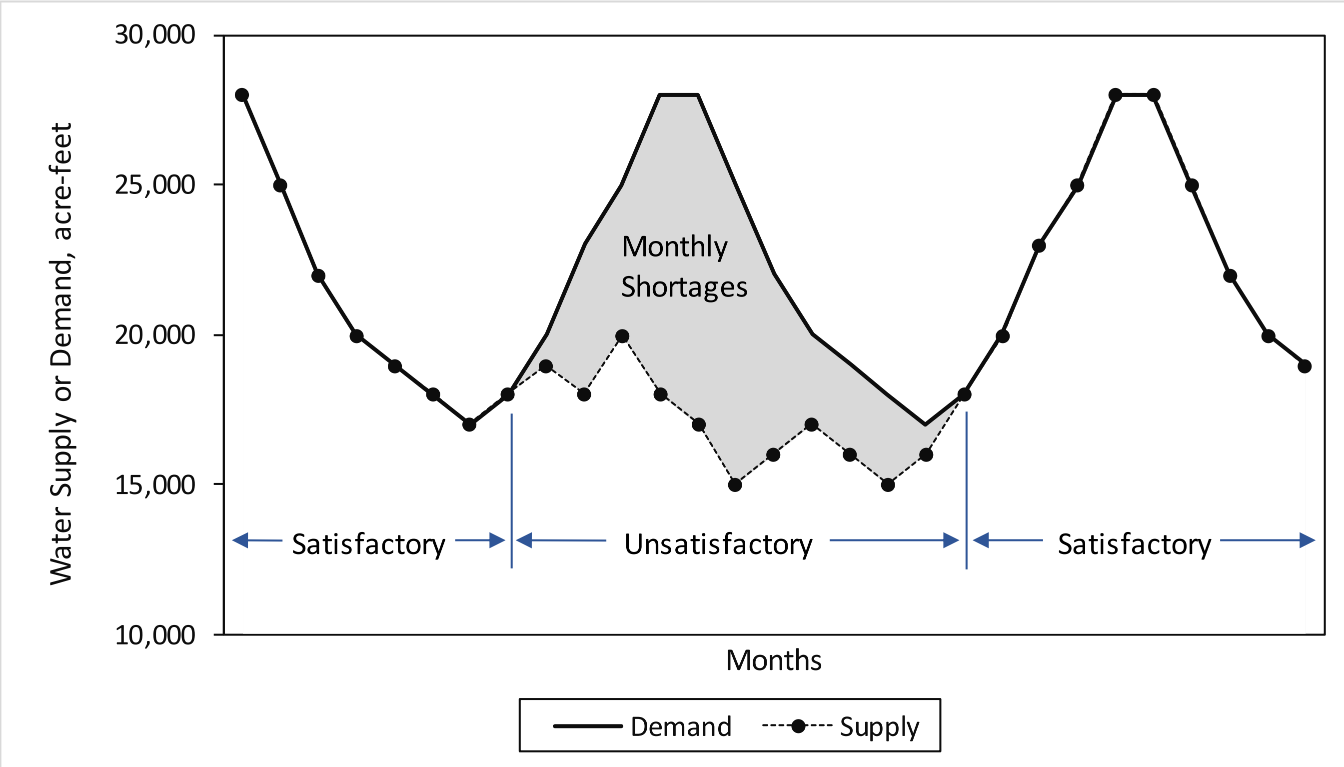

Figure E-16. Conceptual Illustration of Satisfactory and Unsatisfactory States around a Shortage Event

Satisfactory and unsatisfactory states and shortage volumes are measured each month from the simulation outputs, and the metrics of reliability, resilience, and vulnerability can be calculated using the following definitions.

Reliability is the probability that the water resources system is in a satisfactory state throughout the simulation. In other words, reliability is measure of how frequently the supply fully meets demand. Reliability is calculated as the number of satisfactory months divided by the total number of simulated months.

Resilience is the probability that a satisfactory month will follow an unsatisfactory month, or in other words, how likely it is that supplies will be able to fully meet demands again once a shortage has occurred. Resilience can be calculated as 1 divided by the average duration of all periods of unsatisfactory performance.

Vulnerability is a measure of the magnitude of shortage volume if a shortage occurs. Vulnerability can be calculated in a variety of ways. A few possible methods to calculate vulnerability include: (1) averaging the maximum shortage month all unsatisfactory periods, (2) averaging the cumulative shortages measured during all unsatisfactory period, (3) calculating the largest cumulative 12-month period of shortage of the entire modeling period.

The objective of calculating shortage metrics for Water Forward is to ultimately rank portfolios with a relative scoring system. Time series of demands and supplies were output from the simulations for needs analysis evaluations and for understanding the performance of portfolios of options being considered in

Water Forward. In addition to the time series, reliability and vulnerability were calculated as shortage metrics for scoring the portfolios and ranking their relative performance. *Resiliency was not considered in the Water Forward shortage metrics since it is correlated with vulnerability*. The cumulative volume of shortage events is related to duration of the event. Thus, the informational value of resiliency is somewhat captured in vulnerability.

E.5.2 Combining Shortage Metrics

Values of reliability have a range of 0 to 1 to indicate complete failure or no shortages observed, respectively. However, the definition of vulnerability results in a metric with units of volume. So that vulnerability can be compared to reliability in a range of 0 to 1, a relative vulnerability metric can be calculated by dividing by another quantity with volumetric units (ASCE, 1998). For Water Forward, relative vulnerability was calculated as 1 minus the maximum 12-month total shortage volume divided by the Stage 4 demands during the same period. A relative vulnerability of 0 indicates no water was provided during the worst 12 months of drought, whereas a relative vulnerability of 1 indicates there were no shortages during the worst 12 months of drought.

Shortage metrics can be combined into a single measure, or index, to compare the relative performance of different water resource system configurations (ASCE, 1998; Sandoval-Solis et al., 2011). Individual metrics reflect performance in different manners. Reliability considers all months of the simulation and only counts "yes" or "no" for satisfying demands through any hydrologic condition. Vulnerability, on the other hand, focuses only on shortage volumes during times of drought. Combining shortage metrics into a single index is useful for combining disparate measures and comparing alternative water management scenarios in a relative ranking or scoring process.

For Water Forward, the geometric means of reliability and relative vulnerability were calculated for the 2020, 2040, 2070, and 2115 planning horizons for historical hydrologic conditions and climate change adjusted hydrology (for 2040, 2070, and 2115). An index, or score, was created from the weighted arithmetic mean (average) of the geometric means. The geometric mean was used to normalize, or scale, the metrics. This was done because demands increase, and climate change-adjusted hydrologic conditions tend to worsen over the planning horizons. This combination causes a tendency for reliability and relative vulnerability to decrease over time and skew performance comparisons towards later planning horizons. Performance of earlier planning horizons are essential. Normalizing the reliability and vulnerability metrics with the geometric mean improved the weighting of earlier planning horizons in the final index.

E.5.3 Scoring Summary for Overall Performance

Portfolio water supply scoring brings together all of the elements of modeling described in this report. The work documented in this report covers the steps taken to develop WAM inputs: hydrology, water demands, and water management scenarios. The inputs were developed for four planning horizons: 2020, 2040, 2070, and 2115. Reliability and vulnerability metrics indicate the performance of the portfolios for each planning horizon over a wide range of hydrology including wet, average, DOR, and DWDR conditions. A final score for each portfolio combines the reliability and vulnerability metrics into a single number that is used for ranking the portfolios on a relative basis.

Section E.3 of this report describes the methodology to identify and rank droughts worse than the drought of record (DWDR). The selection of candidate DWDR events is based on risk of occurrence within the 100-

year planning horizon of Water Forward. Reliability was calculated for all months of the period of record and also for the extended simulation. Reliability for the extended simulation excludes months falling within periods of drought that exceed the risk of occurrence of the candidate droughts. Relative vulnerability was calculated for the drought of record (DOR) and all candidate DWDR's. For scoring purposes, relative vulnerability metrics were calculated for the worst 12-month period of the DOR and the worst 12-month period of any of the candidate droughts. Portfolio water supply scores for the four planning horizons and hydrologic conditions can be found in **Appendix L**.

E.6 References

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APPENDIX F: WATER NEEDS IDENTIFICATION

F.1 Introduction

The City of Austin has taken significant steps towards securing its long-term water supply. The City has substantial run-of-river water rights in addition to long-term contracts with the Lower Colorado River Authority (LCRA) for firm water. However, the 2008-2016 recent historic drought has highlighted the importance of the City taking steps to enhance the reliability of its water supply. In response to the drought, the Austin community answered calls to decrease water use through lawn watering restrictions and participate in other water use efficiency programs. The Water Forward plan seeks to develop a sustainable, resilient, diversified water supply and demand management portfolio to achieve our desired water future.

All water plans require an assessment of future water needs that determine the timing and sizing of new potential demand-side management and water supply options. Austin's core water supply includes run of river rights to water from the Colorado River backed up by a contract with the Lower Colorado River Authority (LCRA) for stored water primarily from the Highland Lakes. Analysis of this core water supply provides the basis from which the Water Forward needs assessment was developed. In times of drought, lake storage levels can drop significantly. When storage volumes in the Highland Lakes reach certain triggers, customers who have firm water[1] contracts such as the City of Austin implement drought contingency plans, which include mandatory restrictions on certain types of water usage. For example, in the City of Austin Drought Contingency Plan, Stage 1 water restrictions are imposed when combined storage levels in Lakes Travis and Buchanan are below 1,400,000 AF, Stage 2 water restrictions are imposed when combined storage levels are below 900,000 AF, Stage 3 is triggered below 600,000 AF, and Stage 4 is triggered at the discretion of the City Manager.

These City of Austin and other firm customer water restrictions are implemented to stretch out water supplies and help to mitigate falling storage levels during droughts. Even with drought contingency plan implementation on the part of many firm customers, combined lake levels can still drop. In modeling for Water Forward, considering long-term future demand and climate change impacts, all of the water in the lakes is used in certain modeled scenarios such that no stored water would be available. This occurs as early as 2070 in some hydrologic scenarios. While AW would still have access to run of the river water if available, without stored water there would be drastic impacts to AW's customers in terms of health and safety, economy and overall quality of life. While both the Lower Colorado River Authority and the City are looking at ways to address future water supply issues, one of the goals of the Water Forward plan is to manage this type of risk.

For the purposes of developing Austin's Integrated Water Resource Plan, it was necessary to conduct an analysis to define and quantify the identified water needs. A preliminary needs analysis was conducted to

[1] Firm water is defined as a supply that can be provided through a repeat of the drought of record. Prior to the recent historic drought, the drought of record was a drought that occurred from 1947 to 1957. In light of the severity of the late 2007-2016 drought, the Lower Colorado River Authority is in the process of updating assumptions related to the drought of record.

develop an initial understanding the magnitude of the needs. This preliminary needs analysis provided valuable information toensure that, when combined into portfolios, the magnitude of selected demand management and water supply options would be sufficient to meet the identified needs. Through the process of developing and evaluating portfolios, the preliminary needs analysis was later refined to categorize water need quantities, referred to as Type 1, 2, and 3 needs, in various portfolio configurations.

F.2 Preliminary Water Needs Identification

Unlike traditional water planning, the integrated water resource plan is a dynamic process that considers planning for needs under a range of possible future conditions. In traditional water planning, one demand projection line is plotted against one supply line and the identified need is the amount of water in the highlighted area above where those two lines cross, as depicted in **Figure F-1**, below. This assumes that there is only one set of conditions to plan for and that future weather and climate will replicate past weather and climate.

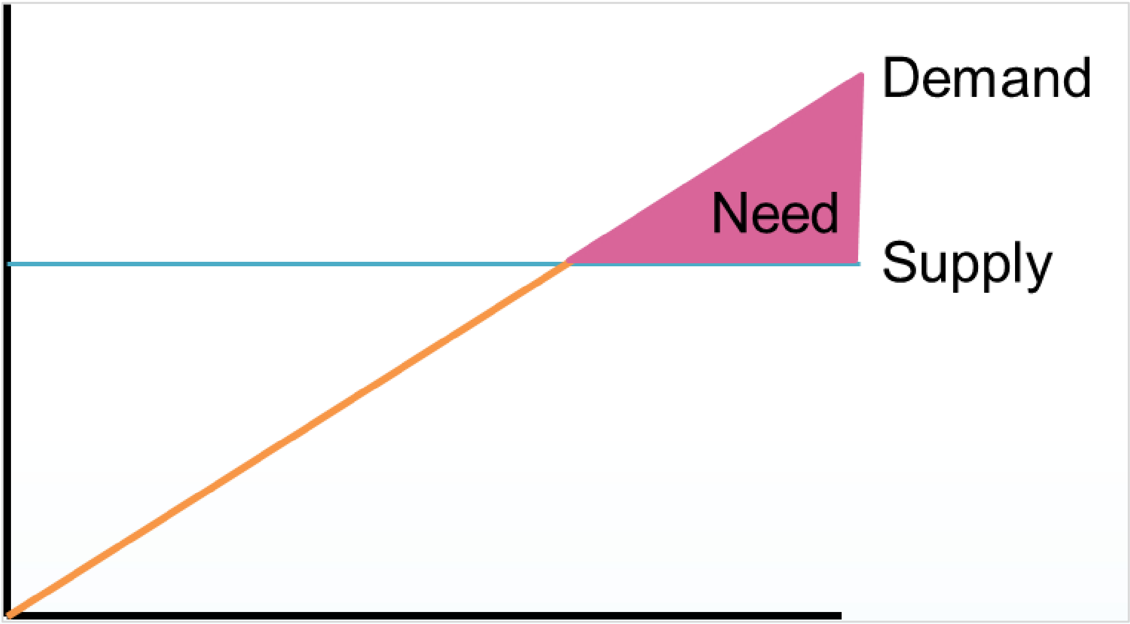

Figure F-1. Traditional water planning paradigm

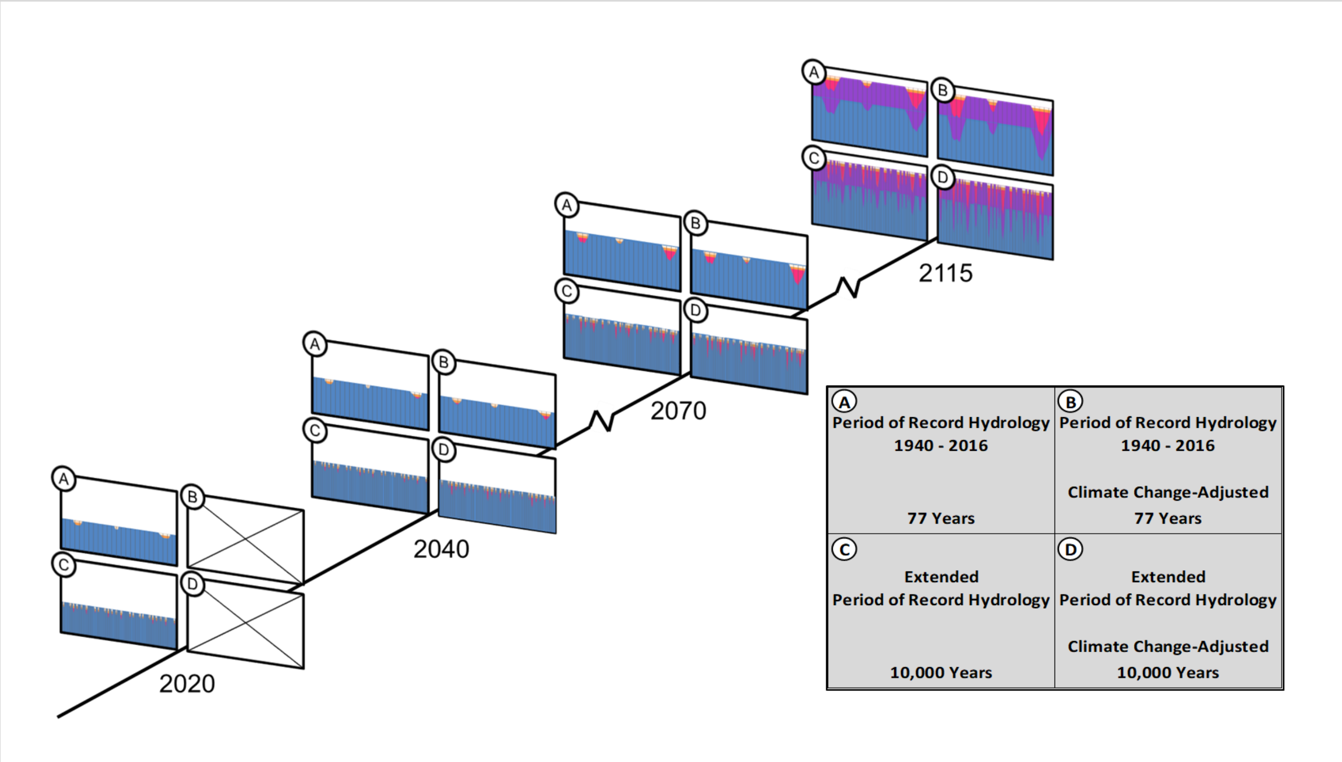

Figure F-2. Water Forward Integrated Water Resource Plan planning horizons and hydrology scenarios

As depicted in **Figure F-2**, the Water Forward integrated water resource plan process analyzed needs considering four different hydrologic scenarios at four different planning horizons. By evaluating the potential impacts of various hydrologic conditions over time, the integrated water resource plan considered options that can provide reliability and sustainability benefits across multiple future conditions. As described in **Section 5** of the main report, the hydrologic conditions evaluated included A) a repeat of the historical hydrology during the period of record, B) the period of record hydrology adjusted to reflect the effects of climate change, C) droughts worse than the late 2007-2016 drought that were selected from a 10,000 year sequence developed by resequencing years from the period of record hydrology , and D) droughts worse than the late 2007-2016 drought that were selected from a 10,000 year sequence developed by resequencing years from the period of record hydrology adjusted to reflect the effects of climate change.

Preliminarily needs were identified in three main categories:

- Austin's needs during drought associated with managing risk of low combined storage levels in Lakes Travis and Buchanan including prolonged implementation of drought contingency plan stages,
- Austin's needs above current 325,000 acre-feet per year contract with Lower Colorado River Authority,
- Regional needs including periods when combined storage levels in Lakes Travis and Buchanan may dip below emergency levels. It was anticipated that future hydrologic scenarios may identify regional water needs. Despite assumed cutbacks on the part of AW and others, reservoir levels may still go below emergency levels under some future drought scenarios.

F.3 Water Needs Refinement

After development of preliminary water needs, three types of water needs were further refined and quantified. These three types of water needs were used to develop the magnitude of portfolios of demand management and supply options to be evaluated. Two of the types of needs are associated with the need to increase supply and reliability in extreme drought conditions, such as droughts worse that the historic drought of record and droughts that incorporate the projected effects of climate change. The third type is more akin to a traditional needs assessment. This third type of need quantifies needs above the City's current Lower Colorado River Authority contract amount. Each type of water need is discussed in more detail in the following sub-sections.

F.3.1 Type 1 Needs

Type 1 needs were identified in an attempt to avoid the numerous potential negative impacts anticipated as a result of being in Stage 4 Drought Contingency Plan measures for a prolonged period in times of severe drought. For reference, Stage 4 Drought Contingency Plan measures would restrict all outdoor water use, such as irrigation, car washing, pools, foundation watering, or washing any outdoor surface. Strategies identified in Water Forward would provide demand management and new supply options so that Austin Water customers could continue to use water outdoors at Stage 3 Drought Contingency Plan levels in a sustainable fashion through a multi-year drought scenario. While customers would still be able to use outdoor water, Water Forward strategies would allow the City to reduce its demand on the river as if the City were enacting Stage 4 restrictions during prolonged drought. Both demand management and water supply options can fill this need. Type 1 needs were established to mitigate societal, environmental, habitat, and economic impacts of staying in Stage 4 drought restrictions.

To quantify Type 1 needs, the needs were defined to be equal to the estimated reduction in water demand from Austin's Colorado River supplies that would occur from implementation of the City's Stage 4 Drought Contingency Plan. Strategies meeting Type 1 needs would then be used to meet that estimated reduction amount. For the purposes of Water Forward Water Availability Modeling (discussed in more detail in **Appendix E**), Stage 4 restrictions were set to begin when the combined storage of Lakes Travis and Buchanan was at or below 450,000 acre-feet (or approximately 22% full) in the model scenario. In an actual prolonged drought scenario, Stage 4 restrictions would begin at the discretion of the City Manager.

Taking climate change into account, the Type 1 need was calculated in the model for the various planning horizons. For the Water Forward baseline demand projection with climate change effects included, the maximum 12-month Type 1 needs recorded when modeling under hydrologic scenario B (period of record with climate change) are, as shown in **Table F-1**, 3,000 acre-feet in 2020, 10,600 acre-feet in 2040, 15,400 acre-feet in 2070, and 24,800 acre-feet in 2115 should a triggering drought event occur. These projections are the estimated outdoor water use savings amounts, using the baseline demands with climate change effects, associated with going from Stage 3 to Stage 4 restrictions in the drought contingency plan.

Table F-1. Baseline Type 1 needs under hydrologic scenario B (period of record with climate change)[1]

Year	2020[1]	2040	2070	2115
Type 1 Needs	3,000 AFY	10,600 AFY	15,400 AFY	24,800 AFY

[1]Because climate change effects were not included for 2020, Type 1 needs were defined by modeling under hydrologic scenario C (extended hydrology without climate change).

In the portfolio evaluation process, water conservation and reuse options combine to reduce the overall potable water demand. Therefore, in every portfolio a portion of the Type 1 baseline amount is met through conservation and reuse. The remaining Type 1 needs after conservation and reuse options are considered is targeted to be met by new water supply options. Note that Stage 4 restrictions may still need to be implemented for short-term emergency situations in the future, but the Water Forward goal for meeting Type 1 needs is to avoid going into Stage 4 for prolonged periods during sustained extreme droughts.

F.3.2 Type 2 Needs

This is a potable supply target developed to manage the risk of Austin having very little or no Colorado River supply due to severe drought, including droughts that may be worse than what the region has seen in the past, and potential climate change effects. Strategies to meet Type 2 needs are readily accessible potable supplies that could be relied upon by the City in the event that combined storage levels drop to extremely low levels during a prolonged drought. This type of need can be thought of as a backup supply or an insurance policy for risk mitigation in extreme drought conditions. Defining this type of need was important in addressing the Water Forward goal of increasing water supply reliability. During the 2008-2016 drought lake levels dropped sharply, causing community impacts and concerns, and new supply options were proving challenging to prepare for implementation in the necessary timeframe. With this in mind, Type 2 needs were developed as part of the Water Forward process to manage similar or possibly more severe impacts and concerns associated with extremely low lake levels in the future as climate change effects are anticipated to increase.

Water availability modeling results were used to quantify Type 2 needs amounts. To increase the reliability of Austin's access to potable water supplies in a severe drought, the Type 2 target was set to equal 50% of the amount of water Austin would expect to receive for meet demands from Lower Colorado River Authority stored water at extremely low lake levels. To define extremely low lake levels in the Water Forward Water Availability Model, Type 2 needs were set to trigger in the model only when combined storage in Lakes Travis and Buchanan was less than 450,000 acre-feet, or about 22% full. If combined storage in the lakes was modeled to empty, Type 2 needs were still calculated as 50% of water expected from Austin's Lower Colorado River Authority contract had there been available storage. This is further explained in the sections below. The remainder 50% of the water expected from Austin's Lower Colorado River Authority contract was categorized as a regional need and Water Forward strategies were not specifically identified to meet this regional need. Since this Type 2 need targets development of strategies that provide Austin access to a substantial supply of potable water during severe drought, only options that can readily provide potable water can fill this need (not conservation or non-potable reuse options).

F.3.2.1 Type 2 Needs Illustration

To illustrate the Type 2 needs concept and how those volumes are quantified, the following sequence of figures (**Figure F-3** through **Figure** F-7) show a progression of graphs which are based on a combination of water availability modeling results and Water Forward inputs. The left-side axis in this graph sequence shows monthly water volumes from various supplies and demand management options for meeting the City of Austin's municipal water demands. The top line in thick green represents the total water demand of the City, which is met by the combination of expected supplies and demand management strategies shown in the layers below the top line. The peaks and valleys in the top line represent annual seasonal change in water use—demand tends to go up in the summer as water use for irrigation and other seasonal uses increases.

The graph sequence presented below represents a combination of Austin's projected demands and expected supplies and modeling results from the recent historic drought from 2008-2016, based on 2115 projected demands with the effects of climate change. The volume of supplies shown in the graphs vary over the drought depending on the combined storage volume. The graphs shown in Figures 3 through 7 are all based on the Hybrid 1 portfolio modeled under Scenario B hydrologic conditions (period of record with climate change). **Figure F-3** is presented to show the starting point demands for calculating the Type 2 needs. The blue area in the graph represents the amount Austin's demand expected to be met by water from Austin's Lower Colorado River Authority contract. Note that the blue demand for total Colorado River supply is a significant portion of the total demand.

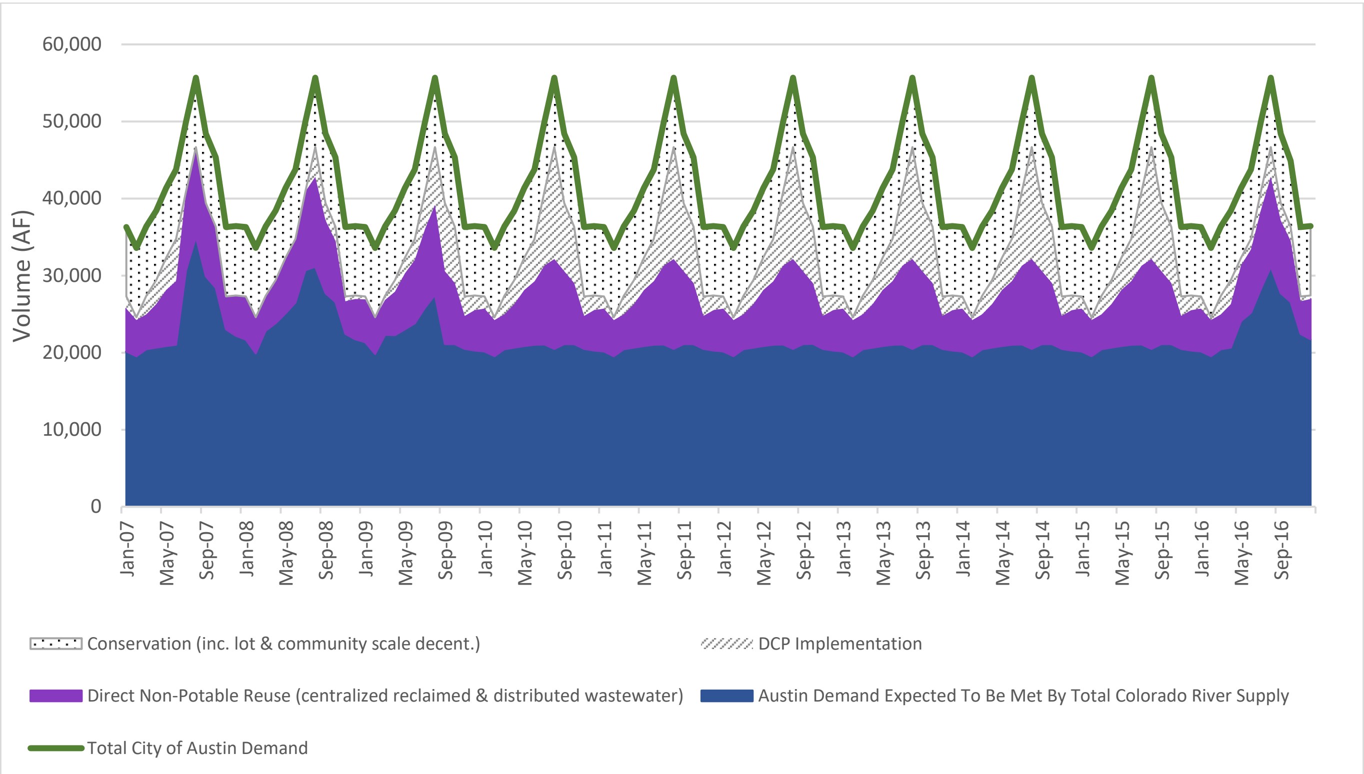

Figure F-3. Hypothetical supply scenario during critical drought sequence

In some model conditions, particularly when modeling climate change impacts and droughts worse than the drought of record, water from the Colorado River supply is not available in the simulation. The next figure shows the first step of determining a Type 2 needs volume for development of supply to provide water for supply augmentation in extreme low lake level conditions. This first step is to determine the maximum Colorado River demand during the critical drought period, with all drought contingency plan measures engaged. In **Figure F-4**, a black line representing the combined storage of Lakes Travis and Buchanan has been added to the graph. The combined storage line is associated with the y-axis on the righthand-side of the graph. Additionally, a grey line indicating 450,000 acre-feet of combined storage has been added. Type 2 needs are amounts calculated only when the model-simulated combined storage volume drops below the gray line. In **Figure F-4**, a gold box has been drawn around the total Colorado River demand when combined storage drops below 450,000 acre-feet. The gold box represents the theoretical maximum demand on Colorado River supplies during the critical drought period. The Type 2 needs are a function of this theoretical maximum demand and how much run-or-river water supply is available, as illustrated in the next figure.

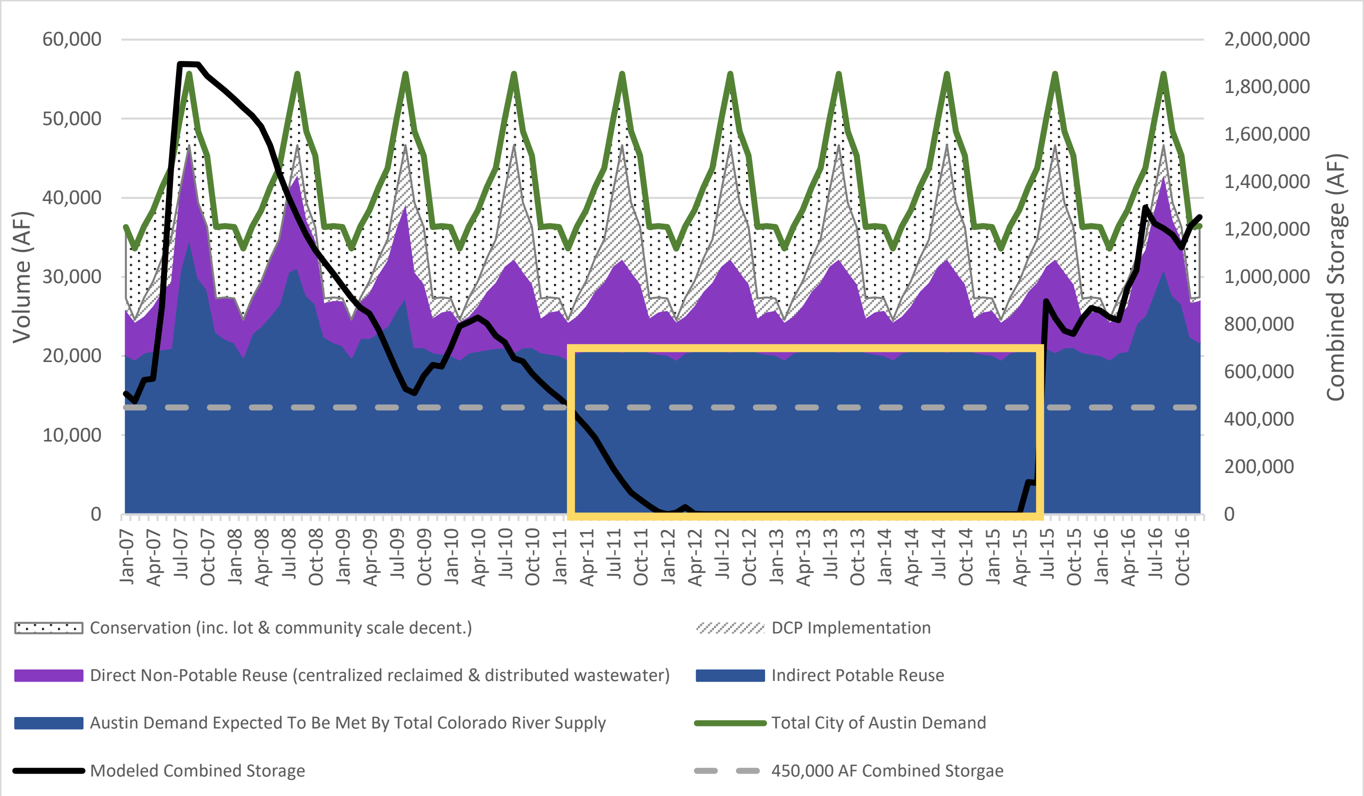

Figure F-4. Hypothetical supply scenario during critical drought sequence with Type 2 Box Shown

In the next step of Type 2 needs determination, the model was used to determine how much supply is available to meet the total demand for Colorado River water from both Lower Colorado River Authority stored water supplies and City of Austin run-of-river supplies. These two supplies make up Austin's current core contractual water supply. **Figure F-5** shows the breakout of these two supplies in the context of meeting Austin's water demand in this simulation sequence. Both Austin's run-of-river supply and the amount expected to be available from Lower Colorado River Authority stored water supply are used in the calculation of Type 2 need, as discussed next.

As in the previous figure, once the black combined storage line drops down below the gray line at 450,000 acre-feet, a Type 2 needs volume was calculated. For the purposes of Water Forward, this volume was set to be 50% of the supply Austin would expect to receive from Lower Colorado River Authority stored water for each month that combined storage is below 450,000 acre-feet. This is calculated by determining Austin's total demand for Colorado River water, subtracting the City of Austin run-of-river (ROR) available in the model, and dividing by 2 to get 50% of the total Lower Colorado River Authority stored water Austin would expect to receive (shown in the equation below). An example of this calculation is presented for April 2013 Type 2 need, as shown in **Figure F-5** and the example equation below.

$$Monthly\ Type\ 2\ Need = \frac{Austin\ Demand\ for\ Colorado\ River\ supply - Available\ City\ of\ Austin\ ROR}{2}$$

$$April\ 2013\ Type\ 2\ Need = \frac{20{,}657\ AF - 11{,}385\ AF}{2} = 4{,}636\ AF$$

To calculate the maximum 12-month Type 2 needs over a whole simulation period (which was the metric used for portfolio evaluation), the twelve greatest continuous monthly Type 2 need volumes were summed. The results of this calculation for the baseline model under hydrologic scenario B are shown in **Table F-2**.

Table F-2. Baseline Type 2 needs under hydrologic scenario B (period of record with climate change)[1]

Year	2020[1]	2040	2070	2115
Type 2 Needs	6,000 AFY	20,400 AFY	77,000 AFY	93,600 AFY

[1]Because climate change effects were not included for 2020, Type 2 needs were defined by modeling under hydrologic scenario C (extended hydrology without climate change).

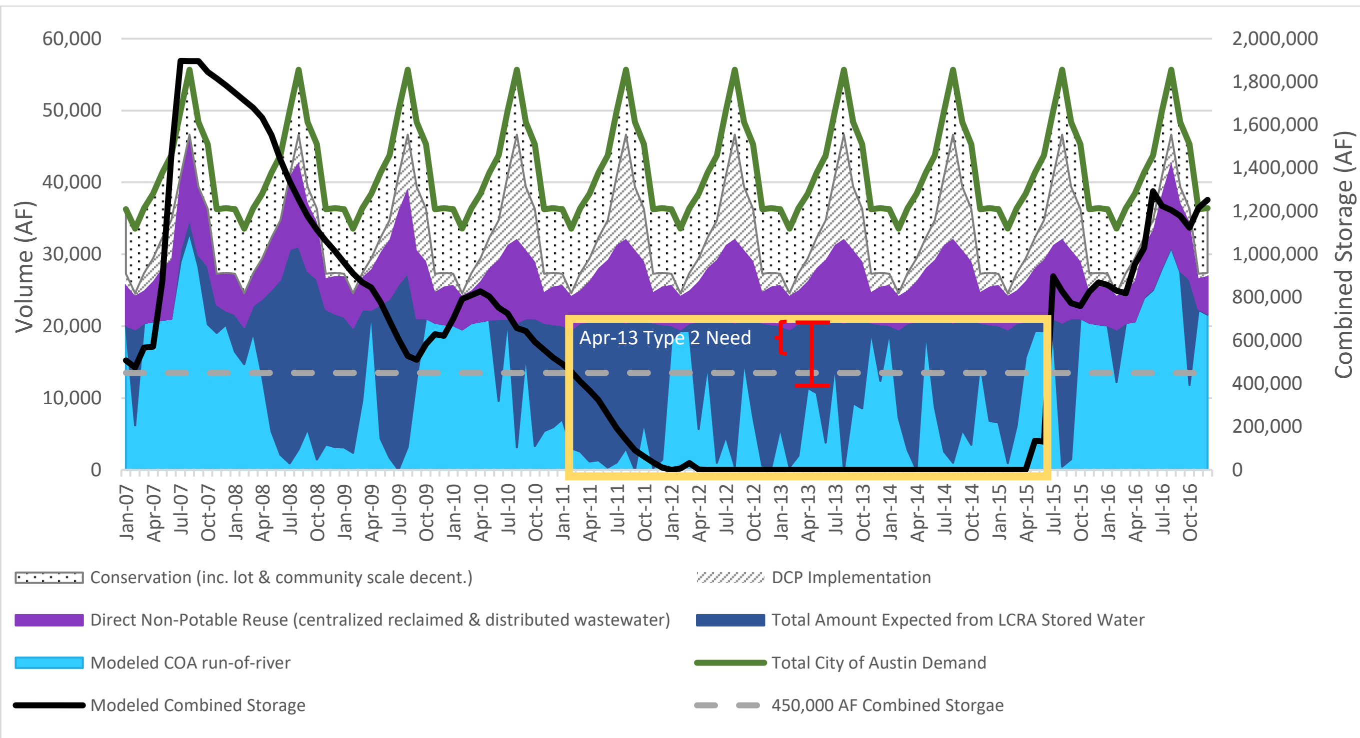

Figure F-5. Hypothetical supply scenario during critical drought sequence with total amount Austin would expect to receive from Lower Colorado River Authority stored water identified.

Type 2 needs were defined as 50% of the amount of water that Austin would expect to receive from Lower Colorado River Authority stored water because it represents the middle of two extremes. On one hand, 100% could have been selected, meaning that the Type 2 needs could have been set at 100% of expected Lower Colorado River Authority stored water, whether or not it was available in the model. Another option would have been to pick 0%, and to, in effect, not have targeted an amount of water to develop as an additional back-up supply to Austin's Colorado River firm supplies. However, this selection would not have helped to address one of the key goals of the integrated water resource plan process, which is to ensure a diversified, sustainable, and resilient water future for Austin. The 50% was selected to be in the middle as a reasonable amount to develop to meet this need.

F.3.2.2 Portfolio Supply Interaction with Type 2 Needs

After identifying Type 2 needs, the next step was to determine supplies that could meet them. Applicable Water Forward options were used to meet Type 2 needs, whereas any available Lower Colorado River Authority stored water was only modeled to meet the other 50% of Austin's total Colorado River demand. Supplies were modeled this way to help manage uncertainty associated with extremely low lake levels. **Figure F-6** shows that the model simulates that Austin may still get some amount of Colorado River system water from Lower Colorado River Authority stored water supplies and City of Austin run-of-river water when modeled combined storage is less than 450,000 acre-feet, as shown in the two blue-shaded areas of the graph (City of Austin run-of-river water is in light blue and Lower Colorado River Authority stored water is in dark blue).

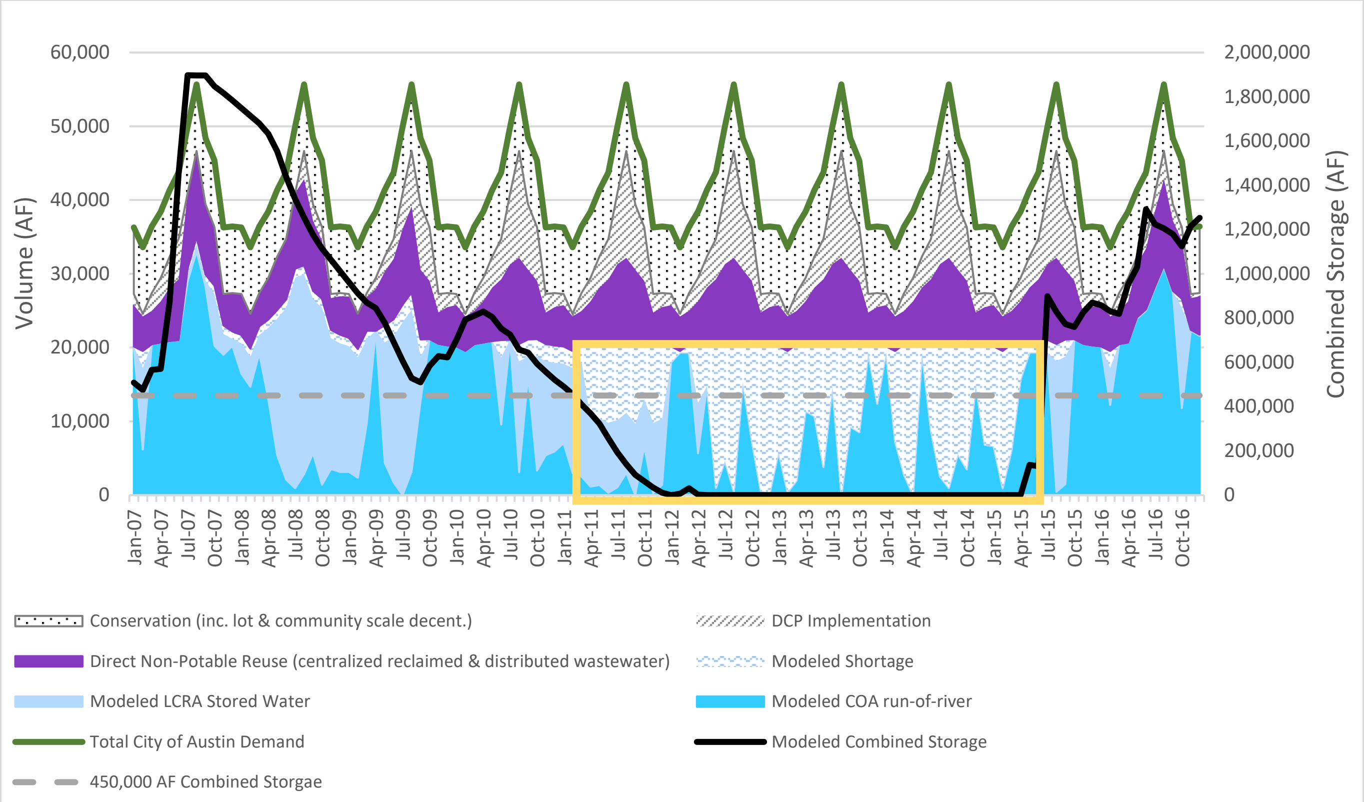

Figure F-6. Hypothetical supply scenario during critical drought sequence with shortages identified

The next step in modeling portfolio supplies to meet Type 2 needs was to model the volume of portfolio supplies available and the remaining regional shortages. **Figure F-7** shows the addition of simulated portfolio supplies in green, which are needed to fill the wavy hatched area in **Figure F-6**. This wavy hatched area represents the simulated shortages in meeting the modeled demand. As shown in the next graph, the portfolio supplies represented in green are able to completely fill the Type 2 needs portion of the wavy hatched area, leaving the pink area associated with regional shortages. These regional shortages are the remainder of Austin's total Colorado River demand and represent the other 50% of the Type 2 needs quantification. Regional shortages will need to be addressed in the future as Austin works with other regional partners in the basin and as others in the basin may develop additional supplies that may address this need.

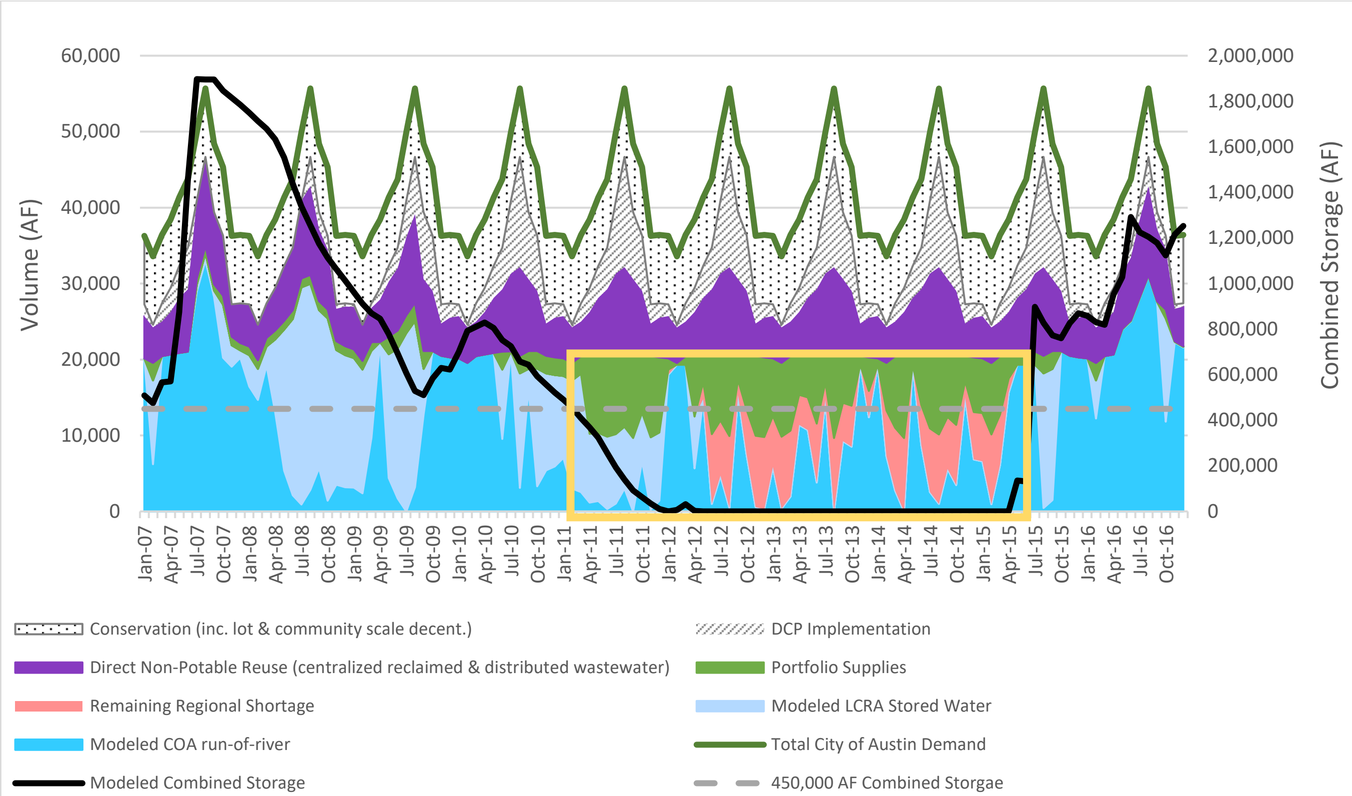

Figure F-7. Hypothetical supply scenario during critical drought sequence with Portfolio Supplies added

F.3.3 Type 3 Needs

Type 3 needs represent an amount of water to meet projected demands above Austin's current 325,000 acre-feet firm water supply contract with Lower Colorado River Authority. From the baseline demand projection with climate change effects on water demands incorporated, the Type 3 need is 170,400 acre-feet per year. It should be noted that Type 3 needs are largely met or are considerably reduced through demand reductions from portfolio demand management and conservation options in the portfolio development and evaluation process. Both demand management and water supply options can fill this need.

Table F-3. Baseline Type 3 needs under hydrologic scenario B (period of record with climate change)[1]

Year	2020[1]	2040[1]	2070[1]	2115
Type 2 Needs	0 AFY	0 AFY	0 AFY	170,400 AFY

[1]There are no Type 3 needs in 2020, 2040, or 2070 because baseline projected demands are expected to remain below Austin's 325,000 acre-feet Lower Colorado River Authority contract.

F.4 Summary of Refined Baseline Identified Water Needs

Table F-4 is a summary table of baseline Type 1, 2, and 3 needs. It should be noted that beyond the Type 1, 2, and 3 needs identified through the integrated water resource plan process, there are also regional needs that will need to be addressed over time. As outlined in the Type 2 section, above, Austin will need to continue to work with other regional partners across the basin as conditions and planning assumptions change over time.

Table F-4. Baseline 12-Month Identified Water Needs for the Period of Record with Climate Change[1]

Water Need Type	2020 (AFY)[2]	2040 (AFY)	2070 (AFY)	2115 (AFY)
Type 1: Met by New Demand Management or Supply Options	3,000	10,600	15,400	24,800
Type 2: Met by New Potable Supply Options	6,000	20,400	77,000	93,600
Type 3: Met by New Demand Management or Supply Options	0	0	0	170,400
Total Identified Water Needs	**9,000**	**31,000**	**92,400**	**288,800**

[1]Because climate change effects were not included for 2020, needs were defined by modeling under hydrologic scenario C (extended hydrology without climate change).
[2]AFY = acre-feet per year