EXECUTIVE SUMMARY

Photo: Sunset at the Great Salt Lake, Utah. Credit: Johnny/Adobe Stock.

This report, generated through a unique collaboration between climate scientists, hydrologists, modelers, and the Weber Basin Water Conservancy District (WBWCD), provides a detailed review of historical climate and hydrology, downscaled projections of future precipitation, temperature and hydrology, and a vulnerability analysis of the WBWCD water system to inform water supply planning in the Weber River basin. State of the art modeling techniques are used to provide site-specific climate projections for the entire Weber River basin and a suite of modeling approaches are used to translate climate projections into streamflow projections for the Weber River.

Use of multiple climate modeling techniques is an approach that uses a range of information to describe future climate scenarios and impacts to water supply. The primary goal of delivering multiple projections of future climate is to provide WBWCD the information necessary to evaluate and plan for multiple future climate scenarios based on the range of future climate projections. *There is no probability to each scenario and each scenario is considered equally likely.* Multiple, plausible scenarios of climate, streamflow, demand, reservoir sedimentation and reservoir evaporation are used in a vulnerability analysis of WBWCD's water system to determine how changing climate will stress the system.

HISTORICAL CLIMATE AND HYDROLOGY

Climate is changing in the Weber River basin. Historical temperatures have increased since the 1980s, but clear changes to precipitation, snowfall and streamflow in the Weber River basin were not observed. Globally, air temperature has increased by 1.8°F since 1850. Utah temperatures warmed by 2° to 3.5°F since 1850, with most of the warming occurring after 1970. Warming, since 1850, is attributed largely to increases in greenhouse gases in the atmosphere that trap heat near Earth's surface. Climate and hydrology are examined critically in five sub-basins of the Weber River basin: the headwaters of the Weber River, Lost Creek, South Fork of the Ogden River, Chalk Creek and East Canyon Creek. Analyses by sub-basin are designed to quantify current spatial variability in climate and streamflow, to identify mechanisms underlying this variability, and to inform spatially-explicit, future projections of streamflow. The analysis of historical climate and hydrology indicates:

- Every sub-basin in the watershed experienced a significant increase in temperature, with the rate of warming accelerating rapidly beginning in 1985.
- Temperatures in each sub-basin, post-1985, are on average 1.6° F warmer than pre-1985 temperatures.
- The highest sub-basin, which produced the most water (Weber above Oakley), exhibits much greater interannual variability in temperature than other sub-basins.
- There was no significant change in annual or seasonal precipitation over time in the Weber River basin.
- There was no significant change in streamflow in any sub-basin of the Weber River basin from 1920-2018.
- Water yield (runoff efficiency) varies across subcatchments ranging from 13% in Lost Creek to 48% in Weber River above Oakley.

- Water yield (runoff efficiency) increases and variability decreases as precipitation increases.
- Snowmelt is beginning earlier, but proceeding more slowly; if this trend continues, water yield is likely to decline in the future.

FUTURE CLIMATE

Scientists study future climate by using global climate models (GCMs), which are computer simulations of the state of the Earth's atmosphere, oceans, land surface, sea ice and land ice. Economic and policy scenarios are used to generate future atmospheric greenhouse gas concentrations which are incorporated into GCM's to simulate future climate. Future climate and hydrology projections will be presented for moderate and high emissions scenarios for mid-century (2050's) and end-of-century (2085). Several climate modeling techniques were used to provide future climate projections for the entire Weber River basin at a spatial resolution of 2.5 miles and at monthly or annual time scales. Projections of temperature, precipitation and potential evapotranspiration using statistically downscaled climate data are provided as the median result from climate models. Projections of temperature, precipitation, snow, extreme precipitation and evaporation are obtained using dynamically downscaled climate data from a single climate model that was selected for its accuracy in recreating northern Utah climate.

While probabilities cannot be applied to specific climate projections in this report, the degree of certainty in a specific climate projection is expressed qualitatively in terms of confidence level: *low confidence*, *medium confidence* and *high confidence*. Confidence level is determined by the underlying scientific understanding resulting from the type, amount, quality, consistency and agreement of evidence. In general there is higher confidence in projections that directly or indirectly involve temperature and lower confidence in projections relating to precipitation. The expression of scientific certainty in terms of confidence is modeled after the method used in the Intergovernmental Panel on Climate Change assessment reports. The following information is a summary of future climate projections for the Weber River basin. Table i summarizes future projections for temperature, precipitation, snow, water use and evaporation.

Temperature

- Moderate greenhouse gas emissions increase maximum temperatures by approximately 4°F by 2050 and 7°F by 2085. *High confidence*.
- High greenhouse gas emissions increase maximum temperatures by 6°F by 2050 and 12°F by 2085. *High confidence*.
- Interannual variability in warming is relatively small; there are many hot years in a row and fewer historically normal years. *Medium confidence*.
- The greatest warming will take place in the springtime as the snowpack melts sooner and bare ground is exposed which absorbs more solar radiation. *High confidence*.
- The strongest warming in the short-term will take place in valley locations such as Morgan and Ogden Valleys; valleys will warm more than the Uinta Mountains. *Medium confidence*.

Precipitation

- Most climate models project a slight increase in precipitation for the Weber River basin. *High confidence*.
- By mid-century, the greatest precipitation increases occur in January and February in the Wasatch and Uinta Mountains. *Medium confidence*.
- Precipitation is projected to decrease in May and June throughout the 21st century. *Medium confidence*.
- Mountain precipitation may increase in November and December throughout the century, but warmer temperatures mean early winter precipitation may fall as rain. *High confidence*.
- A large increase in September precipitation is due to an interaction of monsoon moisture and fall Pacific storms. *Low confidence*.

Snow

- By mid-century, annual snowfall is projected to decrease by 30% along the Wasatch Front and 10-15% in the lower elevations (below 7500 feet) of the Wasatch Back. *Medium confidence*.
- Elevations above 7500 feet in the Wasatch and Uinta Mountains are projected to see a 10% increase in snowfall by the end of the century. *Medium confidence*.
- High elevation (above 7500 feet) locations that historically receive the most snow will have a dramatic shift toward an earlier timing in peak snowpack. *High confidence*.

Extreme precipitation

- Extreme precipitation is an event where rain falls very intensely over a short period of time; these events often cause flash flooding.
- On the Wasatch Front, little change in extreme precipitation is projected for the next several decades. *Medium confidence*.
- By the end of the century, extreme once-per-decade storms will be 10% stronger than in the past. *Medium confidence*.

Table i. Summary of climate change projections. Temperature (T) is expressed as an average temperature increase compared to historical temperatures. Annual precipitation change (P) is expressed as a percent change compared to the historical period. Snow-level is expressed as an elevation in feet that mean snow level changes. Snow is expressed as a percent change in snow-water equivalent compared to the historical period. Potential evaporation (PET) is expressed as a percent change compared to the historical period. Water use is expressed as a percent increase in water use compared to average water use from 2010-2018. RCP4.5, RCP6.0, RCP8.5 are emissions scenarios; RCP4.5 and 6.0 use moderate levels of future emissions, RCP5.8 uses high levels of future emissions. Evaporation is expressed as an annual average increase in the amount of water evaporated from Willard Bay in acre-feet. Climate projections are derived from three datasets, LOCA statistically downscaled, MACA statistically downscaled and University of Utah dynamically downscaled.

PARAMETER	METHOD	LOCATION	RCP4.5		RCP6.0		RCP8.5	
			2050	2085	2040	2090	2050	2085
T	LOCA	Basin-wide	+4°	+7°	-	-	+6°	+12°
T	Dynamic	Ben Lomond	-	-	+2.7°	+5.3°	-	-
T	Dynamic	Thaynes Cyn	-	-	+2.3°	+4.6°	-	-
T	Dynamic	Trial Lake	-	-	+2.4°	+4.8°	-	-
P	LOCA	Basin-wide	0%	+5%	-	-	0%	+5%
P	Dynamic	Basin-wide	-	-	+5%	+10%	-	-
P	Dynamic	Ben Lomond	-	-	+4%	+7%	-	-
P	Dynamic	Thaynes Cyn	-	-	+8%	+13%	-	-
P	Dynamic	Trial Lake	-	-	+9%	+17%	-	-
Snow-level	LOCA	Basin-wide	+1200′	+1200′	-	-	+1800′	+3600′
Snow	Dynamic	Ben Lomond	-	-	-2%	-7%	-	-
Snow	Dynamic	Thaynes Cyn	-	-	+1%	-0.4%	-	-
Snow	Dynamic	Trial Lake	-	-	+2.3%	+3%	-	-
PET	MACA	Ogden	+5%	+9%	-	-	+8%	+16%
Water use	MACA	Ogden	+6%	-	-	-	+10%	-
Evaporation	Dynamic	Willard Bay	-	-	+1565	+3368	-	-

Evaporation

- Evaporation of water from Willard Bay increases in all months for mid-century and December through August in the late century projections. *High confidence*.
- The greatest increases in evaporation occur during the warm months; April – September for mid-century and March – July for end-of-century projections. *High confidence*.
- The mid-century increase in evaporation amounts to a loss of 1500 acre feet per year, and the late-century increase amounts to a loss of 3300 acre-feet per year. *Medium confidence*.

Potential evapotranspiration

- Potential evapotranspiration (PET) is a measure of the atmosphere's "thirst" from water through evaporation of water from soils and transpiration of water from plants.

- In 2050, PET is projected to increase by 5% given a moderate emissions scenario (RCP4.5) and by 8% under a high emissions scenario. *High confidence* that PET will increase. *Medium confidence* regarding level of increase.

FUTURE OUTDOOR WATER USE

Changes in climate are likely to impact the amount of water used to irrigate outdoor landscapes. As temperatures rise and other climate parameters change, potential evaporation (PET) is projected to increase. In general, when it is hotter, PET is higher and plants use more water. A linear regression model is constructed to relate water used in four Ogden neighbors to PET and then used as a tool to project future water use.

- Using water use data from the Ogden area and observations of PET, a model was created to relate PET to water use; PET explained 60% of the variability in water use.
- A low and high PET scenario was used to project water use.
- By 2050, water use in four Ogden-area neighborhoods is projected to increase by 6% for a low PET scenario and by 10% for a high PET scenario.
- The greatest increases in water use are expected to occur in April through June which is validated by predictions of significantly warmer and drier future spring by mid-century. Water use is projected to decrease slightly in August and September.

FUTURE WEBER RIVER STREAMFLOW

Three techniques were used to provide projections of Weber River streamflow for mid- and end-of-century. The three techniques are: a statistical streamflow model informed by historical hydroclimate, a Variable Infiltration Capacity (VIC) model, and a temperature and precipitation sensitivity analysis. Projections of streamflow were developed for the headwaters of the most productive sub-basin of the Weber River basin (the Weber River above Oakley). The three techniques will provide slightly different projections in some cases and similar projections in others. When two different techniques to project streamflow converge on a single projection, there is greater certainty in that projection. As with future climate, certainty in a specific streamflow projection will be expressed by confidence level. Due to disagreement amongst modeling techniques, specific projections of total streamflow were generally assigned low confidence, while streamflow projections related to temperature, like timing of peak flow, were assigned higher confidence. Projections from the three streamflow models should be used as the basis to develop scenarios describing the range of future water availability and not as a tool to determine a most likely future availability of water. Table ii compares the results of all streamflow projection techniques.

Statistical streamflow model

- The importance of a multi-year climate impact on groundwater differentiates the statistical streamflow model from the other two approaches.
- Three climate scenarios (low, medium, and high precipitation) are used.
- Under the medium precipitation scenario with moderate emissions, annual streamflow increases by 5% (*medium confidence*); peak streamflow is 20% higher (*medium confidence*), occurs 10-days earlier and returns to base flow conditions sooner (*medium confidence*). Note that moderate the emissions scenario assumes a 2°F increase in temperature and we are currently at 1.6°F warmer for these catchments.
- Under the medium precipitation scenario with high emissions, there is a 16% decrease in annual streamflow (*medium confidence*), a 32% decrease in peak streamflow (*low confidence*) and melt-induced flow occurs 2 to 3-week earlier (*high confidence*).
- The high precipitation scenario highlights the possibility of severe early-season flooding, with continuous melt-induced flow starting as early as February. *Low confidence*.
- The low precipitation scenario suggests the possibility of severe drought, with annual streamflow 30%

lower than the lowest year on record, or 25% of annual average streamflow. The site-specific statistical model of streamflow indicates a multi-year sensitivity to climate mediated through groundwater recharge which can either buffer or exacerbate the effects of a dry year. *High confidence*.

- Mean daily discharge in January is a function of multi-year climate; deviations from long-term mean January discharge are strong predictors of runoff efficiency for the coming year. *High confidence*.

VIC model

- Four climate scenarios were selected based on a climate model's temperature or precipitation projection relative to the mean of all climate models: warm/dry, hot/dry, warm/wet and hot/wet.
- For a moderate emissions scenario, annual streamflow decreases by 7% in 2055 for a hot/dry scenario, but increases for all other scenarios with the greatest increase (11.2%) for a warm/wet scenario. *Low confidence*.
- In the high emissions scenario, annual streamflow is projected to increase for all scenarios by 2055 with an increase of nearly 13% for a warm/wet scenario. *Low confidence*.
- Streamflow in winter and early spring is likely to increase while late summer and fall streamflow (baseflow) decreases. *High confidence*.
- In one scenario (hot/wet scenario for 2055), peak streamflow occurred nearly two months earlier and the peak's magnitude is greatly reduced. *Low confidence*.

Table ii. Summary of annual streamflow volume projections. Streamflow projections were developed using three techniques: a statistical streamflow model (statistical), a variable infiltration capacity model (VIC) and a temperature and precipitation sensitivity analysis (sensitivity). For each method several different scenarios were used that considers different levels of temperature increase and future changes to precipitation (see section 4 of the report for scenario descriptions). Low P, medium P and high P abbreviates, low, medium and high precipitation. Future projections of streamflow are expressed as a percentage change compared to the historical period. Streamflow projections are provided for two time periods (2050 and 2085) and a moderate (RCP4.5) or high (RCP8.5) emissions scenario.

STREAMFLOW SCENARIO	METHOD	RCP4.5		RCP8.5	
		2050	2085	2050	2085
Low P	Statistical	0%	-	-30%	-
Medium P	Statistical	+5%	-	-16%	-
High P	Statistical	+5%	-	-13%	-
WarmdDry	VIC	+2%	+6%	+1%	+2%
Hot/dry	VIC	-7%	-4%	+0.1%	+8%
Warm/wet	VIC	+11%	+15%	+13%	+26%
Hot/wet	VIC	+8%	+18%	+23%	+14%
Warm/dry	Sensitivity	-16%	-12%	-	-
Hot/dry	Sensitivity	-20%	-37%	-	-
Warm/wet	Sensitivity	+29%	+25%	-	-
Hot/wet	Sensitivity	+12%	-1%	-	-

Temperature and precipitation sensitivity analysis

- Four climate scenarios were used: warm/dry, hot/dry, warm/wet and hot/wet.
- Streamflow projections using this technique were lower than VIC model projections; most scenarios project a decrease streamflow and greater scenario variability.
- Projections for 2055 show the greatest decrease in streamflow for the hot/dry scenario (-20.2%) and the greatest increase in streamflow for the hot/wet scenario (+29%). *Low confidence*.
- In 2055, peak monthly streamflow is projected to occur one month earlier. *Medium confidence*.

BOTTOM-UP SYSTEM VULNERABILITY ANALYSIS

Utah State University conducted a climate vulnerability study for the Weber Basin, Utah. The study used a bottom-up approach (Brown et al., 2019; Brown and Wilby, 2012) wherein we showed how changes to combinations of future uncertain streamflow, demand, reservoir sedimentation, and reservoir evaporation conditions would affect total basin reservoir storage and deliveries to users. Six scenarios of future streamflow—each 30-years in length at a monthly timestep—varied total basin annual flow from approximately 800,000 to 975,000 acre-feet per year. The scenarios were drawn from three periods in the paleo record, two periods in the most recent century of gaged records, and a Western Water Assessment scenario for 2030 to 2060 streamflow under hot and dry climate. Six scenarios of future annual demands ranged from 362,000 to 846,000 acre-feet per year and represented select combinations of a wider set of 63 scenarios of uncertain future population growth, total per capita water use, agricultural to urban water transfers, and increased landscape evapotranspiration. Data for future reservoir sedimentation was scarce so we constructed three scenarios of 0%, 10%, and 30% filling of total storage that represent the current assumption of no buildup, gradual filling over time, and more severe filling. Three scenarios of future evaporation from Willard Bay reservoir had rates of 3.2, 3.7, and 4.0 feet per year. These rates represented the current value used by the Utah Division of Water Resources (UDWRe) and historical and late 21st century values estimated by the University of Utah in the earlier part of this report. *Each streamflow, demand, reservoir sedimentation, and reservoir evaporation scenario is possible in the future. These scenarios cannot be assigned probabilities or likelihoods. These scenarios represent current engineering best practice to describe, quantify, and manage in the face of future conditions that are deeply uncertain*. Together, 324 runs comprising combinations of six streamflow, six demand, three reservoir sedimentation, and three reservoir evaporation rate scenarios were simulated using the prior-existing UDWRe RiverWare model for the Weber basin and the RiverSmart plugin to automate the large number of model runs. The main results and findings are:

System Strengths

- The current modeled historical conditions with about 960,000 acre-feet per year of inflow, 550,000 acre-feet of demand, no sedimentation, and 3.2 feet per year of evaporation from Willard Bay is able to consistently maintain total reservoir storage above the 380,000 acre-feet moderate (yellow) target defined in the drought contingency plan.
- Demands would need to increase by about 160,000 acre-feet per year and/or inflow decrease by about 80,000 acre-feet per year from the modeled historical conditions for total reservoir storage to drop below the 380,000 acre-feet target in 10 to 20% of modeled years.
- For the 10% reservoir sedimentation rate, the yellow, orange, and red reservoir storage targets of 380,000, 320,000, and 280,000 acre-feet are met the same fraction of years for the same inflows and demands as with 0% sedimentation.
- During the modeled historical conditions, delivery requests are met nearly all the time with few shortages. Deliveries are met and shortages are small across all three reservoir sedimentation rates.
- The Weber Basin system storage is insensitive to Willard Bay evaporation rates between 3.2 and 4.0 feet per year. *Despite uncertainty about the future reservoir evaporation rate, this climate factor did not affect system storage in the stream flow, demand, or reservoir sedimentation scenarios tested*.

System Vulnerabilities

- When reservoir sedimentation rates increase to 30%, the yellow, orange, and red reservoir storage targets are violated much more frequently. A unit volume reduction in inflow leads to more violations in storage targets than the same unit volume increase in demand.
- In the hot-dry future climate scenario that has average inflows of 800,000 acre-feet per year, total reservoir storage will fall below the 380,000 acre-feet moderate target in 50% or more of simulated years regardless of the annual demand.
- Several droughts within the tested scenarios last four years and longer. During these droughts, total reservoir storage stays below the red 280,000 acre-feet threshold for multiple years. However, during these droughts, the reservoir sedimentation rate does not affect storage level.
- The historical system is very close to seeing a total basin shortage of 40,000 acre-feet per year or more in at least 1 of 30 years. If demand increases by 100,000 acre-feet per year, the worst shortage would increase to about 160,000 acre-feet per year and some shortage would occur in 50% of years.
- As expected, shortages increase substantially as inflows decrease and demands increase.