WEBER BASIN WATER CONSERVANCY DISTRICT

BOTTOM-UP CLIMATE VULNERABILITY STUDY USING RIVERWARE

by

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A Report submitted in partial fulfillment
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of

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ABSTRACT

Weber Basin Water Conservancy District

Drought Vulnerability Study Using RiverWare

by

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With so much uncertainty of what the future has in store for us, how can we prepare for what lies ahead? The Weber Basin Water Conservancy District (WBWCD) needs to know how they can best prepare for future climate changes and future growth, and where their water system is vulnerable. A bottom-up approach can be used to consider how factors and subfactors effect the vulnerability of their water system's storage and delivery. This approach is accomplished with the use of RiverWare, an advanced water system modeling program. Scenarios to represent the factors are as follows: range of future stream flows, future water demands, reservoir sedimentation, and future reservoir evaporation. The scenarios are input into the RiverWare model created by the Utah Division of Water Resources (UDWRe). The model is then modified to run 324 model runs of combined possible model inflows, demands, reservoir sedimentation and

reservoir evaporation. Calculated shortages of water and storage levels in reservoirs are output from the RiverWare model. These outputs from the 324 RiverWare model runs are then compiled and analyzed using selected drought metrics to tell us where the WBWCD is vulnerable to climate changes and population growth.

The analysis of the shortages and storage levels shows that historically the WBWCD does not face water shortages, with the average annual demands and inflow not ever going below the moderate drought storage metric level of 380 thousand acre-feet (TAF) per year in the simulated 30-year time period. As demand increases an additional 100 TAF per year from historical levels and/or when inflows decrease by 100 TAF per year from historical levels the total storage level is more likely to go below 380 TAF, signaling moderate drought. Reservoir sedimentation at reservoir storage levels lower than 280 TAF, the extreme drought storage level, does not have a large impact on how much storage is in the reservoir storage. As sedimentation rises storage is more sensitive to the change in inflows than to change in demands. The overall impact that reservoir evaporation has on storage and water demand is small.

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For my family ever encouraging me further my education. To my siblings for providing a good example and helping me set my bars high. And for my parents for teaching me the meaning of hard work and diligence, thanks Mom and Dad.

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6. Bottom-Up Climate Vulnerability Analysis

A. Introduction

In times of uncertainty, anticipating future streamflow, water demands, and other conditions can guide decision making (Wang et al. 2020, Marchau 2019). Future climate conditions can be described as point estimates with narrow ranges, as probabilities, and as a few scenarios of possibilities (Wang et al, 2020). It becomes increasingly difficult to model and plan for multiple future conditions that are uncertain, such as for streamflow, demands, reservoir sedimentation, and reservoir evaporation. In this study we apply a bottom-up, multi-dimensional sensitivity approach (Brown et al. 2012 & Brown et al. 2019).

A bottom-up approach uses the water system's base factors (inflow, water demand, evaporation, etc.) The bottom-up approach considers all model input factors instead of just one or two climate prediction inputs. In general, a bottom-up approach looks at each and every factor but is not beholding to any input model or piece of input model data. Any and all climate studies and corresponding data can be used to analyze the effects. The input data in this approach can change and is not dependent on any study or climate prediction method. Therefore, it can consider possibilities that a top-down approach, which only considers specific climate prediction methods, cannot consider and it provides much more knowledge.

This bottom-up approach assesses the impact of combinations of inflow, demand, reservoir sedimentation, and evaporation conditions on water availability for the Weber Basin Water Conservancy District (WBWCD) of northern Utah. The WBWCD is particularly vulnerable to reduced reservoir storage and shortages to users, in part because they are the junior water rights holder in the basin. The bottom-up approach works in the following steps:

1- Identify the inflow, demand, reservoir sedimentation, and evaporation factors that impact system vulnerability
2- Develop scenarios of potential future conditions for each factor and combinations of factors
3- Run a RiverWare model for the Weber River Basin for each scenario
4- Identify criteria that describe satisfactory system performance within the RiverWare results
5- Determine which scenarios perform satisfactorily and unsatisfactorily and then visualize the vulnerabilities
6- Suggest adaptive reservoir and other management strategies that can reduce vulnerabilities.

The bottom-up approach identifies individual factors and combination of factors where the water system succeeds and fails. The bottom-up approach does not just look at the worst case scenarios or reliable probabilities (Ben-Haim, 2019), it "focuses on simulating plans across many plausible states of the world rather than assigning likelihoods to future conditions" (Alexander, 2018). The bottom-up approach helps us have a better understanding of what conditions cause the water system to fail by looking at the large picture. This knowledge provides insight to provide decision-making for water system policies over time (Haasnoot et al. 2019).

In this study, four uncertain future conditions that can only be described with scenarios were considered based on available data, factors most thought to affect district storage and shortages, and interests of the WBWCD:

1. Changes to future inflow. Inflows included past flows observed in the paleo record going back to 1400 AD, the instrumented record, and flows modeled in response to future temperature and precipitation changes,
2. Changes to future water demand due to uncertainties in increasing population, per-capita demand shifts, increased net landscape evapotranspiration, and shifting agriculture to urban land use,
3. Reduced reservoir storage due to sedimentation, and
4. Increased evaporation from Willard Bay Reservoir, the largest reservoir in the Weber Basin Water Conservancy District, due to increasing temperature and other climate factors.

The bottom-up approach applied in this study enables us to see where the water system succeeds and fails to meet the delivery criteria with a much broader view of the possibilities. The remaining sections describe the Weber Basin study area, bottom-up vulnerability method applied to the Weber Basin water system, results, and major findings.

B. Weber Basin Study Area

The Weber River Basin, located in northern Utah, is comprised of eight sub-basins, contains parts of both the Wasatch Mountains and the Uinta Mountains, and supplies water to the Great Salt Lake Valley, Ogden Valley, Morgan Valley and the Snyderville Basin (U of U report). The

Weber Basin has a water system is comprised of 8 reservoirs, 4 water treatment plants, and miles of pipelines (WBWCD, 2020). The WBWCD established in 1950, provides agricultural and urban water for over 620,000 people in 5 counties. (WBWCD, 2020; WBWCD, 2013). Most urban users live along the Wasatch Front between North Salt Lake and North Ogden.

C. Methodology

We developed 6 scenarios of future Weber River Flow at Oakley (the most upstream gage in the basin), 6 scenarios of future demands, 3 scenarios of sediment buildup in reservoirs, and 3 scenarios of evaporation rates for Willard Bay Reservoir. Each scenario represents a possible future condition (Figure 1). We combined the scenarios of future inflow, demand, reservoir sedimentation, and reservoir evaporation into 324 modeling runs. Each run was simulated for 30 years at a monthly timestep in the RiverWare modeling platform. We developed 3 reservoir storage and a water shortage criterion to define when the system performed satisfactorily and when the system was vulnerable. We used contour and time series plots to show the combinations of future inflow, demand, reservoir sedimentation and evaporation that led to satisfactory and unsatisfactory conditions. Preliminary results were shared and discussed with WBWCD personnel.

Previous studies have been done determining the inflow rates of the Weber Basin rivers (WBWCD, 2019; Stagge, 2017). This study uses data from the UDWRe basin study, the WBWCD Drought Contingency Plan, the Paleoflow.org database updated for the Drought Contingency Plan to include Weber River at Oakley flows, and WBWCD Climate Vulnerability Assessment.

The UDWRe study considered historical flows based on the Weber River at Oakley gage. The Drought Contingency Plan expanded on the UDWRe study and used the historical inflows, paleohydrology and climate forecasts. This study looks at the inflows from each of the previous studies and provides a wider view of the effect of hydrology in combination with demands, reservoir sedimentation, and reservoir evaporation on Weber Basin water availability.

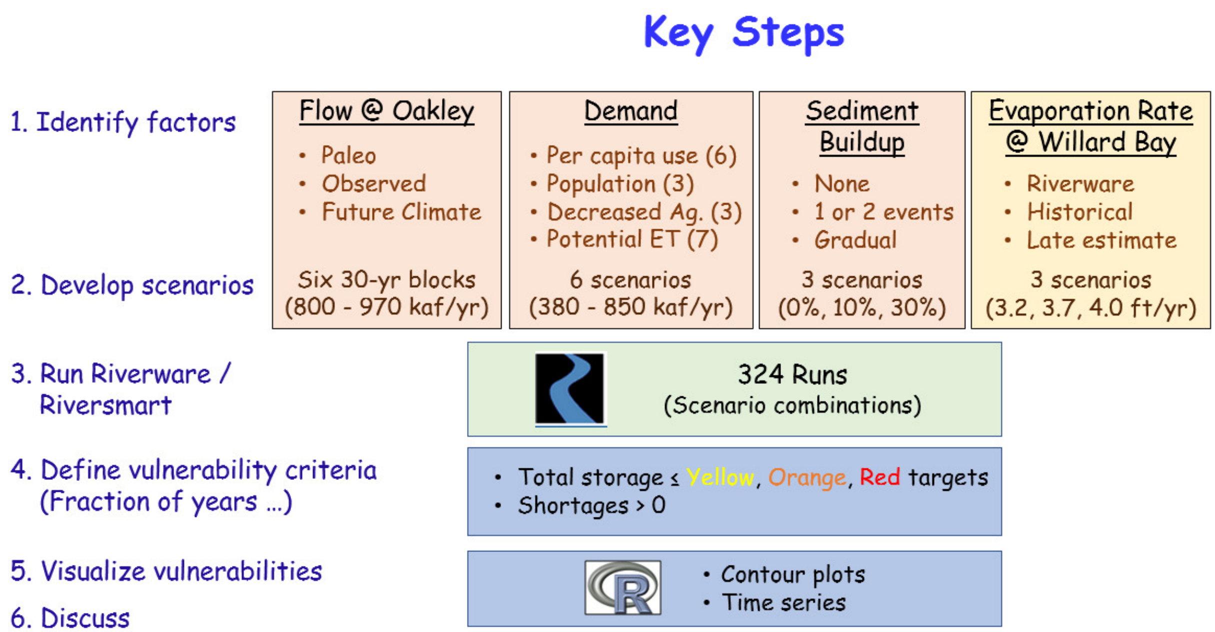

Figure 1. Methodology – Six key steps for this study.

i. Weber River Flow at Oakley, Utah

To select future model inflow scenarios for the Weber River basin, we use three different datasets of streamflow available. The three selected datasets are monthly Paleo-flows for the Weber River Basin reconstructed from tree-rings that date back to 1428 (Stagge, 2017) (Figure 2), the Western Water Assessment (WWA) climate scenarios for 2030 to 2060 (WBWCD, 2019) (Figure 3), and historical gage inflow data from 1905 to 2019 (WBWCD, 2019).

The paleoflows on the Weber River at Oakley date back to 1409 AD and were reconstructed at a monthly timestep by using Weber basin (Bekker et al. 2014) and regional tree ring chronologies for multiple tree species and a reconstruction of the El Nino Southern Oscillation (ENSO) climate index (Stagge et al. 2018). A tree ring chronology is a dendroclimatology term that refers to a time-series of spacings between annual tree rings from one or more trees at a site that are de-trended and adjusted for tree age at the time the ring was formed. A statistical relationship is made between the adjusted tree ring width and streamflow. Typically, the regression is made on annual stream flow but Stagge et al. (2018) exploited regional tree chronologies for different species whose growth occurs in different months of the year and the ENSO index to reconstruct at the monthly time step. The R-squared value for the calculated Weber River monthly stream flow is 0.87. This value expresses the fraction of variance in observed reconstructed flows explained by the variance tree-ring widths (Stagge, 2017). The paleo-flow timeseries used in this study can be found at paleoflow.org (Figure 2).

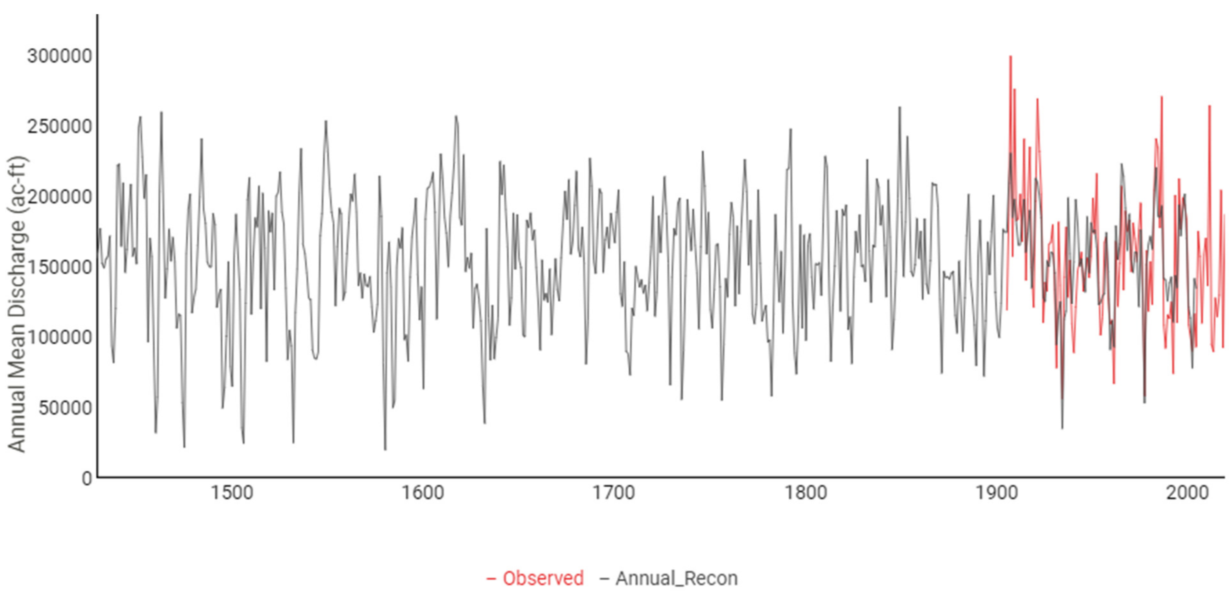

Figure 2. Weber River at Oakley stream flows. Black lines are annual flows reconstructed from tree-rings, and red lines show observed annual flows (Stagge, 2017).

The historical gage data for the Weber River at Oakley is from 1905 to 2018 (USGS gage 10128500). Historical data time periods are selected based on their drought data.

Lastly, we used climate change scenarios developed by the Western Water Assessment (JUB Engineers 2018). The WWA developed the scenarios from many different global climate model runs for three emission scenarios. Results were plotted on axes of temperature and precipitation change and five scenarios were selected that lay near the corner points and centroid of a box overlaid on the results. The scenarios were named: Hot-Dry, Warm-Dry, Hot-Wet, Warm-Wet, and Central Tendency (WBWCD, 2019) (Figure 3). Each scenario was for 30 years from 2030 to 2060.

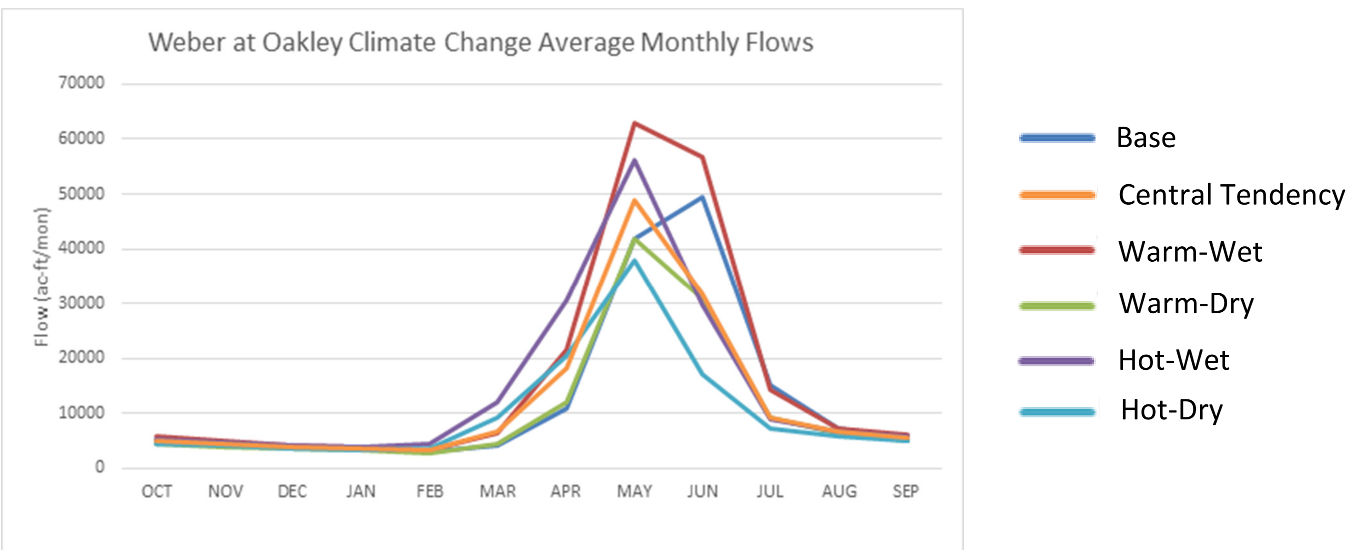

Figure 3. Averaged monthly stream flows for the Weber River at Oakley for 5 scenarios of changing temperature and precipitation (WBWCD, 2019).

For this study we looked at the forward looking linear average annual flow for 1 to 60 years (Figure 4.). The forward looking linear average annual flow was calculated by finding the average of paloe streamflow data averaging up to sixty years and the shifting by one year each box plot shown in figure 4 considers approximately 600 averages.

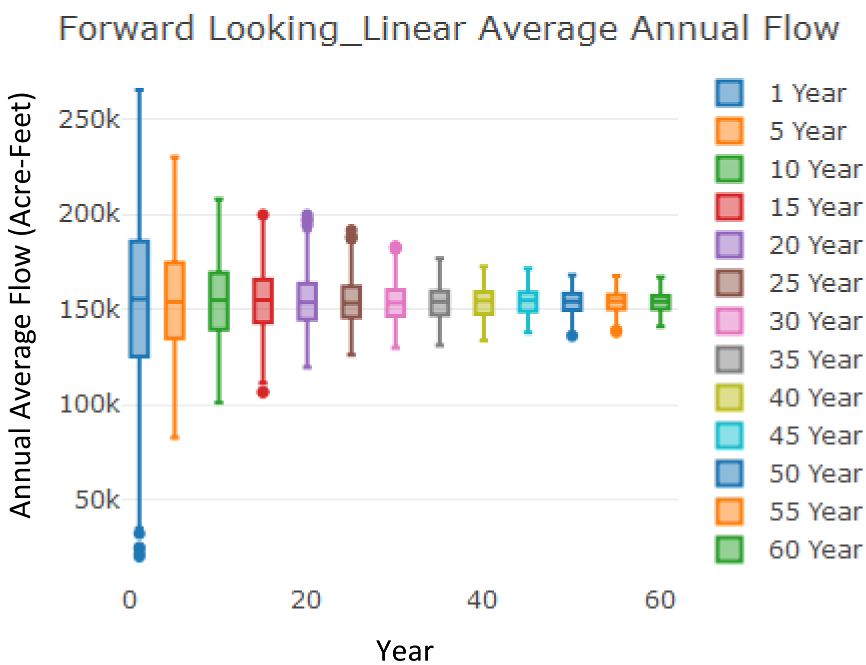

Figure 5. Boxplots of forward looking linear average annual flow. Showing the linear averages of 1 to 60 years of the paleo flow data incremented on a yearly basis, boxplots shown for every 5 years.

By looking at the linear average annual data shown in figure 5 we found that a 30-year segment portrayed a good median range for the averaged results. The top 25% and the bottom 25% of the 1 year average annual flows are shortened using the 30 year average and incompassed in the middle 50%. Therefore 30 years was selected for the streamflow length because it considers a smaller range a average streamflows, but still reflects a large portion of possible stream flows.

From the paleo flow, historical, and future climate stream flows available, we selected six 30-year periods to represent a range of possible low future streamflow scenarios for the Weber Basin (Figure 5). The scenarios could include long drought duration and/or high drought intensity. Three scenarios come from the paleo record. Two scenarios for 1930 to 1960 and 1940 to 1970 emphasize low flow periods in the historical record. To help later in comparing the flow scenarios, we refer to the 1940 to 1970 scenario as a base since this scenario also represents the most recent period. We include the Hot-Dry future climate scenario because it is the most severe of the 5 climate inflow scenarios WWA developed (WBWCD, 2019).

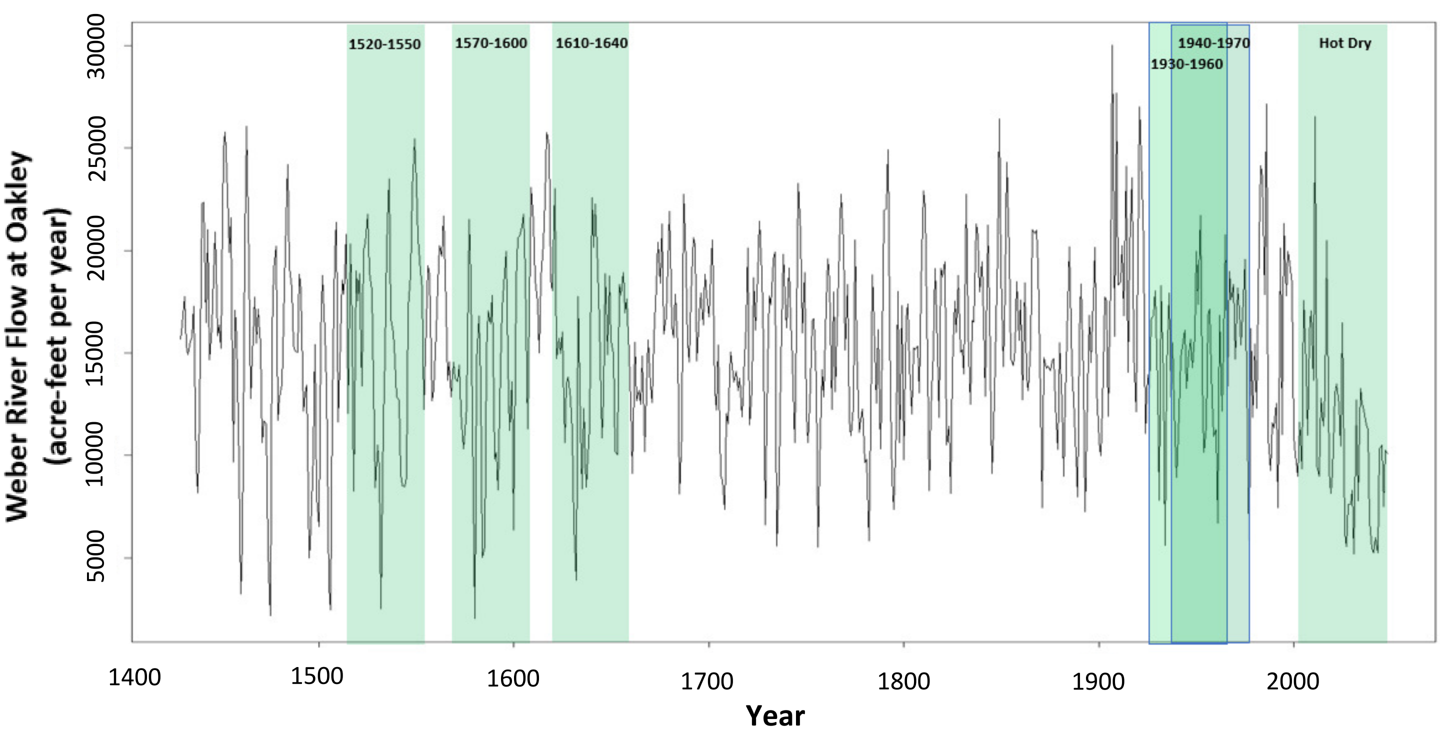

Figure 5. Weber at Oakley streamflow scenarios (green shading) over historical and reconstructed streamflow record.

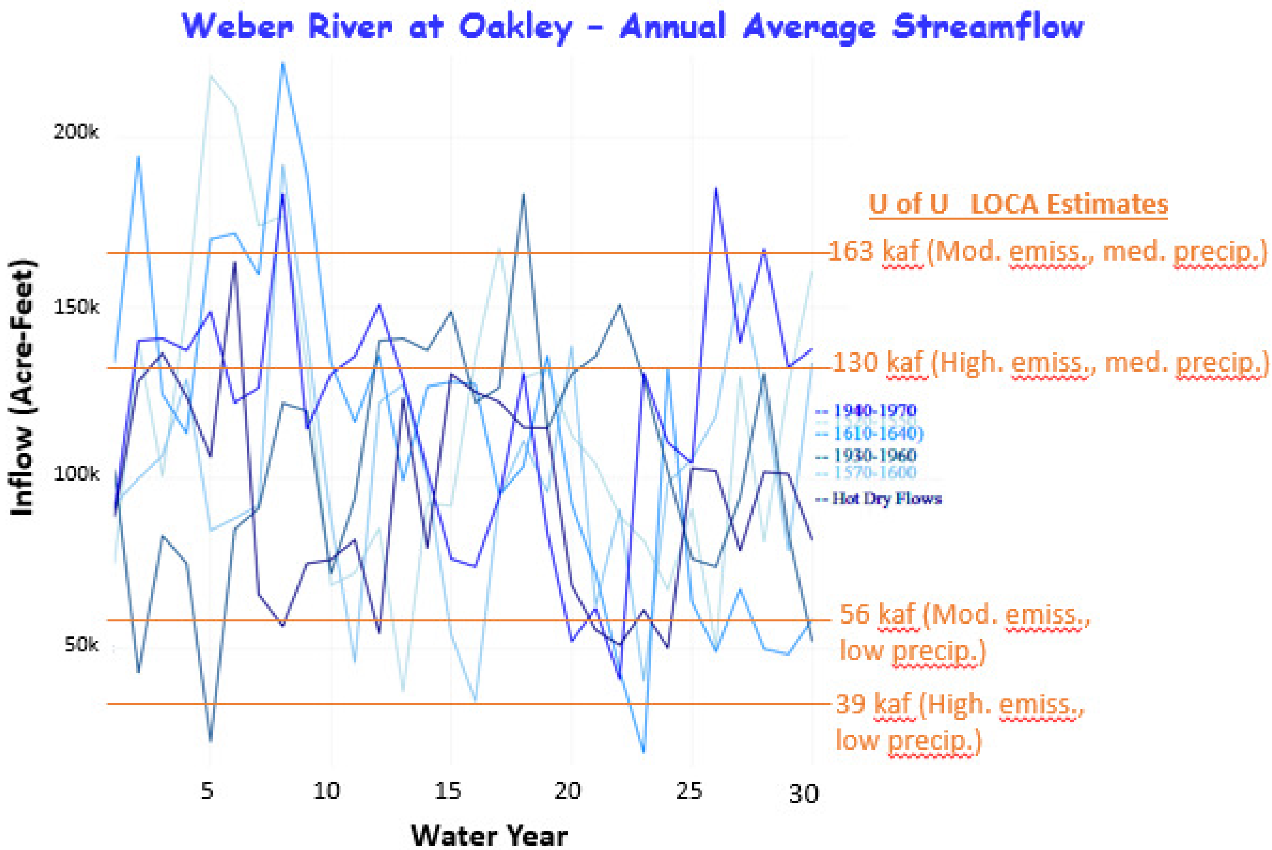

Figure 6. Comparison of the six selected scenarios of Weber River flow at Oakley by water year, and the University of Utah stream flow projections. Showing the mean inflows on the right.

Figure 6 shows streamflow for the five scenarios by water year with the 30-year average flow shown on the right y axis. Annual stream flows can vary by factors of 2 above the means or drop to 25% of the mean. The University of Utah LOCA mean stream flow projections (chapter 2) fall above and below the means of the selected scenarios and suggest that low precipitation, moderate or high emissions conditions will give stream flows even lower than the low scenarios considered here.

Stream flows for every gage in the Weber River Basin besides Oakley were previously calculated by regressing historical flow at other gages to flow at the Weber River at Oakley gage (McGettigan and Melcher., unpublished manuscript, 2018).

ii. Basin Water Demand

Water demand scenarios for this study were calculated by considering four subfactors. The first subfactor is change in population for the years 2015, 2070, and 2150. The second subfactor is the change in per-capita potable and secondary water use for each service area. Secondary water is a Utah-specific term for secondary distribution systems that provide untreated water for outdoor irrigation. The third subfactor is the transfer of agricultural irrigation water to municipal use. And the final subfactor is climate change’s effect on landscape evaporation and its effect on secondary water usage. We considered several levels (values) for each demand subfactor which we explain further below.

<u>Population Growth</u>

The University of Utah projections (U of U, 2019) for the state of Utah show that the population will continue to grow at a high rate through 2150. Through-out the Weber River basin, population is forecast to increase in all counties. There are particularly large population changes in Morgan and Summit Counties (WBWCD, 2013; U of U, 2019). The WBWCD population projections used for is study are taken from both the 2011 Weber Basin Water Conservancy District, *Water Conservation Plan Update 2013* (WBWCD, 2013) report and the

University of Utah Gardener Projections (U of U, 2019). We use three scenarios corresponding to population projections for 2015, 2070 and 2150 (Table 1).

Table 1. The total population for Weber Basin for the selected population scenario years.

Year	Population (Persons)
2015	623,960
2070	978,500
2150	1,263,000

Per-Capita Water Use

Per-capita water usage is the amount of water that one person in a household uses for an average day. There are two types of per-capita water use: secondary water use (outdoor use), and potable use (indoor use). The 2015 values for both secondary and potable per-capita water use were taken from the *2015 Municipal and Industrial Water Use* report by the Utah Division of Water Resources (Table 2) (UDWRe, 2018).

Table 2. The 2015 Weber Basin community system water data by county and water use type (Base Case), (UDWRe, 2018).

County	Box Elder		Davis		Morgan		Summit		Weber		Basin Total	
Population	3,340		336,100		8,500		34,930		241,090		**623,960**	
Potable Water Use	ac-ft/year	GPCD	ac-ft/year	GPCD	ac-ft/year	GPCD	ac-ft/year	GPCD	ac-ft/year	GPCD	ac-ft/year	GPCD
Residential	527.3	141	28,539.3	76	893.3	94	5,895.7	151	18,642.6	69	**54,498.2**	**78**
Commercial	50.2	13	7,232.8	19	73.0	8	3,692.7	94	6,209.7	23	**17,258.3**	**25**
Institutional	21.1	6	3,232.5	9	40.5	4	401.4	10	1,976.3	7	**5,671.8**	**8**
Industrial	0.0	0	1,111.1	3	50.4	5	8.8	0	3,369.9	12	**4,540.2**	**6**
Total Potable[++]	**598.5**	**160**	**40,115.6**	**107**	**1,057.2**	**111**	**9,998.7**	**256**	**30,198.5**	**112**	**81,968.5**	**117**
Secondary Water Use	ac-ft/year	GPCD	ac-ft/year	GPCD	ac-ft/year	GPCD	ac-ft/year	GPCD	ac-ft/year	GPCD	ac-ft/year	GPCD
Residential	281.9	75	40,450.2	107	1,023.6	108	1,277.6	33	34,147.0	126	**77,180.2**	**110**
Commercial	0.0	0	242.8	1	7.3	1	0.0	0	1,046.7	4	**1,296.9**	**2**
Institutional	4.5	1	7,777.0	21	211.4	22	2,233.8	57	3,841.4	14	**14,068.1**	**20**
Industrial	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	**0.0**	**0**
Total Secondary[++]	**286.4**	77	**48,470.0**	129	**1,242.3**	130	**3,511.4**	90	**39,035.1**	145	**92,545.2**	**132**
Potable Reliable Supply	ac-ft/year		ac-ft/year		ac-ft/year		ac-ft/year		ac-ft/year		ac-ft/year	
Springs	309.2		200.4		772.5		3,630.7		4,260.1		**9,172.8**	
Wells	2,163.0		27,763.9		1,771.0		18,691.9		48,674.2		**99,064.1**	
Surface	0.0		29,520.8		3,000.0		14,893.9		40,094.2		**87,508.9**	
Total Reliable	**2,472.2**		**57,485.1**		**5,543.5**		**37,216.5**		**93,028.4**		**195,745.8**	

[++]Total GPCDs are county weighted

The total potable and total secondary gallon per-capita per day (GPCD) values are used to calculate the base demand using the year 2015 population data for each county (Table 3). We assumed Utah County demand would stay constant at 35 TAF/year because the supplied water (35.5 TAF) to Utah County is a contract amount and because Utah County is not within the Weber Basin.

Table 3. Potable and secondary water use by county with the calculated average annual demand (Base values for 2015 population).

Counties	Population	Potable Use (GPCD)	Secondary Use (GPCD)	Demand (AF/Year)
Utah	NA	NA	NA	35500
Box Elder	3340	160	77	887
Davis	336100	107	129	88849
Morgan	8500	111	130	2295
Summit	34930	256	90	13538
Weber	241090	112	145	69404
2015 Total	623960			210473

The Weber River Basin is divided into 20 service areas (Table 4). Using the GPCD data and population projections for each county within a service area, the average annual demand value was calculated. Table 4 shows the calculated municipal demand for each service area in the Weber Basin.

Table 4. The calculated annual municipal demand by service area, and county.

Weber Basin Service Areas	Service Areas by County	Demand (AF/Year)
SA1 Weber Provo Diversion Canal	Utah	35500
SA2 Oakley to Wanship	Summit	8701
SA3 Wanship to Echo	Summit	3002
SA4 Echo to Devils Slide	Morgan	419
SA5 Lost Creek	Morgan	293
SA6 Devils Slide to Stoddard	Morgan	1010
SA7 Park City	Summit	1835
SA8 East Canyon	Morgan	503
SA9 Stoddard To Gateway	Morgan	70
SA10 Gateway Canal	Davis	52306
SA11 Davis Weber Canal	Davis	36543
SA12 Weber Basin Project Ogden Valley	Weber	7027
SA13 Ogden Brigham and S Ogden Highline Canals	Weber	8050
SA14 Ogden River Below Pineview	Weber	6109
SA15 Slaterville	Weber	19245
SA16 Warren Canal	Weber	4982
SA17 Ogden Bay Bird Refuge	Weber	15863
SA18 GSL Minerals	Weber	3356
SA19 Gateway to Slaterville	Weber	4772
SA20 Additional WB Demand	Future	Future

To simulate the change in per-capita water usage, we use a percentage reduction to the per-capita water usage. The first percentage reduction is based on the 2025 water usage goals created for the state of Utah of a 25% reduction from 2015 values (UDWRe, n.d.). To reach the 25% reduction of per-capita water usage, a 10% reduction is implemented to potable water use and a 34% reduction is implemented to secondary water use. In addition to reach the 25% reduction, a 35% reduction of per-capita usage is also considered in this study. This 35% reduction is implemented with a 20% reduction to potable use and a 44% reduction to secondary use. This demand reduction only considers the demand from municipal water not water used for agriculture.

Evapotranspiration Impacts on Secondary Water Use

Projections of potential evapotranspiration (PET) throughout the WBWCD vary from 5-9% under moderate emissions and to 8-16% under high emissions (U of U Report). This study considers evapotranspiration by accounting for it in future municipal and industrial outdoor water use. To model the effect of evapotranspiration we use the values for projected change in secondary water usage. The University of Utah calculated the change in water usage for four Ogden area neighborhoods using a linear regression model (U of U report). The values they calculated are a 6% increase in secondary water usage from a low PET scenario and a 10% increase from a high PET scenario. These values of a 6% and a 10% increase in secondary water use are the values used for the PET scenarios in this study.

Agricultural-to-Urban Water Transfers

Total water usage is made up of two parts in the Weber Basin, municipal (urban usage), and agricultural usage (field irrigation or animal water). Agricultural lands in Utah today are being urbanized and the amount of irrigated agricultural land is decreasing (Li et al., 2019). The conversion of agricultural land to urban uses is implemented in this study by looking at the Utah Division of Water Rights Conversion Report from October 2018 (Greer, personal communication, 2019). This report provides the conversion of water rights from one type of use to another. Using Equation 1, we calculate a unitless Water Conversion Factor from the volume of Agricultural Irrigation Water (acre-feet) converted to Municipal Water (acre-feet).

$$Water\ Conversion\ Factor = \frac{Municipal\ Water}{Agricultural\ Irrigation\ Water} \quad \textbf{(Equation 1)}$$

Considering the 721 change applications for the Weber Basin, water conversion factors vary from 12.8% to 100% with bottom quartile and mean values of 63% and 71%. A conversion factor of 63% means 1 acre-foot of agricultural water usage translates into 0.63 acre-feet of municipal water usage. These values only consider the conversion of agricultural irrigation water to municipal use and do not account for the many other types of water usage such as industrial or agricultural stock water. Therefore, this data may not fully reflect agriculture to urban transfers occurring in the Weber basin; but are the best available data to represent agricultural conversions.

We use scenarios of 0% (base case), 63%, and 71% conversions. The analysis method used assumes that all increased municipal water use comes from retired agricultural land. First, we calculated the change in municipal water use from 2015 to 2070 and 2150. Second, we calculated the change to agricultural irrigation water (from 2015 to 2070 and from 2015 to 2150) by dividing the change in municipal water by the agricultural conversion factor (0%, 63%, and 71%). Third, we calculate the 2070 and 2150 amount of agricultural usage by subtracting the 2015 agricultural usage by the 2070 and 2150 change in agricultural usage. Lastly, we add the future agricultural usage for 2070 and 2150 to the municipal usage. The agriculture to municipal water usage was done on a service area basis. The change to from agriculture water usage to municipal water usage is a rough estimate for this study and should help provide a broader range of water usage demand changes to select from.

Selecting Demand Scenarios

We combined the three population growth scenarios, six per capita use values, three scenarios of potential evapotranspiration, and three scenarios of agricultural to urban conversions into 63 demand scenarios. These combinations of demand subfactors suggest a range of future annual basin-wide demands from 360 TAF to 850 TAF per year (Figure 7, each connected set of blue line segments represents an annual demand scenario; the line segments cross the grey vertical axes at the value for the demand factor; light to dark blue lines indicate increasing total annual demand and are also indicated on the right-most vertical annual demand axis). This range contrasts with the current demand of 550 TAF per year (Figure 7, red line). An interactive version of the plot found at http://rpubs.com/Jeveritt/612064 allows the users to filter scenarios and see the effects of subsets of factors on water use.

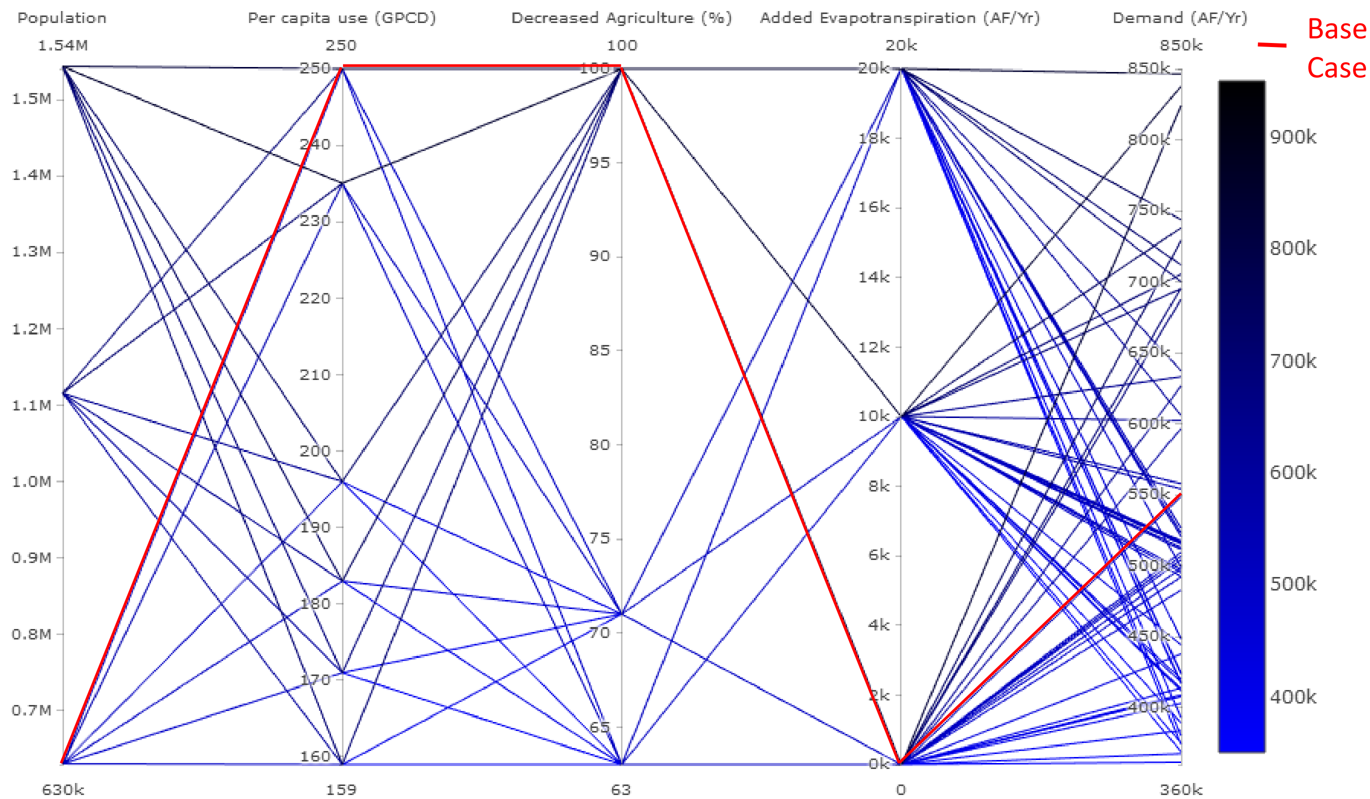

Figure 7. Parallel plot of demand subfactors shows the effects each subfactor has on the overall demand. Total annual demand scenarios are shown on the right axis. Light blue to dark blue line color also shows the increase in total demand (color bar legend). The 2015 base case for demand is shown as a red line. An interactive version of the plot is at: http://rpubs.com/Jeveritt/612064.

Out of the 63 different demand combinations, we selected 6 demand scenarios as the lower and upper bounds for each population projection year (Figure 8, large, red circles). These selected demands also span the range of all demand combinations (Figure 8, small, light blue circles).

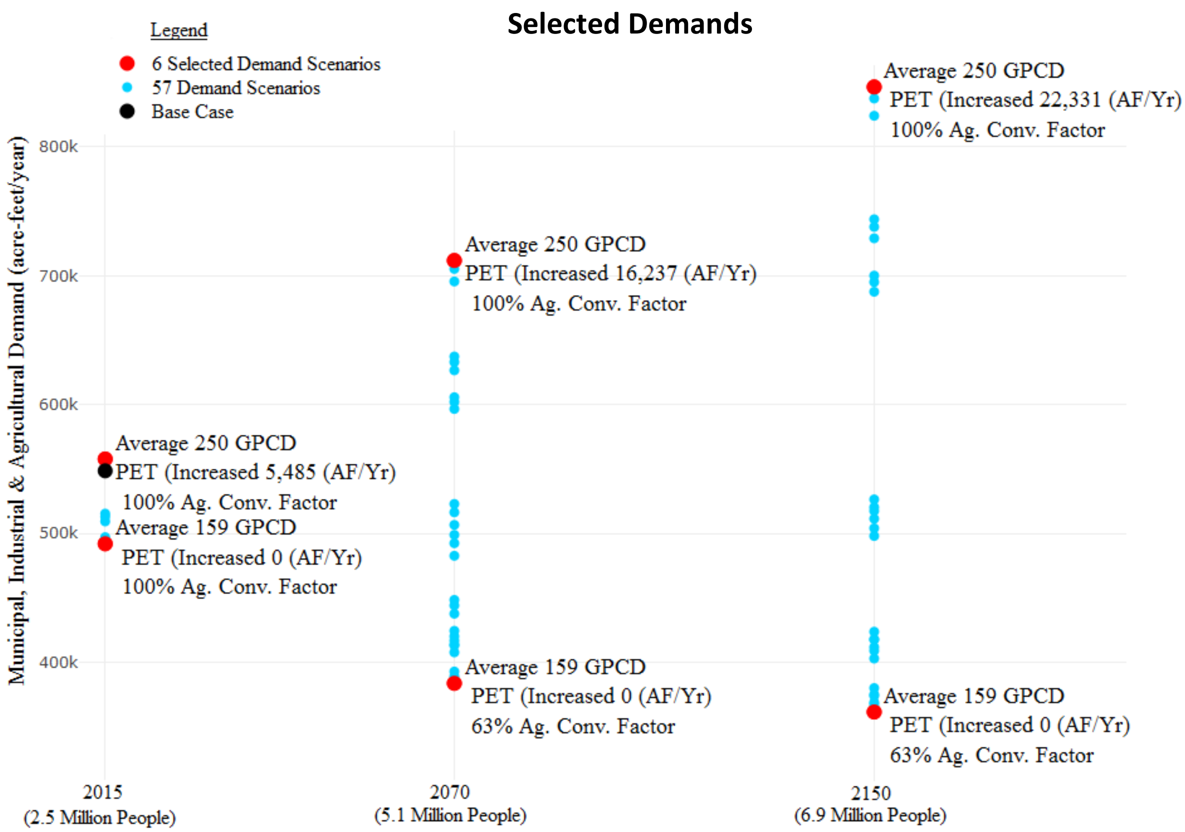

Figure 8. Total annual averaged demands by forecast year show all 63 demand scenarios (small light blue circles), 6 selected demand scenarios (larger red circles), and base case annual demand (black circle).

iii. Reservoir Sediment Buildup

There are two types of reservoir sedimentation, long-term and short-term. Long-term sedimentation is the accumulation of sediment through gradual erosion and other processes over long periods of time. The calculated average for Utah's reservoirs is considered to be 0.2% of total capacity lost per year. Values of 0.1%, 0.2%, and 0.1% are reported for Echo, Wanship, and East Canyon Reservoirs respectively in the WBWCD (UDWRe, 2010). Short-term sedimentation is the quick accumulation of sediment over a short period of time such as from a flashflood, floods after wildfires, or a rockslide during one or two events (Belmont and Murphy, 2019). Short-term events can mobilize 5,000 to 10,000 acre-feet of material in a single event and completely fill in a small reservoir such as Smith and Morehouse or Causey (Belmont and Murphy, personal communication, 2019). Belmont and Murphy suggest that for larger reservoirs in the region, it was plausible that up to 10% of the reservoir storage could be lost due to either long-term or short-term sedimentation (Belmont and Murphy, personal communication, 2019). To find a range of changes to total reservoir storage in the Weber Basin due to sedimentation, Weber Basin reservoirs were separated into three reservoir sizes (Table 5). The time to fill 50% of active reservoir volume with sedimentation rates of 0.1% to 0.2% is 500 years and 250 years respectively (UDWR, 2010). Because the variability of sedimentation yields into reservoirs is extremely large, true sedimentation is based on the individual characteristics of each watershed and reservoir (Moody and Martin, 2001, 2009). Absent an individual sediment flow study for each watershed, no precise values for the effect on the WBWCD's system can be estimated.

Table 5. Weber Basin reservoir storage capacity and storage lost due to two sedimentation scenarios (acre-feet).

Weber Basin Reservoir Storages				
No.	**Name**	**Max Storage**	**Reservoir Storage Lost to Sedimentation**	
			10%	30%
Res 1	Smith and Morehouse	8350	835	2505
Res 2	Rockport	61260	6126	18378
Res 3	Echo	73940	7394	22182
Res 4	Lost Creek	22510	22510	6753
Res 5	East Canyon	51200	5120	15360
Res 6	Causey	7870	787	2361
Res 7	Pineview	110150	11015	33045
Res 8	Willard Bay	247302	24730	74191

Three scenarios of reservoir storage loss are used in this study: 0% (no change, assumes no loss), 10%, and 30%. For this study, the storage reduction due to. The selected changes to reservoir storage (0%, 10% and 30%), provide a range of possible scenarios for reservoir storage lost due to both long-term sedimentation and short-term sedimentation. In RiverWare modeling of each sedimentation scenario, all reservoirs are assumed to begin the thirty-year simulation period with the specified percentage of storage filled (sedimentation is implemented at the beginning of the model runs not throughout time).

iv. Evaporation Rate at Willard Bay

Three different reservoir evaporation rates for Willard Bay Reservoir were used in this study to calculate the reduction of reservoir storage (Table 6). Willard Bay was used because Willard Bay is the biggest reservoir with the biggest surface area in the Weber Basin.

Table 6. Evaporation rate scenarios for Willard Bay shown as a feet per year value.

Scenario	Data Source	Evaporation Rate (ft/year)
Base	UDWRe RiverWare Model	**3.2**
Historical	University of Utah Study (1995 to 2005)	**3.7**
Late 21st Century	University of Utah Study (2085 to 2095)	**4.0**

The base rate of 3.2 feet per year was used in the UDWRe RiverWare model for the Weber Basin and derived from an earlier Fortran version of the model by the UDWRe (UDWRE, unpublished, 2018). The origins of this evaporation rate are unknown but may derive from evaporation pan coefficients. Considering the Willard Bay at full capacity, the UDWRe historical evaporation rate of 3.2 feet per year translates to approximately 31 TAF/year of evaporated volume. In contrast, the U of U used the Weather Research and Forecasting (WRF) model for the years 1995 to 2005 to estimate a historical evaporation rate of 3.7 feet per year which translates to 37 TAF/year evaporation with Willard Bay at full capacity (U of U, 2019). The U of U also used the WRF model with Representative Concentration Pathway (RCP) 6.0 to estimate a late 21st century (2085 to 2095) reservoir evaporation rate of 4.0 feet per year of 39 TAF per year which represents the high estimate of evaporation projections for this study.

We apply the three Willard Bay evaporation scenarios to the other reservoirs in the basin by scaling up the base case monthly evaporation rate for each other reservoir by the same percentage increase. Reservoir evaporation for all reservoirs is zero during winter months (November to February) to represent ice on the reservoirs. The layer of ice on top of the reservoirs creates a barrier, which during winter months prevents evaporation from the reservoir surface and also prevents precipitation (snow or rain) from reaching the reservoir water body.

v. RiverWare Modeling

RiverWare is a water system modeling program created by the Center for Advanced Decision Support for Water and Environmental Systems (CADSWES) at the University of Colorado, Boulder (Zargona et al., 2001). The Utah Division of Water Resources (UDWRe) created a RiverWare model for the Weber River Basin from a prior custom-coded Fortran model (UDWRe, unpublished, 2018) which has 9 reservoir objects, 19 inflow objects, 20 demand/service areas, and 43 rules that are organized into 7 groups and a set of finalization rules. The rule groups specify the order water (i) is drawn from reservoirs and delivered to service areas, and (ii) stored in protected reservoir pools. Simplified, the model balances inflows and reservoir storage on a monthly basis. Water starts at an inflow objects and moves through the water system based on the demand and storage rules set up by the UDWRe.

The model is used to analyze the impact of inputs such as inflows, demands, reservoir capacity, and reservoir evaporation over a 30-year, monthly simulation period. The model outputs reservoir storage for each reservoir, water deliveries to each service area, and shortages (the difference between a service area's delivery request and actual delivery).

We used the CADSWES RiverSMART plugin tool to automatically set up and run a large number of model runs comprised of various combinations of inflow, demand, reservoir evaporation, and reservoir sedimentation scenarios. We set up the RiverWare model and RiverSMART plugin tool as follows.

<u>RiverWare Setup Steps:</u>

1- Setup the Data Management Interface (DMI) configuration to define inputs for stream flow, demands, reservoir sedimentation, and reservoir evaporation (see DMI setup section)
2- Setup the Multiple Run Module (MRM) to define different scenarios for stream flow, demands, and reservoir inputs (See MRM setup section)
3- Create a total storage slot in the Other Data, data object. This slot sums storage for each reservoir object

DMI Setup Steps:

1- Create a new Excel DMI for the hydrology, demand, sedimentation, and reservoir evaporation scenarios. (See the RiverWare documentation), (CADSWES, 2019). This DMI points to the Excel files that have the data values for each scenario.

2- Open the DMI configuration check and confirm warnings

3- To run the RiverSmart plugin, the DMI configuration must be formatted exactly as shown in Figure 9.

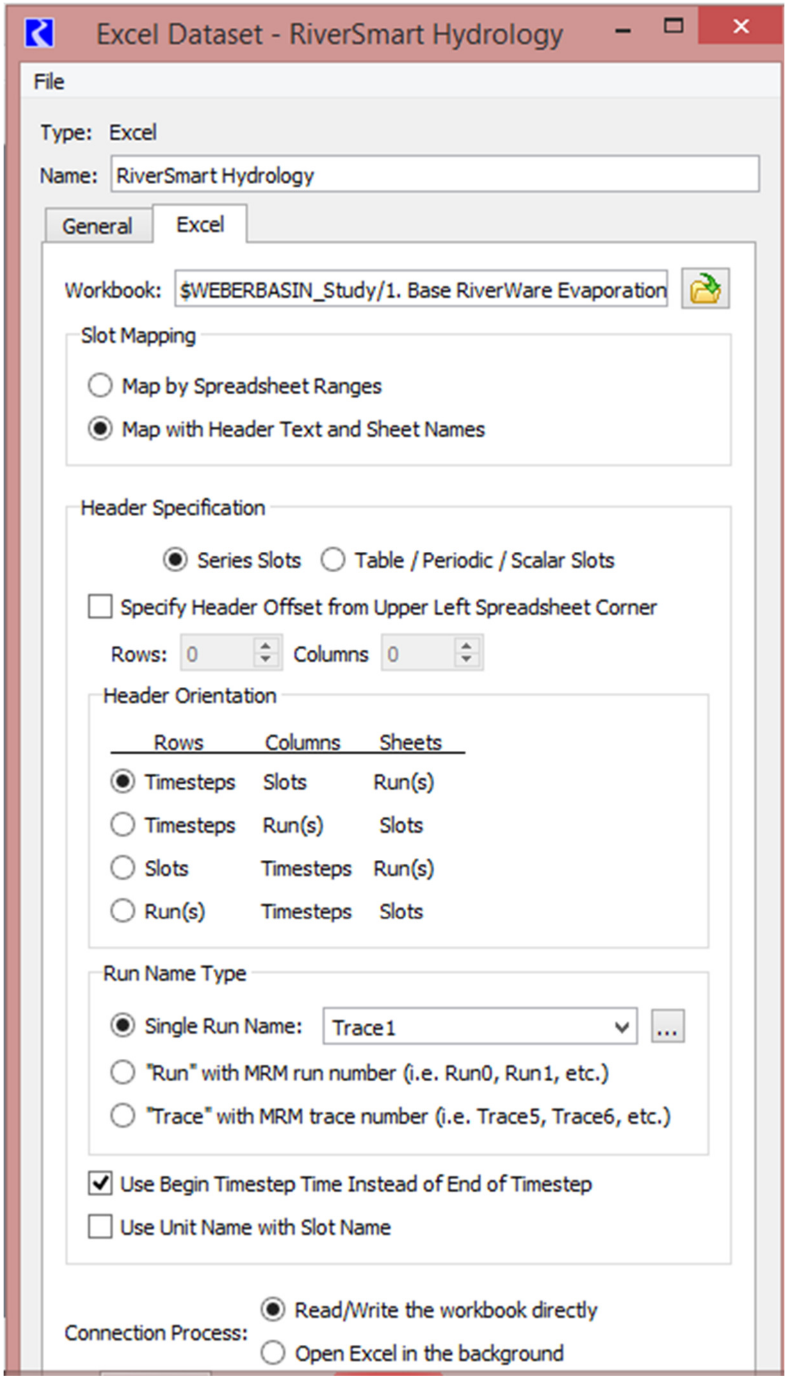

Figure 9. Screenshot of the Data Management Interface (DMI) configuration that shows the required settings to run RiverWare and RiverSmart model runs.

The inflow data is set up for each of the 19 inflow gage objects in an Excel file and read into RiverWare using the RiverWare DMI tool. The DMI tool reads in the Excel file and saves the data in RiverWare slots. There are six Excel sheets read in, one for each of the selected factor scenarios. These selected data sheets are called traces in RiverWare (see Table 7).

Table 7. RiverWare inflow traces and their correcting inflow scenario with average June 1st values.

RiverWare Trace Notation	Inflow Scenarios Run Name	Average June 1st Inflows (AF/Yr)	Why Selected
Trace 1	Western Water Assessment (Hot Dry Climate Scenario)	796,000	Worst case scenario – Intensity drought
Trace 2	1940 to 1970 (Historical Inflows)	954,700	Historical inflows – Base case
Trace 3	1930 to 1960 (Historical Inflows)	880,200	Historically known droughts
Trace 4	1610 to 1640 (Paleo-Flows)	925,000	Intensity droughts
Trace 5	1520 to 1550 (Paleo-Flows)	971,500	Duration droughts
Trace 6	1570 to 1600 (Paleo-Flows)	852,000	Duration and intensity droughts

The DMI tool reads six Excel data sheets of the annual demand values (See Table 8). Each Excel sheet has the annual demands for 20 service areas in the Weber Basin.

Table 8. Selected average annual demand input run scenarios (traces).

RiverWare Trace Notation	Population Simulation Years	Average Annual Demand Scenarios Values (AF/Yr)	Why Selected
Trace 1	2015	492,000	Lower bound of 2015 scenarios
Trace 2	2015	557,800	Upper bound of 2015 scenarios
Trace 3	2070	384,000	Lower bound of 2070 scenarios
Trace 4	2070	711,800	Upper bound of 2070 scenarios
Trace 5	2150	361,000	Lower bound of 2150 scenarios
Trace 6	2150	846,500	Upper bound of 2150 scenarios

The annual demand values are assumed to remain the same for the full 30-year RiverWare simulation time. There is no methodology in the RiverWare model to implement varied annual reservoir sedimentation. Thus, RiverWare reads in an Excel file that designates Trace 1 runs as the 0% change, Trace 2 runs as 10% change, and Trace 3 runs as 30% change to maximum reservoir storages. Lastly, evaporation for this study is considered by changing the evaporation rate for each of the reservoir objects in RiverWare. Each reservoir object receives values interpolated outside of RiverWare and input into the model using the evaporation DMI. The three evaporation scenarios are input in three separate RiverWare models.

To run more than one scenario, RiverWare has a multirun function. The RiverWare multirun function is setup as follows.

Multirun Setup Steps:

1- Create a Multi Run Module (MRM)
2- Set the mode to concurrent
3- Check input DMIs, Traces
4- Check generate comma-separated values (CSV) file and create the output files wanted on the outputs tab.
5- Set the run parameters to run from for a 30-year period. Oct. 2459 to Sept. 2489 were used because Oct. 2459 was the previous start period of the UDWRe's Model runs. RiverWare only allows simulation for 1900 onwards. The year 2459 was used to accommodate paleoclimate periods that date back to 1400 AD.
6- Select the RiverWare ruleset
7- Set the first trace to 1 and the number of traces to 1. The trace notation denotes each scenario.

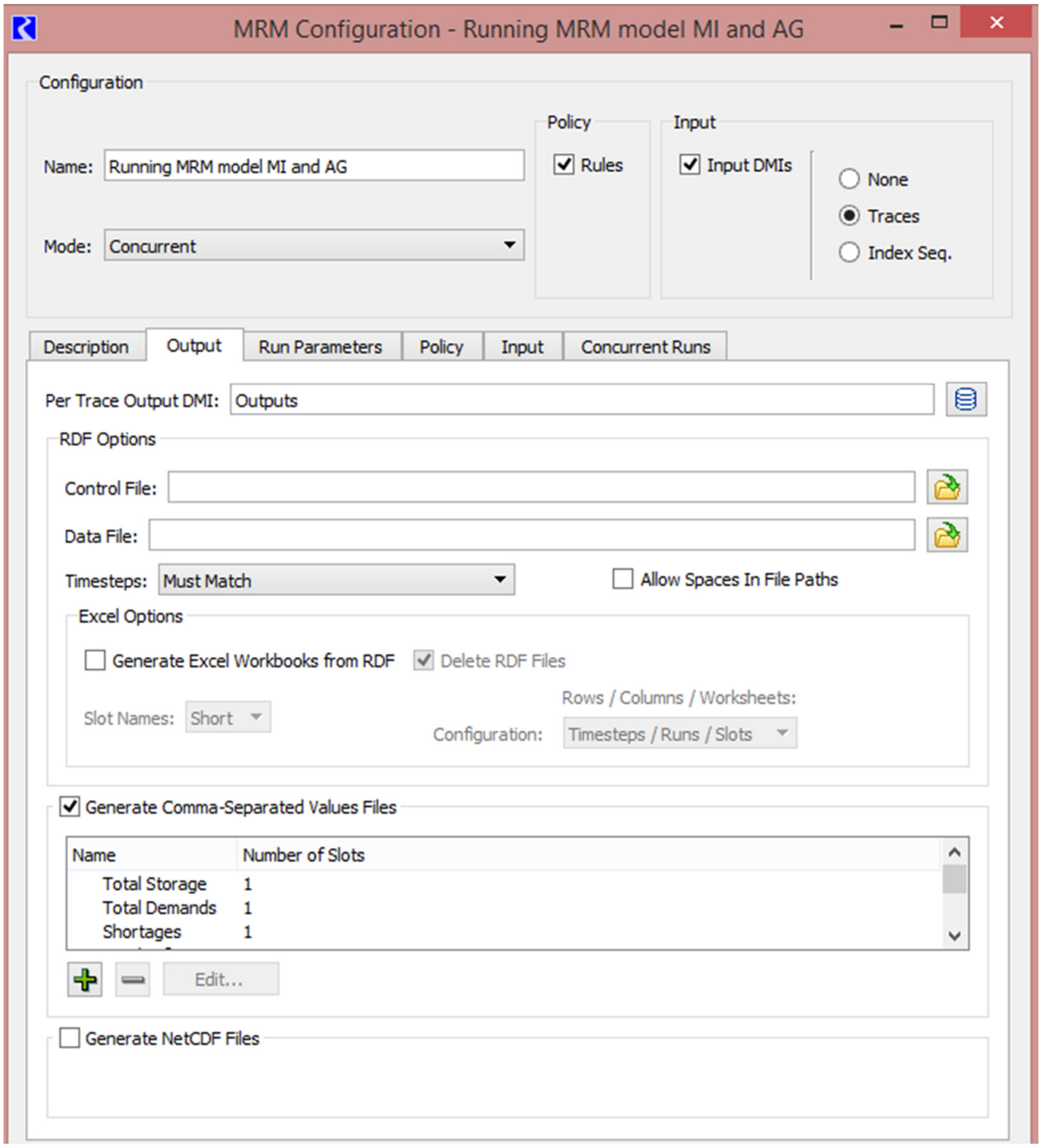

Figure 10. Screenshot of the Multi Run Module (MRM) configuration that shows set up for correct RiverWare and RiverSmart model runs.

To combine traces for the hydrology, demand, and sedimentation inputs, the RiverSmart plugin was used. RiverSmart additionally allows combinations of RiverWare inputs, rules, and the MRM.

<u>RiverSmart Setup Steps:</u>

1- Create RiverSmart objects: the RiverWare program, RiverWare model, RiverWare policy, RiverWare MRM, and the DMI sequence.

2- Setup the RiverWare program, RiverWare model, RiverWare ruleset, and RiverWare MRM, using the RiverSmart Documentation (RiverSmart, 2019).

3- Setup the DMI sequence configuration

    a. Select the name of the DMI

    b. Select the DMI as Direct Connect

    c. Set the DMI sequence 1 through 6, for hydrology, 1 to 6 for demands, and 1 through 3 for sedimentation

    d. Add the Excel files to read, with the worksheet sequence set as Trace

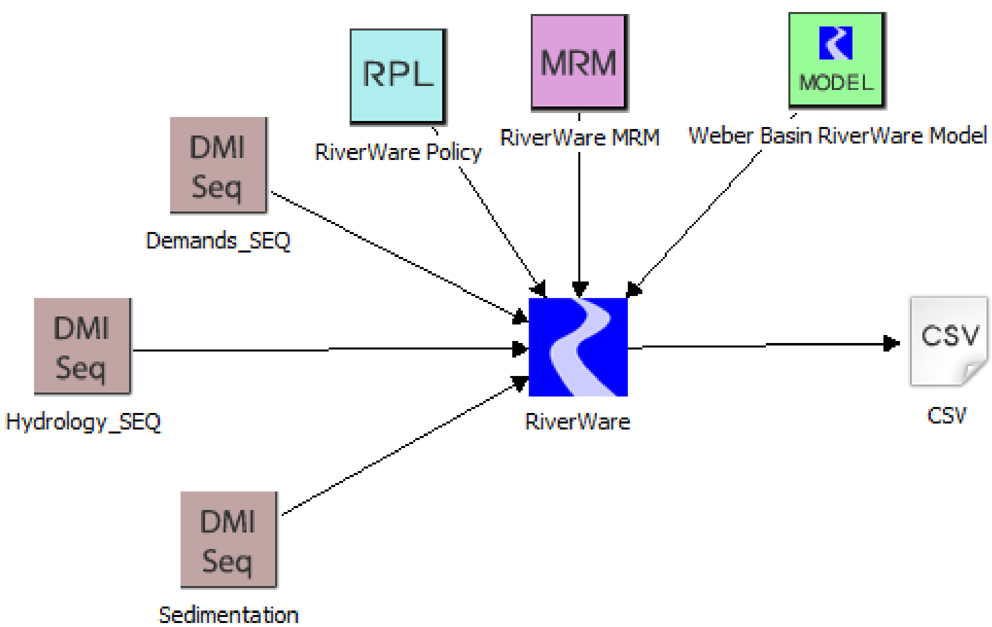

Figure 11. Snapshot of set up of RiverSmart that shows the input data objects used.

The RiverSmart plugin is used to run the combination of hydrology, demand, and reservoir sedimentation inputs in RiverWare (Figure 11, brown DMI Seq boxes). The RiverSMART plug in inputs the Hydrology, Demand and Sedimentation traces to the RiverWare model. The different evaporation rates for the reservoirs are implemented using three separate RiverWare and RiverSmart models.

vi. RiverWare Runs

This study uses the RiverWare multirun function in combination with the RiverWare plugin called RiverSmart to automatically run 324 combinations of 6 inflow, 6 demand, 3 reservoir sedimentation, and 3 Willard Bay evaporation scenarios (6x6x3x3 = 324 runs). A run is a selected combination of an inflow, demand, reservoir sedimentation, and reservoir evaporation scenario and their associated values. For example, the first run uses inflows of 796 TAF per year from the Hot Dry Scenario, the 492 TAF per year average annual demands, 0% reservoir sedimentation, and 3.2 ft/year in evaporation of Willard Bay. The three reservoir evaporation scenarios were setup as separate RiverWare models, so for each model (reservoir evaporation value), there were 108 combinations of 6 inflow, 6 demand, 3 reservoir sedimentation, and one reservoir evaporation scenario.

The outputs from RiverWare model runs are monthly total basin reservoir storage and total basin delivery shortages. Total basin storage is the sum of all the reservoir storage in the Weber River Basin reservoirs. Total basin delivery shortage is the sum of the delivery shortages of the WBWCD demands.

RiverSmart generates model outputs as a comma separate value (csv) file in a separate folder for the run and reservoir evaporation rate model used. For example, in the *Base RiverWare Evaporation* folder, *Scenario* subfolder, the *Trace1,Trace1,Trace1* subfolder contain results for the first run for the Base RiverWare Evaporation model. Here *Trace1,Trace1,Trace1* indicates 362 TAF average annual demand (the first demand scenario), the 1520 to 1550 (Paleo-Flow) monthly inflows (first inflow scenario), and 0% change to reservoir storage due to sedimentation (first sedimentation scenario). The RiverWare model then outputs the shortage and storage levels for each month into a csv file into the *Trace1,Trace1,Trace1* folder. R scripts (R a free statistical analysis software) are then used to gather the output files from the 324 separate folders, organize, clean, sort, filter, analyze, and show results as time series and contour plots.

vii. Performance metrics

The performance metrics used to evaluate RiverWare results are a storage metric and a shortage metric. First, we use the storage level metrics to quantify the fraction of years (reliability) the June 1st total reservoir storage meets moderate, severe, and extreme storage levels (380, 340, and 280 TAF) defined by the WBWCD in their drought contingency plan (WBWCD, 2019) (Figure 12). These targets were confirmed in an early project meeting with staff.

	PROJECTED JUNE 1ST TOTAL BASIN STORAGE		AVERAGE NUMBER OF YEARS BETWEEN EVENTS	
Drought Level	Acre-Feet	% of Total Basin Storage Capacity	1430 - 1970	1971 - 2017
Moderate	340,000 to 380,000	64% - 72%	36	7
Severe	280,000 to 340,000	53% - 64%	60	No Events
Extreme	Less than 280,000	Less Than 53%	135	No Events

Figure 12. Description of the storage metric levels, and their associated storage characteristics, used for this study. From the Weber Basin Water Conservancy District Drought Contingency Report, (WBWCD 2019).

June 1st values are used because June 1st is the end of the snowmelt runoff season and beginning of the demand season when storage typically peaks for the year. We calculate reliability as the number of years where June 1st total reservoir storage is above the drought level thresholds divided by the total number of years in the simulation period (30 years). (See Equation 2).

$$\text{Reliability} = \frac{\textit{Number of times June 1st Storages are above the Threshold}}{\textit{Number of years}} \qquad \textbf{Equation 2}$$

Second, the UDWRe RiverWare model calculates a delivery shortage based on the difference between the amount of demand called for by each service area and the amount of water available. The thresholds for the UDWRe shortage calculation are based on the previous Weber Basin Fortran model.

D. Results

System vulnerability is defined by the frequency of total reservoir storage falling below the storage level targets if and when there are water usage shortages.

i. Reservoir Storage Levels

We use contour plots to show how storage reliability changes in response to different combinations of inflow (y-axis) and demands (x-axis) (Figure 13). For example, there are 36 inflow-demand combinations shown as black circles that represent RiverWare model runs. The blue square shows the historical (base) values of approximately 550 TAF/year average annual demand and approximately 960 TAF average inflow. Axis labels on the top and right label the demand and inflow scenarios. For Figure 13, the reservoir sedimentation scenario is 0%, and the Willard Bay evaporation rate scenarios used is the RiverWare base case 3.2 feet/year.

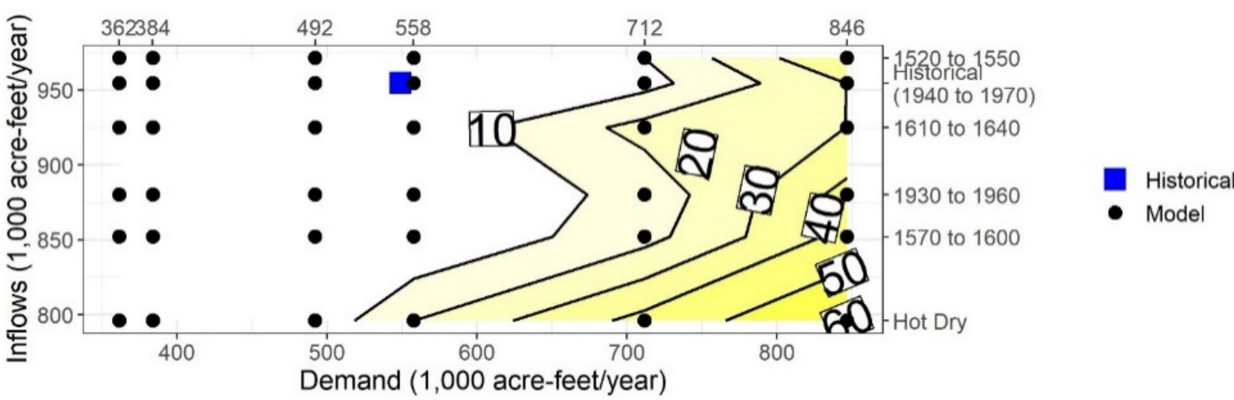

Figure 13. Percent of time (contours) Weber Basin June 1st system storage will fall below the moderate drought criteria of 380,000 acre-feet total system storage for different demands (x-axis) and inflows (y-axis) with 0% reservoir sedimentation and 3.2 feet/year reservoir evaporation. Top and right axis label the demand and inflow scenarios.

There is no yellow contour on or near the historical blue marker of 550 TAF per year of demand and 960 TAF per year of inflow, meaning that at these demands, inflows, 0% sedimentation, and 3.2 feet/year evaporation levels, June 1st total reservoir storage *always* stays above 380 TAF for each year of the 30-year simulation period.

However, move right from the historical point and increase annual demands by ~160,000 acre-feet per year. Additionally, move down and decrease inflows 80,000 acre-feet per year by to 880 TAF on the y-axis. The point with 712 TAF per year of demand and 880 TAF per year of inflow (scenario of 1930-1960 inflows) is located between the 10 and 20 percent contour lines. For these changes in inflows and demands, the system will see total June 1 reservoir storage fall below the 380 TAF level in 10-20% of years.

Figure 13 shows that WBWCD storage is vulnerable to increases in demand of 100 TAF per year or reductions in inflow of 100 TAF per year relative to historical conditions. Further, when demands exceed approximately 700 TAF per year, total June 1st reservoir storage will always fall below the 380-TAF threshold at some point during the 30-year simulation period no matter what inflows are. Additionally, the frequency of June 1st total reservoir storage falling below the 380,000 acre-feet threshold will increase as demands increase and inflows decrease.

Figure 14 compares storage reliability for the three different reservoir storage targets (columns of subplots) and three different sedimentation rates (rows of subplots). To give context, the top left subplot is Figure 13. The contours of storage reliability in each column of Figure 14 subplots interpolate a fraction of years the storage target will not be met among the 108 runs of varied demands, inflows, and sedimentation rates. In all subplots, the reservoir evaporation rate for Willard Bay is still 3.2 feet/year.

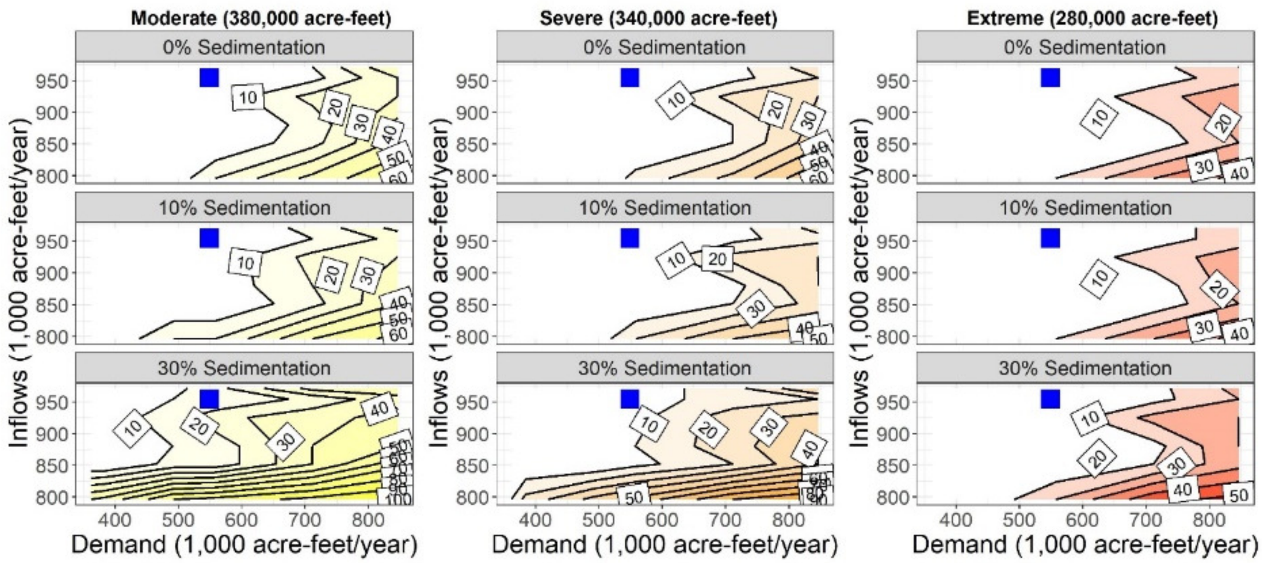

Figure 14. Storage reliability expressed as percent of years (contours) Weber Basin June 1st system storage does not meet different reservoir storage targets of 380,000, 340,000, and 280,000 acre-feet (yellow, orange, and red columns) for different demands (x-axis), inflows (y-axis), and reservoir sedimentation rates of 0%, 10%, and 30% (rows). The historical blue marker showing the annual average demand of 550 TAF and the average annual inflow of 960 TAF.

Figure 14 shows that the June 1st storage is only mildly sensitive to a 10% storage loss from sedimentation. However, at 30% storage loss, storage targets are violated for many more combinations of inflow and demand. Figure 14 also shows that a reduction to the inflow leads to more violations of the storage targets than an increase in demand of the same annual volume, especially when inflows fall below 850 TAF. For the 30% sedimentation scenario and inflows below 850 TAF per year, total reservoir storage will fall below the 380 TAF threshold in 10% or more of simulated years regardless of the annual demand. For inflows of 800 TAF/year such as estimated for the Hot-Dry future climate scenario, total reservoir storage will fall below the 380 TAF threshold in 50% or more of simulated years regardless of the annual demand. In contrast, a 50 TAF increase in demand to 600 TAF/year will only see total reservoir storage fall below the 380 TAF threshold in 20% or more of simulated years.

Figure 15 compares total storage to inflows for three reservoir sedimentation rates (0%, 10%, 30%, blue lines) and three scenarios of increasing demands/declining flows (upper to lower subplots). In subplot A, Model Years 14 and 19 mark the beginning of 4 years of sustained low inflows. In Model Year 19, reservoir storage immediately falls below the extreme reservoir level of 280 TAF for the scenario with a reservoir sedimentation rate of 30%. But storage also recovers to 380 TAF that same year. Reservoir storage for Model Years 20-22 falls below the 280 TAF extreme level for all reservoir sedimentation rates during the summer of each year. But storage also rebounds to at least the moderate target of 380 TAF every year. In Subplot B, one critical 6-year drought occurs in Model Years 1-6. A second 7-year drought occurs in Model Years 24-30. The second drought has one intermediate year of increased flow (Model Year 28). At the end of the first two years of the first drought, reservoir storage falls to about 120 TAF with 0% reservoir sedimentation and near 0 TAF for the 30% reservoir sedimentation scenario. Storage for all the sedimentation scenarios rebound in the same year to at least 280 TAF. In subsequent years of the drought, minimum storage for the year is consistently below 100 TAF and near 25 TAF in Model Year 5 for each reservoir sedimentation scenario. By Model Year 5, storages are the same regardless of the reservoir sedimentation rate. This pattern of the same reservoir storage for the different reservoir sedimentation rates persists into Model Years 7 and 8 – the first two years of the post-drought recovery. The second drought, reservoir storage falls below the 280 TAF extreme target then recovers to 320 TAF or higher. Model Year 30 shows very low storages that are comparable to Model Years 2 and 3. Subplot C has the highest demands and lowest inflows and shows that the total system storage goes below the extreme storage level of 280 TAF every year regardless of the sedimentation rate. Extreme droughts in Model Years 8-12 and 20-24 with sustained inflows of less than 200 TAF per year show reservoir storage stays below the extreme level of 280 TAF for most of each year and storage is the same regardless of the reservoir sedimentation rate. For reference, this last high demand-low supply scenario appears in the bottom right of Figure 14 subplots.

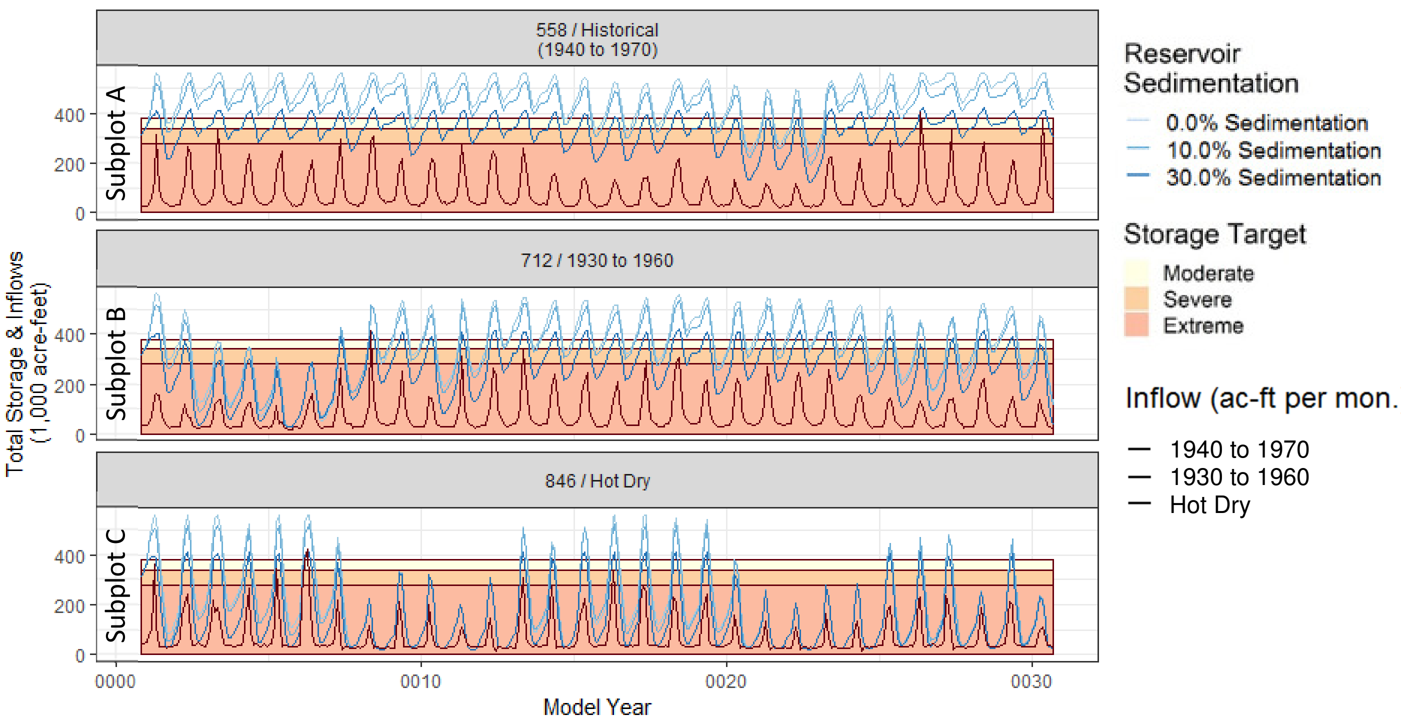

Figure 15. Comparison of inflows (black lines) to total reservoir storage for different sedimentation rates (blue lines) and scenarios of increasing demand and decrease inflows (subplots). Yellow, orange, and red shaded regions show the moderate, severe, and extreme reservoir storage targets.

ii. Shortages

Plots of time series of total shortages to all service areas for the three reservoir sedimentation rates and demand/inflow scenarios show shortages are largely the same across the three sedimentation rate scenarios (Figure 16). As expected, shortages increase as demand increases and inflows decrease. In the largest 846 TAF/year demand/Hot-Dry scenario, shortages over 100 TAF/month are seen in many of the drought years. Contour plots of the mean annual shortages for different demand and inflow scenarios show annual demand would have to increase 150 TAF/year to incur average annual shortage of 40 TAF (Figure 17). However, demand would only need to increase by 25 TAF/year to incur a shortage of 40 TAF in at least one of the 30 modeled years. The near vertical slopes of the contour lines show annual shortages are much more sensitive to demand than inflows. Additionally, Figure 17 shows that shortages are nearly insensitive to reservoir sedimentation.

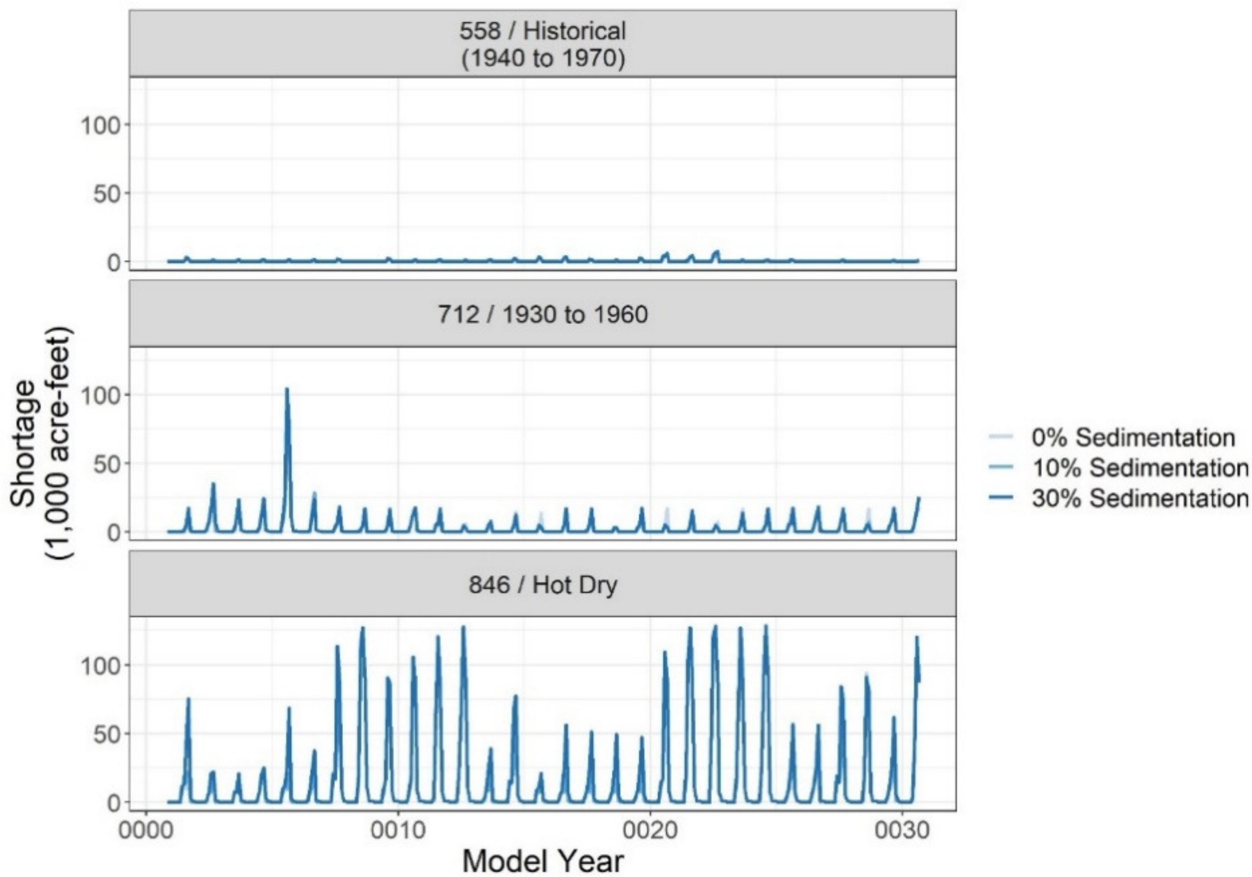

Figure 16. Time series of total shortage to service areas for different sedimentation rates (blue lines) and scenarios of demand/inflows (panels).

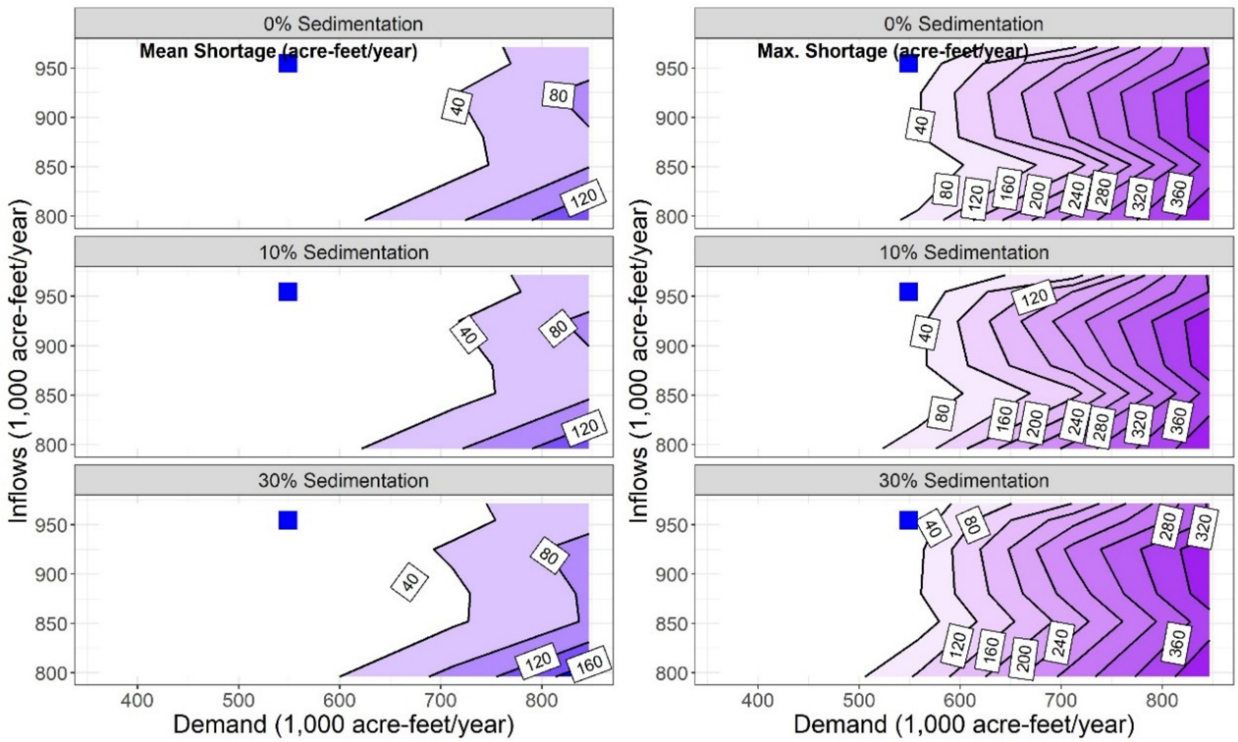

Figure 17. Mean and maximum annual shortage in acre-feet to service areas (contours) for each sedimentation scenario (row), annual demand (x-axis), and inflows (axis). Shortages increase with increased demand and reduce inflows.

iii. Evaporation

Contour plots show the percent of years that the June 1st reservoir storage level is below the moderate threshold storage level of 380 TAF for different combinations of inflow, demand, the base case reservoir sedimentation rate, and base case, historical, and late century reservoir evaporation rates of 3.2, 3.7, and 4.0 feet per year (Figure 19). To give context, subplot A is Figure 13. The three subplots for the three reservoir evaporation rates are very similar and show that the Weber River water system is not very sensitive to the evaporation rate. Because the system is not sensitive to evaporation considering 0% sedimentation, the evaporation scenarios considering 10% and 30% reservoir volumes lost due to sedimentation are not shown.

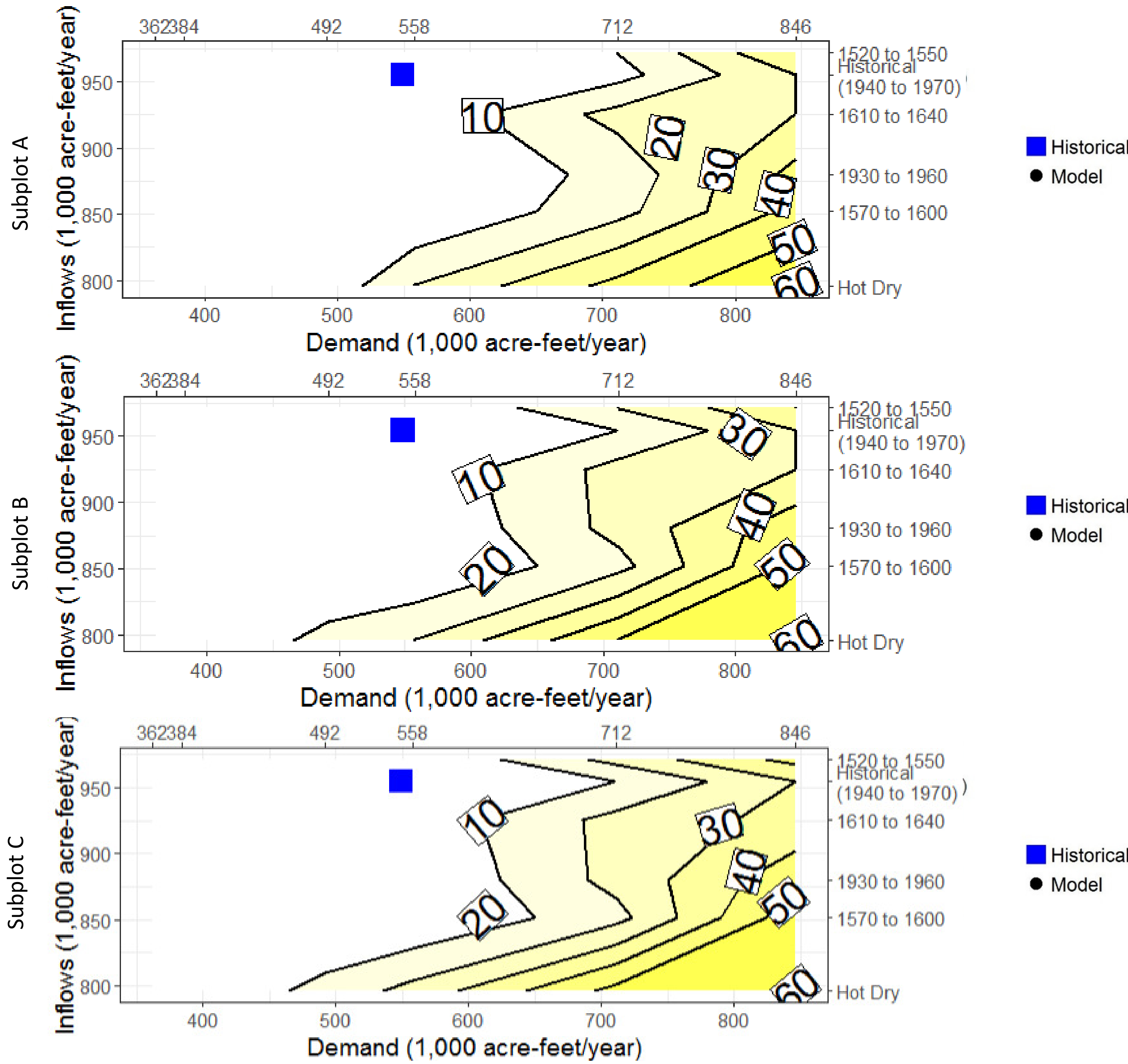

Figure 19. Percent of years (contours) Weber Basin June 1st system storage falls below 380,000 acre-feet for evaporation rates of 3.2 (Subplot A), 3.7 (Subplot B), and 4.0 feet/year (Subplot C) at different annual demands (x axis), inflows (y-axis) and a base case reservoir sedimentation rate of 0%.

E. Conclusion

Water system managers want to know the future conditions to which their water system is vulnerable. Here we use a bottom-up vulnerability analysis to show the combinations of uncertain future demands, inflows, reservoir sedimentation rates, and reservoir evaporation rates that the WBWCD water system will not be able to deliver requested water or sustain reservoir storage above target levels. Six 30-year inflow scenarios included 3 paleo droughts, two droughts from the recent historical record, and an extreme hot-dry future climate scenario for the basin developed by the Western Water Assessment. 324 runs representing different combinations of the uncertain future factors (inflows, demand, sedimentation, evaporation) were then simulated in the UDWRe RiverWare model for the Weber basin using the RiverSmart plugin. Total reservoir storage levels and total shortages were outputted and compiled for each run.

Visualization of the results show several areas where the system can tolerate changes in conditions. First, the Weber Basin system can presently sustain June 1st total reservoir storage at or above 380 TAF across all years for existing demands of up to 600 TAF/year and inflows at or above 825 TAF/year. Under these conditions, there are no shortages. Second, reservoir storage is only mildly sensitive to 10% reservoir storage lost due to sedimentation. Third, system demands would need to increase by 150 TAF/year before average annual shortages would rise to 40 TAF/year. And fourth, reservoir storage is only mildly sensitive to increases of reservoir evaporation rates up to 4.0 feet/year.

The results also identify several key system vulnerabilities. First, if demand increases by a 100 TAF per year or inflows decrease by 100 TAF per year relative to historical conditions, managers will see June 1st reservoir storage fall below the moderate storage threshold of 380,000 acre-feet in at least 10% of years. The percent of years storage falls below 280 TAF will increase to 50% if demands increase to 850 TAF/year. Second, sustained low inflows of 3 years and longer will drop the June 1 reservoir level into the extreme storage level below 280 TAF regardless of the reservoir sedimentation rate. For several simulated drought events, June 1 reservoir storage will fall below 100 TAF and persist for multiple years. In the later years of these drought events, reservoir storage will persist below the 280 TAF extreme target for the entire year. Third, as reservoir sedimentation rates rise, reservoir storage is more sensitive to inflows than to demands. Fourth, demand need only increase by 25 TAF/year over historical conditions to see at least one year with an annual shortage of at least 40 TAF/year.

There are several study limitations. We selected a limited number of model inflow, demand, sedimentation rate, and evaporation rates that do not necessarily span all possible future values for these inputs. For example, there could be even more extreme, low inflows such as with the University of Utah LOCA scenarios of low precipitation and moderate or high emissions. If simulated, these LOCA inflow scenarios would likely yield even lower reservoir storages and higher shortages. Different intermediate demand scenarios could be used that represent different combinations of population growth, per capita water use, agricultural to urban conversion rates, and potential evapotranspiration. There was very limited reservoir sedimentation data and thus a wide range of sedimentation rates spanning 0% to 30% were simulated. Model outputs and vulnerability criteria of June 1 reservoir storage targets and total annual shortages reflect current WBWCD operations. Use of other targets like higher June 1 storage levels, October storage levels, or service areas specifically served by the WBWCD would give basin managers a different, possibly better image of how basin storage responds to individual and combinations of future inflows, demands, reservoir sedimentation, and reservoir evaporation conditions. An October storage level criterion would represent an end-of-the irrigation season condition and the yearly low point in timeseries plots of reservoir storage. If we could identify the modeled service areas or portions of them that are managed by the WBWCD, further work could identify WBWCD-specific output.

Lastly, the study only considers existing modeled reservoir operations where service areas call on water from one or more reservoirs in a priority order. Further work could identify how existing reservoir operations and deliveries could be adapted to increase reservoir storage and reduce shortages across uncertain future inflow, demand, and reservoir sedimentation conditions. Together, the bottom-up vulnerability analysis identifies future inflow, demand, reservoir sedimentation, and reservoir evaporation conditions for which the Weber Basin system can likely cope and future conditions where the system will see low reservoir storage and high shortages.

Data Availability

The input data, model, code, and directions for this study are available on GitHub at, https://github.com/jacobeveritt/WeberBasinVulnerability, Everitt (2020).

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