Tucson Water
One Water 2100 Master Plan

Technical Memorandum
CLIMATE CHANGE: IMPACTS TO TUCSON WATER AND THE TUCSON WATER INTEGRATED WATER MASTER PLAN

FINAL | NOVEMBER 2021

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Executive Summary

Tucson has a distinct advantage among U.S. cities regarding its ability to adapt to climate change as climate extremes are, to some degree, part of living in the Sonoran Desert. Whether it is the occasional snowstorm in winter, 110°F plus days in the dry season, or heavy, intense thundershowers during monsoon season, the people of Tucson understand adaptation to changing conditions. The findings of this study quantify the climate of Tucson from a historic perspective, as well as from a perspective of a projected future climate. This quantification has led to the following findings regarding climate change on a regional (Colorado River Basin) and a local (Tucson Water Service Area) basis:

- The current 20-year drought in the Colorado River Basin (CRB) is classified as a "heat drought" that has resulted in flow reduction due to changes in air temperatures rather than annual precipitation (Udall, 2017).
- Historic trends (NCDC, 2020) and climate projections predict a 4 percent reduction in CRB flows per 1°F of annual average temperature increase.
- Precipitation in the CRB is expected to slowly increase over the remainder of this century, but with increasing year-over-year and seasonal variability as well (USBR, 2012, Udall, 2017).
- Annual precipitation in the Tucson Water Service Area (TWSA) is expected to slightly increase over the remainder of this century, but with increasing year-over-year variability and increasing precipitation intensities (Vose et al, 2017, USBR 2020).
- Historic trends and projected climate trends (NCA, 2018, Udall, 2017, Vose et al, 2017) both indicate significant increases in annual average temperatures during the remainder of this century in the southwestern U.S.
- The number of hot days (>100°F) is expected to increase and reach 76 days/year by 2100 in Tucson. The number of 110°F days is expected to be approximately 30 days/year by 2100 in Tucson (USBR, 2018, NCDC, 2020)

These key understandings regarding climate change led to the development of the anticipated impacts to the Tucson Water system, and consequently, should become considerations during the continued development of the One Water 2100 Master Plan. These impacts are as follows:

- Continued reductions in CRB flows are anticipated as a result of climate change, but Federal, State, and Local stakeholders are taking steps to better manage this situation as it evolves through policies like the Drought Contingency Plan (DCP) and the work of the Arizona Reconsultation Committee.
- Water harvesting will remain an efficient, potable water offset in the region, but may be impacted by increasing precipitation intensities.
- Water remediation and reclaimed water are not expected to experience any significant impacts from climate change other than those associated with increased evaporation and evapotranspiration for the end user.

- Due to the fact that the vast majority of Tucson's water supply comes from the Central Arizona Project (CAP), which is consequently stored as groundwater, water quality issues as a result of increased air temperatures due to climate change are not expected to become an issue for the City.
- Due to increasing air temperatures, particularly in regard to the increasing number of extremely hot days, Tucson is expected to feel like present-day Phoenix by the year 2050 (30 day/year with high temperatures of 110°F or higher). These extremely hot days are expected to significantly increase seasonal water usage.

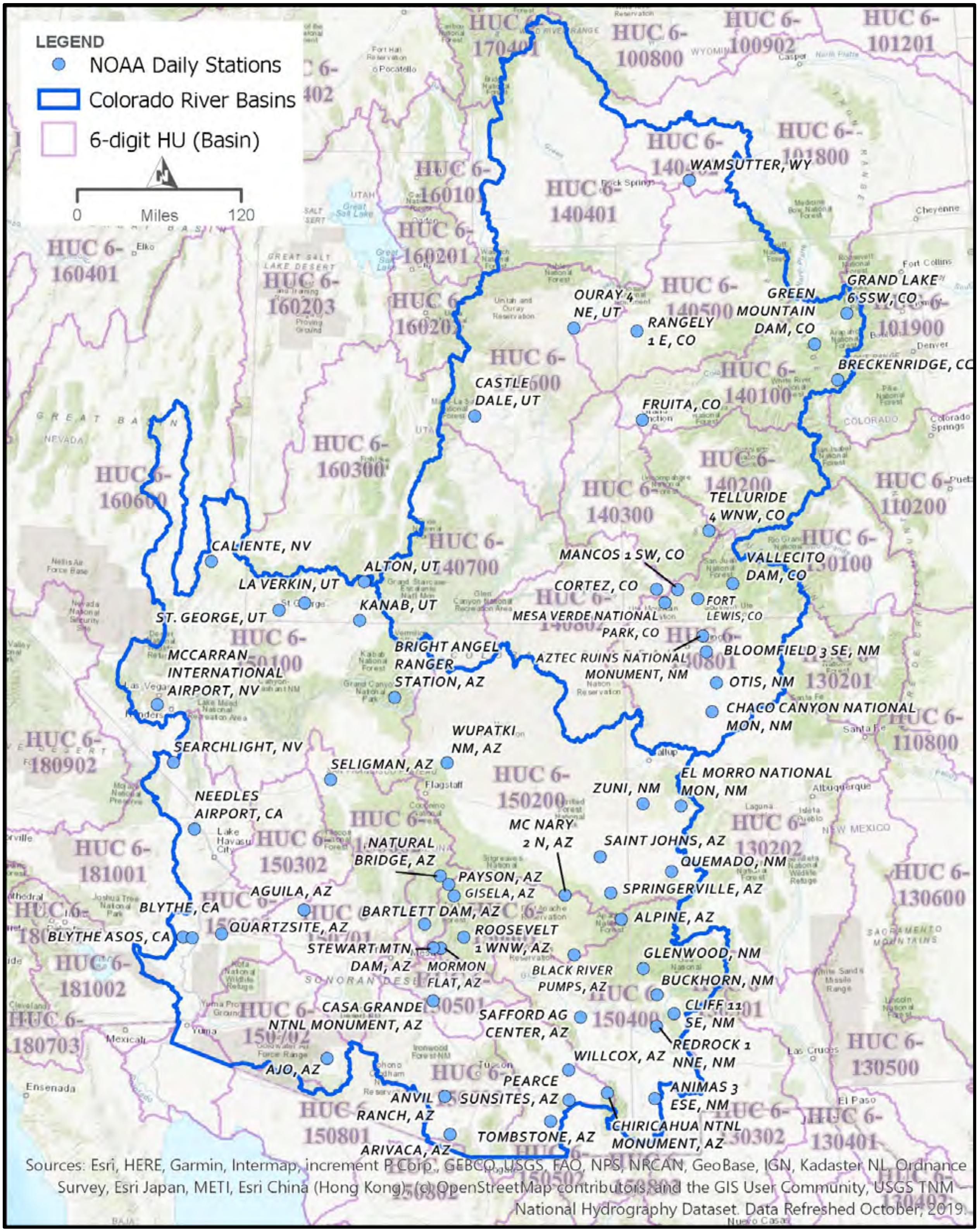
1 Introduction

HDR was tasked with developing an understanding of the potential impacts of climate change as they apply to the One Water 2100 Master Plan that Tucson Water is in the process of developing. Water supplies within the Tucson Water Service Area (TWSA) are made up of groundwater, reclaimed water, remediated water, water harvesting (stormwater capture), and imported renewable water through the Central Arizona Project (CAP), as well as any precipitation that may fall on the region itself throughout a given Water Year (WY).

Climate change is already impacting the physical and social aspects of life in Tucson. According to a recent Climate Central report (Climate Central, 2019) based on data from 1970-2018, average annual temperatures rose 4.48°F in Tucson (NCDC, 2020). While some of this increase is related to the Urban Heat Island effect (UCAR, 2011), much of this increase is attributable to the influence of global climate change (NCA, 2018).

Prior to the initiation of this investigation, a literature review was undertaken to enable a holistic understanding of all the research that has been done in the past and is still ongoing in regard to the impacts of climate change in Tucson and the greater southwestern U.S. This literature resides in Appendix A of this report with citations used in this report existing in the references section as well.

This report is broken down into several components so that a complete understanding of a chronology of historic climate trends and projected climate change impacts on a local and regional scale, as well as a consideration for seasonal components, can be probabilistically quantified. Since the Colorado River Basin (CRB, Figure 1) is responsible for producing flow in the CAP for use in Tucson, the analysis of climate trends and future projections over this region will be provided in tandem with the investigation of local (Figure 2) climate trends and future impacts. These two geographic regions were used to identify specific impacts from changes in air temperature, precipitation, and streamflow that will be summarized and reported in Section 4 of this report.



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community, USGS TNM – National Hydrography Dataset. Data Refreshed October, 2019.

Figure 1. Map of Colorado River Basin within the United States (blue outline) with identified long-term meteorological reporting stations (blue dots).

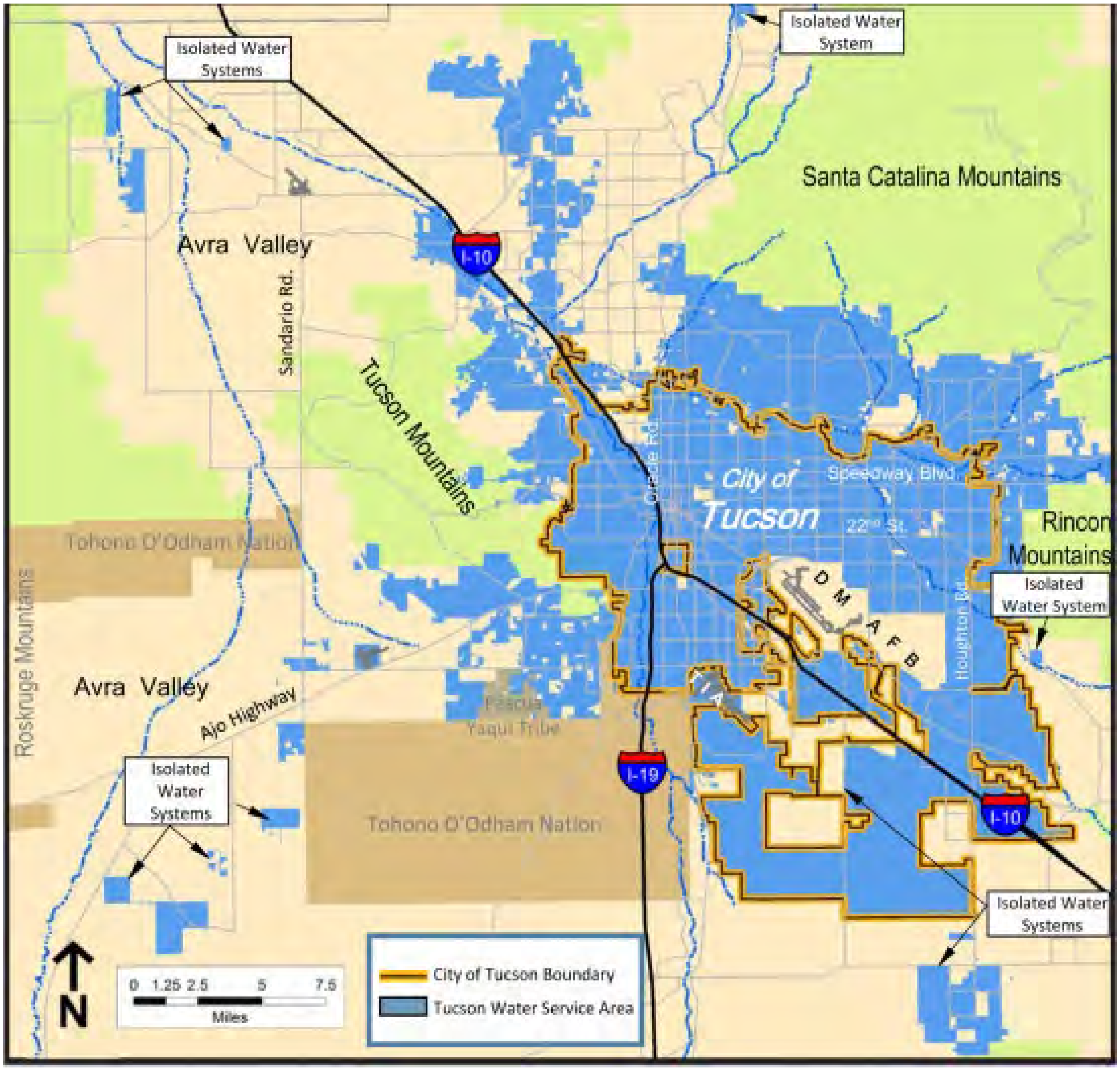


Figure 2. Map of Tucson Water Service Area.

2 Historic Climate Trends

Historic climate trends, particularly climate trends within the last 30 years, are extremely important to understanding the current climate direction, and are a key component of understanding the magnitude of future projected change. These trends, when extrapolated, provide a baseline for anticipated future climate change. Like stock or financial market trends, historic trends help identify overall changes despite short-term variability.

2.1 Colorado River Basin

As can be seen in Figure 1, the CRB covers an enormous area (approximately 250,000 sq. miles) over seven western states and a portion of northwestern Mexico from Yuma southward to the river’s terminus in the Sea of Cortez. While this basin is expected to experience continued hydrologic changes due to climate change, long-term hydro-meteorological data help identify both historical and anticipated trends.

2.1.1 Precipitation and Hydrologic Flow

The stations on the map in Figure 1 represent the meteorological reporting stations in the CRB that have a very long period of record (POR) for precipitation data (NCDC, 2020). These are the same stations that were used to provide guidance for the United States Bureau of Reclamation (USBR) 2012 study of climate change impacts on the CRB (USBR, 2012). An analysis of precipitation data from these stations from the POR 1895-2020 reveals (Figure 3) an increasing long-term trend with considerable yearly and decadal variability. This is particularly true during the last 30 years of POR, which, of course, includes the last 20 years of CRB drought.

The precipitation and hydrologic trends discussed in this section provide some perspective for the *projected* trends expected to occur as a result of climate change impacts in the CRB in Section 3.1.1.

The southwestern U.S. has a climate that is conducive to assembly of a paleo-historic reconstruction of stream flows well beyond the range of available observed streamflow data. This is possible through the correlation of the study of tree-ring growth (dendrochronology) to known stream flows within the CRB (Woodhouse, 2007). Figure 4 provides an understanding of the reconstructed and observed Colorado River flow at Lees Ferry, AZ from 762-2019. These data provide a long-term perspective regarding the historic potential for decadal drought periods. The long-term trend in river flows is increasing during this POR; however, during this same POR there have been periods, such as between the years 1200-1350 that saw several multi-decadal drought periods.

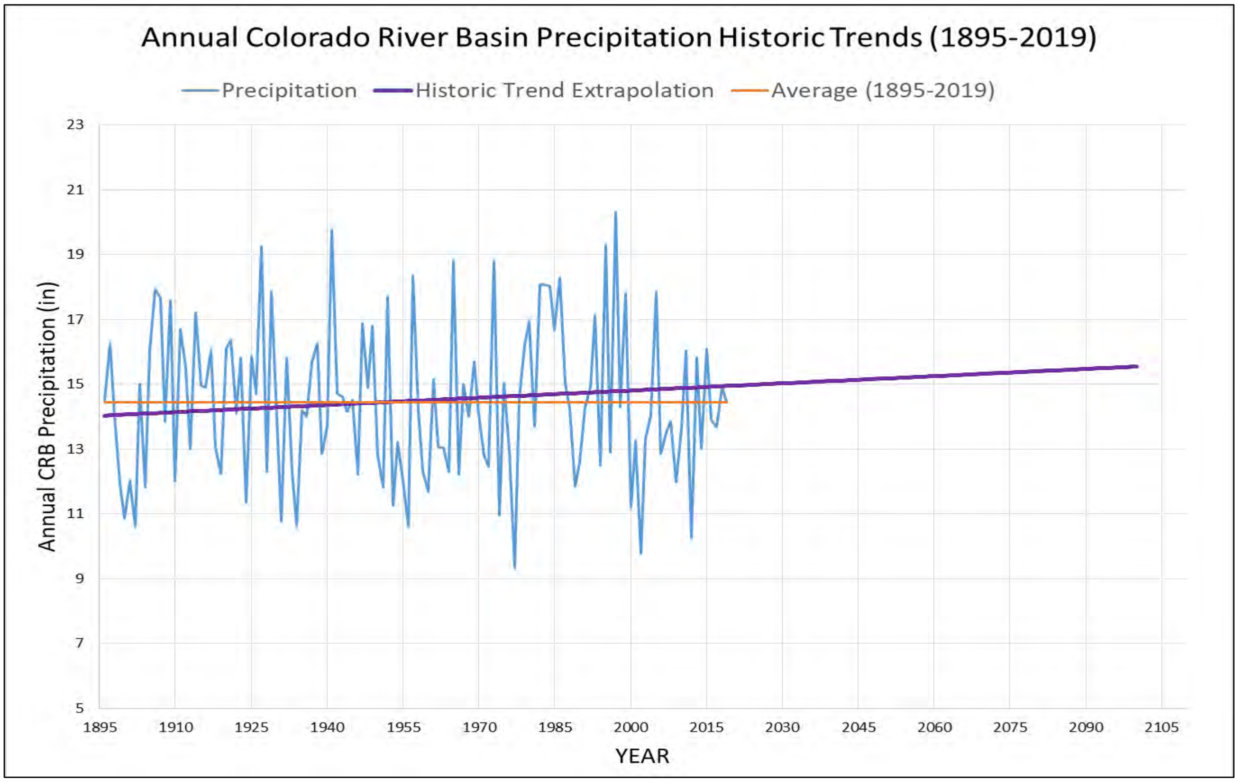


Figure 3. Annual CRB precipitation trend (1895–2020). Trendline in purple. Average in orange. Source data NCDC (2020).

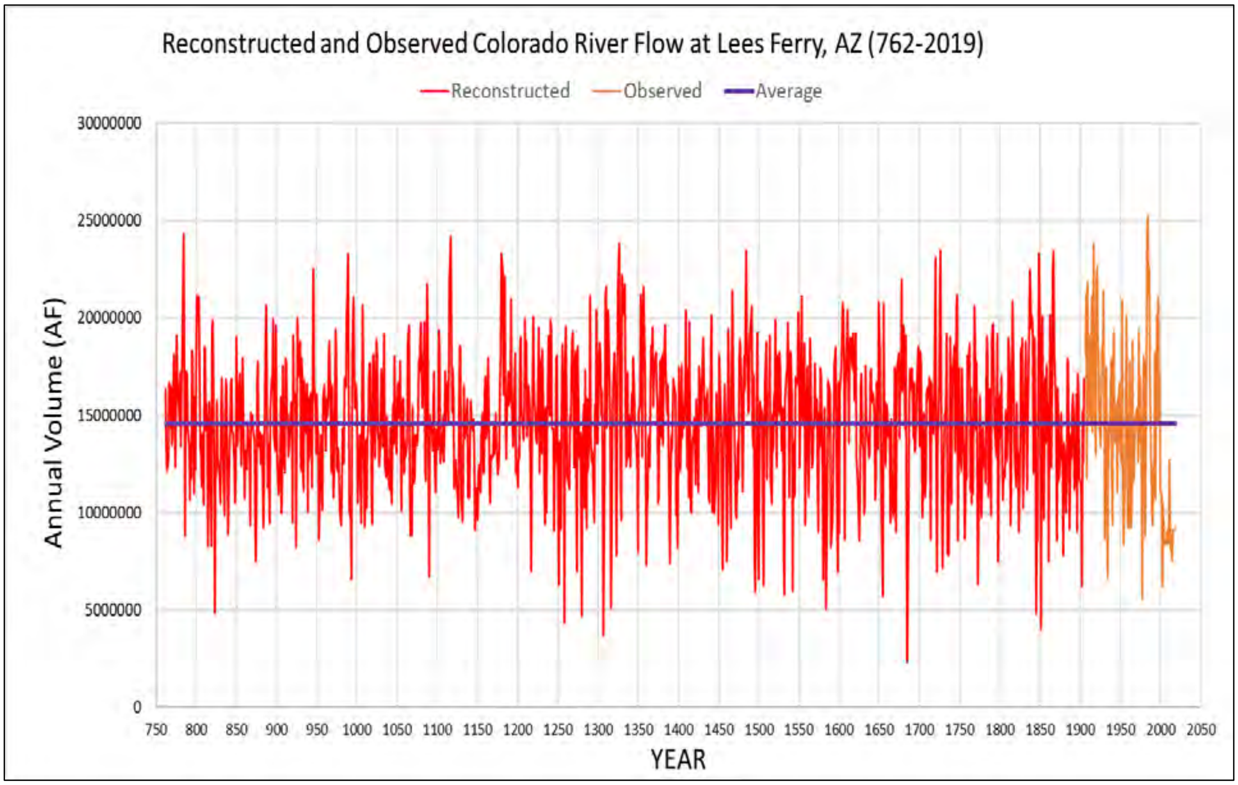


Figure 4. Reconstructed and observed Colorado River Flow (AF/year) at Lees Ferry, AZ (762-2019). Source data Woodhouse (2007) and USGS (2020).

Figure 4 (Woodhouse, 2007 and USGS, 2020) also provides some prospective regarding the magnitude of the drought that the CRB has experienced during the period 2000-2020 in the much larger scheme of the last 1250 years. This drought, which is classified as a "hot drought" (Udall, 2017) is related to temperature in the CRB rather than lack a precipitation as in the drought of 1200-1350. An understanding of a "hot drought" can be gleaned by comparing the graphs in Figure 3 and Figure 5 (Section 2.1.2) with the recent flows identified in Figure 7. Figure 3 shows basin average precipitation at or near the historic average during the period 2000-2019, while basin average air temperatures have shown a significant increase during that same period (Figure 5). Thus, as precipitation has been at or near average, flows in the CRB have dramatically decreased (Section 2.1.2, Figure 7).

2.1.2 Temperature

Air temperatures play a significant role in determining flows on the Colorado. Increasing air temperatures over time have contributed to increases in the levels of evaporation, evapotranspiration, and, ultimately, water demand in the CRB. Figure 5 shows the trend in average annual basin air temperatures within the CRB from 1895-2018. This figure indicates that the long-term trend has been approximately a 2.7°F increase per 100 years during this time period; however, the secondary (orange) trendline in this figure shows that the trend from 1964-2019 (55 years) has shown a 3.23°F increase, which would equate to a rate of increase of 5.87°F per 100 years going forward from 1964.

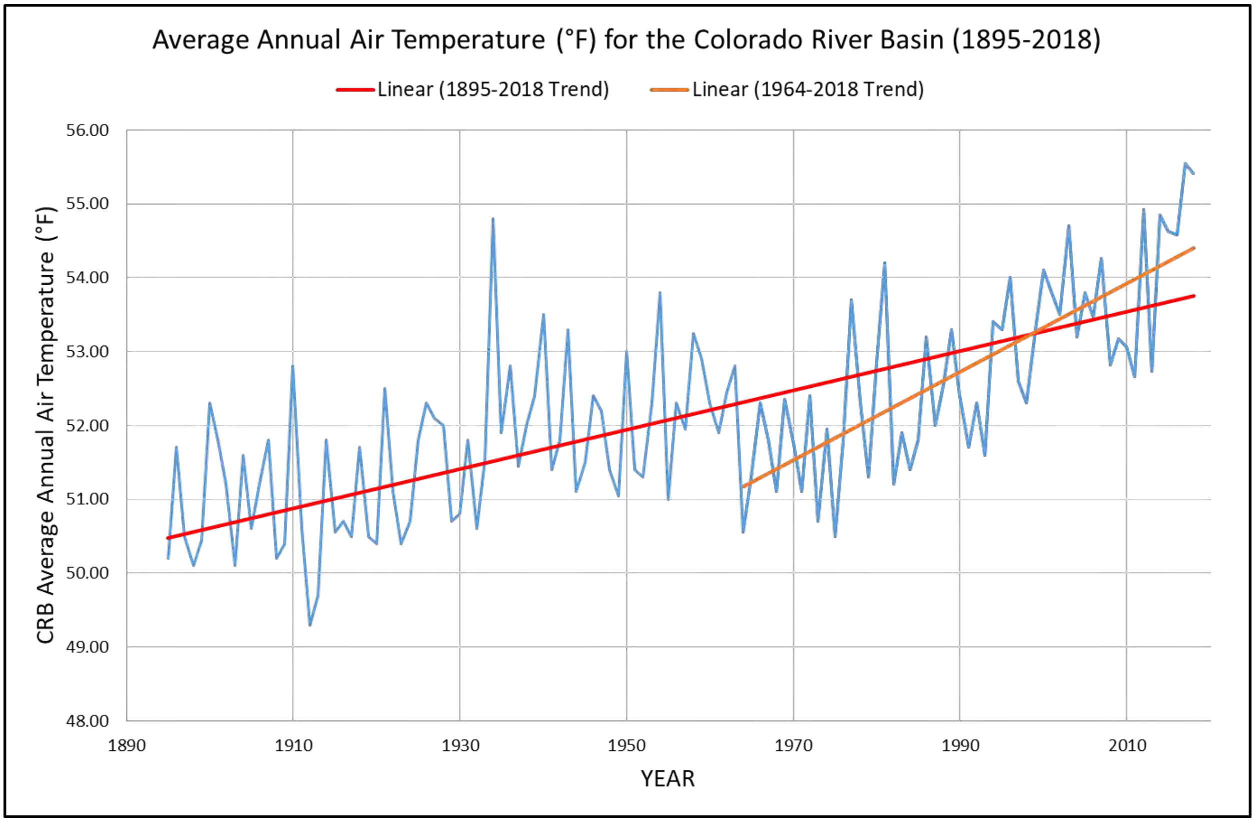


Figure 5. Basin average annual air temperature for the CRB (1895–2018). 1895–2018 trendline in red. 1964–2018 trendline in orange. Source data NCDC (2020).

Figure 6 shows the same graph as in Figure 5 but includes an extrapolation of these data out to year 2100 for both trends identified in Figure 5. As per the research identified in Section 2.1.1 (Udall, 2017), these extrapolations would result in an approximately eight percent (8%) decrease in Colorado River flows from the long-term (1895-2018) trend and a 16% to 18% decrease in Colorado River flows from the near-term (1964-2018) trend by the year 2100. These trends represent important input regarding the understanding of *projected* climate change as it relates to the CRB in Section 3.1.2.

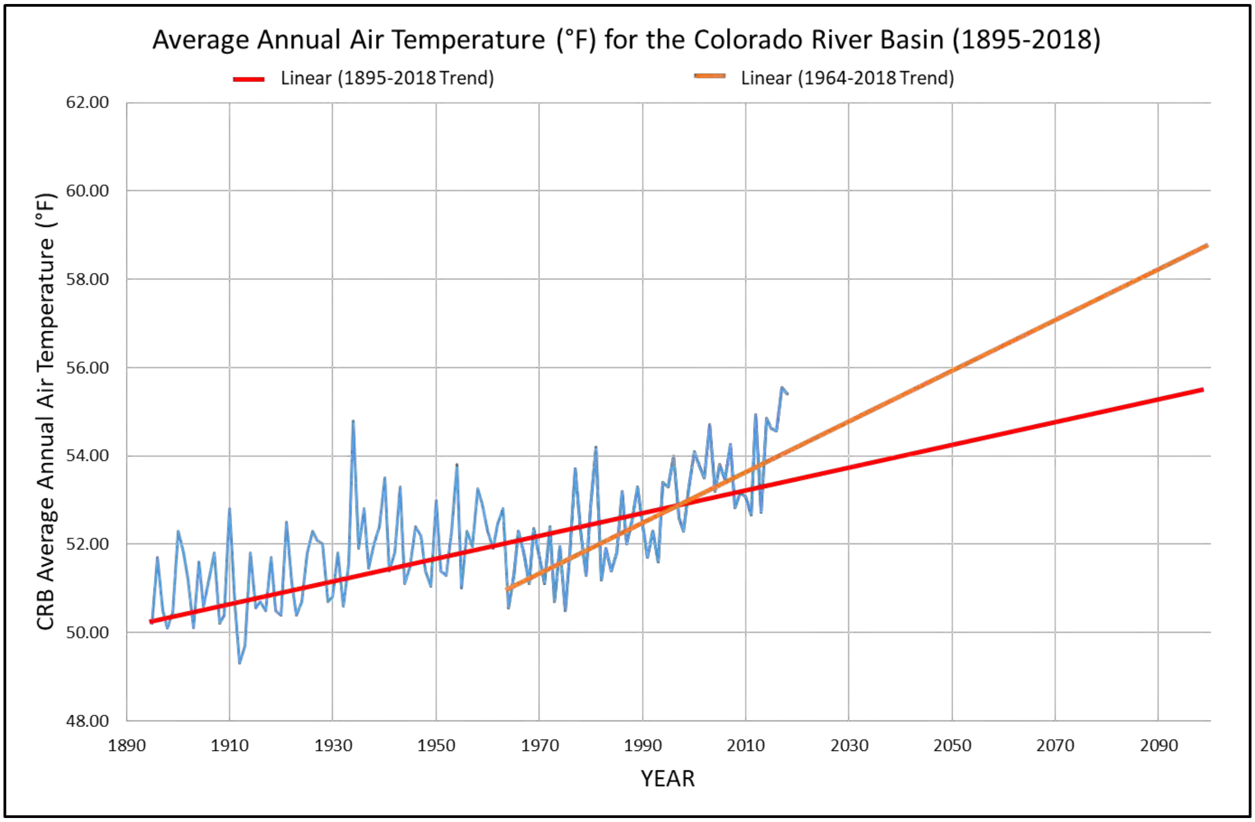
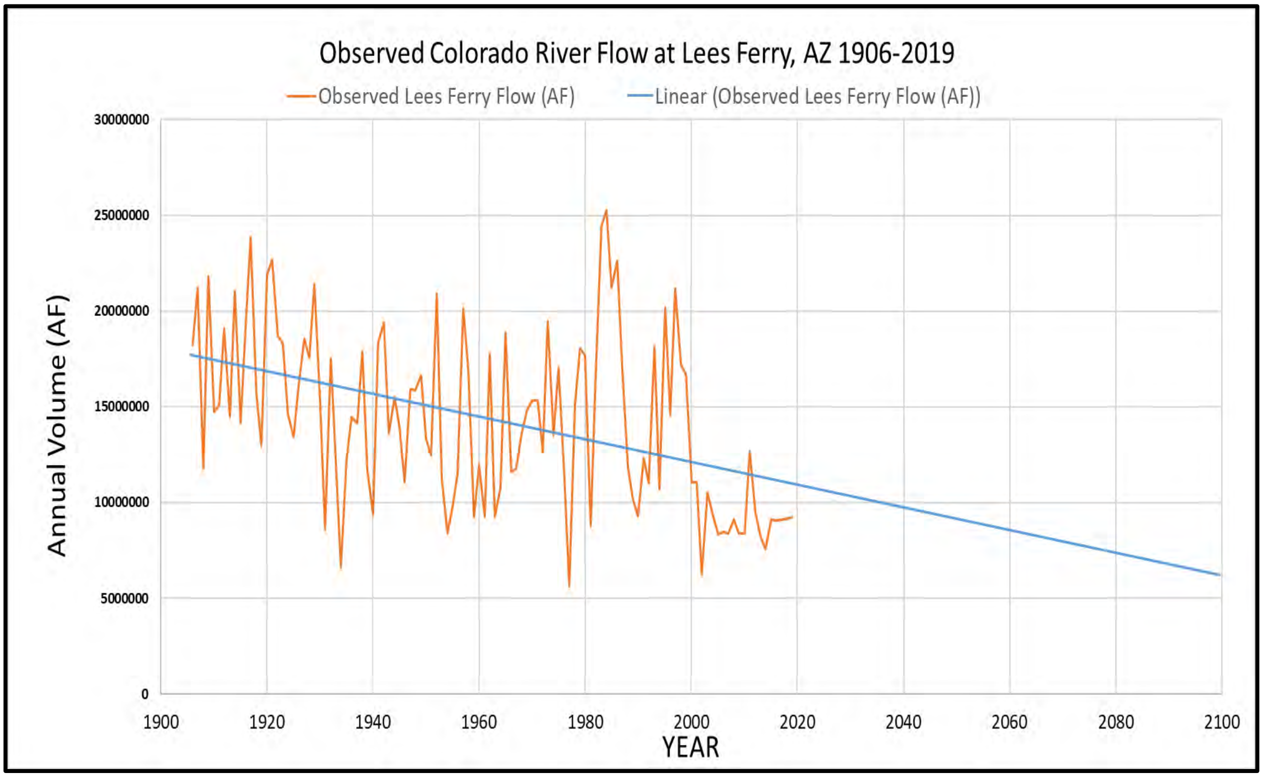


Figure 6. Extrapolations of the long-term (red) and near-term (orange) trends in average annual CRB air temperatures to the year 2100. Source data NCDC (2020).

As reported in a recent article (Udall, 2017) that was the result of climate research by Colorado State University in conjunction with the University of Arizona, flows on the Colorado River decline by about four percent per degree Fahrenheit increase in basin average temperature. As was seen earlier in this section, the temperature trend for the last 120 years has greatly added to the reduction in river flows during that time. The extrapolation of the trendline in Figure 5 indicates that by the year 2100 flows on the Colorado River are expected to produce only half the volume that they produce today.

One issue that has been working against the reported increase in precipitation over time in the CRB is the increased demand for the water resources, particularly in the upper

CRB. While the lower CRB water use was recently shown (Circle of Blue, 2020) to have the lowest level in 33 years in 2019, the upper CRB has been continuously increasing their usage and exercising their water rights over the last 120 years, which includes water for agriculture and a substantial increase in upper CRB water being transferred to the eastern slope of the Rockies through trans-basin diversions. While the upper CRB continues to meet their Colorado River Compact agreement of at least 7.5 million acre-feet (MAF) delivered to the lower CRB, the annual flow trend at Lees Ferry continues downward partially due to upper CRB demands.



2.2 Lower Santa Cruz River Basin (Tucson Water Service Area)

The TWSA historic climate can be divided into three distinct climate regimes: winter wet season, dry season, and monsoon season. As per the climate information from the very long-term POR from the NWS Weather Forecast Office (WFO) meteorological reporting station in Table 1, the winter wet season is typified by cooler temperatures with occasional 24-48-hour precipitation events (November-March), the dry season by hot, dry weather (April-June), and the monsoon season by hot, humid weather with occasional thundershowers (July-October), respectively.

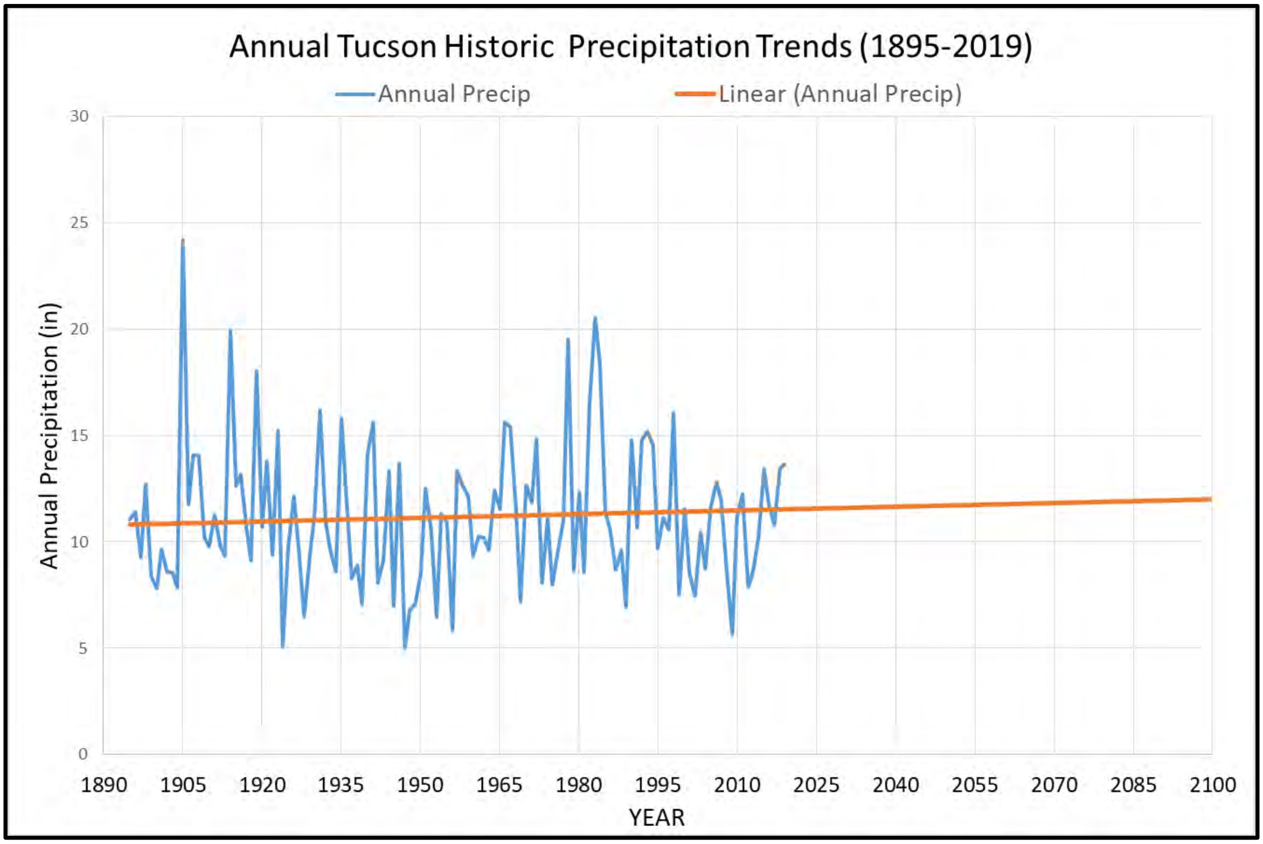
Table 1. Climate statistics from the WFO meteorological reporting station (1894–2020). Source data National Weather Service (2020).

TUCSON NWS WFO, ARIZONA

Period of Record Monthly Climate Summary (Period of Record : 9/ 1/1894 to 02/29/2020)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Average Max. Temperature (F)	65.5°	68.5°	74.1°	82.1°	91.6°	100.3°	99.7°	97.4°	94.5°	84.8°	73.5°	64.8°	**83.1°**
Average Min. Temperature (F)	39.8°	42.2°	46.2°	52.0°	60.5°	69.3°	74.4°	73.3°	68.6°	57.3°	46.1°	39.1°	**55.8°**
Average Temperature (F)	52.6°	55.3°	60.1°	67.0°	76.0°	84.8°	87.0°	85.3°	81.6°	71.0°	59.8°	51.9°	**69.4°**
Average Total Precipitation (in.)	0.94"	0.86"	0.73"	0.31"	0.23"	0.20"	2.25"	2.39"	1.29"	0.89"	0.57"	0.93"	**11.59"**

Annual precipitation in Tucson, similar to the CRB, has been slightly increasing over time. Figure 8 shows the significant variability in annual precipitation within the region (standard deviation 3.30 inches), as well as an extrapolation of this trend into the future. The long-term trend shows a slight but steady increase in annual precipitation, which provides the basis for *projected* changes in precipitation in Section 3.2.1.



2.2.2 Precipitation Intensities

One of the basic tenets of climate change science is that as the atmosphere warms its ability to hold more moisture will also increase. This is based on what is called the Clausius-Clapeyron equation, which indicates that the moisture that the atmosphere can hold will increase 3.5 percent per 1°F. This fact becomes very consequential when considering the historic trends in temperature in Section 2.2.3, as well as the projected trends for the region in Section 3.2.2.

A recent study investigating the intensification of the North American Monsoon rainfall in the southwestern U.S. (Demaria, et al., 2019), as part of a United States Dept. of Agriculture and University of Arizona study, has shown that monsoon rains have become more intense. This study, which utilized a high-density rain gauge network (59 gauges) within a 57.5 sq. mile area known as the Walnut Gulch Experimental Watershed, identified that since the 1970's precipitation rates have increased by six to eleven percent. Thus, while storm durations have remained about the same, storm intensities have increased. This historic trend in precipitation intensities has implications regarding the resilience of water infrastructure within the TWSA that will be discussed in Section 4.

2.2.3 Temperature

Air temperatures in the TWSA have been on a steady increase over time. Figure 9 shows the trends in maximum, minimum, and average annual air temperatures in the region from 1895-2018. During this 120+year POR, daytime high air temperatures increased approximately 5.0°F, while nighttime minimum air temperatures increased approximately 10.0°F. While these statistics are on par with changes in much of the southwestern U.S., so are the inflections in these graphs that occur right around 1964. 1964 is the year where the trends show a very noticeable increase in minimum air temperatures. This same inflection point is something that can be partially attributable to increased development in the region (i.e. urban heat island effect) during the 1960's and 1970's, but it is an inflection point that repeats itself during this same time period in data from cities and countries all over the world.

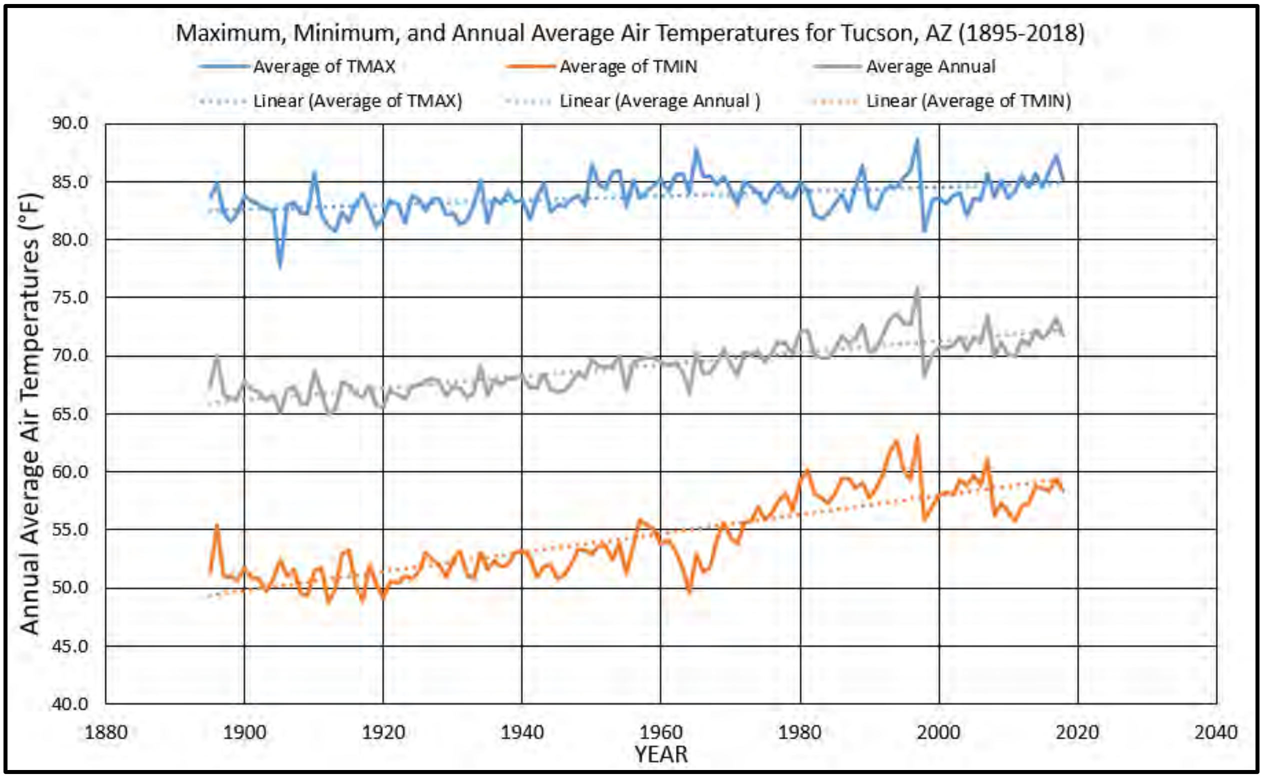
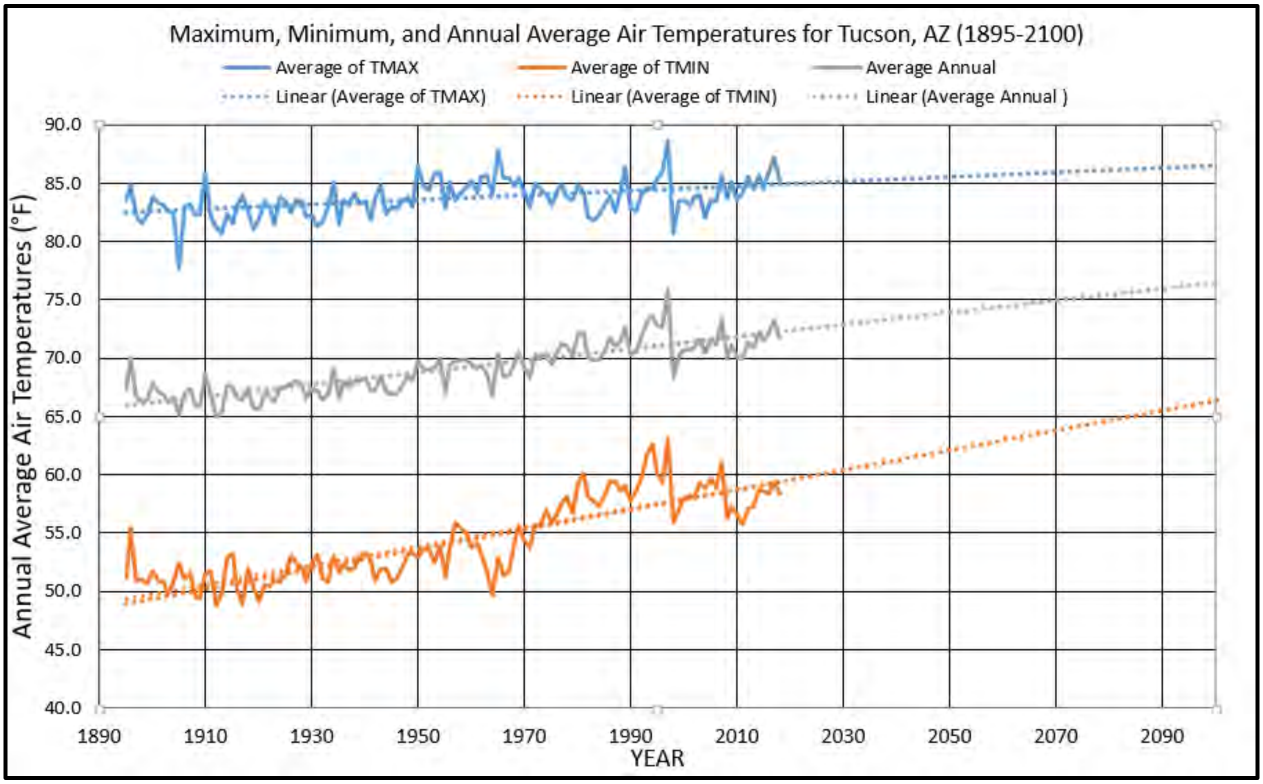


Figure 10 provides an extrapolation of these historic trends in air temperature to the year 2100. These trends indicate an increase in average annual maximum temperatures of approximately 1.5°F by 2100, an increase in average annual air temperatures of approximately 4.1°F, and an increase in average annual minimum air temperatures of approximately 7.8°F. A comparison to the projected changes in annual air temperatures reported in Section 3.2.2 finds these historic trends in good agreement with projections from lower future emissions scenarios (RCP 4.5).



3 Climate Scenarios

As has been shown in Section 2, the historic trends in precipitation, streamflow and air temperature point to the direction that the climate is going within both the CRB and the TWSA. Climate projections are used to provide a physical understanding of what can be expected based on different future climate scenarios that may impact the climate going forward. While there are many different Global Climate Models (GCM), and currently four different climate (emissions) scenarios that have been adapted for use in these models, this study will rely on the output from a variety of recent climate studies that cover both the CRB and the Lower Santa Cruz River Basin, which encompasses the TWSA. These studies primarily utilize the current climate, RCP 4.5 and RCP 8.5 to compare and contrast potential future outcomes.

One of the consequences of using climate projections is that as these projections move into the future, the range of potential outcomes based on a given GCM or RCP will increase over time. This range of potential outcomes will be identified within this section. The findings in this section should compared and contrasted with observed/historic trends in Section 2.

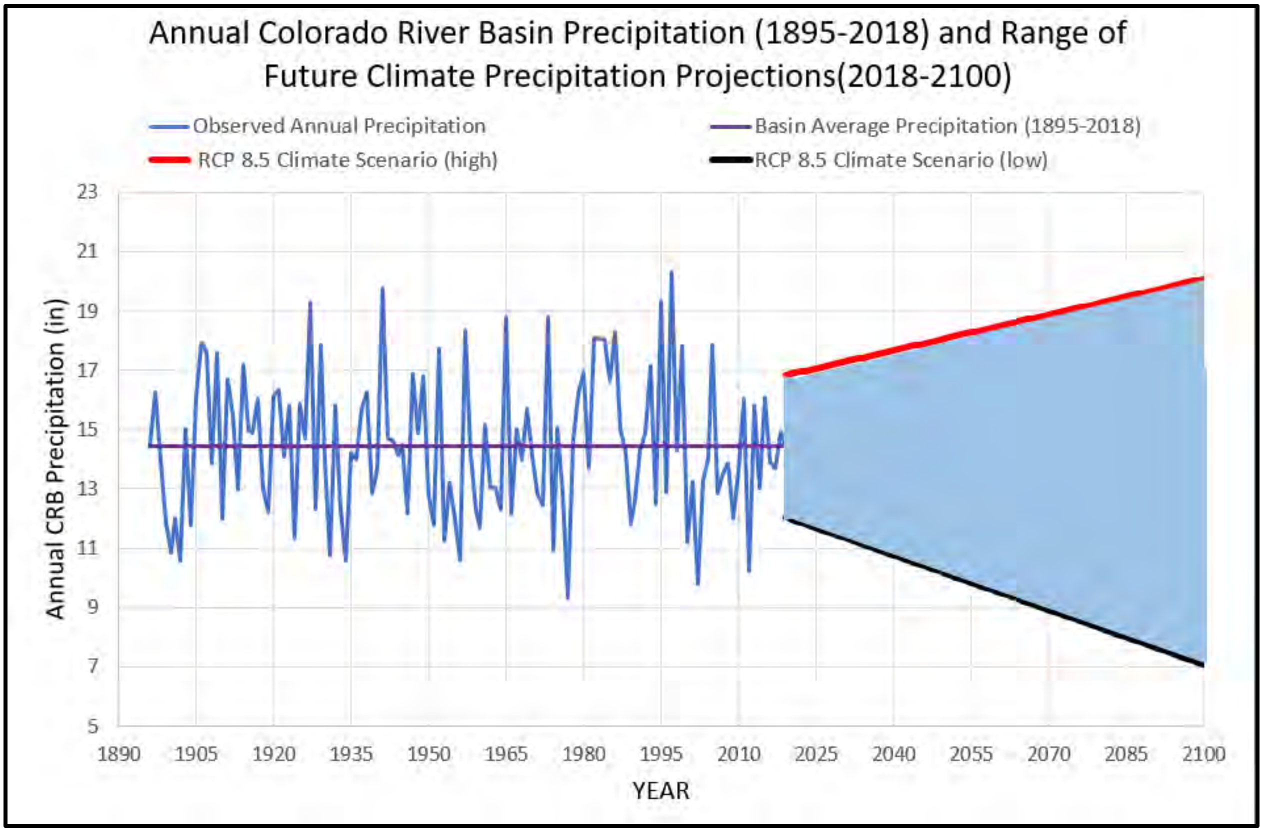
3.1 Colorado River Basin Climate Projections

A recent report developed as part of the USBR's 2016 SECURE Water Act report (USBR, 2016) identifies climate challenges the CRB could likely face. These include the following:

- On average, temperatures in the CRB are projected to increase by 5–6 °F during the 21st century, with slightly larger increases projected in the Upper Basin.
- In the CRB precipitation is projected to remain variable with a slight increase in the Upper Basin.
- In high-altitude and high-latitude areas of the CRB headwaters, snowpack is projected to increase during the 21st century, but at lower elevations warmer conditions are projected to transition snowfall to rainfall, producing more December–March runoff and less April–July runoff.

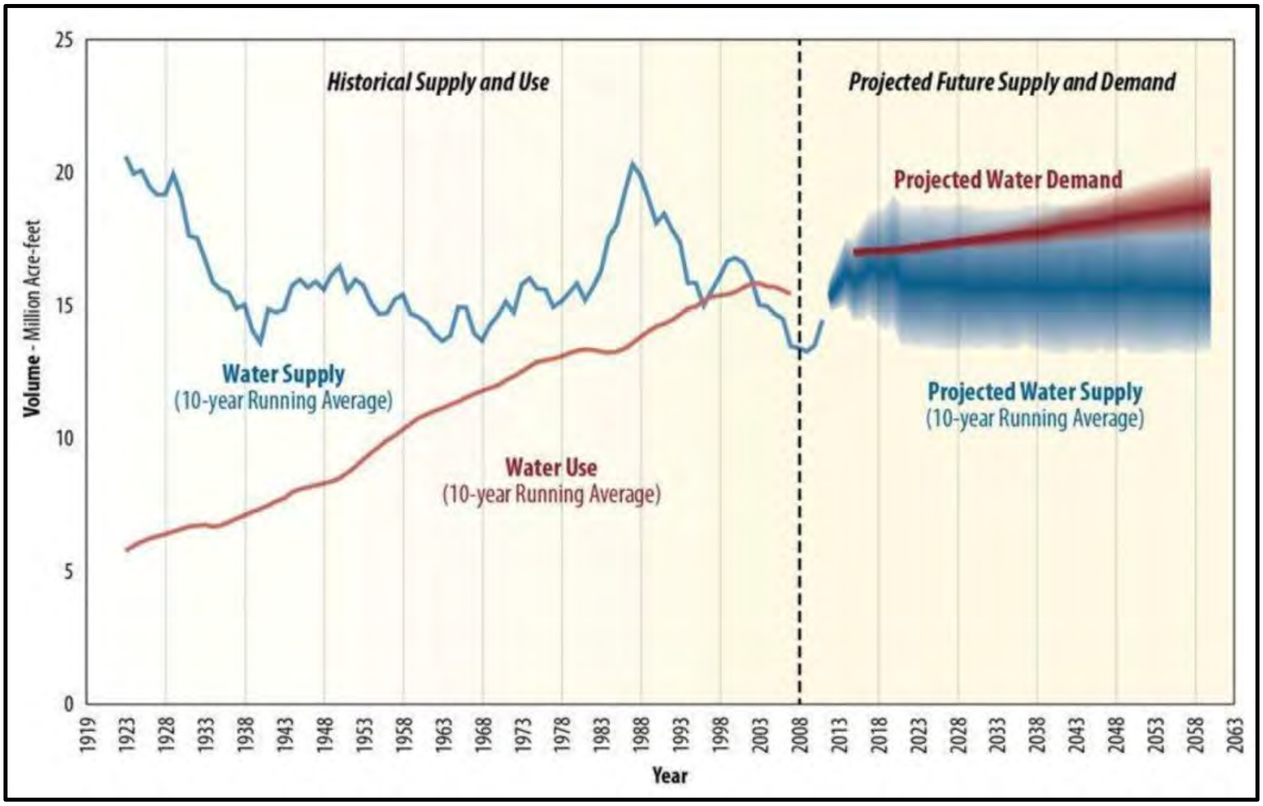
3.1.1 Precipitation and Hydrologic Flow Projections

GCM with their associated emissions scenarios (4.5 and 8.5), when back-checked using historic data, show significant skill in projecting future air temperatures, but, unfortunately, cannot show that same level of skill when it comes to precipitation in a given region. Therefore, the range of future precipitation outcomes usually has a much greater range than that associated with future air temperatures. Figure 11 shows this range of potential CRB precipitation outcomes as a result of the RCP 8.5 climate scenario. RCP 8.5, the scenario that represents the highest anticipated level of future emissions, shows the large range (shaded area) of precipitation outcomes associated with this projection. Figure 11 highlights the increased year-over-year variability, rather than some definitive quantification of an increase or decrease in precipitation through the year 2100. The initial variance in future precipitation represented in this chart is based on a standard deviation of 2.385 from the historic data. These future precipitation projections were from the USBR Colorado River Basin Water Supply and Demand Study (USBR, 2012).



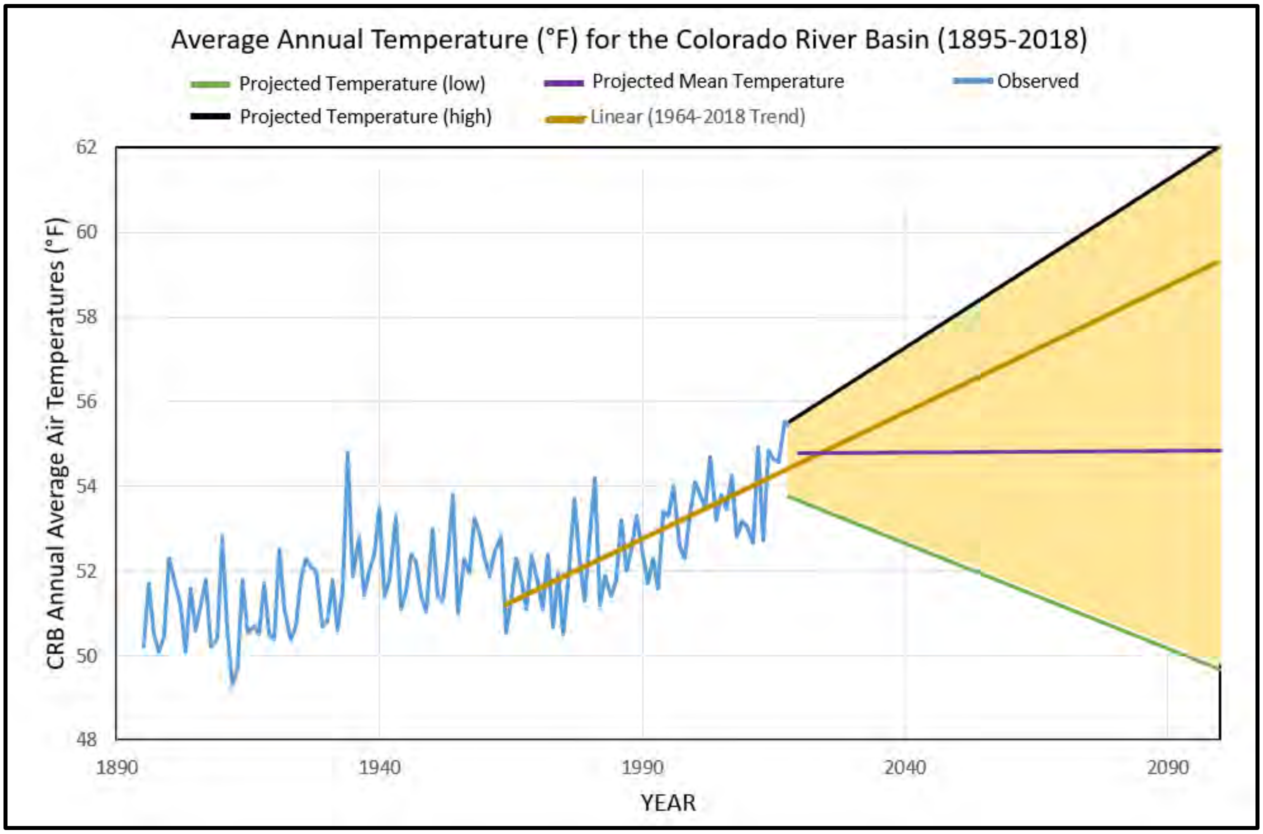
The climate model projections indicate that while the basin average precipitation is not necessarily expected to dramatically increase or decrease over time, the variability is expected to significantly increase with climate change. This would, under historic conditions, make for an increased water management challenge within the CRB but, as explained in Section 2.1.1., increased air temperatures that are expected to occur within the CRB are expected to tip the scale towards reduced flows regardless of the fact that average precipitation within the basin is expected to remain nearly the same.

Figure 12, from USBR 2016 SECURE Water Act Section 9503(c) report on CRB climate change and water (USBR, 2016), identifies the historic water supply and demand on the Colorado River and the anticipated range of future water supply and demand within the CRB. Based on the data as seen in Section 2.1.1 (Figure 4), these USBR projected trends indicate a slightly greater year-over-year variability than in the historic past.



3.1.2 Temperature Projections

Air temperature trends in the CRB have been steadily on the rise over the last 120 years (Figure 6) but have significantly increased in the basin during the last 40 years. Climate projections indicate that under RCP 4.5 (low) emissions scenario temperatures are expected to increase through approximately 2060 and then begin slowly decreasing thereafter, while the RCP 8.5 (high) scenario indicates an acceleration in the historic trend of warming temperatures in the basin. Figure 13, using data from the 2012 USBR CRB study (USBR, 2012) shows the observed annual air temperatures from the CRB from 1895-2018, as well as the trend from 1964-2018 extrapolated out to the year 2100. Climate projections (RCP 4.5 and 8.5) have been combined on this chart to show the large range (shaded area) of potential outcomes associated with these projections. The historic trend (1964-2018) displayed on this chart provides an excellent perspective to projected outcomes from the global climate modeling data. The initial range (2018) of future basin air temperature outcomes is based on the standard deviation (1.29) from the POR 1895-2018.



3.2 Lower Santa Cruz River Basin (Tucson Water Service Area) Climate Projections

This section considers climate projections based on both the preliminary findings of the ongoing USBR study in the Lower Santa Cruz River Basin (LSCRB) and those of other, earlier studies.

3.2.1 USBR Lower Santa Cruz River Basin Study Methodology

The USBR is currently engaged in the development of a Climate and Surface Water Analysis as part of the LSCRB study, which is one portion of a three-part study that includes the West Salt River Basin Study and the Eloy Maricopa-Stanfield Basin Study. During a recent presentation to the Citizens' Water Advisory Committee (CWAC) Technical Planning and Policy (TPP) Subcommittee on December 10, 2020 the USBR (USBR, 2020) provided a summary of their findings-to-date on this project in regard to climate outcomes in the region. Although this study is not expected to be complete until late 2021, preliminary findings are being released so that decisions can be made regarding long-term planning and policy.

The LSCRB study utilizes a combination of several modeling techniques and methodologies to derive projected impacts to water in the basin based on future scenarios that involved Global Climate Models (GCM), surface hydrologic modeling, groundwater modeling, socio-economic trends and drivers (demand), all within the realm of the Central Arizona Project (CAP) service area model. A schematic of the interaction between these models can be seen in Figure 14.

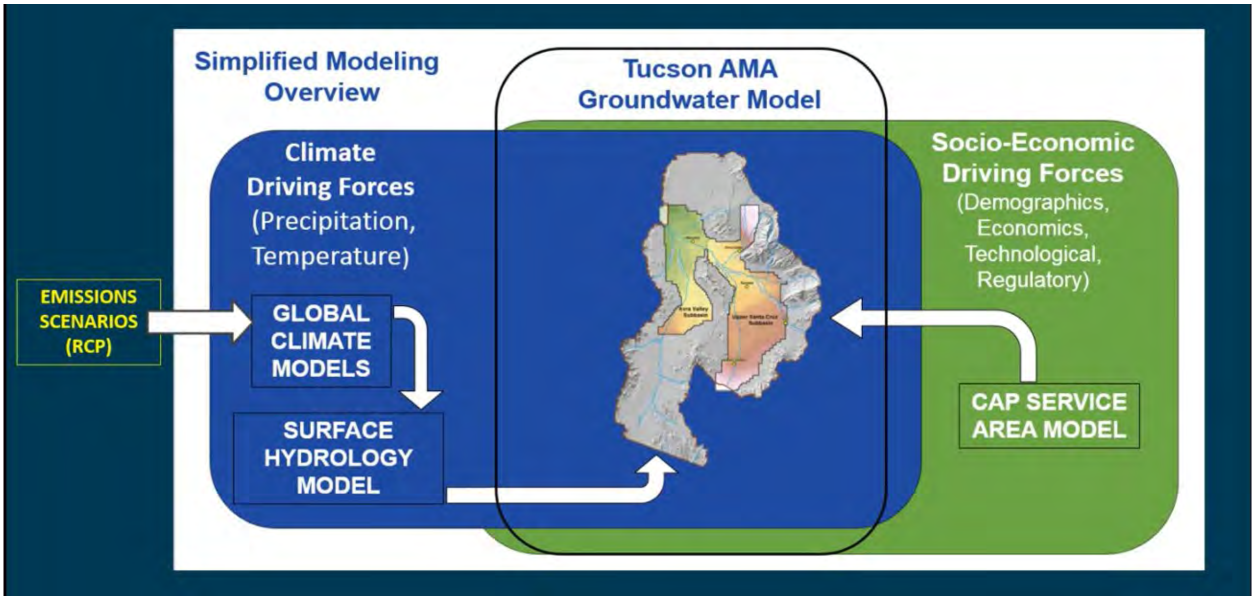
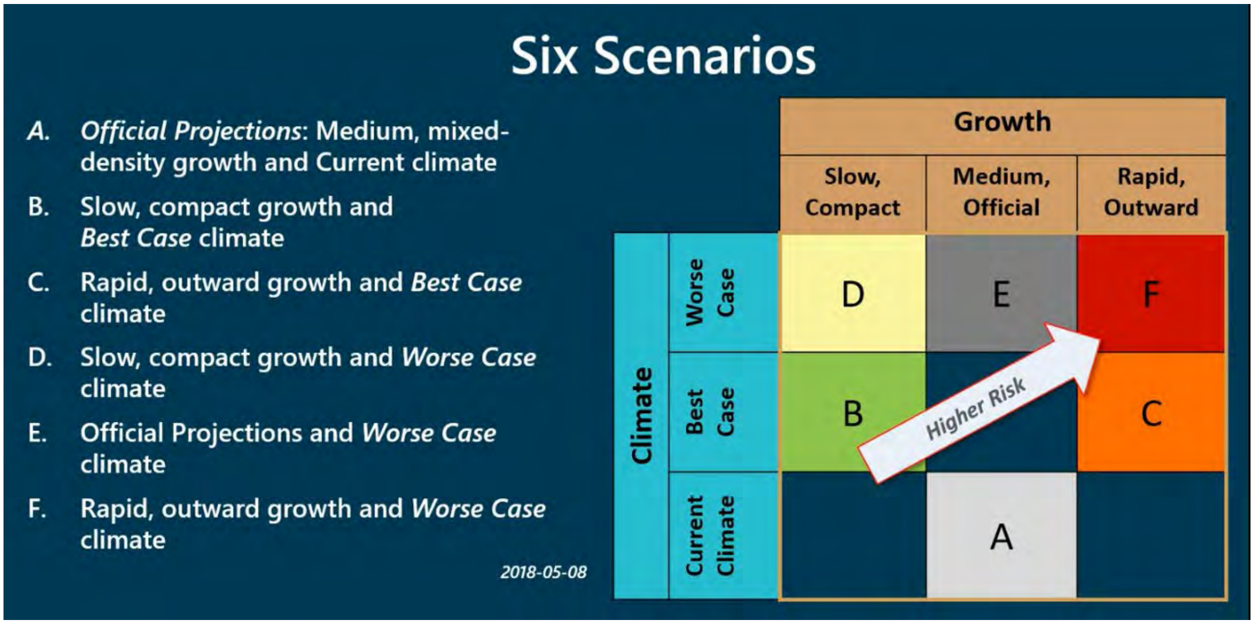


Figure 14. Schematic showing the combination of model methodologies used to develop future water-related outcomes within the Lower Santa Cruz River Basin (USBR, 2020).

The study is based on six future scenarios that consider a risk matrix of potential future impacts fromu three future emissions scenarios; best case, worse case, and current case, and three future growth (demand) scnearios; slow- compact, medium official, rapid-outward. This risk matrix can be seen in Figure 15, which indicates lowest risk in the lower left hand corner moving to highest risk in the upper right hand corner.



Six Scenarios

A. *Official Projections*: Medium, mixed-density growth and Current climate
B. Slow, compact growth and *Best Case* climate
C. Rapid, outward growth and *Best Case* climate
D. Slow, compact growth and *Worse Case* climate
E. Official Projections and *Worse Case* climate
F. Rapid, outward growth and *Worse Case* climate

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		Growth		
		Slow, Compact	Medium, Official	Rapid, Outward
Climate	Worse Case	D	E	F
	Best Case	B		C
	Current Climate		A	

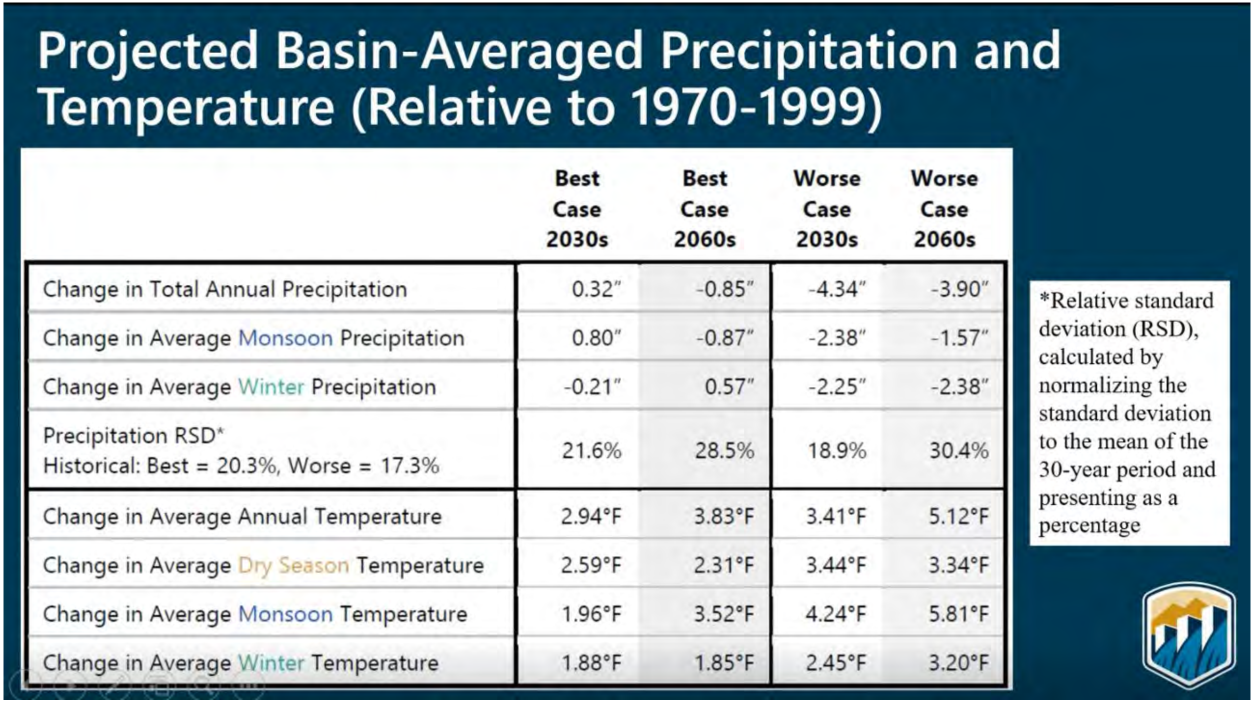
Figure 15. Risk matrix based on future climate and growth scenarios with the LSCRB (USBR, 2020).

LSCRB Study Air Temperature and Precipitation Projections

As identified in Section 3.2.1, the LSCRB study utilizes the current climate, a best case scenario, roughly equivalent to RCP 2.5, and a worse case scenario, roughly equivalent to RCP 8.5. These various scenarios and model projections yielded the changes as seen in Table 2, which include seasonal considerations during the dry season, wet season, and monsoon season, as well as considerations for the various future growth scenarios (Figure 15). Unlike many of the previous studies regarding climate projections within the region (Section 3.2.2) that provided a range of future outcomes for a given year, the LSCRB study provided specific outcomes for a range of years (i.e. 2030's).

Some of the highlights from the projected precipitation and temperature changes identified in Table 2 include the reduction in annual precipitation, especially in the worse case scenario, which is contrary to the long-term historic trend identified in Section 2.2.1. Contrary to this projection's disagreement with the historic precipitation trend, projected annual average temperatures in the region are expected to be very similar to those projected through the extrapolation of the historic temperature trends as seen in Figure 10 (Section 2.2.3).

Table 2. Projected basin-averaged precipitation and temperature changes at future time scales relative to 1970–1999 averages.



Projected Basin-Averaged Precipitation and Temperature (Relative to 1970-1999)

	Best Case 2030s	Best Case 2060s	Worse Case 2030s	Worse Case 2060s
Change in Total Annual Precipitation	0.32"	-0.85"	-4.34"	-3.90"
Change in Average Monsoon Precipitation	0.80"	-0.87"	-2.38"	-1.57"
Change in Average Winter Precipitation	-0.21"	0.57"	-2.25"	-2.38"
Precipitation RSD* Historical: Best = 20.3%, Worse = 17.3%	21.6%	28.5%	18.9%	30.4%
Change in Average Annual Temperature	2.94°F	3.83°F	3.41°F	5.12°F
Change in Average Dry Season Temperature	2.59°F	2.31°F	3.44°F	3.34°F
Change in Average Monsoon Temperature	1.96°F	3.52°F	4.24°F	5.81°F
Change in Average Winter Temperature	1.88°F	1.85°F	2.45°F	3.20°F

*Relative standard deviation (RSD), calculated by normalizing the standard deviation to the mean of the 30-year period and presenting as a percentage

3.2.2 TWSA Climate Projections Based on Other Regional Studies

This section provides an additional viewpoint on future climate projections specfic to the TWSA from a variety of peer-reviewed sources over the last 12 years. These projections serve a two-fold purpose of providing a perspective on how projections and methodologies change over time as climate science evolves, and an opportunity to understand the importance of exploring new methodologies such as those used in the USBR LSCRB study.

Precipitation Projections

Precipitation in the TWSA is projected to remain at about the same long-term historic trend of slowly increasing precipitation, but with increasing precipitation intensities. Figure 16 shows the observed trends (1895-2018) and climate projections represented by the full range of RCP 8.5 scenario outcomes associated with precipitation in the TWSA from 1895-2100 (Vose et al. 2017). Like the other projections, either in the local region or the greater CRB, a slightly increasing trend in precipitation is expected with year-over-year variability in annual precipitation becoming quite significant.

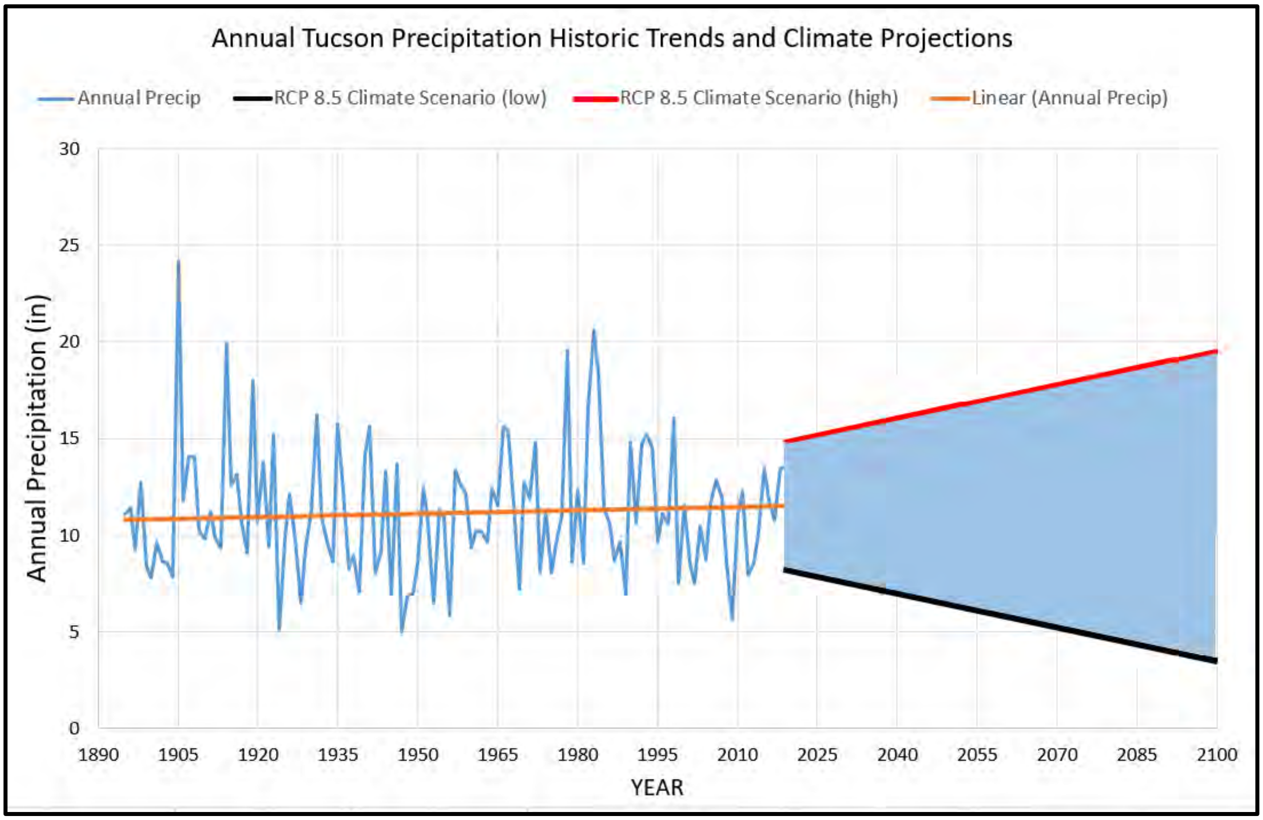


Figure 16. Historic observed and projected trends in annual Tucson precipitation from 1895–2100. Sources NCDC, 2020 and Vose et al., 2017.

While annual precipitation is expected to increase, as seen in Section 2.2.2., more of this precipitation is expected to come in the form of intense, short-duration rain showers or thundershowers. This presents a difficult challenge to stormwater capture and management as system capacity will need to be able to handle these intense, short-duration events going forward. This finding will be further detailed in Section 4.

Increases in precipitation intensities are expected to be particularly noticeable during the southwest Monsoon season. Study and modeling (CLIMAS, 2010) of the impacts of climate change on the southwest Monsoon season point to the following series of qualifying statements:

- Most climate projections indicate an increase in the duration and intensity of the Monsoon season.
- Increased heating as a result of climate change is expected to increase available atmospheric moisture. 3.5%/1°F (Clausius-Claperyon).

- GCM project a northward migration of the Jetstream, which favors monsoonal development earlier in the season.
- Increased heating should strengthen the thermal low at the surface, while entrenching the upper level area of high pressure over the four corner region, which will result in stronger and longer southwest Monsoon season.

GCM run for the IPCC 4th Assessment Report (IPCC, 2007) showed an almost across-the-board consensus that an increase in precipitation intensities is not only expected during the summer monsoon season, but, also, to some degree during the winter wet season as well. Figure 17 identifies the various GCM that were run as part of a similar analysis (Lin et al., 2008) that investigated the anticipated change in regional precipitation by season. The black line near the bottom of the spaghetti diagram in Figure 17 represent the observed precipitation data. This figure indicates that the GCM predict both an earlier and more robust monsoon season.

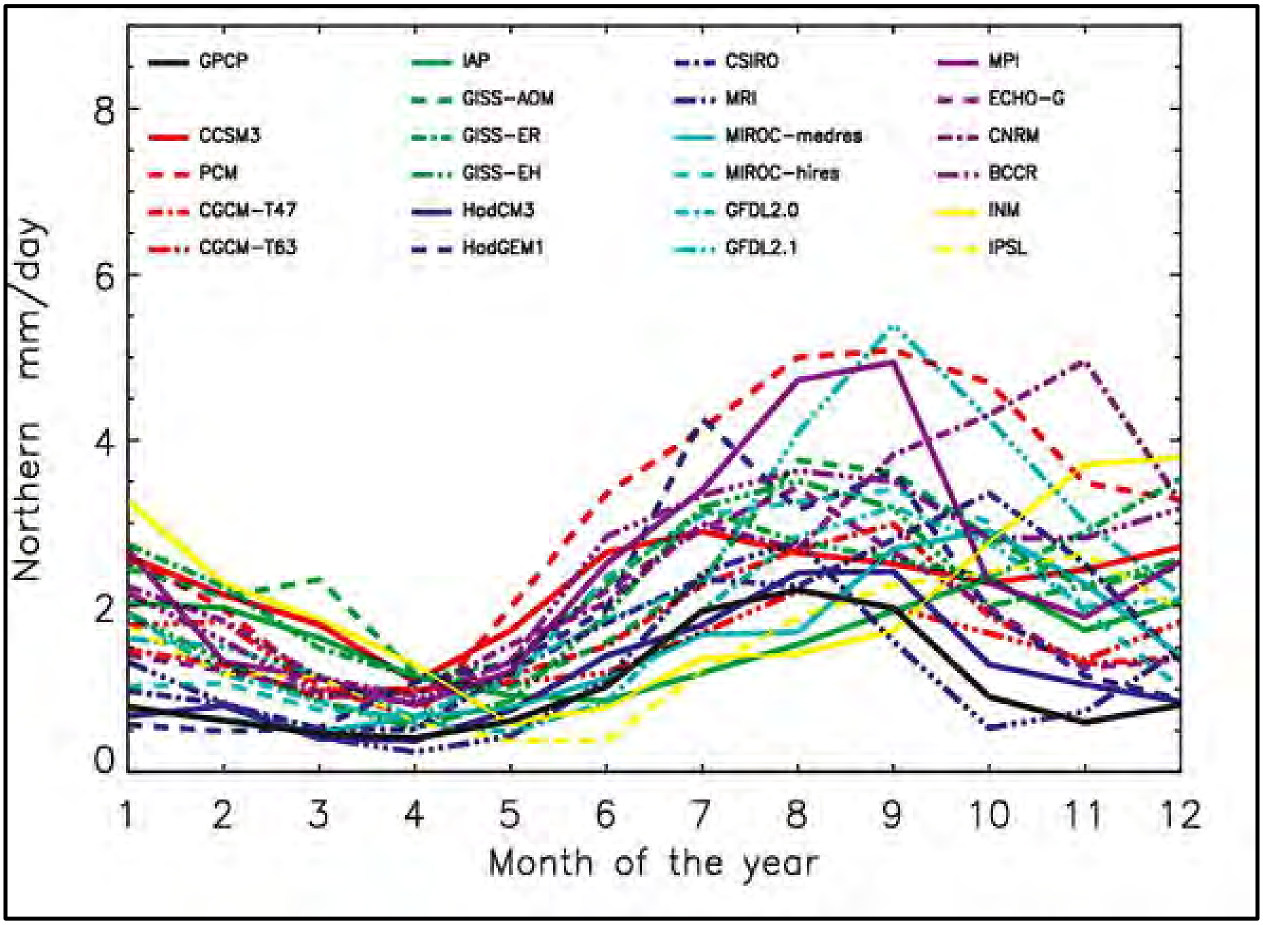


Figure 17. Projected precipitation by month in the southwestern U.S. associated with various GCM. Black line represents the observed precipitation data. Source: Lin et al., 2008.

The projection of future water surface flows, as recently reported in preliminary findings of the USBR Climate and Surface Water Analyses summary for the Lower Santa Cruz River study (USBR, 2019), are expected to show an increasing number of no-flow days in local rivers and streams (i.e. Davidson Canyon, Santa Cruz River nr Nogales, Sabino Creek). This number of no-flow days is expected to see a significant increase in the months of April, May and August, primarily due to increasing air temperatures. This study indicated that the number of no-flow days would be dramatically higher under the RCP 8.5 scenario versus the RCP 4.5 scenario, particularly by the year 2060.

Air Temperature Projections

As seen in the study of historic trends air temperature change within the CRB (Section 2.1.2) and the TWSA (Section 2.2.3), projected temperatures are expected to continue and/or accelerate this already increasing trend. Unlike the precipitation trends, the projected temperature trends show a very significant difference between the two future scenarios (RCP 4.5 and 8.5). Based on data from the NCA (NCA, 2018), TWSA annual air temperature are expected to increase by the temperatures indicated in Table 3 at the time scales identified in this table. These increasing temperatures in the TWSA can be seen graphically depicted in Figure 18.

Table 3. Projected annual average air temperature increase for TWSA for 2035, 2050, 2100 (NCA, 2018).

Projected Annual Average Air Temperature Increase for TW Service Region			
Scenario	Year		
	2035	2050	2100
RCP 4.5	2.11	3.72	4.25
RCP 8.5	2.3	4.8	10.63

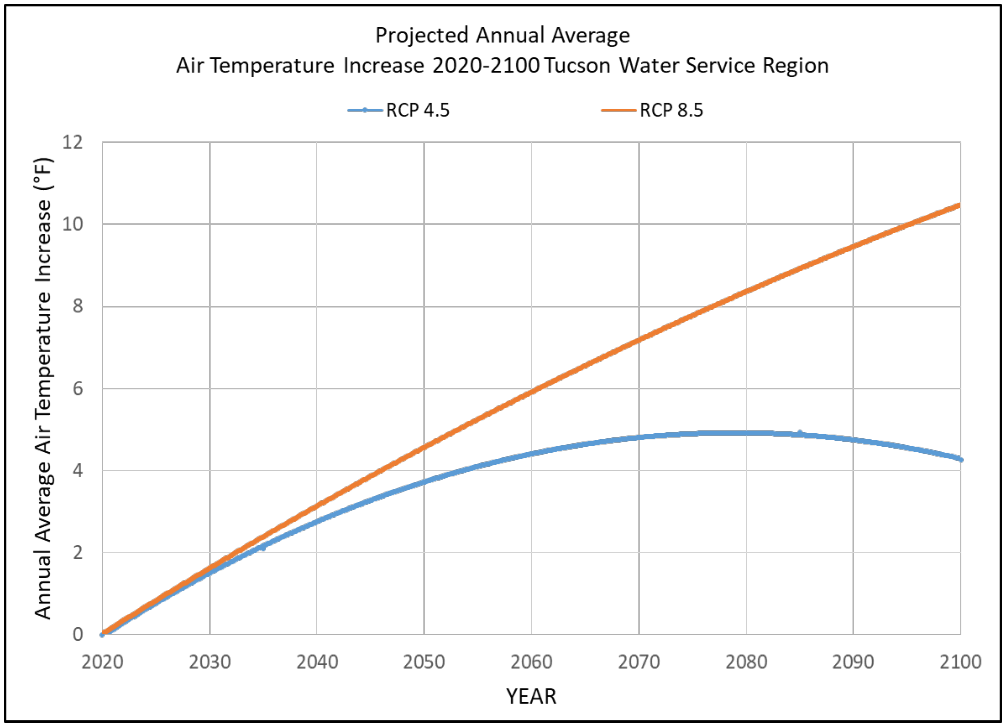


Figure 18. Projected annual average air temperature for TWSA 2020–2100 under RCP 4.5 and 8.5. Data source NCA, 2018.

One of the outcomes of these air temperature climate projections that cannot be seen in Figure 18 will be the increased number of extremely hot days (e.g. heat waves over 105°F). These days had increased 17.2 days a year since 1970 in Tucson by the year 2018 to 30 days/year. Based on the air temperature projections for annual average temperature in Figure 18, this increase in extremely hot temperatures is not only expected to continue but should accelerate through at least 2080 for RCP 4.5 and past 2100 for RCP 8.5. One of the comparisons that climate scientists use in order to explain what climate projections mean is the analogy that is drawn from a climate projection and observed climate data from another city or state. Thus, based on the climate projections for air temperature in the TWSA, Tucson should feel like Phoenix currently does (e.g. approximately 30 days of 110°F days/year) by the year 2050.

4 Summary of Tucson Water Climate Change Impacts

In the prior sections, all the expected changes in climate parameters have been detailed and quantified. This section is devoted to identifying the potential impacts of these changes to the Tucson Water system with considerations for both supply and demand.

4.1 Impacts of Climate Change to the Colorado River Basin and the CAP

As seen in the historic trends in precipitation in Section 2.1.1 and the projected trends in the CRB in Section 3.1.1, precipitation is expected to increase slightly in the CRB. This is in sharp contrast to the current 20-year drought, the increasing air temperatures, and the rapidly decreasing flow volumes in the basin over time. A recent study (Udall, 2017) has indicated that flows, on average across the CRB, are expected to decrease 4% for every 1°F of increasing temperature. As per the literature review in the appendix of this report, this is not the only research into the impacts of climate change on CRB flows, but it is the only one that quantifies the correlation between air temperatures and CRB flows.

Based on the historic trend extrapolation in Figure 13, this would indicate a reduction in CRB flows of approximately 20% by the year 2100, either through an extrapolation of the 1964-2019 trend or through the RCP 8.5 projection. Figure 12 indicates that CRB flow volumes are projected to be quite variable within a wide range of possible outcomes, while demand continues to increase.

4.1.1 CRB Impacts

The Colorado River Compact is a 1922 agreement regarding the amount of CRB water the seven U.S. states in the basin receive (Figure 1). In 1928, as part of the Boulder Canyon Project Act, the current specific annual allotments in the Lower Basin (California, Arizona, and Nevada) were established. These are equal to 7.5 MAF/year with Arizona below Lees Ferry receiving 2.8 MAF. This same amount (7.5 MAF) is allocated to the Upper Basin states of Colorado, Utah, Wyoming, New Mexico, and Arizona above Lees Ferry. According to the original compact agreement, if the Upper Basin does not deliver the required allotment (technically, 7.5 to 8.25 MAF), it would force the upper basin into managing water (i.e. releases from Flaming Gorge Reservoir) in a way as to meet the original allotment.

In 2019, the City of Tucson received its full allocation from the CAP of 144,191 AF and provided 91,616 AF in total potable water deliveries to Tucson Water customers. Tucson recharges their entire CAP allocation and recovers about two-thirds of it to meet customer demand on an annual basis. The remaining third is stored underground for future use. Tucson is able to save a third of their annual CAP allotment every year because their conservation program has been successful at managing demand. More information about the conservation program can be found in the “Water Conservation Program 10-Year Savings Projection” technical memo for the One Water 2100 master plan. More information about Tucson Water's CAP savings and groundwater supply can be found the "Water Use Projections" technical memo for the One Water 2100 master plan.

An accounting of the future impacts for water and environmental resources was developed (USBR, 2016) that are expected to have potential impacts in the CRB in the future. They are as follows:

- Snowpack runoff in the Upper CRB is expected to occur earlier in the spring, which will force a change in operational rule curves for the major reservoirs downstream in order to better manage releases later in the year.
- Spring and early summer runoff reductions could translate into less water supply for meeting irrigation demands and adversely impact hydropower operations at reservoirs.
- Warming could also lead to significant reservoir evaporation, increased agricultural water demands and losses during water conveyance and irrigation.
- Growing demands in the Colorado River system, coupled with the potential for reduced supplies due to climate change, may put water users and resources relying on the Colorado River at risk of prolonged water shortages in the future.

On April 16, 2019 the Colorado River Drought Contingency Plan Authorization Act became federal law. This law (H.R. 2030) overlaid the 2007 interim guidelines or what is known as the Seven States Agreement (DOI, 2007), which were a plan for operating Lake Mead and Lake Powell in coordination to stave off dramatic drops in water levels at either reservoir. The DCP is an agreement among the seven states of the Colorado River Basin that take the steps necessary to protect Lake Mead in the event of a shortage declaration on the Colorado River. The plan is made up of two drought contingency plans; one for the Upper Colorado River above Lees Ferry, and one for the Lower Colorado River below Lees Ferry. It is based on USBR updates to its projections each month, but the April report and the August report are the most critical in determining how much water will be released from Lake Powell and Lake Mead in the coming year. The elevation levels forecasted to be in each of those reservoirs at the end of each year trigger those releases.

Climate change has been identified as one of the drivers for the DCP. The James E. Rogers College of Law at the University of Arizona (Whitehill, 2019) identifies the DCP as, “an idea to give up more, concrete quantities of water now before we reach critical shortage levels in order to minimize the risk of losing even more water at unpredictable levels in the future".

The DCP, although complex and dependent on many different factors coming together, has been viewed by Federal and State lawmakers and local stakeholders as a big step forward towards dealing with water shortages in the southwestern U.S. According to a review of the plan at the University of Arizona College of Law, (Whitehill, 2019), the DCP is made up of three key mechanisms for addressing water shortages:

> Under the new DCP, the cuts in water supply are spread across multiple users, in accordance with three main mechanisms. The first is "mitigation water." Because the 2007 Guidelines list agriculture as the lowest priority user, farmers and other entities that face cuts will receive mitigation water, so the cuts are not as extreme. Right now, farmers in the Agriculture Excess Pool get 275,000 AF of water per year. Without mitigation water, farmers would see that CAP water completely cut under the Tier 1 shortages. Under the new plan, for three years (2020-2022), the farmers using the Agriculture Excess Pool would receive 105,000 AF of water per year. This mitigation water will come from cities that otherwise would have banked the water underground, the private water company EPCOR, and CAP owned water that is currently stored in Lake Mead and Lake Pleasant. Along with the mitigation water, Pinal County agriculture will receive funding to build groundwater infrastructure so it can rely less on CAP water in the future
>
> The second mechanism is monetary compensation to those who contribute some of their allotted water to mitigate the losses of other users. Over the length of the new DCP (2020-2026), the Gila River Indian Community will receive $60 million to forgo most of the NIA water it would otherwise be allotted.
>
> The third mechanism is offsets, which involves trading credit for the water stored in Lake Mead instead of that water being used between different water agencies and other entities. The goal is to leave more water in Lake Mead so that additional cuts will not be needed down the road. In exchange for leaving 10,000 acres of farmland fallow, tribes will receive $30 million over three years. This will result in 150,000 AF of water staying in Lake Mead. The total offsets under the DCP will be 400,000 af over the six years of the plan.

On June 25, 2020, the Arizona Department of Water Resources (ADWR) and the CAP reconvened the Lower Basin Drought Contingency Plan (LBDCPO) Steering Committee delegates to form the Arizona Reconsultation Committee (ARC). The ARC will develop an Arizona perspective on the reconsultation of the Colorado River Interim Guidelines for Lower Basin Shortages and the Coordinated Operations for Lake Power and Lake Mead, which are known as the aforementioned 2007 Guidelines or Seven States Agreement (DOI, 2007).

The ARC will play an important role formulating Arizona-centric input for the long-term management of the Colorado River system, which is expected to be developed by the U.S. Secretary of the Interior by the end of the year 2026. As detailed during the ARC Meeting 2, on September 17, 2020, the following initial key issues are at the forefront of these planning discussions:

- Balance the need for certainty with the need for flexibility to address changing conditions and circumstances
- Differing perspectives on mitigation post-2026
- Consider balancing perspectives on ICS storage and releases to avoid interstate impacts to priorities and user
- Desire to discuss the role and opportunities for senior priority users to offer water to junior priority users

Thus, as per the first bullet, which expresses the need for a flexible plan to address changing conditions and circumstances, understanding climate change and climate variability are going to be paramount to decision support for this effort. In order to address these needs, the ARC has created a Modeling and Analysis Workgroup (MAWG). This group is leading the implementation of a framework that will be used to identify and develop basin scale hydrologic models for demands and depletions, use behaviors, operations, priorities and initial model visualizations. Initial scenario development is expected to begin in April 2021.

4.1.2 CRB Demand impacts

Agriculture is a major component of the CRB’s economy with over 3.5 million acres of cropland in production each year (Cohen et al. 2013), of which, as of 2012, 1.8 million acres were irrigated (Laituri, 2012). Of this cropland area, approximately 60 percent of the acreage supports forage crops and pasture, which are used to support the livestock industry (Cohen, et al., 2013).

Increasing air temperatures are expected to reduce CRB flows due to increased evaporation and evapotranspiration, but these same increased air temperatures will also force water demand higher, especially as it relates to agriculture in the basin. In addition to anticipated losses to evaporation, irrigators will likely have to divert more water to grow the same types and quantities of crops due to higher evapotranspiration rates. Additionally, the timing of planting and harvesting will need to be altered to accommodate both longer growing seasons and earlier snowmelt in the headwaters of the CRB. Changes in runoff caused by increased evaporation and evapotranspiration coupled with variable precipitation patterns is predicted to produce an 8-10 percent decrease in CRB inflows by the year 2075 (Christensen et al., 2007).

4.2 Impacts of Climate Change to the Tucson Water Service Area

As noted in Section 4.1, renewable water supply from the CAP makes up a large portion of the City's overall water portfolio. The rest of the portfolio is made up of groundwater/recharge and its sources supplies including, remediated water, recycled water, and, to an increasing degree, water harvesting (active and passive stormwater collection). The following section will detail possible impacts to each of these water supply sources in Tucson as a result of climate change, as well as provide an overview of potential impacts to water demand in the TWSA.

4.2.1 Water Supply Impacts – Groundwater/Recharge

Groundwater recharge via CAP deliveries from the Colorado River is a significant source of water supply for the City of Tucson. In a report by the City from 2018 (City of Tucson, 2018), the status and quality of the groundwater supply is discussed. This paper details the successful turnaround that occurred within the groundwater system as a result of a very proactive approach to recharge. The map in Figure 19 (City of Tucson, 2018) shows the increase or decrease in water levels that has occurred in the Tucson/Avra Valley aquifer from 2000-2016 in the Tucson region. This trend has reversed the groundwater overdraft that had been occurring since the 1940's to the early 2000's.

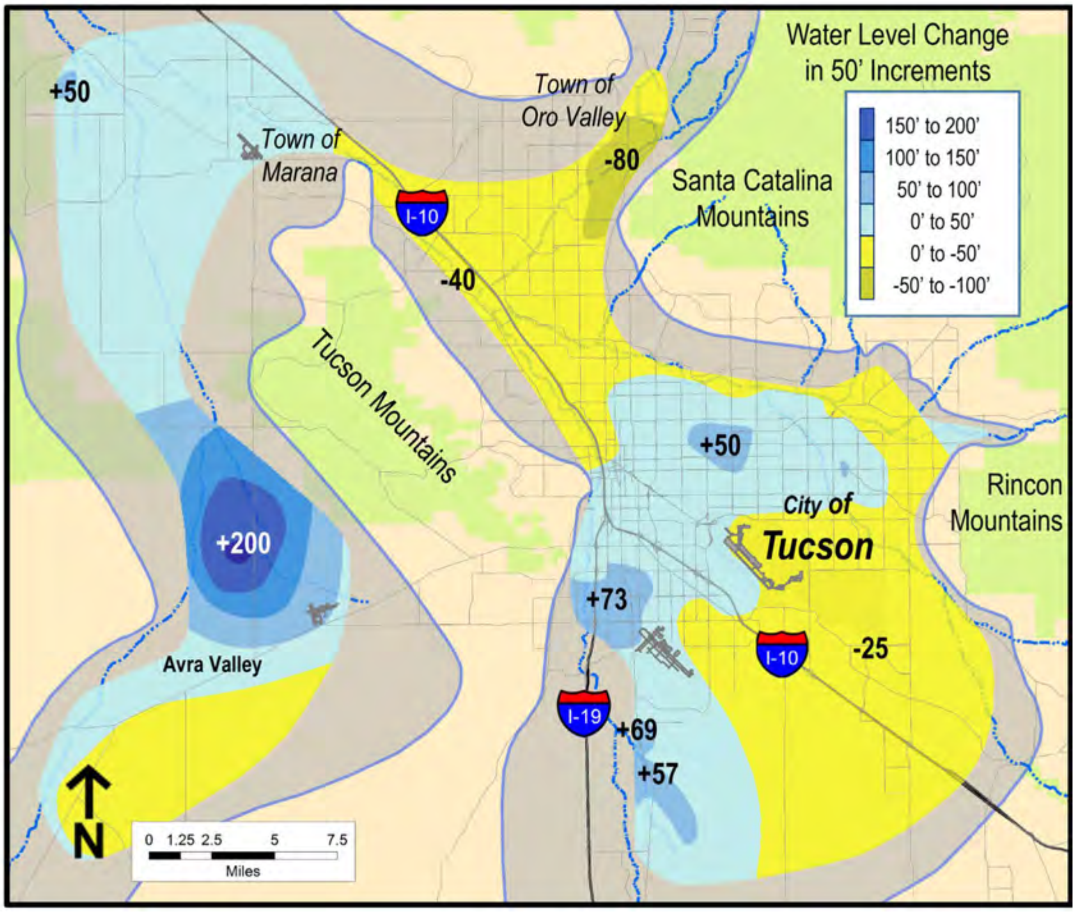


Figure 19. Map showing the change in water levels (ft.) in the Tucson/Avra Valley aquifers.

Based on the climate trends and projected climate parameters reported in the Sections 2 and 3, respectively, the climate change impacts to the City's groundwater and groundwater recharge program are expected to be a result of temperature-related impacts to the CRB and the local demand equation. While both the CRB that produces the CAP water as part of the groundwater recharge program, and the TWSA are expected to see a slightly increasing annual precipitation, air temperatures are expected to greatly impact evaporation, evapotranspiration, soil moisture, and demand in those regions.

The impact of increasing temperatures is expected to produce a small overall decrease in both naturally infiltrating groundwater and water that is awaiting recharge in recharge facilities (i.e. Clearwater facility) and other sources within the TWSA. This would be the result of increased evaporation due to increasing air temperatures. Based on the Clausius-Clapeyron equation, this increase in evaporation should be equivalent to approximately 3.5% per 1°F increase in air temperatures. As per the Penman Equation for evaporation, this approximation could vary considerably based on other factors (i.e. solar radiation, wind, dewpoint, etc.), but represents a middle-of-the-road value. Using this anticipated increase in evaporation combined with the historic trend in annual average air temperatures extrapolated from the data in Figure 10, this reduction would be 14.4% by the year 2100. Based on the projected temperature change projected in Figure 16, this would result in a 13% (RCP 4.5) or a 14.8% (RCP 8.5) reduction in water available for recharge by 2050, and a 13.5% (RCP 4.5) or a 37% (RCP 8.5) reduction by 2100.

In a relatively recent paper concerning the aspects of climate change and its potential impact on groundwater recharge (Meixner, et al., 2015), the author identifies that climate impacts depend on the following:

- Basin structure, depth to water
- Aquifer recharge type: streambed, mountain front recharge, agricultural and municipal return flows, etc.
- Groundwater/surface water interactions
- Temperature, ET
- Intensity and seasonality of precipitation and resulting runoff
- Channel morphology, erosion, flooding
- Changes in land use and technology
- Changes in vegetation

Thus, mitigation efforts should be geared towards addressing these issues within the Tucson/Avra Valley recharge and recovery basins; CAVSARP and SAVSARP. Fortunately, the City's proactive efforts toward basin recharge (improvements in depth to water) have been successful during the last 20 years of drought in the region. As pointed out previously in this section, while the City of Tucson has been proactive in addressing the components on this list, the one in regard to temperature/evapotranspiration is one that will be very difficult, if not impossible, to mitigate.

4.2.2 Water Supply Impacts – Stormwater Capture (Water Harvesting)

As the City has already realized, rain and stormwater harvesting has numerous benefits and is a potential source of increased future water supplies for the region. The Water Harvesting Guidance Manual (City of Tucson, 2005) is still applicable today, but probably could use an update to both enhance community involvement and provide guidance for the future of water harvesting in the region.

As discussed in Section 2.2.2, precipitation intensities have already begun to change in the region and are expected to continue to become more intense with continued climate change in the future. This presents a distinct capacity problem as stormwater capture becomes a bigger part of Tucson's water portfolio. Stormwater capture can range from a 50-gallon barrel under a downspout to retention/percolation/infiltration basins to large above ground storage facilities. These types of infrastructure can provide a significant source of water supply in the region but can also be overwhelmed in extreme precipitation events. Therefore, infrastructure for stormwater capture may need to be upsized to accommodate for more intense precipitation events.

4.2.3 Water Supply Impacts – Remediated Water/Recycled Water

Water remediation as a source of water supply for the City comes from the Tucson Airport Remediation Project/Advanced Oxidation Process (TARP/AOP) Treatment Facility. This is primarily a closed system, so it is unlikely that this system will undergo any significant impact from climate change other than that related to the impact of increased air temperatures on the oxidation process (which may require adjusting the hydrogen peroxide levels).

Recycled water is primarily a closed system, as well, until the end product reaches its destination as a source for irrigation water or groundwater recharge. At this point in its processing, it becomes vulnerable to increased evaporation from anticipated increases in air temperature in the region. Thus, the same amount of recycled water that is being produced today, is expected to not have the same irrigation capabilities in the future. Additionally, the overall impact of evaporation and evapotranspiration on the end user is likely to produce a reduction in return flows to the system.

As with all of the water supply infrastructure with the TWSA, recycled or remediated water will need to be conveyed through pipes or conduits. As noted in Section 4.2.2., precipitation intensities are expected to increase as the climate in the region becomes warmer. These increasing precipitation intensities are likely to produce an elevated flood risk that could damage water supply conveyance such as that associated with remediated or recycled water. This would be particularly true in situations where these pipes cross washes or arroyos.

4.2.4 Water Supply impacts – Water Quality

The City is fortunate to have a very large aquifer for groundwater storage. The usual sources of water quality issues as a result of climate change; stormwater runoff, erosion and sedimentation, and harmful algae blooms (EPA, 2019) are all threats that have a much greater impact on surface water supplies than that associated with groundwater sources. Again, increasing air temperatures, which result in increased surface water temperatures (ratio is 0.6°F to 0.8°F of water temperature rise per 1°F air temperature rise), are the biggest culprit, but minimal water quality impacts are expected to the TWSA now and into the future.

As active and passive stormwater capture have gained popularity around the country, and particularly in the arid southwestern U.S., concerns regarding water quality issues have increased as well. While climate change is expected to increase the likelihood that stormwater capture programs continue to expand, it may also need to an expansion of stormwater treatment techniques so that water quality issues do not become a problem (San Diego Coastkeeper, 2020). Accommodations for potential issues with water quality will need to be considered as the use of stormwater capture grows as a water supply source in the TWSA.

4.2.5 Water Supply Impacts – Drought and Mega-drought Impacts

As reported earlier in Section 2.1.1, and graphically depicted in the climate reconstruction in Figure 4, several multi-decadal (mega-) droughts have occurred in the southwestern U.S. in the past 1000 years. A recent study by Columbia University (Steiger, et al., 2019) investigated the physics behind these phenomena and their initiation in and impact on global weather patterns. They found that mega-droughts were associated with a significant cooling of the Pacific Ocean waters as a result of radiative forcing (less energy from the sun) as represented by a reconstruction of the NINO3.4 index from the year 800 to the year 2000.

The NINO3.4 index is a "hydro-climate" index that basically represents energy within the global system in a given region. This energy exists primarily as heat energy stored in the oceans (both sea surface and sub-surface temperatures are a large component of these values). During the period between the years 800 to 1600, the reconstructions found that there were multiple periods of years with very low NINO3.4 index values that were associated with 14 periods of multi-decadal droughts in the southwestern U.S.

These periods of cool Pacific waters, much cooler than today's La Nina periods, produced dry, stable conditions over the region, and very little precipitation fell for long multi-decadal periods. So, are they likely to return? This question was not answered within the referenced document, but based on current climate trends, it is likely that any future multi-decadal periods of low NINO3.4 values in the Pacific as a result of radiative forcing would be offset by a warming environment as a result of global climate change. Thus, it is possible that global climate change could play a role in limiting future mega-droughts in the southwestern U.S.

Impacts to the City from a mega-drought are not expected to be immediately felt as their groundwater aquifer could produce water for many decades when combined with increased water conservation practices. However, a drought in the southwestern U.S. lasting for 50 years or more would, eventually, force the City into a situation where water imports from faraway sources may be the only option.

4.2.6 Water Demand impacts – Physical, Social, and Behavioral

Physical water demand is expected to increase as the atmosphere warms in the TWSA. In a 2013 report in the Journal of Physical Geography (Balling and Cubaque, 2013), estimates of the increase in the per capita water demand by the year 2050 was expected to be an increase of 3% in the Phoenix area. This report only applies to residential water use in the Phoenix region, which is not supplied by Tucson Water.

Agricultural water demand is expected to increase as well. A study (Kosa, 2009) investigating the relationship of air temperature (X) to generalized evapotranspiration (Y) found that this relationship can be represented by the equation:

$$y = -0.028x^2 + 1.7608x - 22.932$$

If this were to be applied to the TWSA, based on the historic TWSA air temperature trends (Figure 9) and the projected TWSA air temperature trends, Section 3.2.2, Table 3 and Figure 18, the resultant increase in evapotranspiration expected in the TWSA is 0.04 inches/day for the historic trend by the year 2100, 0.042 inches/day for RCP 4.5 by the year 2100, and 0.087 inches/day for RCP 8.5 by the year 2100. These numbers seem quite small, but they represent a per day rate over many acres of irrigated plantings in the region.

Climate change is expected to impact water demand through changes in social behavior, primarily as it relates to health issues because of increased air temperatures and heat waves. The Center for Disease Control (CDC, 2016) identifies an air temperature of 95°F as the temperature at which health problems are likely to occur within a community/society, particularly within the more vulnerable populace. An increase in the number of extremely hot days is expected to be a consequence of climate change and is expected to have a significant impact on water usage during these extremely hot periods; possibly for both physiological and psychological reasons. Figure 20 identifies the historic trend (1895-2019) in the number of 100°F days in the TWSR. While the trend shows a steady increase in the number of 100°F days over time, the same inflection point that showed up in the temperature graphs in Figure 9 is plainly seen around 1964 in the number of 100°F days. Figure 21 shows an extrapolation for this same trend out to the year 2100. Thus, if the historic trend were to continue in the absence of any consideration for climate change, the number of 100°F days in Tucson would be expected to reach approximately 76 days/year by the year 2100.

Additionally, these increasing air temperatures are expected to make an impact on water demand during all seasons (i.e. winter wet, dry, and monsoon), but are expected to be particularly impactful during the end of the winter wet season. Warming during this time of year is expected to decrease soil moisture during the months of March and April, at a time when most plants and agriculture need it the most. As reported in the preliminary findings for the USBR Lower Santa Cruz River study (USBR, 2019), while hotter weather would normally increase evapotranspiration, reduced soil moisture during this time is expected to reduce evapotranspiration due to lack soil moisture.

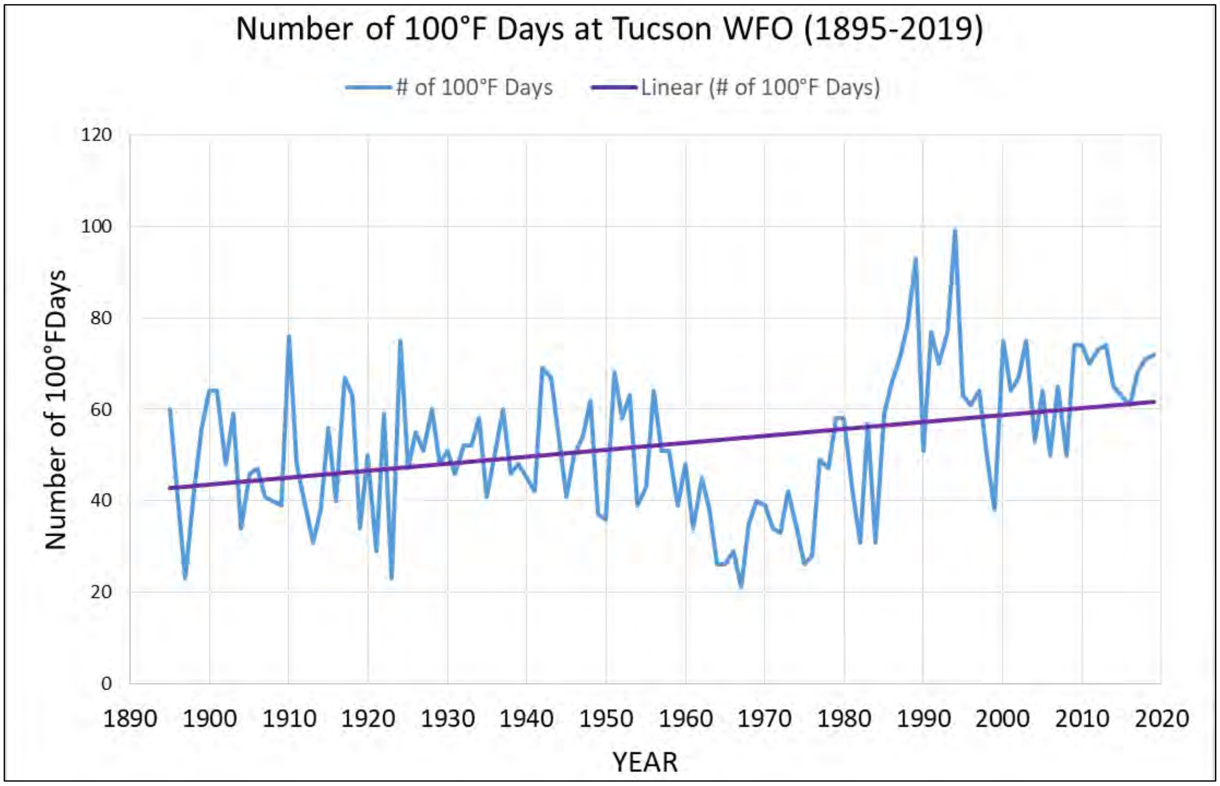


Figure 20. Observed number of 100°F days at Tucson National Weather Service Weather Forecast Office (WFO) 1895–2019.

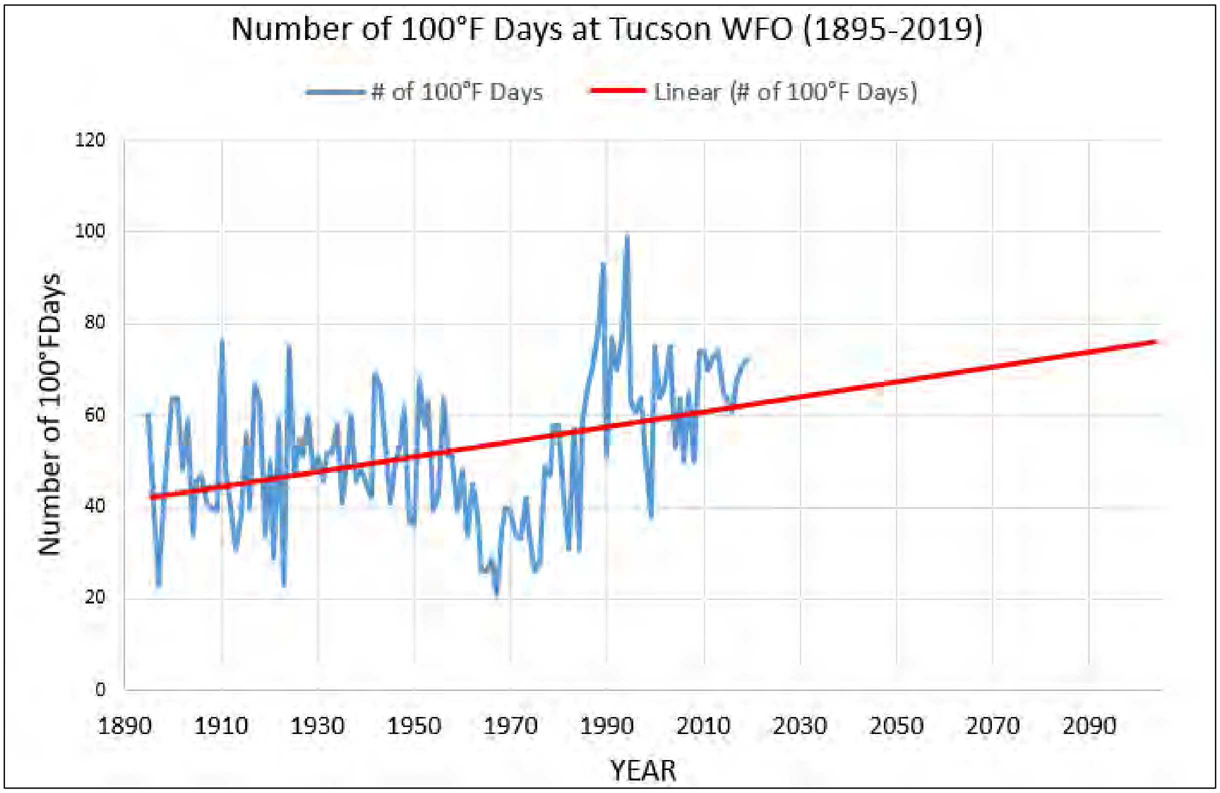


Figure 21. Extrapolation of number of observed 100°F days in Tucson National Weather Service Weather Forecast Office (WFO) (1895–2019) to the year 2100 (red line).

5 Conclusion

The impacts of climate change are expected to provide an iterative challenge to Tucson Water’s efforts to formulate the One Water 2100 Master Plan and during its implementation in the future. While recent observed climate trends show significant changes from the long-term historic record, climate projections, particularly those associated with water availability, indicate that a pro-active response will be necessary to mitigate potential water management impacts. As identified in the objectives for the recent USBR LSCRB Study (USBR, 2020), physical water resources infrastructure are going to be needed to mitigate supply and demand imbalances, and strategies are going to be needed to improve water reliability for municipal, industry, agriculture, and environmental sectors through the year 2060.

Fortunately, through the combined efforts of the Federal (i.e. USBR, USACE, DOI, etc.), State (i.e. ADWR, ARC, CAP), and Local stakeholders (i.e. Tucson Water) , the right questions are being asked and solutions are being discussed, modeled, vetted, and developed in what thus far has proven to be a collegial environment. The next steps towards water supply resilience will come from all levels of government and will require input from groups such as ARC’s Modeling and Analysis Workgroup to provide the highest level of decision support for initial mitigation efforts.

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United States Bureau of Reclamation (USBR). 2016. *2016 SECURE Water Act Report - Colorado River Basin Fact Sheet. Website: https://www.usbr.gov/climate/secure/docs/2016secure/factsheet/ColoradoRiverBasinFactSheet.pdf*

United States Bureau of Reclamation (USBR). 2019. Colorado River Basin Drought Contingency Plans. Website: https://www.usbr.gov/dcp/. Washington, D.C. May 2019.

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Website: https://www.usbr.gov/lc/phoenix/programs/lscrbasin/mdocs/20191121climate.pdf

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Website: https://www.tucsonaz.gov/files/clerks/uploads/bccfiles/31639.MP3

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Appendix A. Climate Change Literature Review

This literature review is provided as a precursor to the analysis of the anticipated impacts of climate change on the Tucson Water system. Among the multiple anticipated effects of climate change within the southwestern U.S. are the long-term change in precipitation variability and air temperatures. These changes are expected to result in impacts to both water supply and demand in the region. This literature review will investigate significant study of these anticipated impacts as a basis of reference for this study. As with many climate science literature reviews, although there is a need for geographic specificity, climate change is a global phenomenon. Thus, this literature review covers local and regional, as well as important global research and study efforts regarding this topic.

Summary of Local, Regional, and Global Climate Change Literature

Balling, R.C., Cubaque, H.C. 2009 Estimating Future Residential Water Consumption in Phoenix, Arizona Based on Simulated Changes in Climate, Physical Geography, 30:4, 308-323, DOI: 10.2747/0272-3646.30.4.308. Previous studies have shown that residential water consumption in Phoenix, Arizona is significantly related to changes in climate, although that sensitivity varies substantially from one census tract to another. In this investigation, the authors determine the empirical relationship between water consumption and variations in temperature and precipitation. They found the sensitivity of water consumption to either climate variable is positively related to the percent of land covered in mesic irrigated landscaping, mean household income, lot size, and percent of single-family residential lots containing swimming pools. They used estimated changes in temperature and precipitation for 50 model-scenario combinations presented by the IPCC, and they determined that mean water consumption should increase by an average of over 3% by ~2050, but the climate-induced change in consumption varies considerably across census tracts.

Website: https://www.tandfonline.com/doi/abs/10.2747/0272-3646.30.4.308 (requires access).

Beller-Simms, N., E. Brown, L. Fillmore, K. Metchis, K. Ozekin, C. Ternieden, K. Lackey. 2014. *Water/Wastewater Utilities and Extreme Climate and Weather Events: Case Studies on Community Response, Lessons Learned, Adaptation, and Planning Needs for the Future*. Water Environment Research Foundation. This report summarizes that extreme climate and weather events are occurring more frequently and with more intensity across the nation. They often leave communities, and the water utilities that serve them, reeling from costly aftermath. These extreme events have the potential to disrupt water services including drinking water supply, wastewater conveyance and treatment, and stormwater management.

This report is intended to facilitate peer-to-peer sharing on how water resource managers are coping with extreme events and building resiliency. Research was conducted at six local workshops, organized to include participants that experienced different types of extreme events throughout a river basin or watershed. The localities included:

Apalachicola-Chattahoochee-Flint River Basin, Georgia, Central Texas, Lower Missouri River Basin, Kansas and Missouri, National Capital Area, Russian River Basin, California, Tidewater Area, Virginia.

Website: https://www.waterrf.org/research/projects/waterwastewater-utilities-and-extreme-climate-and-weather-events-case-studies-0

Brown, C. and R.L. Wilby. 2012. *An alternate approach to assessing climate risks*. Eos Transactions American Geophysical Union, Volume 93. This paper concerns the inconsistencies and variations that come out of the analysis of Global Climate Models (GCM) during the course of a climate risk analysis and how those methodologies can be improved through the use of varying alternatives to GCM-based analyses. This paper states that, “Climate scenarios can be generated parametrically or stochastically to explore uncertainty in climate variables that affect the system of interest [Prudhomme at al., 2010; Brown et al., 2011]. This allows sampling changes in climate that include but are not constrained by the range of GCM projections. The definition of scenarios can be developed as part of a stakeholder-driven, negotiated process, and climate projections can be used in this process [Hallegatte et al., 2012]. In other words, institutional knowledge of from a given stakeholder can assist in developing a more efficient, and, perhaps, negotiated process for the use of climate projections.

Website: https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2012EO410001

City of Tucson, 2018. *Status and Quality of the Aquifer.* Tucson Water, September 2018. This document provides an overview of the condition of the groundwater aquifer and the various supplements to the system from existing groundwater, CRB water (CAP), remediated water (TARP plant), recycled water, and stormwater from active and passive systems. A comparison of the state of the system to what the condition of the system was 1998 is proffered. Maps are provided showing the level changes in aquifer water during the period 2000-2016.

Website: *https://www.tucsonaz.gov/files/water/docs/Aquifer.pdf*

Chief, K., A. Meadow, and K. Whyte. 2016. *Engaging Southwestern Tribes in Sustainable Water Resources Topics and Management*. Water, 8, 350. This paper has three objectives:

1. To provide an overview of the context of current indigenous water management issues, especially for the U.S. federally recognized tribes in the Southwestern United States.
2. To synthesize approaches to engage indigenous persons, communities, and governments on water resources topics and management.
3. To compare the successes of engaging Southwestern tribes in five examples to highlight some significant activities for collaborating with tribes on water resources research and management.

For the five select cases of collaboration involving Southwestern tribes, the success of external researchers with the tribes involved comprehensive engagement of diverse tribal audience from grassroots level to central tribal government, tribal oversight, on-going dialogue, transparency of data, and reporting back. There is a strong recognition of the importance of engaging tribal participants in water management discussions particularly with pressing impacts of drought, climate change, and mining and defining water rights.

Website: *https://www.mdpi.com/2073-4441/8/8/350*

Climate Assessment for the Southwest (CLIMAS), University of Arizona. 2010. Author: Truebe, S. The Southwest Monsoon Under Climate Change: *What the Models Tell (and Don't Tell) Us*. Climate Assessment for the Southwest (CLIMAS). A brief review of the global climate model output as it pertains to impacts on the SW monsoon. This was a blog post that summarized the current (at the time) understanding of what to expect in regards to changes in the SW monsoon.

Website: *https://climas.arizona.edu/blog/southwest-monsoon-under-climate-change-what-models-tell-and-don%E2%80%99t-tell-us*

Climate Central. 2019. *American Warming: The Fastest-Warming Cities and States in the U.S.* Research brief by Climate Central Published April 17, 2019. This article highlights the fact that in April 1970, Americans celebrated the first Earth Day, an event meant to heighten public awareness of of environmental protection. Since then, humanity has dumped an enormous amount of heat-trapping gas into the atmosphere. Atmospheric CO2 concentrations rose by more than twice as much in the half century after the first Earth Day than they did in the entire century before 1970. There is now more CO2 in the atmosphere than at any point in at least the last two million years.

Humanity's greenhouse gases have made the world hotter. That warming is at the root of many of climate change's dangers, from droughts and sea level rise to heatwaves and agricultural problems. Warming is increasing the frequency and intensity of extreme weather, damaging public health, stressing food and water supplies, shifting seasons and ecosystems, boosting sea levels, damaging infrastructure and local economies, and threatening ways of life.

Website: *https://www.climatecentral.org/news/report-american-warming-us-heats-up-earth-day*

Crimmins, M., D. Ferguson, A. Meadow, and J. Weiss. 2017. *Discerning "Flavors" of Drought Using Climate Extremes Indices*. Journal of Applied Meteorology and Climatology, Volume 56. This study reviewed numerous climate extremes indices to investigate historical hydroclimatic variability across tribal lands of the Four Corners region in the southwestern United States over the period of 1950–2014. Five extremes indices were identified that provided additional insight into interannual hydroclimatic variability. Results from this study indicate that operational drought monitoring and historical drought assessments in arid and semiarid regions would benefit from the additional insight that daily-based hydroclimatic extremes indices provide, especially in light of expected climate change–driven changes to the hydrologic cycle.

Website: *https://journals.ametsoc.org/doi/10.1175/JAMC-D-16-0270.1*

Dascher, E., J. Kang, G. Hustvedt. 2014. *Water sustainability: Environmental attitude, drought attitude and motivation*. International Journal of Consumer Studies, 38. This study examined the relationships among US consumers' perceptions of drought severity, perceived importance of water conservation drivers, participation in water/energy conscious consumption, and perceived consumer effectiveness (PCE) in both general environmental issues and drought. A survey of 273 consumers in the US State of Texas was conducted during the most severe single-year drought in the region's history. Exploratory factor analysis, confirmatory factor analysis, and structural equation modelling were used for data analysis. The results of this study support the importance of PCE in sustainable consumer behavior and suggest that PCE for a specific issue has a more direct impact on relevant consumer behavior than PCE for a generalized issue. The results of this study also suggest that policy makers should focus upon water restrictions and educational campaigns as part of their demand side management of water resources rather than providing incentives for water conservation technologies. Lastly, the exploratory variable used to measure water/energy conscious consumption has been validated in this study and suggests that at least a partial percentage of consumers are consciously making water/energy purchase decisions within a larger framework of reduced resource availability.

Website: https://www.researchgate.net/publication/263670573_Water_sustainability_Environmental_attitude_drought_attitude_and_motivation

Davis, T. 2018. *Long drought makes outlook for Tucson's share of CAP water grim*. Arizona Daily Star. This article summaries the U.S. Bureau of Reclamations longer-range outlooks for Lake Mead and the Central Arizona Project (CAP). At the time of the article, they predicted the CAP, which provides drinking water to Tucson and Phoenix, would have over a 50 percent shortage in 2020 and over 60 percent in 2021 through 2023. These shortages would cut CAP deliveries by about 20 percent, and would impact groups such as the Central Arizona farmers, Arizona Water Bank, and Central Arizona Groundwater Replenishment District.

Website: https://tucson.com/news/local/long-drought-makes-outlook-for-tucson-s-share-of-cap/article_a6880ebc-16a5-5468-944f-f2bd167de8e2.html

Demaria, E., P. Hazenberg, R. Scott, M. Meles, M. Nichols, D. Goodrich. 2019. *Intensification of the North American Monsoon Rainfall as Observed From a Long-Term High-Density Gauge Network*. Geophysical Research Letters. This study addresses the challenge of detecting temporal changes in rainfall intensities in response to climatic change due to highly variable and localized nature of rainfall during the North American Monsoon in southwestern United States and northwestern Mexico. The study uses the dense, subdaily, and daily observations from 59 rain gauges located in southeastern Arizona. It was found there was intensification of monsoon subdaily rainfall intensities starting in the mid-1970s that has not been observed in previous studies or simulated with high-resolution climate models. The results highlight the need for long-term, high spatiotemporal observations to detect environmental responses to a changing climate in highly variable environments and show that analyses based on limited observations or gridded data sets fail to capture temporal changes potentially leading to erroneous conclusions.

Website: https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2019GL082461

Eden, S., E. Canfield. 2019. *Water Harvesting Resurges in Tucson*. WEF Stormwater Institute – Stormwater Management, Volume 7, Issue 2. Water harvesting has been used in the Tucson, Arizona region since prehistoric times and is now in resurgence. Within the past 30 years, Tucson has become a leader in desert rainwater and stormwater capture to build resilience and address growing concerns about water scarcity. Beginning with grassroots efforts focused on collective impacts of individual and neighborhood actions, a new attitude toward rainfall as a resource is flourishing. Local programs encourage citizen participation and support small-scale, distributed infrastructure, with an emphasis on retrofitting properties and roadways, while a large-scale stormwater harvesting project collects enough water to irrigate a regional sports park.

Website: https://wrrc.arizona.edu/sites/wrrc.arizona.edu/files/attachment/tucson-leads-way.pdf

Environmental Protection Agency (EPA). 2019. *Climate Impacts on Water Quality.* The adaptation strategies provided in this document are intended to inform and assist communities in identifying potential alternatives. They are illustrative and are presented to help communities consider possible ways to address anticipated current and future climate threats to contaminated site management.

Website: *https://www.epa.gov/arc-x/climate-impacts-water-quality*

Ferguson, D., M.Finucane, V.Keener, and G. Owen. 2016. *Evaluation to advance science policy: lessons from Pacific RISA and CLIMAS*. In Climate in Context: Science and Society Partnering for Adaptation, Chapter 10. Chichester, West Sussex: John Wiley & Sons Ltd. This chapter discusses the evaluation activities Pacific Regional Integrated Sciences and Assessments (RISA) and the Climate Assessment for the Southwest (CLIMAS) and providing examples of metrics and methods for evaluating the programs that are implemented in a complex, real-world environment. It argues that to inform science policy across scales, evaluations should be designed so that results are meaningful and legitimate, and, at the same time, also allow for the highly iterative and adaptive nature of the environments in which RISA work is done and utilized. Lessons learned from the evaluation initiatives are also described.

Website: https://onlinelibrary.wiley.com/doi/pdf/10.1002/9781118474785.ch10

Finster, M. 2016. *Climate Change and the Wastewater Sector*. Risk and Infrastructure Science Center, Argonne National Laboratory. This presentation, which was based on a research paper from Argonne National Labs, provided an overview of the anticipated impacts of climate change, observed climate trends, anticipated impacts to the wastewater industry and an accounting of potential system vulnerabilities. A case study regarding the impacts of extreme storms (Superstorm Sandy) and its impact on the New Jersey region's wastewater treatment systems were given as an example. The presentation was concluded with a summary of potential adaptation tools and a diatribe on the implications and cost efficiencies of infrastructure planning.

Website: N/A

Frisvold, G. 2017. ***A Colorado River Shortage Declaration: Planning, Responses, and Consequences.*** **Climate Assessment for the Southwest (CLIMAS).** Based on interstate and international agreements, a Colorado River shortage declaration would reduce surface water deliveries to primarily to Central Arizona, with nearly all the cuts applied to agriculture, representing a 25%–40% reduction in surface water to the region's farms. The U.S. Bureau of Reclamation provides forecasts of the probability of a shortage declaration based on Lake Mead water levels. Little is known about whether early warning systems are meeting farmers' needs and what a shortage would mean for income, jobs, and groundwater use in rural economies. The study will assess how stakeholder groups currently use Colorado River supply forecasts in decision-making and what contingencies they are making in the event of a shortage declaration, the economic consequences of a shortage declaration on agriculture and the local economies in central Arizona, and potential impacts of a shortage declaration on groundwater pumping and water levels in central Arizona Active Management Areas.

Website: https://climas.arizona.edu/research/colorado-river-shortage-declaration-planning-responses-and-consequences

Frisvold, G. 2019. ***Climate Policies as Water Policies, Applied Methods for Agriculture and Natural Resource Management*****. Climate Assessment for the Southwest (CLIMAS)**. This study uses an updated version of the U.S. Agricultural Resource Model (USARM)—a multi-region U.S. agricultural sector programming model—to examine effects of climate change mitigation policies on U.S. water resources. One scenario considers effects of increasing prices of energy and energy-intensive inputs (primarily fertilizers) through a carbon tax or cap-and-trade program. A second scenario combines the first scenario with an agricultural offset program where farmers are paid to retire cropland for carbon sequestration. The consequences of climate mitigation policies for agricultural water use and pollution control have received relatively little attention in part because—unlike USARM—many national agricultural sector models do not explicitly include water as an input. USARM also allows for input substitution among seven inputs in a CES framework, while accounting for all major crops as well most specialty crops, federal commodity programs, and crop exports. Major results are as follows. First, climate mitigation policies have scope to significantly reduce agricultural water use. Whether domestic offsets are included has little effect on the total amount of water conserved, but has a large effect on which parts of the country the conservation takes place. Second, either carbon taxes or cap-and-trade combined with domestic offsets combines two policies often modeled as potential solutions to the hypoxic "dead zone" in the Gulf of Mexico—increased fertilizer prices and land retirement. Climate policies may have unanticipated, near-term, environmental benefits by addressing the hypoxia problem. Third, while domestic offsets reduce total fertilizer and agricultural chemical use, they increase their use per acre. Particularly in watersheds with significant land retirement, there could be unintended intensive margin effects where fertilizer and chemical use are increased. Despite this last, cautionary finding, a key insight into decision makers is that climate policies can have unanticipated, near-term benefits of water pollution control and water conservation that could be included in benefit-cost analyses of climate policy proposals.

Website: *https://climas.arizona.edu/publication/book-chapter/climate-policies-water-policies*

Garfin, G, S. LeRoy, D. Martin, M. Hammersley, A. Youberg, and R. Quay. 2016. *Managing for Future Risks of Fire, Extreme Precipitation, and Post-fire Flooding. Report to the U.S. Bureau of Reclamation*, from the project Enhancing Water Supply Reliability. Tucson, AZ: Institute of the Environment, University of Arizona. This report summarizes a workshop conducted September 22–23, 2014 in Las Vegas, Nevada to discuss research and management needs related to severe fires and post-fire flooding in the Intermountain West. Workshop participants included scientists, resource managers, and urban planners. The main purpose of this workshop was to further the understanding of the scientific and management decision-making research needs and gaps at the confluence of wildfire, post-fire floods, and extreme precipitation. Participants accomplished this by sharing lessons learned and best practices from case studies, through group discussions identifying research and management needs, and through the suggestions of participants to inform the development of a toolkit of processes and products to inform water and floodplain managers. Research, data, and management needs were identified by workshop participants in areas related to: extreme precipitation, fire ecology, flooding and sediment transport, water supply and reservoir infrastructure, and water quality.

Website: *https://www.researchgate.net/publication/308962175_Garfin_G_S_LeRoy_D_Martin_M_Hammersley_A_Youberg_and_R_Quay_2016_Managing_for_Future_Risks_of_Fire_Extreme_Precipitation_and_Post-fire_Flooding_Report_to_the_US_Bureau_of_Reclamation_from_the_project_*

Garfin, G., A. Comrie, B. Colby, G. Frisvold, J. Weiss. 2012. *Climate Change Analysis for the City of Tucson*. Climate Assessment for the Southwest. This is vulnerability assessment for the City of Tucson and its contractors related to anticipated climate change impacts. Studies are intended to estimate projections of future climate and hydrology of both the Tucson Basin and Colorado River surface water supplies that are part of Tucson Water's water resources portfolio. Researchers will also compile research related to: Tucson energy-water nexus issues, Tucson's urban heat island, risk related to selected diseases, local food security, and projected impacts and risks related to urban ecosystems and ecosystems surrounding the City. CLIMAS researchers and University of Arizona researchers will synthesize this research on vulnerability assessment and adaptation-related economic research pertaining to Tucson and southern Arizona.

Temperature and precipitation projections were made for the City of Tucson for 1950-2099. These include maps of extreme temperature risk; flood risk; and combinations of flood risk and socio-economic status and extreme temperature risk and socio-economic status. The projections and maps aid the City of Tucson Office of Sustainable Development, and the City's Climate Change Committee in anticipating and planning for future risk.

Website: *https://climas.arizona.edu/research/climate-change-analysis-city-tucson*

Garfin, G., S. LeRoy, and H. Jones. 2017. *Developing an Integrated Heat Health Information System for Long-Term Resilience to Climate and Weather Extremes in the El Paso-Juárez-Las Cruces Region*. Tucson, AZ: Institute of the Environment. This paper summarizes a workshop held in El Paso, Texas, on July 13, 2016. The workshop was conducted as part of the National Integrated Heat Health Information System (NIHHIS) initiative and served as the formal launch of the NIHHIS Southwest regional pilot. Participants included government, practitioner, and academic communities from Mexico and the United States. The purpose was to discuss the intersection of the region's climate and weather with factors affecting public health risks related to extreme heat.

Workshop participants provides a number of recommendations related to heat health resilience, which include:

1. Vulnerability assessment and data synthesis and analysis are key priorities for further actions to improve understanding of extreme heat risks.
2. Medical data is the most needed information. An improved understanding of the relationship between heat parameters and interventions is the biggest hurdle for improving policy
3. Forecast communication and research related to forecast lead time are key action priorities.
4. Communicating to vulnerable populations and increasing trust in organizations that deliver heat health messages should be prioritized.
5. Collaboration and capacity-building planning and process are the highest priorities for enhancing capacity and developing and deploying training on heat health issues, preparedness, and response.

Website: https://repository.library.noaa.gov/view/noaa/13067

Garfin, G., C. Scott, M. Wilder, R. Varady, and R. Merideth. *Metrics for assessing adaptive capacity and water security: Common challenges, diverging contexts, emerging consensus*. Current Opinion in Environmental Sustainability, Volume 21. This paper reviews conceptual framings and empirical findings of the thirteen articles related to the assessment of adaptive capacity and water security remains elusive, due to flaws in guiding concepts, paucity or inadequacy of data, and multiple difficulties in measuring the effectiveness of management prescriptions at scales relevant to decision-making. The paper has three conclusions:

1. A systematic cross-comparisons of metrics, using the same models and indicators, are needed to validate the reliability of evaluation instruments for adaptive capacity and water security.
2. The robustness of metrics to applications across multiple scales of analysis can be enhanced by a 'metrics plus' approach that combines well-designed quantitative metrics with in-depth qualitative methods that provide rich context and local knowledge.
3. Changes in the governance of science–policy can address deficits in public participation, foster knowledge exchange, and encourage the co-development of

adaptive processes and approaches (e.g., risk-based framing) that move beyond development and use of static indicators and metrics.

Website: https://www.sciencedirect.com/science/article/abs/pii/S187734351630077X

Georgakakos, A., P. Fleming, M. Dettinger, et al. 2014. *Climate Change Impacts in the U.S.: The Third National Climate Assessment*. This 20-page booklet provides a high-level compendium of climate change impacts in the United States. The overview covers the most important impacts at the national level, but does not attempt to provide a comprehensive summary of the entire assessment. Numbered references can be found in the Highlights. To supplement this Overview, regional fact sheets are available that offer highlights from each of the eight regions (i.e. northeast, southeast and Caribbean, Midwest, Great Plains, southwest, northwest, Alaska and Hawaii and Pacific Islands).

Website: N/A

Hirschman, D., D. Caraco, S. Drescher. 2011. *Adapting Stormwater Management for Climate Change*. Watershed Sciences Bulletin. This paper focused on the significant variability associated with climate change projections and how that variability plays into stormwater design factors. This study was focused on the South Carolina coastal region and dealt with the projection of future sea level rise, increased storm intensities, drought and a shift in plant communities. Green Infrastructure and Low Impact Development strategies were offered as potential adaptation solutions to stormwater issues.

Website: N/A

Howard, J. 2019. *Megadroughts could return to southwestern U.S*. National Geographic. This article summaries a recent study from Science Advances where scientists understand the causes of the megadroughts common during the medieval period. They also predict more megadroughts in the future with climate change. Their analysis identifies three main factors causing megadroughts in the American Southwest: Cooling water temperatures in the Pacific Ocean, warming water in the Atlantic Ocean, and radiative forcing. It was found that during periods of positive radiative forcing (warming in the American Southwest led to the series of megadroughts during the medieval period.

Website: https://www.nationalgeographic.com/environment/2019/07/megadroughts-could-return-southwestern-us/#close

Hydros Consulting Inc. 2018. *Colorado River Risk Study: Executive Summary.* Submitted to the Colorado River District and Project Partners, August 1, 2018. This paper summarizes the findings of the risk study for the Upper CRB as it relates to water flows to the Lower CRB and Lake Powell. It states that The Colorado River Basin is in the midst of a drought that began in 2000 and continues today. Average naturalized flows at Lee Ferry during this period are approximately 12.6 maf (million acre-feet), or 4.0 maf annually less than would be needed to meet the full compact allotments of the seven basin states and to the Mexican Treaty obligation to Mexico. Recent droughts have significantly reduced storage levels in Lake Powell. If these droughts were to repeat themselves today, the ability of Lake Powell to satisfy its compact-obligation and power-generation purposes would be threatened (Figure 1). Drought Contingency Plans (DCP) are being developed for both the Upper and Lower Basins (See Hydros 2015 report "Summary Report on Contingency Planning in the Colorado River Basin"). While those plans, if implemented, would reduce the risk of a compact deficit or critically low storage levels at Lake Powell, they do not completely eliminate the risk for the Upper Basin States.

Website: https://waterinfo.org/wp-content/uploads/2018/10/West-Slope-BRT-Risk-Study-Executive-Summary-Phases-I-and-II.pdf

Intergovernmental Panel on Climate Change (IPCC). 2007. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K. B.Averyt, M. Tignor and H. L. Miller (eds.)]. Cambridge University Press, Cambridge,United Kingdom and New York, NY, USA, 996 pp. This Synthesis Report (SYR) distils and integrates the findings of the three Working Group contributions to the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC), the most comprehensive assessment of climate change undertaken thus far by the IPCC: Climate Change *2013*: The Physical Science Basis; Climate Change *2014*: Impacts, Adaptation, and Vulnerability; and Climate Change *2014*: Mitigation of Climate Change. The SYR also incorporates the findings of two Special Reports on Renewable Energy Sources and Climate Change Mitigation (*2011*) and on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (*2011*).

Jacobs, K., J. Buizer, and S. Moser. 2016. *The Third US National Climate Assessment: Innovations in Science and Engagement*. Climatic Change, 135. This paper discusses lessons learned from the Third US National Climate Assessment (NCA3). The author's intent of discussing lessons leanred is that those sponsoring, designing, and assisting in assessments at the regional, national and international levels can benefit from this experience.

Website: https://link.springer.com/article/10.1007/s10584-016-1621-5

LADPW, USACE, USBR. 2014. *Los Angeles Basin Stormwater Conservation Study – Task 4 Existing Infrastructure Response & Operations Guidelines Analysis*. Reclamation: Managing Water in the West. The purpose of Task 4 was to assess the response of existing infrastructure and analyze the operation guidelines under both the current and future climate conditions. It is important to recognize that this effort relies upon the existing water conservation and flood control network as the baseline condition. This evaluation included a ranking assessment of the current and future stormwater volumes conserved or discharged, and impacts to the water conservation and flood control system. Six climate scenarios were chosen from a broad range of 47 initial scenarios. From this scenarios various runoff scenarios were created to test infrastructure response and operations.

Website: https://www.usbr.gov/lc/socal/basinstudies/LABasinStudyFinalTask4Report.pdf

Lin, C.-Y., W.-C. Chen, S. C. Liu, Y. A. Liou, G. R. Liu, and T. H. Lin (2008), *Numerical study of the impact of urbanization on the precipitation over Taiwan*, Atmos. Environ.,42, 2934–2947, doi:10.1016/j.atmosenv.2007.12.054. This landmark study regarding the impact of urbanization on precipitation was found to have significant correlations to the City of Tucson's evolving precipitation regime. It states that a highly developed industry and a large population density have turned the western plain of Taiwan into a mega-suburb with many cities and small towns and countless factories, and roads. As a result, the western plain is experiencing a regional heat-island effect. The MM5 mesoscale model was conducted in order to study and evaluate the impacts of the heat-island effect on regional weather, including thunderstorms, over Taiwan. According to land use data provided by the US Geological Survey (USGS), we assumed three different urban sizes in the simulation study to theoretically evaluate the impact of urbanization on the precipitation.

Website: *https://www.sciencedirect.com/science/article/abs/pii/S1352231007011995*

Meadow, A., Z. Guido, M. Crimmins, and J. Mcleod. 2016. *From principles to action: Applying the National Research Council's Principles for Effective Decision Support to the Federal Emergency Management Agency's Watch Office*. Climate Services, Volume 1. This paper discusses application of the National Research Council (NRC) proposed six principles for effective decision support via a collaborative project between the Federal Emergency Management Agency Region R9 (FEMA R9), the Western Region Headquarters of the National Weather Service (WR-NWS), and the Climate Assessment of the Southwest (CLIMAS). The goal of the project was to provide FEMA R9's Watch Office with climate information scaled to their temporal and spatial interests to aid them in assessing the potential risk of flood disasters. It was found that specific strategies and activities were needed in order to apply the principles effectively. By using a set of established collaborative research approaches, FEMA R9's information needs and WR-NWS's capacity to meet those needs were easier to assess. Barriers were encountered to transitioning the decision support tool from research to operations. This paper describes the methods for planning and executing a three-party collaborative effort to provide climate services, the decision support tool developed through this process, and the lessons that will be applied to future work and implications of the NRC principles for the broader field of climate services.

Website: https://www.sciencedirect.com/science/article/pii/S240588071530008X

Meixner, et al. 2016. *Implications of projected climate change for groundwater recharge in the western United States.* Journal of Hydrology 534 (2016) 124-138. This study notes that existing studies on the impacts of climate change on groundwater recharge are either global or basin/ location-specific. The global studies lack the specificity to inform decision making, while the local studies do little to clarify potential changes over large regions (major river basins, states, or groups of states), a scale often important in the development of water policy. An analysis of the potential impact of climate change on groundwater recharge across the western United States (west of 100° longitude) is presented synthesizing existing studies and applying current knowledge of recharge processes and amounts. Eight representative aquifers located across the region were evaluated. For each aquifer published recharge budget components were converted into four standard recharge mechanisms: diffuse, focused, irrigation, and mountain-systems recharge. Future changes in individual recharge mechanisms and total recharge were then estimated for each aquifer

Website: https://www.sciencedirect.com/science/article/pii/S0022169415009750

National Climate Assessment (NCA). 2018. *Fourth National Climate Assessment (AR4: Chapter 25 Southwest.* U.S. Global Change Research Program, Washington D.C. This, the fourth installment of the NCA, unequivocally states that long-term temperature observations are among the most consistent and widespread evidence of a warming planet. Global annually averaged temperature measured over both land and oceans has increased by about 1.8°F (1.0°C) according to a linear trend from 1901 to 2016, and by 1.2°F (0.65°C) for the period 1986–2015 as compared to 1901–1960. The last few years have also seen record-breaking, climate-related weather extremes. For example, since the Third National Climate Assessment was published,[1] 2014 became the warmest year on record globally; 2015 surpassed 2014 by a wide margin; and 2016 surpassed 2015. Sixteen of the last 17 years have been the warmest ever recorded by human observations.

For short periods of time, from a few years to a decade or so, the increase in global temperature can be temporarily slowed or even reversed by natural variability (see Box 2.1). Over the past decade, such a slowdown led to numerous assertions that global warming had stopped. No temperature records, however, show that long-term global warming has ceased or even substantially slowed over the past decade. Instead, global annual average temperatures for the period since 1986 are likely much higher and appear to have risen at a more rapid rate than for any similar climatological (20–30 year) time period in at least the last 1,700 years.

Website: https://nca2018.globalchange.gov/chapter/25/

National Oceanic and Atmospheric Administration. 2019. *U.S. Climate Resilience Toolkit: Water Utility Plans for Climate Uncertainty*. Determining which of your group's assets are most likely to be damaged or degraded by a climate threat can help your group decide where to start. One consideration in the decision is how close each asset may be to a tipping point—a point when incremental change in a system results in a new, irreversible response. Some people refer to tipping points as critical thresholds.

Look back to the potential or historical consequences you identified for each asset-hazard pair. In some cases, the consequence you described might be considered a tipping point. Looming tipping points aren't the only factor groups need to consider when deciding which assets to protect, but the potential for a large change in the system can elevate the level of concern for those assets.

Website: https://toolkit.climate.gov/case-studies/water-utility-plans-climate-uncertainty

O'Neill, J. A. 2010. *Climate Change's Impact on the Design of Water, Wastewater, and Stormwater Infrastructure*. This study briefly outlines actual climatic changes that have occurred and recently published predicted changes. It looks at the impacts these changes will have on water, wastewater, and stormwater infrastructure and provides recommendations to assist engineers and owners who are working to address these impacts. In addition, cautions are provided relating to evaluating and using current climate data, models, and studies for planning and design purposes. While societal and socioeconomic factors also impact the design of water, wastewater, and stormwater infrastructure, this study only summarily covers those impacts associated with climate change.

Website: *http://hydrologydays.colostate.edu/Papers_2010/ONeill_paper.pdf*

Ortiz-Bobea, A., H. Wang, C.M. Carrillo, T.R. Ault. 2019. *Unpacking the climatic drivers of US agricultural yields*. Environmental Research Letters, Volume 14. This study links land surface model data and fine-scale weather information with a long panel of county-level yields for six major US crops (1981–2017) to understand their historical and future climatic drivers. A statistical approach was developed that flexibly characterizes the distinct intra-seasonal yield sensitivities to high-frequency fluctuations of soil moisture and temperature. Results suggest there is an important role of water stress in explaining historical yields. However, the models project the direct effect of temperature (interpreted as heat stress) remains the primary climatic driver of future yields under climate change.

Website: *https://iopscience.iop.org/article/10.1088/1748-9326/ab1e75*

Parris, A., G. Garfin, K. Dow, R. Meyer, and S. Close. 2016. *Climate in Context: Science and Society Partnering for Adaptation*. Chichester, West Sussex: John Wiley & Sons Ltd. This textbook describes what it takes to help scientists and stakeholders work together to "co-produce" climate science knowledge, policy, and action. This state-of-the-art synthesis reflects on lessons learned by RISA programs and provides a sober assessment of the challenges ahead. Through case studies from various US regions, this book provides lessons and guidance for organizations and individuals who want to work at the science-society interface on a range of climate challenges.

Website: *https://www.eastwestcenter.org/node/35728*

Pirnie, M. 2013. *Recycled Water Master Place, Volume I: Master Plan*. Tucson Water. The overall purpose of the Recycled Water Master Plan is to provide an integrated recycled water program that maximizes the benefits of the City's recycled water resource. This document provides information to City of Tucson decision makers, Tucson Water customers, and other stakeholders on the planned use of the City's recycled water both in its Reclaimed Water System (RWS) and through other means. In addition, the Recycled Water Master Plan provides a framework for next steps and continued activities that will help ensure the timely implementation of the necessary recycled water projects and programs. These in turn will help achieve Tucson Water's objectives, ensure the long-term sustainability of the Utility's water resources, and enable it to keep its commitment to "Water Reliability" for its customers.

Website:
https://www.tucsonaz.gov/files/water/docs/Volume_I_Recycled_Water_Master_Plan.pdf

Pouget L., B. Russo, I. Escaler, Á. Redaño, J. Ribalaygua, H. Theias. *CETaqua Water Technology Center*. Dept. of Astronomy and Meteorology, University of Barcelona. This paper presents a study on the impacts of climate change on extreme rainfall events for the city of Barcelona and describes how results were use to perform a flood risk assessment. In a first step, a statistical downscaling method was used to generate future rainfall time series at a daily time step. This analogue based downscaling method used the results of five Global Climate Models (GCMs) to produce time series corrected for extremes events at six raingauge stations of the urban area. In a second step, these data were used to create new Intensity Duration-Frequency (IDF) curves. A method based on fractal properties of rainfall was applied to downscale the future rainfall intensity from daily to hourly information. In a last step, current and future IDF curves were compared and design storm uplift factors were calculated for all the scenarios considered.

Website: N/A

Star, J., E. Rowland, M. Black, C. Enquist, G. Garfin, C. Hoffman, H. Hartmann, K. Jacobs, R. Moss, A. Waple. 2016. *Supporting adaptation decisions through scenario planning: Enabling the effective use of multiple methods*. Climate Risk Management, Volume 13. Supporting adaptation decisions through scenario planning: Enabling the effective use of multiple methods. This paper describes applications that combine previously distinct scenario methods in new and innovative ways. It draws on numerous recent independent case studies to illustrate emerging practices, such as far stronger connections between researcher-driven and participatory approaches and cycling between exploratory and normative perspectives. The paper concludes with a call for greater support for, and collaboration among, practitioners with the argument that mixed methods are most effective for decision-making in the context of climate change challenges.

Website: https://www.sciencedirect.com/science/article/pii/S2212096316300262

Steiger, N.J., J.E. Smerdon, B.I. Cook, R. Seager, A. Park Williams, E.R. Cook. 2019. *Oceanic and radiative forcing of medieval megadroughts in the American Southwest.* Science Advances, Volume 5. This study uses Paleo Hydrodynamics Data Assimilation product, in conjunction with radiative forcing estimates, to demonstrate that megadroughts in the American Southwest were driven by unusually frequent and cold central tropical Pacific sea surface temperature (SST) excursions in conjunction with anomalously warm Atlantic SSTs and a locally positive radiative forcing. This assessment of past megadroughts provides the first comprehensive theory for the causes of megadroughts and their clustering particularly during the Medieval era. This work also provides the first paleoclimatic support for the prediction that the risk of American Southwest megadroughts will markedly increase with global warming.

Website: https://advances.sciencemag.org/content/5/7/eaax0087

Udall, B. and J. Overpeck. 2017. *The twenty-first century Colorado River hot drought and implications for the future*. Water Resouces Research. This paper reviews annual Colorado River flows between 2000 and 2014. These flows averaged 19% below the 1906–1999 average, the worst 15-year drought on record. On average, at least one-third of this loss is due to unprecedented temperatures (0.9°C above the 1906–1999 average), confirming model-based analysis that continued warming will likely further reduce flows. There has been no observed trend toward greater precipitation in the Colorado Basin, nor are climate models in agreement that there should be a trend. Additionally, there is a significant risk of decadal and multi-decadal drought in the coming century, indicating that any increase in mean precipitation will likely be offset during periods of prolonged drought. Recently published estimates of Colorado River flow sensitivity to temperature, combined with a large number of recent climate model-based temperature projections, indicate that continued business-as-usual warming will drive temperature-induced declines in river flow, conservatively −20% by midcentury and −35% by end-century, with support for losses exceeding −30% at midcentury and −55% at end-century. Precipitation increases may moderate these declines somewhat, but to date no such increases are evident and there is no model agreement on future precipitation changes. These results, combined with the increasing likelihood of prolonged drought in the river basin. This suggests that future climate change impacts on the Colorado River flows will be much more serious than currently assumed, especially if substantial reductions in greenhouse gas emissions do not occur.

Website: https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2016WR019638

United States Bureau of Reclamation (USBR), 2012. *Colorado River Basin Water Supply and Demand Study - Technical Report A-Scenario Development. 18 pages.* The Colorado River Basin Water Supply and Demand Study (Study), initiated in January 2010, was conducted by the Bureau of Reclamation's (Reclamation) Upper Colorado and Lower Colorado regions, and agencies representing the seven Colorado River Basin States (Basin States) in collaboration with stakeholders throughout the Colorado River Basin (Basin). The purpose of the Study is to define current and future imbalances in water supply and demand in the Basin and the adjacent areas of the Basin States that receive Colorado River water over the next 50 years (through 2060), and to develop and analyze adaptation and mitigation strategies to resolve those imbalances. The Study contains for major phases to accomplish this goal: Water Supply Assessment, Water Demand Assessment, System Reliability Analysis, and Development and Evaluation of Options and Strategies for Balancing Supply and Demand.

Website: http://www.riversimulator.org/Resources/USBR/BasinStudy/Final/03TechnicalAReportScenarioDevelopment.pdf

United States Bureau of Reclamation (USBR). 2016. *2016 SECURE Water Act Report - Colorado River Basin Fact Sheet.* This document summarizes the findings of the 2016 SECURE Water Act Report at is relates to new findings since the 2012 Colorado River Basin Water Supply and Demand Study. This fact sheet provided guidance for future changes in climate and hydrology of the CRB, as well as findings regarding future impacts for water and environmental resources in the CRB. This document is the synthesis of a much large report, but provided the necessary concentration of overarching findings regarding climate change and the CRB.

Website: https://www.usbr.gov/climate/secure/docs/2016secure/factsheet/ColoradoRiverBasinFactSheet.pdf

United States Bureau of Reclamation (USBR), 2019. *Climate and Surface Water Analysis Summary - Lower Santa Cruz River Study.* Presentation by Lindsay Bearup, November 21, 2019 - Preliminary findings. This online presentation provided insight into the preliminary findings of the climate and surface water analysis performed as part of the Lower Santa Cruz River Basin study by the USBR. It includes the understanding of a best case scenario for the basin where relatively minimal change in seasonal precipitation occurs, but in the worst case scenario, total precipitation decreases in the monsoon and winter wet seasons. Precipitation becomes increasingly variable. it provides rather detailed information regarding the expected increase in the number of no-flow days on 28 of the local/regional streams and rivers.

Website: *https://www.usbr.gov/lc/phoenix/programs/lscrbasin/mdocs/20191121climate.pdf*

U.S. EPA Climate Adaptation Working Group. 2013. Water and Wastewater Utility Climate Change Mitigation and Adaptation Efforts in EPA Region 3 – Climate Adaptation Implementation Plan. Washington D.C. In February 2013, the EPA released its draft Climate Change Adaptation Plan to the public for review and comment. This plan relies on peer-reviewed scientific information and expert judgment to identify vulnerabilities to EPA's mission and goals from climate change. The plan also presents 10 priority actions that EPA will take to ensure that its programs, policies, rules, and operations will remain effective under future climatic conditions. The priority placed on mainstreaming climate adaptation within EPA complements efforts to encourage and mainstream adaptation planning across the entire federal government.

This report, specific to California and the rest of EPA Region 9, listed the following criteria for these, aforementioned priority actions:

- Does the action target one of the most severe and immediate vulnerabilities?
- Does the action focus on one of the most vulnerable populations and/or geographic areas?
- Does EPA Region 9 have the capacity (personnel and funding resources) and ability (knowledge, skills, and authority) to take the action and contribute to a solution?
- Is this a priority action for our partners (federal/state/territory/tribal/local government and nongovernment) and are they able to work with us towards a solution?
- Does the action support and align with other EPA Region 9 priorities and actions?

This paper is a guidebook or "how to" primer for addressing the impacts of climate change and does not delve into the technical analysis of impacts or adaptations.

Website: *https://www.epa.gov/sites/production/files/2016-04/documents/final_2013_nwp_climate_highlights_report_print_file.pdf*

University of Arizona, Tucson. 2015. S*cenario Planning for Climate Change Adaptation Decision Making: The State of the Art Workshop Report*. Center for Climate Adaptation Science and Solutions. This report summarizes the activities and outcomes of the March 31-April 1, 2015 workshop, "Scenario Planning for Climate Change Adaptation Decision Making: The State of the Art" at the University of Arizona. This workshop was focused on understanding alternative approaches to scenario planning, lessons learned in using them, and ways of extending and combining the approaches that are currently in use.

Decision-makers and managers are increasingly being asked to make decisions in the context of uncertainty, with climate change adding new sources of complexity. We've observed that scenario planning is being used as means of providing managers with insights into options for responding appropriately to change in the near and long term. The increasing use of scenario planning prompts some questions, such as:

- What is the state-of-the-art in scenario development?
- How can uncertainty within scenarios be communicated effectively to stakeholders and what types of scenarios are appropriate and beneficial to pursue in a given context?
- In using scenario planning methods: What works where, when, and why?
- How can the effectiveness and utility of scenario planning processes be enhanced?

The workshop explored lessons learned in applications of specific scenario planning techniques as well as connections between the different methods that have emerged, with respect to how they frame uncertainty and how they function in a decision support context. We also discussed several alternative science-based approaches and modes of engaging stakeholders in scenario planning, while promoting scholarly work to assess the state of the art.

Website: https://www.ccass.arizona.edu/sites/default/files/Scenario%20Planning%20Workshop%20Report.pdf

University Corporation for Atmospheric Research. (UCAR). 2011. *Urban Heat Islands.* Boulder, CO. This webpage provides a brief overview of heat islands and how they are related to global warming. An urban heat island (UHI) is a metropolitan area which is significantly warmer than its surroundings. They are formed when vegetation is replaced by asphalt and concrete for roads, buildings, and other structures necessary to accommodate growing populations. Temperatures are therefore increased due to the new surfaces absorbing heat and displacing the natural cooling effects of vegetation. Although heat islands explain more local-scale temperature increase, they may contribute to larger-scale global warming by increasing demand for air conditioning, which results in additional power plant emissions of heat-trapping greenhouse gases.

Website: https://scied.ucar.edu/longcontent/urban-heat-islands

US Department of Agriculture - Agricultural Research Service. 2019. *Monsoon rains have become more intense in the southwest in recent decades*. ScienceDaily. This article provides a high level summary on how monsoon rains have become more intense in the southwest in recent decades, according to a study recently published by Agricultural Research Service scientists.

Website: https://www.sciencedaily.com/releases/2019/07/190723110528.htm

Vano, et al. 2014. *Understanding Uncertainties in Future Colorado River Streamflow.* Journal of Meteorology - American Meteorological Society. Bulletin of the AMS, January 2014. This syntheses report is a study of CRB streamflow projections that examines methodological and model differences and their implications for water management in the basin. It identifies the Colorado River is the primary water source for more than 30 million people in seven rapidly growing, mostly arid American states and Mexico. And, further states that the Colorado River water supply system, which consists

of two large reservoirs (Lakes Mead and Powell) and numerous smaller reservoirs, is already stressed because of growing water demand and an ongoing drought that is outside the historical norm of twentieth-century climate variability. Concerns have been voiced that this recent prolonged drought could be a harbinger of a permanent shift to a drier climate.

Website: *https://journals.ametsoc.org/doi/pdf/10.1175/BAMS-D-12-00228.1?version=meter+at+null&module=meter-Links&pgtype=article&contentId=&mediaId=&referrer=&priority=true&action=click&contentCollection=meter-links-click*

Vose, R.S., D.R. Easterling, K.E. Kunkel, A.N. LeGrande, M.F. Wehner. 2017. *Temperature changes in the United States*. Climate Science Special Report: Fourth National Climate Assessment, Volume I. The Climate Science Special Report (CSSR) is designed to be an authoritative assessment of the science of climate change, with a focus on the United States, to serve as the foundation for efforts to assess climate-related risks and inform decision-making about responses. In accordance with this purpose, it does not include an assessment of literature on climate change mitigation, adaptation, economic valuation, or societal responses, nor does it include policy recommendations.

As Volume I of NCA4, CSSR serves several purposes, including providing 1) an updated detailed analysis of the findings of how climate change is affecting weather and climate across the United States; 2) an executive summary and other CSSR materials that provide the basis for the discussion of climate science found in the second volume of the NCA4; and 3) foundational information and projections for climate change, including extremes, to improve “end-to-end” consistency in sectoral, regional, and resilience analyses within the second volume. CSSR integrates and evaluates the findings on climate science and discusses the uncertainties associated with these findings. It analyzes current trends in climate change, both human-induced and natural, and projects major trends to the end of this century. As an assessment and analysis of the science, this report provides important input to the development of other parts of NCA4, and their primary focus on the human welfare, societal, economic, and environmental elements of climate change.

Website: https://science2017.globalchange.gov/chapter/6/

Wall, T., A. Meadow, and A. Horangic. 2017. *Developing Evaluation Indicators to Improve the Process of Coproducing Usable Climate Science*. Weather, Climate, and Society, Volume 9. This paper combined information three sources to develop an evaluative framework that consists of 45 indicators grouped into context; process; and output, outcome, and impact indicators. These sources include:

1. Identifying the key principles in coproducing knowledge from the existing literature
2. Examined how usable climate research is currently evaluated by federal agencies.
3. Interviewed experienced climate science integrators. Interviews focused on which activities, actions, and conditions they believe most influence the process and outcomes of knowledge coproduction.

The indicators were then tested using two case studies. Results of the tests helped identify lessons about the process of evaluating the coproduction of knowledge and collaboratively producing climate knowledge.

Website: https://journals.ametsoc.org/doi/pdf/10.1175/WCAS-D-16-0008.1

Wilder, M., D. Liverman, L. Bellante, and T. Osborne. *Southwest climate gap: poverty and environmental justice in the US Southwest.* Local Environment, Volume 21. This paper examines the climate and poverty relationship in the Southwest US (Arizona and New Mexico). This was completed using multi-scaled analysis across three indicators of climate vulnerability, focusing on connections to health, food, and energy during the period of 2010 to 2012. A significant Southwest climate gap was identified based on census data and interview findings about climate vulnerability, especially relating to high levels of poverty, health disparities, and increasing costs for energy, water, and food. It was found that grassroots and community organizations have mobilized to respond to climate and social vulnerability, yet resources for mitigation and adaptation are insufficient given the high level of need. The author's recommend that more research is needed to understand the social and spatial characteristics of climate risk and how low-income populations embody and experience climate risk and adapt to a changing climate.

Website: https://www.tandfonline.com/doi/full/10.1080/13549839.2015.1116063?scroll=top&needAccess=true

Woodhouse, C.A., D.M. Meko, C.A. Baisan, T. Knight, J.J. Lukas, M.K. Hughes, M.W. Salzer. 2007. *Medieval Drought in the Upper Colorado River Basin.* Geophysical Research Letters 34, L10705. New tree-ring records of ring-width from remnant preserved wood are analyzed to extend the record of reconstructed annual flows of the Colorado River at Lee Ferry into the Medieval Climate Anomaly, when epic droughts are hypothesized from other paleoclimatic evidence to have affected various parts of western North America. The most extreme low-frequency feature of the new reconstruction, covering A.D. 762-2005, is a hydrologic drought in the mid-1100s. The drought is characterized by a decrease of more than 15% in mean annual flow averaged over 25 years, and by the absence of high annual flows over a longer period of about six decades. The drought is consistent in timing with dry conditions inferred from tree-ring data in the Great Basin and Colorado Plateau, but regional differences in intensity emphasize the importance of basin-specific paleoclimatic data in quantifying likely effects of drought on water supply.

Website: https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2007GL029988

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