Climate Change, Water Resources, and Potential Adaptation Strategies in Utah

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SUMMARY

The climate of the Southwest U.S., including Utah, is highly variable and strongly influenced by topographic contrasts as well as the mid-latitude storm track, the North American monsoon, and proximity to the Pacific Ocean, Gulf of California, and Gulf of Mexico. Utah historical weather records from 1950 to 2017 show that average temperatures increased by about 2°F with only modest changes in average annual precipitation. However, precipitation varies substantially by season and year-to-year across Utah depending on exposure to the mid-latitude westerly storm track during the cool season, the monsoon circulation during the warm season, and elevation. Observed Snow Water Equivalent (SWE) records show a decreasing trend of snowpack over time, and the rates of change in southern Utah's SNOTEL stations are significantly higher than in the north. Utah has frequently experienced droughts and flash floods in the past.

The majority of regional future climate studies indicate that average temperatures in Utah may increase by 3 to 6°F by 2060s and 4 to 10°F by the end of current century. The precipitation projections have an uncertainty range with changes spanning from (-5) to 10% by 2060s and (-10) to +5% by the end of the current century. The projections indicate significant seasonal variability in temperature and precipitation. The climate models predict an increase in the fraction of precipitation falling as rain rather than snow. SWE values are projected to be reduced by about 10 to 15% by 2060s and up to 30% by the end of current century. The compounded effects of changes in precipitation type, escalated warming, and changes in snowmelt timing will lead to shifts in the timing of spring runoff by one to three weeks by 2060s and about four weeks by the end of the current century. Frequent extreme weather events related to changing climate could result in heat waves, heavy precipitation, droughts, and floods. The projected increase in the intensity of naturally occurring droughts could escalate the occurrence and severity of wildfires. The magnitude of changes and impacts will vary locally with climatic regions in the state and are often difficult to predict.

Changing climate will alter the hydrologic cycle and will have direct and indirect impacts on both water availability and demand. On the supply side, many components of the water cycle including rate of evapotranspiration, snow hydrology processes, timing of streamflow, reservoir inflow and storage, and groundwater recharge rates will be directly impacted by climate change and climate variability. On the demand side, all sectors of water demand including residential, industrial, institutional, agricultural, and ecosystems will be escalated with the warming climate. Among the most significant of these anticipated effects, in Utah, are changes in snowpack accumulation and snowmelt, changes in streamflow and timing, risks of droughts and flooding events, increased agricultural/outdoor water uses, and increased industrial water demand.

The main objective of this report is to review the historical observations and projected trends of the major climate variables, summarize potential impacts on Utah's water resource management, and recommend adaptations strategies. This report has four sections. Section 1 introduces climate change observations from the regional perspective. Section 2 summarizes historical and future climate change trends focusing on temperature, precipitation, snowpack, streamflow, extreme weather events and impacts on water resource systems. Section 3 summarizes possible adaptation strategies to address the impacts of climate change on water resources and management. Section 4 includes a summary and recommendations for future work. It is noted that most of the results included in this report draw on data developed by key federal agencies including U.S. Geological Survey (USGS), National Oceanic and Atmospheric Administration (NOAA), U.S. Environmental Protection Agency (USEPA), and The U.S. Bureau of Reclamation (USBR).

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1. INTRODUCTION

The fourth U.S. National Climate Assessment (NCA4) report indicates that the U.S. average temperature has increased by 1.3 to 1.9°F since record keeping began in 1895 and most of this increase has occurred since 1970 (Melillo et al., 2014; USGCRP, 2018). The Western U.S. has warmed approximately 2°F over the same period and is projected to warm an additional 5 to 7°F during the 21st century (Reclamation, 2016). The climate of the Southwest U.S. is highly varied and strongly influenced by topographic and land-surface contrasts, the mid-latitude storm track, and the North American monsoon as well as proximity to the Pacific Ocean, Gulf of California, and Gulf of Mexico (Sheppard et al. 2002).

The Southwest including Utah is the hottest and driest region in the U.S. Historical records of average annual and maximum temperature show that rates of warming are larger over the western U.S. in general, including Utah (Figures 1(a) and 1(b)). The average rates of change in the U.S. vary spatially from north to south with values around 0.50 to 2°F per century. The observed rates of change in the winter and the summer seasons (Figures 1(c) and 1(d)) are higher than the annual average rates of change. Warming trends have been observed in many river basins in the Western U.S. since the 1970s (e.g., lower Colorado River basin) and over the 20th century (e.g., Columbia River Basin, Sacramento and San Joaquin River basins, the Rio Grande basin), and the observed rates of change are around 5 to 7°F depending on location (Reclamation, 2016).

The historical annual and winter precipitation trends over the period 1895 to 2016 in the U.S. are generally weaker and less extensive than the temperature changes (Figures: 2a and 2b), which is consistent with a lack of trend in global land precipitation over the same period. Across most of the Southwest, a trend toward more precipitation falling as rain and less as snow is already apparent (Knowles et al., 2006). This is being observed both topographically (lower elevations receiving less precipitation in the form of snow) and seasonally (a shortening of the snow accumulation period). Both wet (i.e., heavy precipitation events) and dry extremes (i.e., length of dry spells) are expected to increase substantially throughout the West during the current century (Georgakakos et al., 2014).

Projections of future hydrology suggest that warming and associated loss of snowpack will persist over much of the Western U.S. (Hamlet et al., 2005). Streamflow due to snowmelt in many snowmelt-fed streams trended toward earlier arrivals from 1950–1999, likely in response to warmer temperatures (Hoerling et al., 2013). It is anticipated that the changes in snow hydrology along with severe and sustained drought will stress water resources in the Southwest including Utah (Garfin et al., 2013).

The main objective of this report is to review the historical observations and projected trends of major climate variables, summarize potential impacts on Utah's water resources management, and recommend adaptation strategies. This report presents trends and general statistics of climate variables with reference to the prior and posterior of year 2000. The reference year 2000 is neither motivated by any change point analysis nor holds any physical science meaning. Rather, it was chosen for simplicity to assess and highlight changes in the recent decade. Moreover, this work is not an exhaustive review on how the climate is changing or what adaptation measures can be implemented to address for specific impacts in Utah water sectors. The aim is instead to serve as a first reference document to precede climate and water related studies in the future. The next section presents historical and future climate change trends focusing on temperature, precipitation, snowpack, streamflow, extreme weather events, and impacts on water resource systems.

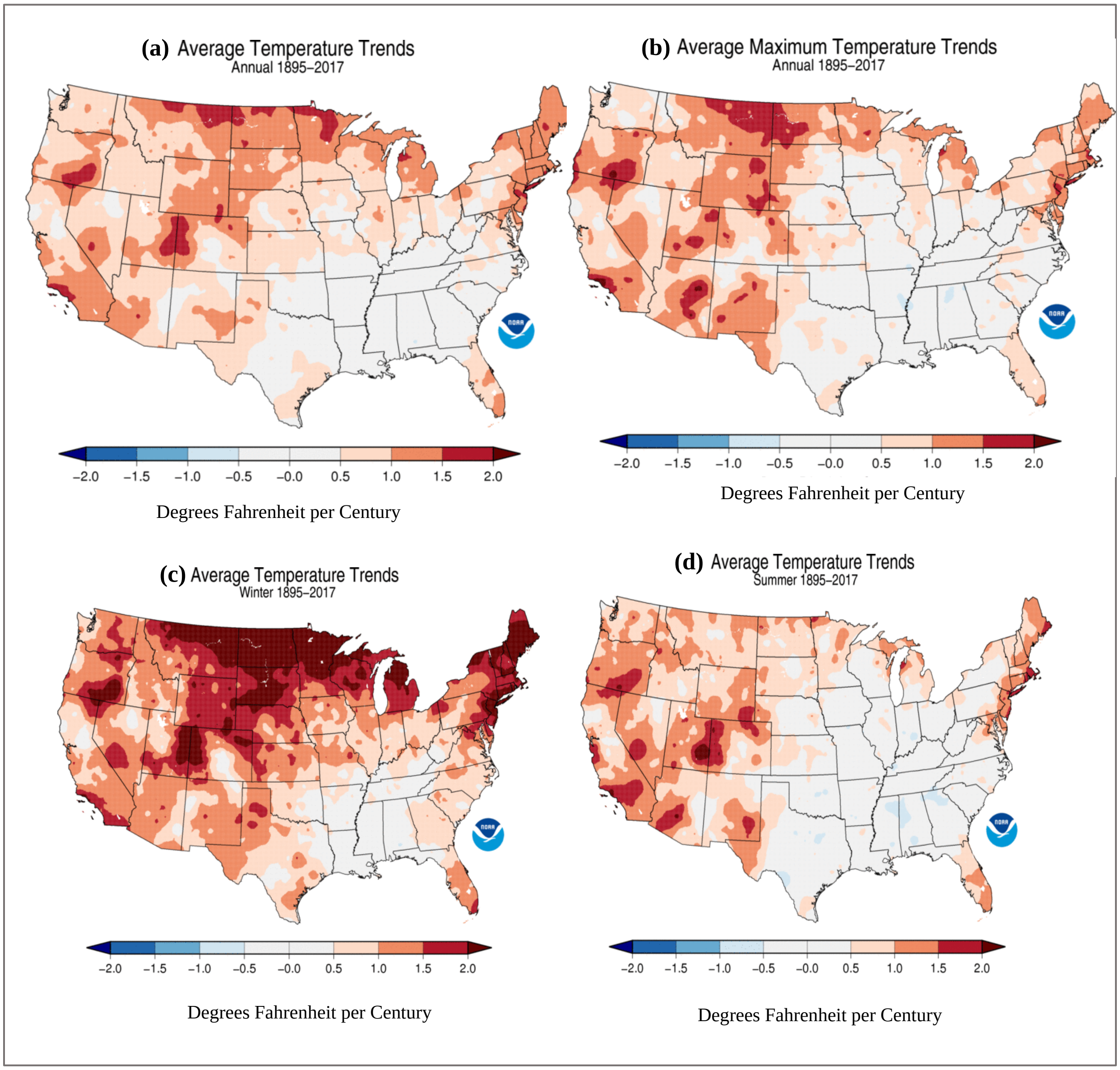

Figure 1: Historical temperature trends for 1895 to 2017: (a) average annual temperature trends, (b) average maximum temperature trends, (c) average temperature trends in winter, and (d) average temperature trends in summer. S*ource: https://www.ncdc.noaa.gov/temp-and-precip/us-trends/tavg/ann#us-trends-select*.

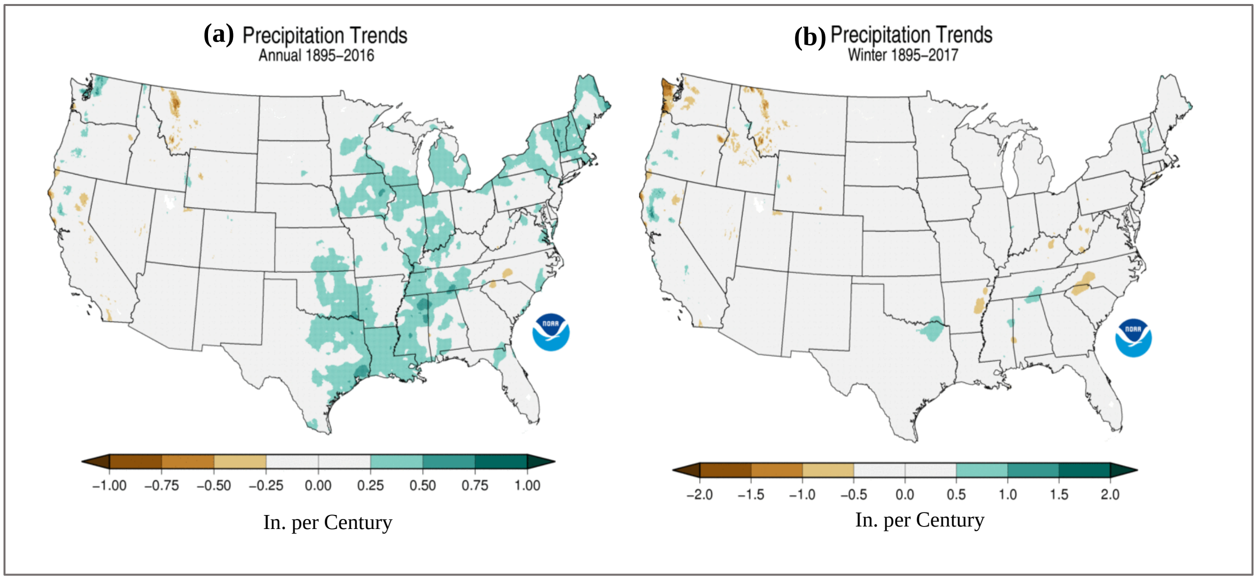

Figure 2: Historical precipitation trends for 1895 to 2016: (a) average annual precipitation trends, (b) average winter precipitation trends. S*ource: https://www.ncdc.noaa.gov/temp-and-precip/us-trends/prcp/ann#us-trends-select*.

2. CLIMATE CHANGE AND IMPACTS ON WATER RESOURCES IN UTAH

2.1 Temperature Changes: Continue to Rise

Historical Temperature Change: Average temperature in the western U.S. and Utah increased by about 2°F over the last century. Figure 3 presents the historical temperature trends in Utah at an annual and monthly time scale (i.e., January, April, and July) from 1950 to 2017. The data used in this analysis were downloaded from Western Climate Mapping Initiative (WestMap, 2019). The WestMap website hosts monthly PRISM temperature (maximum, mean, and minimum) and precipitation data at 4-km resolution.

The average annual temperature observed in Utah, over the period of 1950 –2000, was 47.90°F with a standard deviation of 1.08°F, whereas the average temperature in the recent years (2000 –2017) was 1.3°F higher (Figure 3(a)). Using July to illustrate changes in summer, temperatures averaged 2.20°F higher in the period of 2000 –2017 compared to 1950 –2000 (Figure 3(d)). There was also a rise in winter temperature (here January) of about 1°F in the recent decade as compared to the period 1950 –2000 (Figures 3(b)). In the period 1950 to 2017, the positive trend in annual temperature accounts for only 6% of the total variance but is highly statistically significant ($p < 0.001$). The Mann Kendall trend test shows $Z = 3.346$, $p = 0.008$, and $\tau = 0.273$, indicating a significant increase in annual mean temperature. Similarly, the calculated Sen's Slope of the observed annual average temperatures is 0.0252°F per year or 2.5°F per century. It is noted that the results presented here are averaged over the state; however, the rates of change of temperature vary seasonally and with elevation.

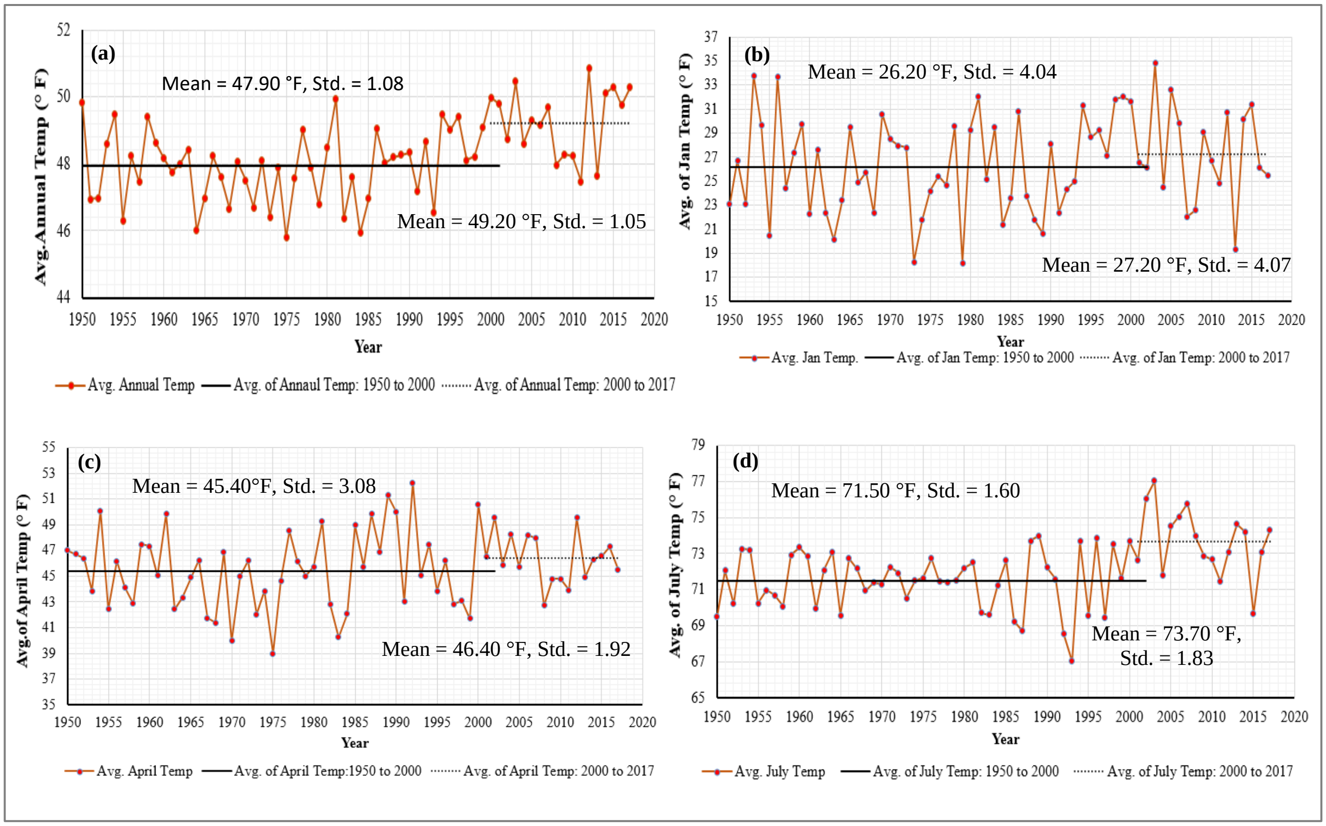

Figure 3: Historical temperature trends in Utah for the period 1950 –2017 based on the PRISM climate data: (a) average annual temperature, (b) average temperature in January, (c) average temperature in April, and (d) average temperature in July. Data source: https://cefa.dri.edu/Westmap/Westmap_home.php?page=timeseries.php.

Figures 4 (a) and (b) show the number of days per year with extreme hot and cold temperatures in Utah. Over the record, the average number of days per year with maximum temperature above 100°F was about 10.6 days, and with minimum temperature below 0°F was about 8 days. The number of extremely hot days per year increased in Utah over the past century (Figure 4a), whereas the number of extremely cold days per year decreased (Figure 4b). The trends in extreme temperatures in Utah are similar to the observed and projected nationwide trends, meaning days of extreme heat could become more frequent and days entirely below freezing could become less frequent (USGCRP, 2018). The implications of the extreme temperature events as reported in most of the climate studies will have effects on snow fall and snowmelt processes, droughts, escalated wildfire risks, and impacts on water supply and demand (USGCRP, 2018).

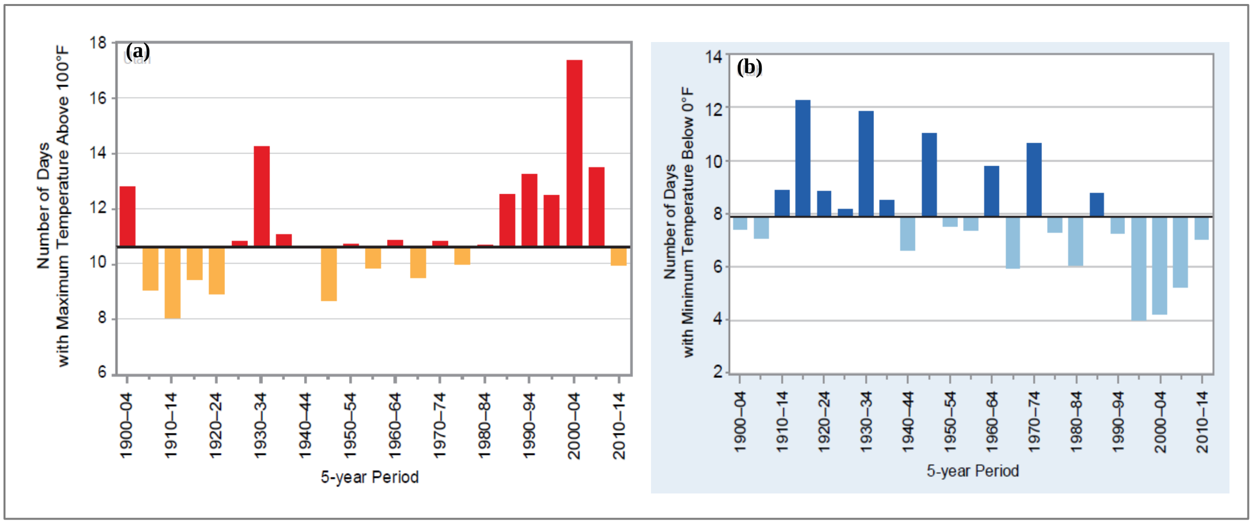

Figure 4: Observed number of hot and cold days per year for 1900–2018 averaged over 5-year periods. (a) The observed number of extremely hot days: annual number of days with maximum temperature at or above 100°F, (b) The observed number of extremely cold days with minimum temperature below 0°F. Black horizontal lines indicate averages in each panel. Source: *https://statesummaries.ncics.org/ut.*

Future Temperature Projections: Most of the Global and Regional climate models project increased average annual temperatures across the U.S. and Utah. The results of future temperature projections for a moderate and high greenhouse gas emission scenario (i.e., RCP 4.5 and RCP 8.5, respectively) are presented for the middle and late 21st century in Figure (5) (USGCRP, 2018). Projected temperature increases are larger at higher latitudes and also larger under higher greenhouse gas emissions compared to lower emissions. Central estimates of this continued warming vary from approximately 5 to 7°F depending on location (USGCRP, 2018). Several studies have dynamically downscaled Utah's future climate using the Weather Research and Forecasting (WRF) model under the moderate RCP6.0 greenhouse gas emission scenario (Strong et al. 2014; Scalzitti et al., 2016a; Scalzitti et al. 2016b). The studies indicated that by the 2040s (2035 to 2044) and 2090s (2085 to 2094) average temperatures will increase by 3.60 to 7.30°F and 5.4 to 10.80°F, respectively (Strong et al., 2017; Khatri et al. 2018).

Figure 6 presents observed and projected changes in near-surface air temperature for Utah together on one graph (Frankson et al, 2017). The results are based on observed data for the period 1900–2014 and projected changes for the period 2006–2100 from global climate models for two possible future scenarios (higher and lower emissions). The results show that temperatures in Utah (orange curve) have risen almost 2°F since the beginning of the 20th century. The shading in the figure indicates the range of annual temperatures from the set of models. Less warming is expected under a lower emissions scenario (green shading; up to 8°F) and more warming under a higher emissions scenario (red shading; up to 14°F). It is noted that the climate models and projections have ranges of uncertainties, therefore evaluations of multiple scenarios and climate models is always recommended prior to any adaptation decision-making for the water sector.

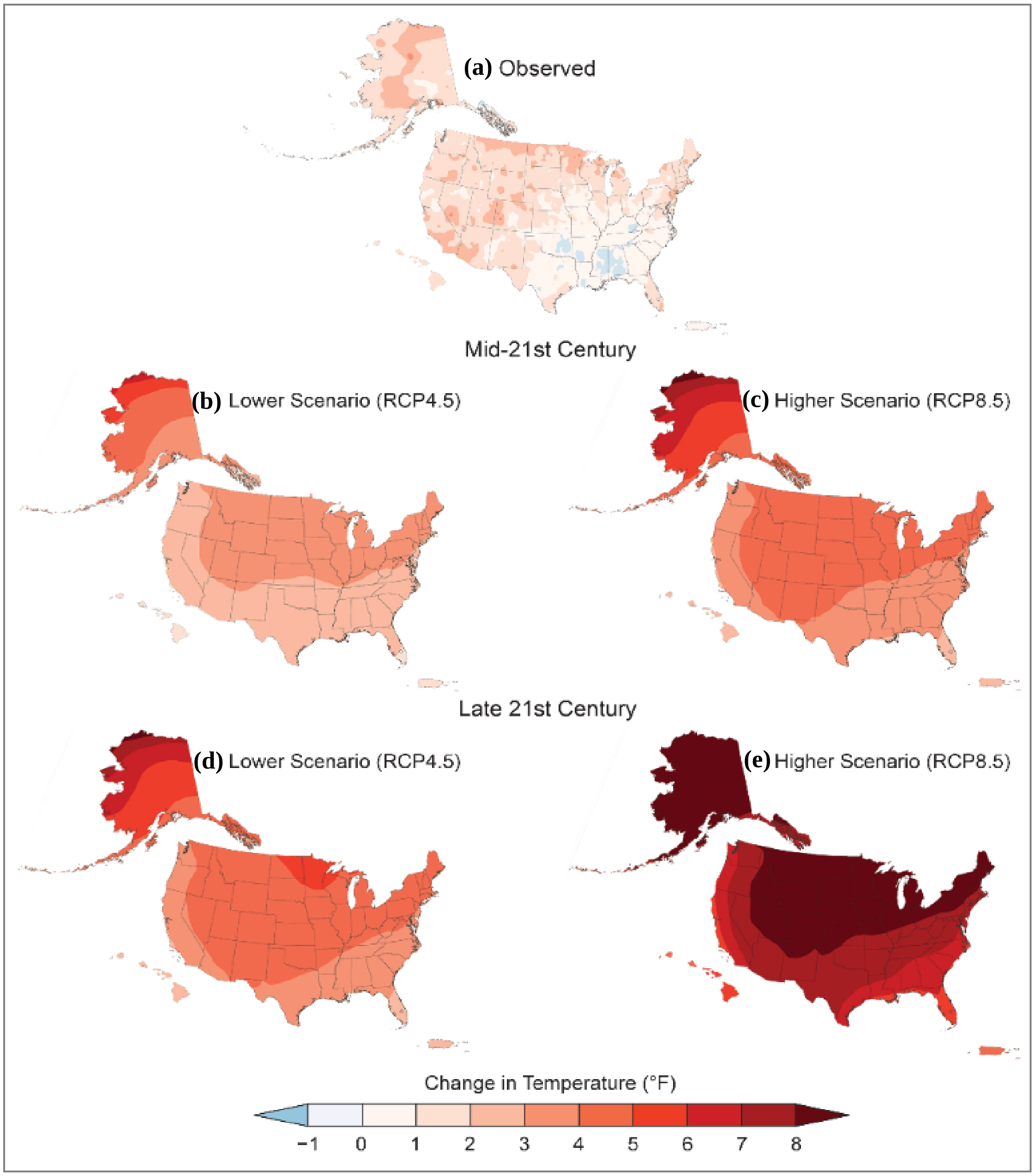

Figure 5: Changes in temperature observed and projected under a lower and higher greenhouse gas emission scenario: (a) observed change for 1986–2016 relative to 1901–1960, (b & c) projected differences in annual average temperature for mid-century (2036–2065, middle) and (d & e) end-of-century (2070–2099 relative to the near present (1986–2015). Source: USGCRP (2018).

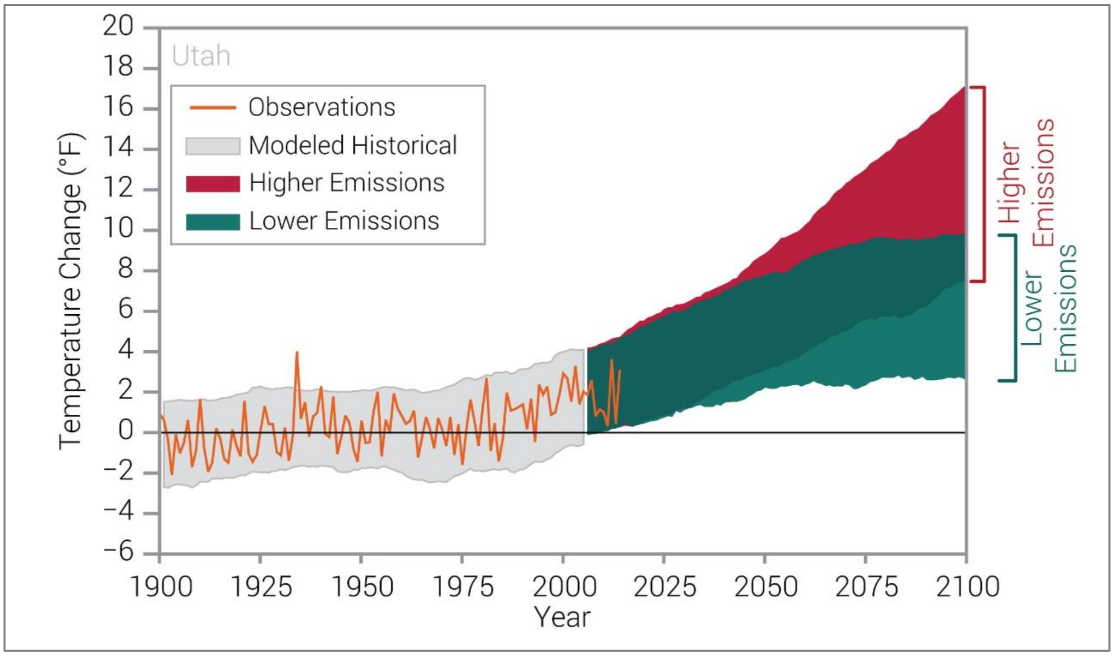

Figure 6: Utah observed and projected temperature change. Source: Frankson et al (2017).

2.2 Precipitation Changes: Small and Uncertain

Historical Precipitation Change: Similar to the temperature data, the precipitation data were also obtained from Western Climate Mapping Initiative (WestMap, 2019). Figure 7 presents historical precipitation in Utah as an annual total and for two seasons (winter and summer). The magnitude of the observed precipitation changes are insignificant compared to the changes in temperature.

The historical records of 1950 to 2017 show that the average annual precipitation in Utah was about 13.9 in. and the average value did not change significantly into the recent decade (Figure 7(a)). In contrast, the seasonal average values changed more noticeably in the early of 2000s and recent years (Figures 7(b &d)), meaning total precipitation increased slightly in winter and reduced slightly in summer. The results of time series regression analysis of the annual average precipitation for the period of 1950 –2017 indicated a weak but statistically significant upward trend ($r^2 = 0.013$, $p < 0.001$). The associated Mann-Kendall trend test results were Z = 1.303, p = 0.1926, and tau = 0.107. The calculated Sen's Slope of the observed annual average precipitation was 0.0213 in. per year or 2.1% per decade. It is noted that the presented results are averaged over the entire state and there is considerable spatial variability with terrain and latitude across the state.

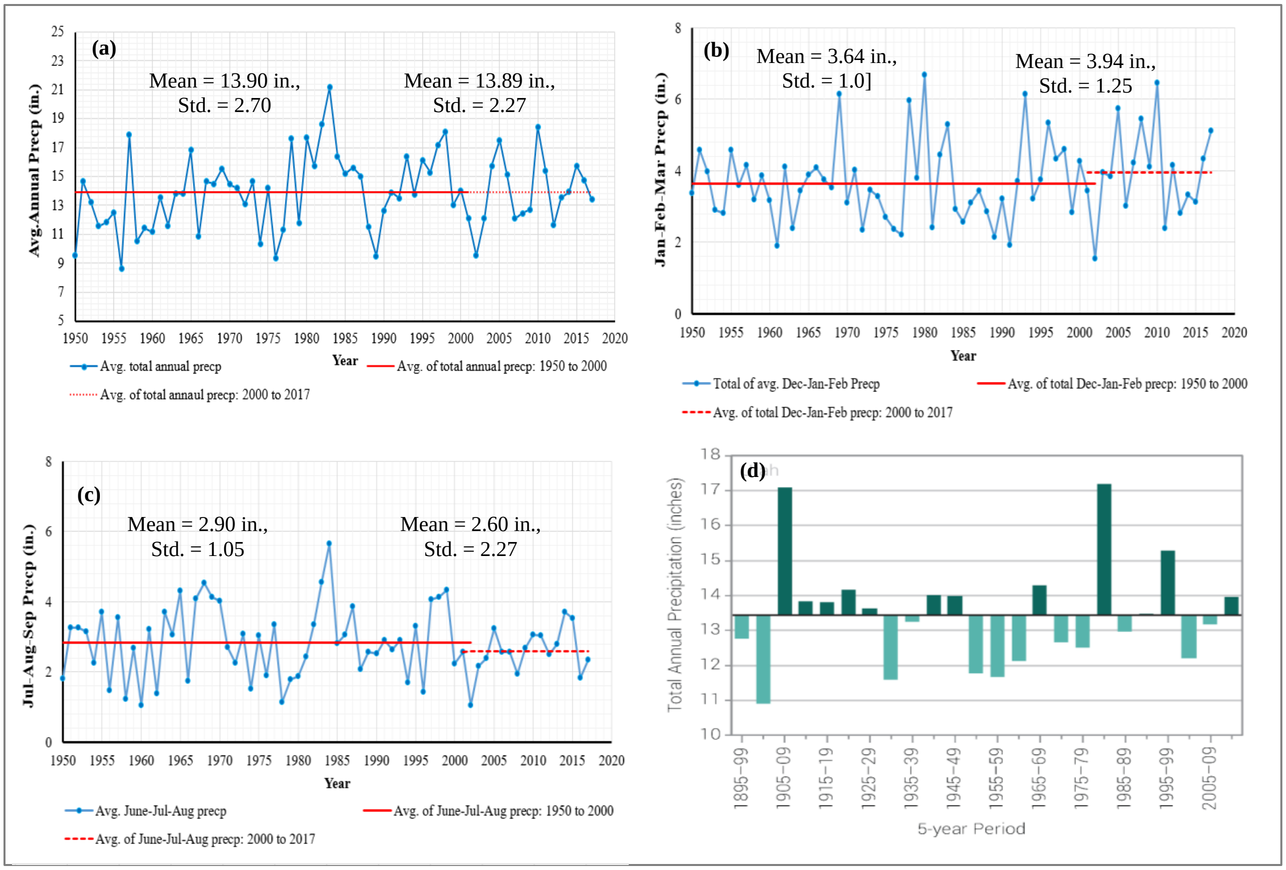

Figure 7: Average precipitation observed in Utah for 1950 to 2017: (a) average annual, (b) average in winter, (c) average in summer. (d) Observed annual precipitation averaged into 5-year periods. Data source for panels (a-c) is https://cefa.dri.edu/Westmap/Westmap_home, and data source for (d) is CICS-NC, NOAA NCEI.

Utah received average annual precipitation ranging from 10.7 in. during the driest period on record (1952–1956) to 17.2 in. during the wettest period on record (1980–1984) (Frankson et al, 2017). Figure 7(d) presents precipitation since 1895 averaged into 5-year periods. Utah's driest multi-year periods were in the early 1900s and 1950s to early 1960s, and the wettest periods were the early 1980s and late 1900s. As reported by Steenburgh et al. (2013), the seasonality of precipitation varies substantially across Utah depending on exposure to the mid-latitude westerly storm track during the cool season, the monsoon circulation during the warm season, and elevation. Southern parts of Utah observe a pronounced peak in precipitation in late summer due to the influence of the monsoon. Because monsoon precipitation is produced primarily by thunderstorms, large spatial contrasts in seasonal precipitation can be found within these areas during individual summers (Steenburgh et al., 2013).

Future Precipitation Projections: Projected changes in precipitation are much less consistent than temperature among various climate models and are thus characterized by greater uncertainty. Figure 8 presents projected precipitation changes in Utah and other parts of the U.S. based on the high-emissions RCP8.5 scenario. Most regional climate studies report that changing climate will lead to shifts in the seasonality and variability of precipitation (see, Pendergrass et al., 2017). Several studies indicate that spring has been arriving earlier over the past 50 years, and this trend is likely to continue (Bonfils et al. 2008; Cayan et al. 2001; Stewart et al. 2004; Strong and McCabe 2017). Climate models predict that the late-winter storm track over the western U.S. may weaken and shift northward, leading to a drier spring season likely to begin earlier in the year (McAfee and Russell 2008; Seager et al. 2007). It is noted that the projections show wetter or no change in average precipitation in 2060s and 2090s, but the magnitude of change depends on the season, region within the state, the RCP, and the global climate model (GCM) considered.

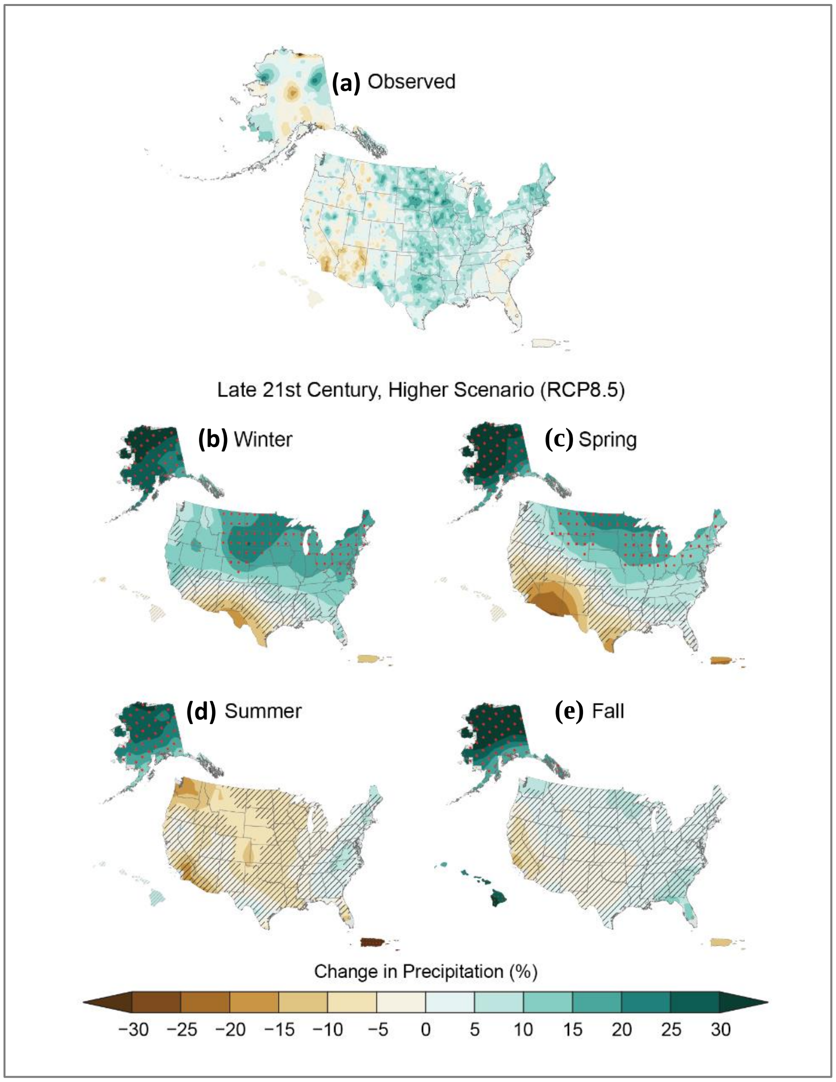

Figure 8: Average change in precipitation in late 21st century for a high-emission (RCP8.5) scenario: (a) observed precipitation for 1986–2016 shown for reference, (b, c, d, & e) projected precipitation changes in winter, spring, summer, and fall, respectively. Red dots indicate areas where projected changes are large compared to natural variations and hatching indicates areas where changes are small and relatively insignificant. Source: https://nca2018.globalchange.gov/chapter/2/

2.3 Snowpack Extent: A Decrease in April 1st Snowpack

Snow-Water equivalent (SWE) is the depth of liquid water that would result if the snowpack were melted down. Snow sources provide about 50% to 90% of the total runoff occurring during the April to July snowmelt season in most Southwest drainage basins (Stewart et al., 2005; Steenburgh et al., 2013). April 1 SWE has a close relationship with April-July streamflow. The contributions from snowmelt in Utah are estimated to be around 80% up to 95% (Julander and Clayton, 2015). Peak snow accumulation in Utah typically occurs around the beginning of April and lasts until late May to mid-June, depending on site and water year.

Historical SWE Change: Historical SWE observations in Utah, similar to other southwestern parts of the U.S., show a decreasing trend (Reclamation, 2016). Figure 9 shows historical variations of April 1st SWE for three stations in northern, central, and southern Utah. The Tony Grover Lake SNOTEL station (elevation 8474 ft.) in Cache County represents the northern part of Utah and has historical records from 1979 to 2018. Indian Canyon (elevation 9171 ft.) in Duchesne County represents central Utah and has SWE observations available from 1981 to 2018. For the southern portion of the state, Castle Valley (elevation 9607 ft.) in Iron County has SWE observations available from 1981 to 2018.

All three stations suggest slight decreasing trends in April 1st SWE (Figure 9, left column), with the signal being most apparent at the southern station (Figure 9(e)). Other regional studies have indicated decreases in snow accumulation and earlier melt in the Sierra Nevada Mountains and through the western U.S. (Kapnic and Hall, 2012; Mote, 2006; Burke et al., 2017). The variance accounted for by the downward trends highlighted here is very small ($r^2 < 0.02$) compared to year-to-year variability, but the trends are statistically significant based on a conventional *t*-test ($p < 0.001$). The Man-Kendall tau statistics for the 95% confidence interval, however, are weak (i.e., Tony Grover Lake = - 0.0195, Indian Canyon = 0.0623, and Castle Valley = - 0.0698). The Sen's Slope statistics for the SNOTEL stations (i.e., Tony Grover Lake = - 0.0369, Indian Canyon = 0.10, and Castle Valley = - 0.0645 in. per year) collectively indicate an unclear trend sign.

Julander and Clayton (2015) suggest that SWE decreases in the SNOTEL observations could be the result of biases from multiple factors including changes in station location and also vegetation changes related to the spatial extent of the forest canopy, vegetation type, and vegetation cover. Mahat and Tarboton (2010) also found that forest areas collected about 10-20% less snow than adjacent open areas, which is relevant to potential issues stemming from SNOTEL site characteristics. Therefore, regional analyses suggest weak decreasing SWE trends but need further evaluation using a longer period of observations.

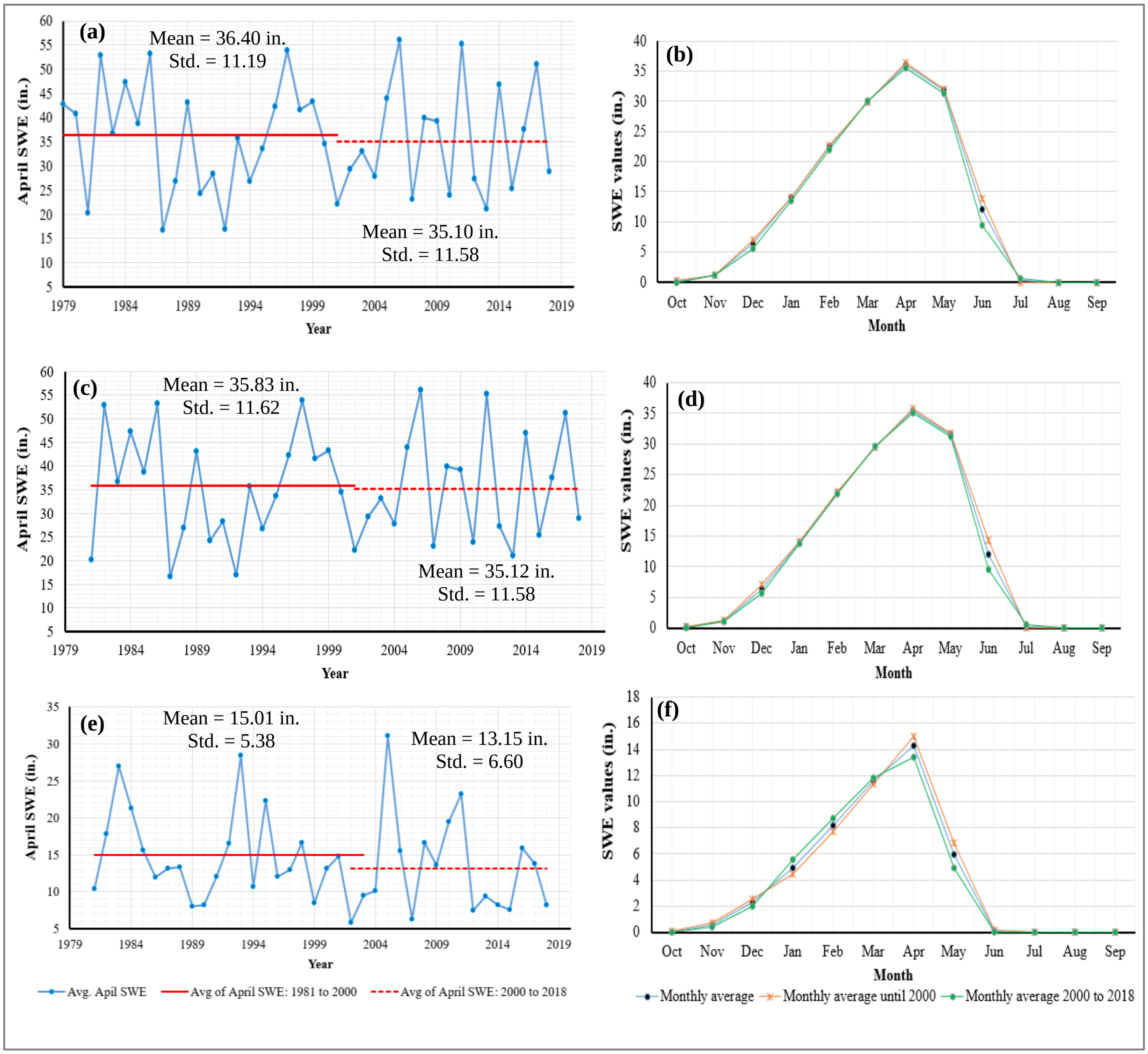

Figure 9: Observed time series of April 1st SWE values and average monthly SWE values for three SNOTEL stations: (a & b) Tony Grove Lake in Cache County in Northern Utah, (c &d) Indian Canyon in Duchesne County in central eastern part of Utah, and (e & f) Castle Valley in Iron County in Southern Utah. Source: https://www.wcc.nrcs.usda.gov/basin.html.

Future SWE Projections: Most climate models suggest that higher mean temperatures will decrease snowpack storage and lead to earlier melting of snowpack in the higher-elevation mountain ranges of Western North America (Mote et al., 2005). A large fraction of the precipitation in the upper elevations of Utah falls as snow, which serves as the primary source of water. As the climate warms, less precipitation will fall as snow, and more snow could melt during the winter. This will lead to changes in the snowpack and earlier melt and runoff. At higher elevations snowpack is primarily sensitive to the amount of precipitation, while at lower elevations it is mainly sensitive to temperature. The elevation threshold between these two regimes is expected to lower by up to 300 m by the end of this century leading to reduced water accumulation and increased runoff (Scalzitti et al., 2016a).

Figure 10 shows projected SWE for the Southwest U.S. based on the A2 greenhouse gas emissions scenario reported in the third climate change impact report in 2014 (Garfin et al., 2014). Values are shown as a percentage of the period 1971–2000 climatology, and the size of bars are proportional to the amount of snow each state contributes to the regional total. Therefore, the bars for Utah are smaller than those for Colorado, which contributes the most to region-wide snowpack. Utah receives approximately two-thirds (66%) of its historical SWE by the end of the current century under this scenario. The report indicates that declines in peak SWE are strongly correlated with earlier timing of runoff and decreases in total runoff (Garfin et al., 2014). The changes to the snow-to-rain ratio and higher spring temperatures could cause earlier melting of the snowpack, decreasing water availability during the already dry summer months.

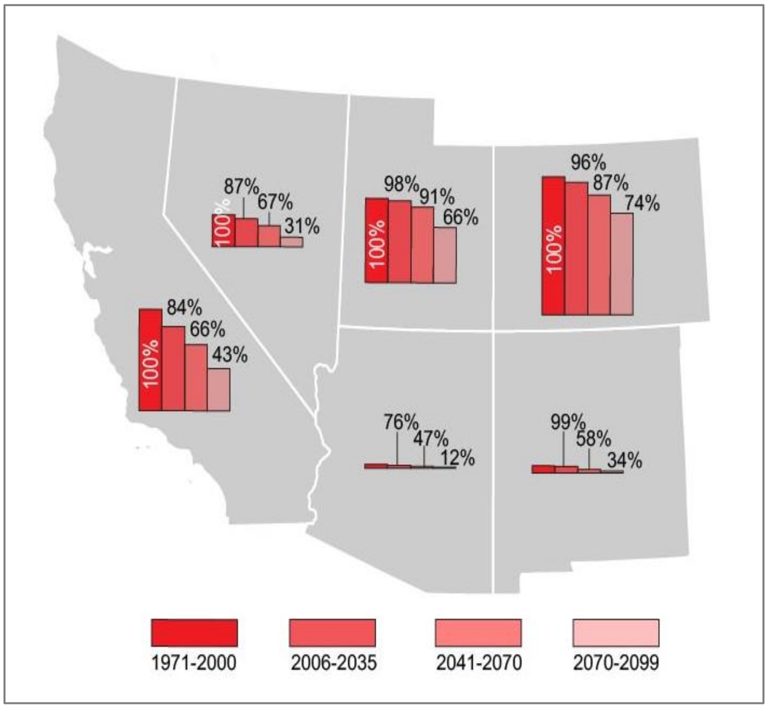

Figure 10: Projected SWE values in Utah and other states for three 30-year periods relative to the historical period 1971–2000 climatology assuming continued increases in global emissions (A2 scenario). Source: https://data.globalchange.gov/report/nca3/chapter/southwest/figure/projected-snow-water-equivalent.

2.4 Streamflow: Change in Shape of Hydrograph

The impact of climate change on mountain hydrology has already been observed in the Western U.S., with changes in streamflow resulting from earlier snowmelt and more precipitation falling as rain (Stewart et al., 2005). Over the past 50 years across most of the Southwest, there has been less late-winter precipitation falling as snow, earlier snowmelt, and earlier arrival of most of the year's streamflow. For example, Christensen et al. (2004) found a 10% decrease in annual runoff in the Colorado River basin in the middle of the century (2040 to 2069) for the business-as-usual greenhouse gas emission scenario. Another study for the Upper Colorado River Basin (Ray et al., 2008) showed decreases in runoff ranging from 6% to 20% by 2050 compared to the 20th century average based on the multi-model average projections. However, the streamflow trends in Utah are uncertain, with increased or decreased streamflow based on the geographical location of the river basin from the northern part of the Wasatch range to the southern part. The hydrographs of historical and future streamflow at three major river basins in Utah simulated by the variable infiltration capacity (VIC) model are shown in Figure 11 (Wood and Bardsley, 2015).

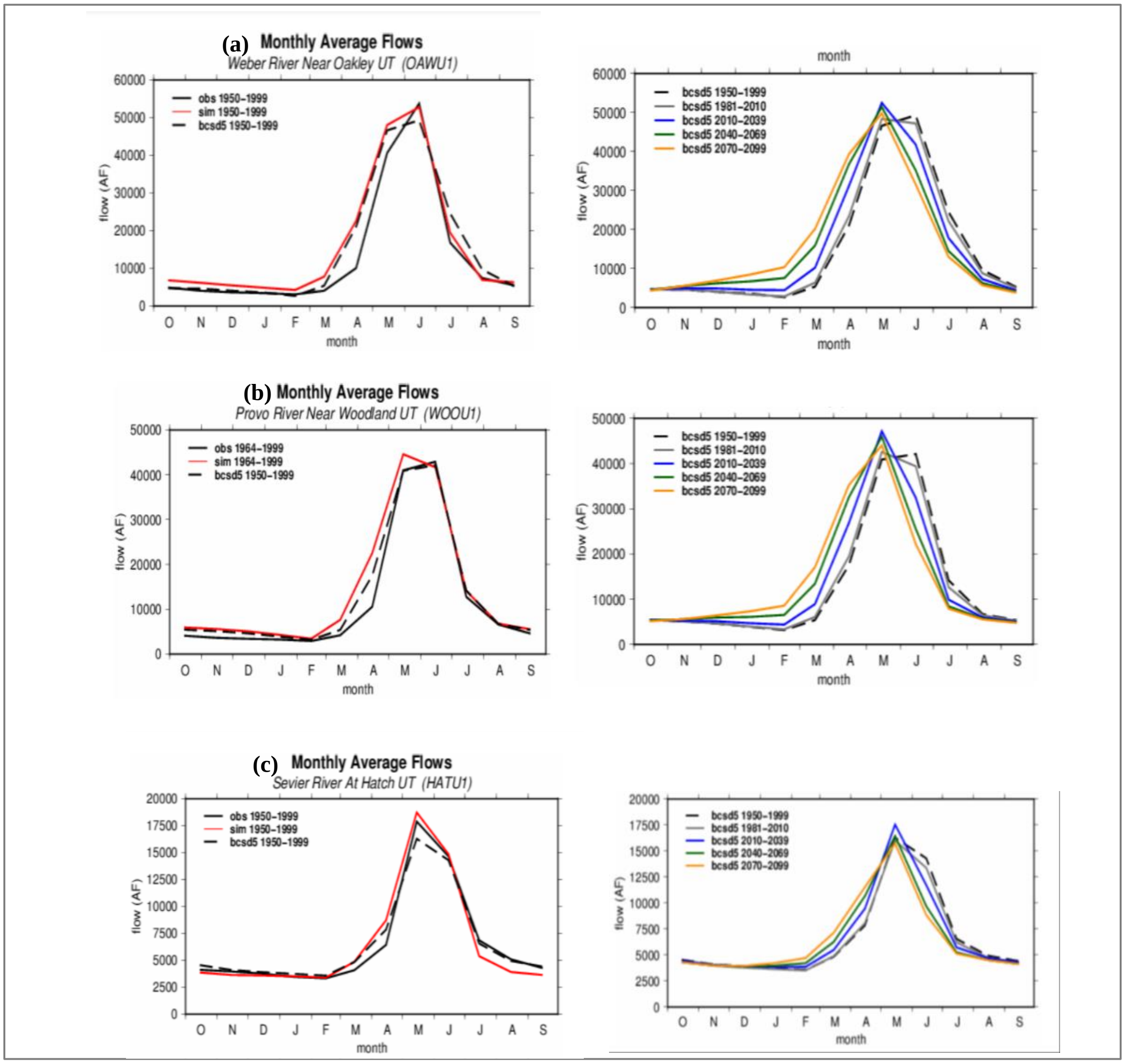

Figure 11: Mean monthly hydrographs: The left panel of each figure compares the observed historical flow for a base period of 1950 –1999 (solid black curves), simulated flow for the same base period (red curves), and the Bias Corrected Spatially Downscaled Monthly CMIP5 Climate (BCSD5) ensemble mean flow for the base period (dashed black curves). The right panel of each plot shows the BCSD5 ensemble means for the base period and for four other periods: 1981–2010, 2010–2039, 2040–2069, and 2070-2099 (using water years). The columns correspond to the three basins: (a) Weber River near Oakley, (b) Provo River, and (c) Sevier River at Hatch.

The model was not calibrated for all the basins; however, the presented results indicate changes in the hydrologic characteristics. This study found that median flow volumes increase in the future period relative to 1950–1999 at most locations, with increased spread (i.e., lower quantiles decrease and upper quantile increase) in the future projections relative to the past. In general, the results show shift of flow timing toward an earlier peak runoff.

It is noted that the magnitude of changes and timing will vary according to basin characteristics including the size, elevations, slope, soil types, and vegetation in the basin. It has been anticipated that smaller catchments will likely be more sensitive to changes. For example, Clow (2010) showed timing of two to three weeks earlier in the high mountains of the Colorado region; Stewart (2009) found advancement of about 15 to 20 days in the western United States. A study of a small watershed in the Jordan River Basin in Utah showed the historical 50^{th} percentile timing of streamflow and sediment load is projected to be shifted earlier by three to four weeks by mid-century and four to eight weeks by late-century (Khatri et al., 2019). The escalated timing of the snowmelt-dominated streamflow is due to change in the extent and timing of the annual snowpack (i.e., later snowpack initiations and earlier snowpack disappearance), change in the length of the snow-covered season, and increasing springtime air temperatures (Clow, 2012; Harplod et al., 2012; Stewart, 2009).

Figure 12 shows the Colorado River basin historical water supply and uses, and projected water supply and demand (Reclamation, 2012). The dark lines are the median values and the shading represents the 10^{th} to 90^{th} percentile range. These results illustrate potential imbalance between future supply and demand but with considerable long-term variability that is not well understood for the future (Reclamation, 2012). The applicability of these results to Utah is plausible but would require detailed study.

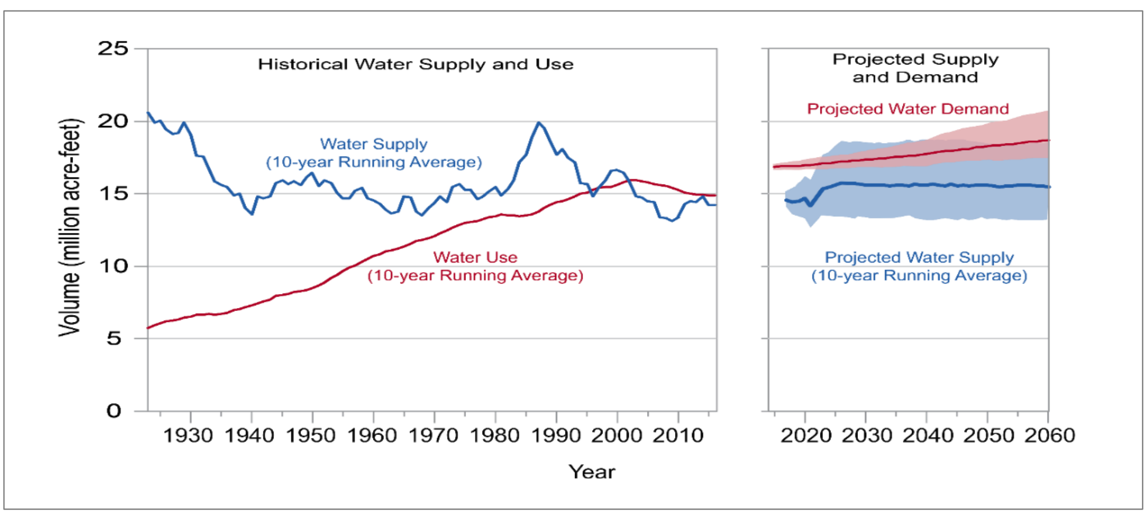

Figure 12: Historical water supply and uses, and projected water supply and demand in the Colorado River basin. Source: Reclamation (2012).

A recent study on water criticality in Utah (Khatri et al., 2018) investigated the current and future (i.e., 2040s and 2090s) water stress levels of 11 river basins in Utah (Figure 13). Water criticality was defined as the ratio of annual water availability to water withdrawals at a basin level. The water criticality index, used to measure the water stress level, compared the water availability and withdrawals in all basins. The objective was to assess if a river basin can support potential water demand internally and to what extent the basin is dependent on other basins, considering the effects of climate change on water supply and of future population change on demand.

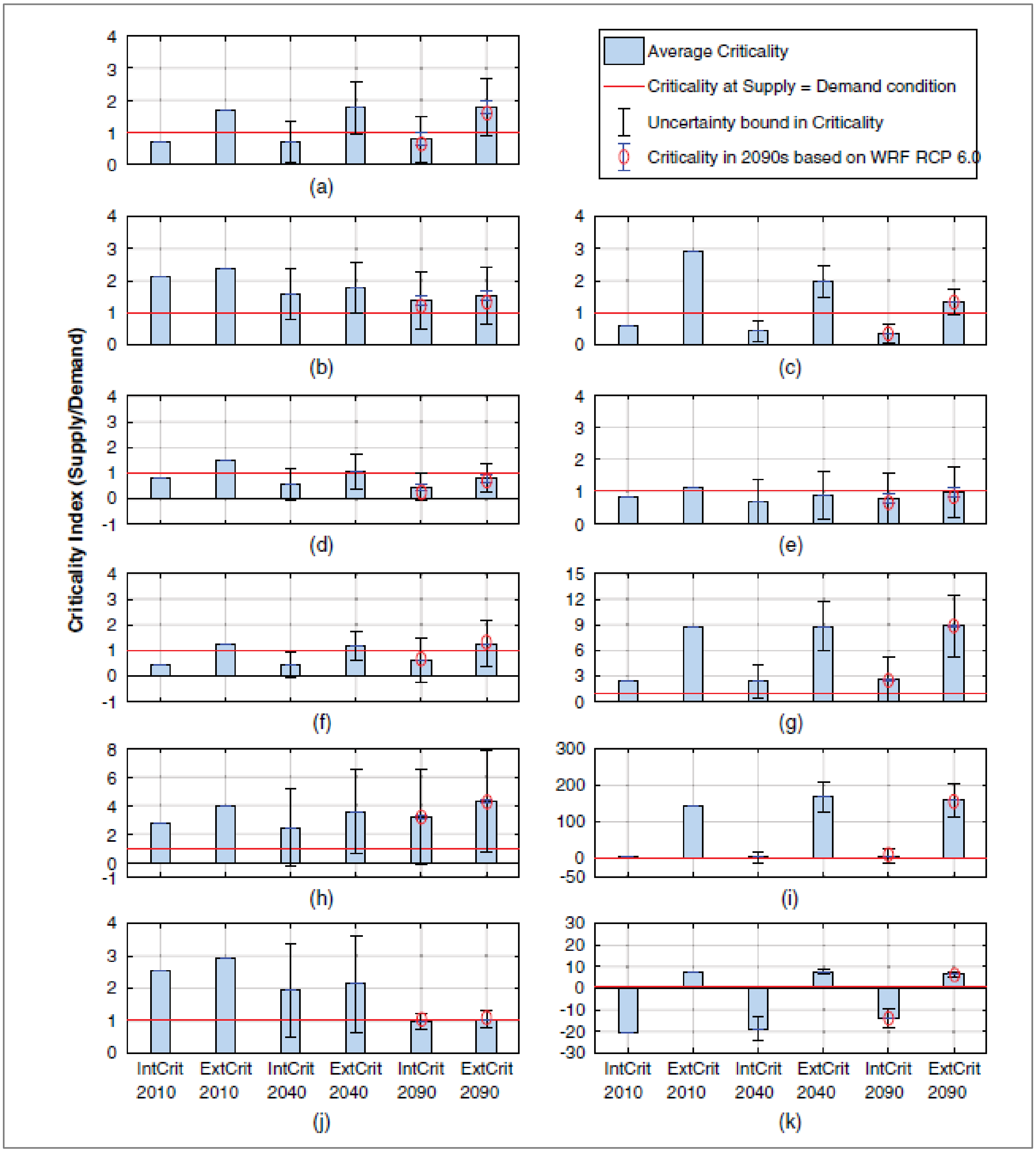

Figure 13. Internal and external water criticality indices for each basin over Utah for 2010s, 2040s, and 2090s: (a) Bear River, (b) Weber River, (c) Jordan River, (d) Utah Lake, (e) Sevier River, (f) Cedar/Beaver, (g) Uintah, (h) West Colorado River, (i) Southeast Colorado River, (j) Kanab/Virgin River, and (k) West Desert.

In Figure 13, the bar indicates mean criticality across all years in the period, the red line indicates that supply just balances demand, and the whiskers on future decade bars indicate how results differ when driven by climate change outcomes corresponding to the 2.5th and 97.5th percentiles of the statistically downscaled CMIP5 ensemble for RCP 6.0. A river basin with criticality ratio of 1.0 indicates that the basin demand has been exactly met by the available supply sources. As a result, a basin that has criticality ratio less than 1.0 will have serious water stress. The study showed that most of the river basins will be in the water state of "water stressed" in 2040s to 2090s and Utah water demand will be met by the external water supply sources. The main cause of the water stress would be increased water demand due to the projected population compared to the impact of climate change to the water supply side (Khatri et al., 2018).

2.5 Extreme Weather Events: Increased Drought and Flooding

A change in the frequency, duration, and/or magnitude of extreme weather events is one of the most important consequences of the warming climate. Specific examples include extreme high temperature events, heavy precipitation, droughts, and floods. All of the events will pose direct and indirect risks to water resources and water management.

Drought: Frequent and Intense Events: Drought events over a given region generally represent prolonged and abnormal dry periods (from months to years) due to moisture deficiency (Palmer, 1964). Different classes of droughts commonly used to describe water deficits include meteorological drought, hydrological drought, and agricultural drought (Heim, 2002). In practice, various types of drought indices are used to encapsulate drought severity to assess and monitor droughts in terms of their severity, location, duration, and timing (Heddinghaus et al., 1991). Examples include the Palmer Drought Severity Index (PDSI), Percent of Normal Precipitation, Surface Water Supply Index (SWSI), Crop Moisture Index (CMI), and Standardized Precipitation Index (SPI). Utah State adopts the Surface Water Supply Index (SWSI) to calculate the drought condition in a river basin by assimilating multiple data including snowpack, streamflow, precipitation, and reservoir storage in a river basin.

The historical drought conditions in Utah based on the Palmer Modified Drought Severity Index (PMDI) are shown in Figure 14. The standardized measure ranges from about -10 (dry) to +10 (wet) with values below -3 representing severe to extreme drought. The records indicate frequent drought observed in the last 100 years, most severely in the 1930s, 1960s, 1970s, 1990s, and 2000s. The most significant and severe droughts in Utah result from a diminished frequency or intensity of winter storms.

Droughts in Utah also tend to be strongly related to large-scale shifts in the atmospheric circulation associated with the El Niño-Southern Oscillation (ENSO). ENSO refers collectively to episodes of warming and cooling of the equatorial Pacific Ocean and their related atmospheric circulation changes. Warm and cool ENSO episodes are known as El Niño and La Niña, respectively. La Niña years are associated with reduced cool-season precipitation over the southern portions of the Southwest region (Redmond and Koch, 1991; Cayan et al., 1999), with the extent of the precipitation anomalies being sensitive to other Pacific and Atlantic modes of variability (Wise, 2010).

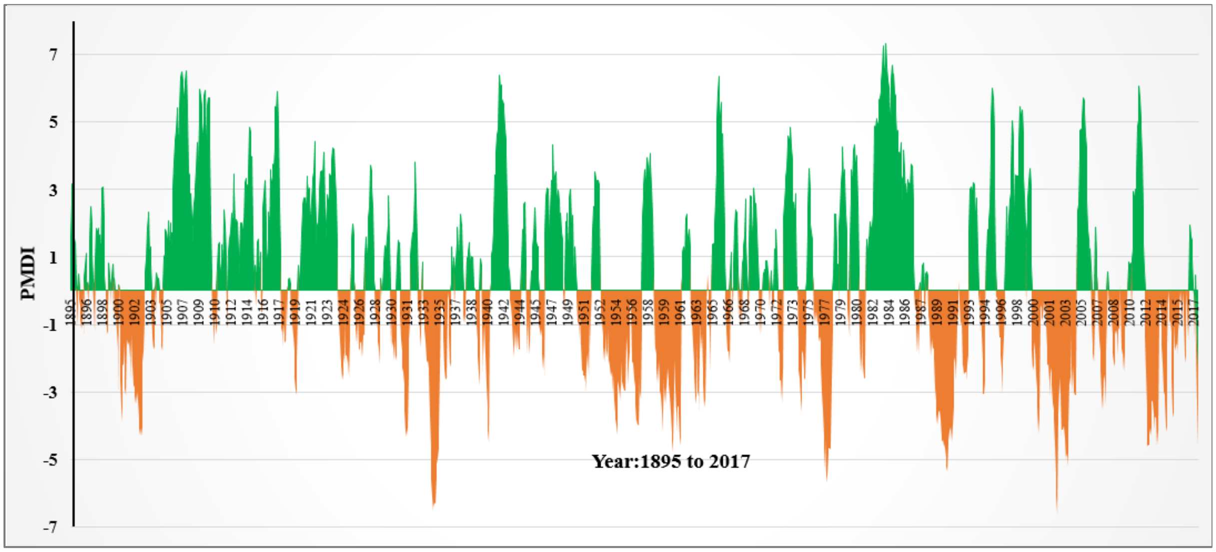

Figure 14: Historical drought records in the Utah based on the Palmer Modified Drought Index (PMDI) for the period 1895 through 2017. Data source: https://www7.ncdc.noaa.gov/CDO/CDODivisionalSelect.jsp#

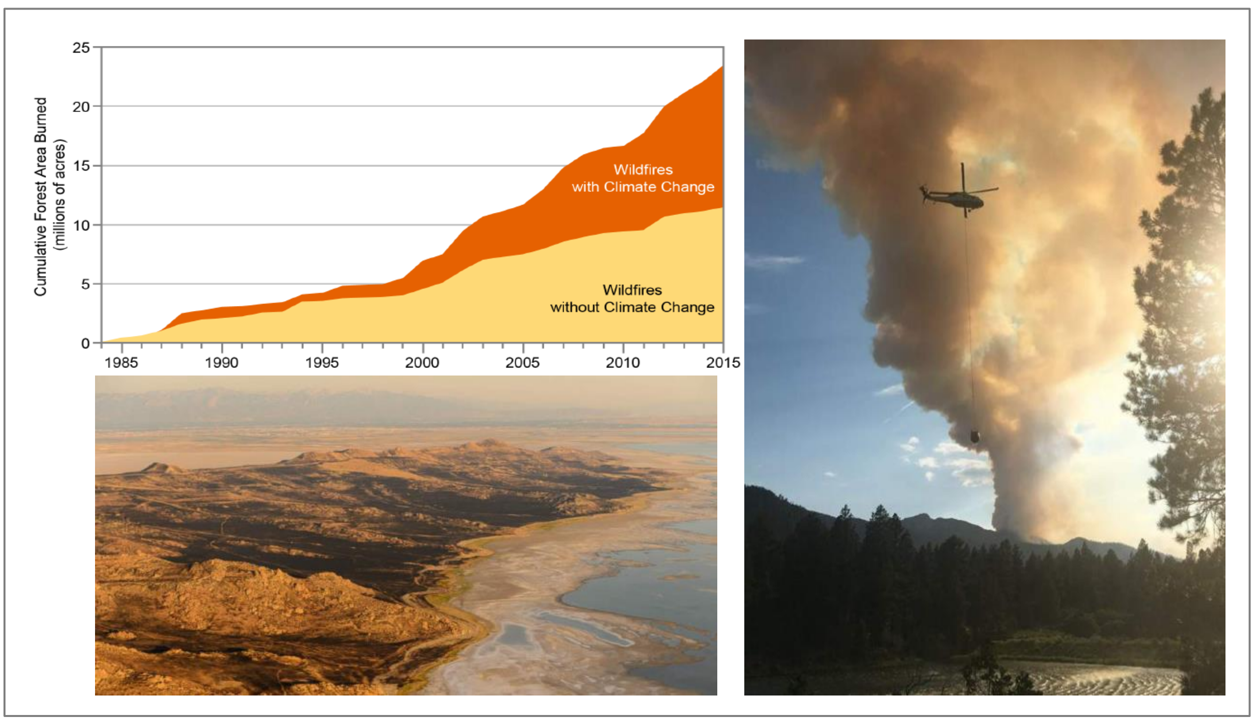

Figure 15: Top left: cumulative forest area burned in the western U.S. during 1984 to 2015 *Source: https://nca2018.globalchange.gov/chapter/southwest).* Photos: the West Antelope wildfire that burned about half the Great Salt Lake's Antelope Island. Source: Courtney Tanner, the Salt Lake Tribune, December 12, 2016.

The state of Utah similar to the Southwest is susceptible to periods of dryness that can span months to years. Figure 15 (top left) shows wildfire cumulative forest burned in Southwest US

(Abatzoglou, and Williams, 2016). The graph indicates an increasing prominence of wildfires, with an illustrative example in the photo at lower left. It is expected that higher temperatures and more frequent drought will escalate the potential for wildfires. However, supporting research is limited in Utah.

Most climate variability studies indicate that more intense droughts are expected in the future. Higher temperatures will amplify the effects of naturally-occurring dry spells by increasing the rate of loss of soil moisture. The projected increase in the intensity of naturally occurring droughts may increase the occurrence and severity of wildfires. Burned vegetation within watersheds can exert direct impacts on local hydrologic cycles, infiltration rates, runoff, sediment loads and ecological life in water bodies.

Flooding: Rare but Potential Flash Flooding: The four primary causes of flooding observed in Utah are extended rainfall, rapid spring snowmelt, dam breaks, and flash flooding. In snowmelt-dominated watersheds, flooding usually results from heavy rain falling on melting snow, or from a rapid springtime warm-up leading to sudden snowmelt. The report on Assessment of Climate Change in the Southwest U.S. (Garfin et al., 2013 and cited resources there) concludes that there is a high probability of winter flooding due to projected increases in winter storm intensity in the Southwest and Utah. Transition from hail to rain on the Front Range of the Rocky Mountains is expected to result in higher flash-flood risk specifically in eastern Colorado. Flash floods associated with thunderstorms occur throughout the Southwest, many during the months of the North American monsoon.

Figure 16(a) presents the occurrence of three major flood event types in Utah from 1993–2011. Flash floods observed in the last two decades have increased significantly (i.e., by a factor of four) despite the decreased incidence of extreme rainfall events (Figure 16(b)). This could be due to changes in the landscape, land use changes, or vegetation changes and wildfire in the river basins. In 1983, melting of a large snowpack during the months of April to June caused mudslides and extensive flooding in the Salt Lake Valley (Frankson et al., 2017). A more recent severe flooding events is illustrated in Figure 17.

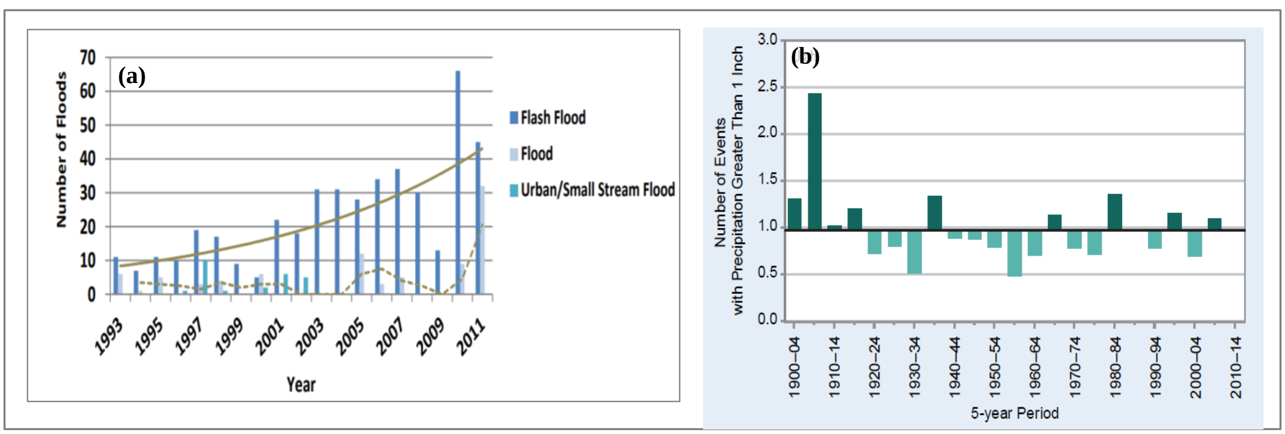

Figure 16: (a) Number of flood events in Utah by flood type (1993-2011). Source: National Climatic Data Center at http:// www7.ncdc.noaa.gov/CDO/CDODivisionalSelect.jsp, (b) Number of events with precipitation greater than 1 in. Source: CICS-NC and NOAA NCEI.

Figure 17: Flooding in Virgin River near Washington, Utah, just upstream of the Santa Clara River. In January 2005, heavy rains in the Virgin River basin caused severe flooding along the Virgin and Santa Clara Rivers in Washington County, resulting in over $150 million in damage. Discharge was approximately 12,000 cubic feet per second on January 10, 2005. Source: https://pubs.usgs.gov/fs/2006/3085/PDF/FS2006-3085.pdf

Increasing flooding events will pose risks to water infrastructure (weirs, dams, canal, pipes, reservoirs, etc.), ecosystem services, public life, and economy. Extreme weather events under a changing climate and burned watersheds due to wildfire could be some of the major causes of flash flooding and sediment loading in coming decades. Projecting trends in the frequency and intensity of extreme weather events is, however, challenging and an area of high uncertainty.

2.6 Impact of Climate Change on Water Resources: High and Multisectoral Challenges

As presented, climate change is altering the water cycle in multiple ways over different time scales and geographic areas. Projected changes in temperature, precipitation, and snowpack are expected to alter the magnitude and seasonality of runoff. Warming is expected to result in more rainfall-runoff during the cool season rather than snowpack accumulation, leading to increases in December–March runoff and decreases in April–July runoff. The Southwest to the Southern Rockies is expected to experience gradual runoff declines during the 21st century (Saunders and Easley, 2018). Climate variability has caused droughts, floods, heat waves, cold snaps, heavy snow falls, severe winds, and intense storms. All the climate parameters including temperature, precipitation, relative humidity (Harpold and Brooks, 2018), and solar radiation have direct and indirect impacts on water resources and hence water management. Table 1 briefly summarizes potential impacts of climate change on water resources and water resources management in the context of Utah.

Table 1: Potential impact of climate change on water resources systems.

Areas of Interest	Potential Impacts
Water demand: Increase in total water demand.	**Increase in total water demand:** Rise in temperatures and seasonal climate variability will lead to increased water usage in domestic (mainly outdoor), industrial, and agriculture (increased evapotranspiration) sectors. The rate of change will vary with location and user type but the effects of climate change will compound total water demand in the future. The competing water demands in local and regional watersheds will create water scarcity and the need for additional reservoirs and infrastructure systems.
Water availably: Change in snowpack and rainfall proportion, earlier snowmelt, reduction in ground water recharge, shift in the timing of runoff and loss of reservoir storage capacity.	**Change in snowpack versus rainfall:** Snowpack generally is projected to decrease as more precipitation falls as rain and warming temperatures cause earlier snowmelt.
	Reduction in water supply: Climate assessments project that the manageable water supply, in general, will decline in much of the West-wide. This is due to potential increases in temperature and water losses from water systems. A decrease of up to 8% in average annual streamflow is projected in several river basins, including the Colorado, the Rio Grande, and the San Joaquin. Similar trends can be expected in Utah. The shifts in runoff timing, lengthening of the growing season, and greater reliance on stored water will motivate changes in water management practices.
	Changes in timing of runoff: West-wide, runoff is expected to shift to earlier times of the year (less in summer, more in winter and spring), making it more difficult to manage water deliveries using past strategies. General findings of the shift are in a range of one to four weeks by 2050 and up to six weeks by 2100. The shift in timing will have direct effects on peak-season hydropower operations and reservoir management.
	Reduced groundwater resources: The reduced snowpack, an increased fraction of precipitation falling as rain rather than snow, and increased occurrence of high-intensity rainfall may lead to decreases in aquifer recharge and groundwater availability in the future. The direction and magnitude of these changes vary with local conditions.

	Reservoir operation: Changes in the magnitude and intensity of extreme runoff events may prompt reconsideration of operating rules to manage flood risks while maximizing storage opportunities.
	Reservoir storage: Reservoirs are anticipated to fill earlier in the year, with a corresponding reduction in the water supply available through the summer season. In addition, there may be a need to deal with shorter-duration high-flow events and to reassess the reservoir storage capacity.
	Reservoir sedimentation: Projected increasing frequency of extreme precipitation and droughts will lead to increases in wildfires and flash flooding that will result in increased sediment load in the reservoirs. The degree of impact will vary based on geomorphological features and reservoir practices.
Extreme events: Frequent droughts and floods as well as potential increased wildfires.	**Prevalence of droughts:** Most climate variability studies indicate that more intense droughts are expected in the future. Increased temperatures will amplify the effects of naturally-occurring dry spells by increasing the rate of loss of soil moisture. The projected increase in the intensity of naturally occurring droughts will increase the occurrence and severity of wildfires. Increasing droughts and higher temperatures are likely to affect farms and cattle ranches.
	Forest fires: Higher temperatures and intense droughts will stress forest vegetation and increase the potential risk of wildfires. The wildfires pose risks to property, livelihoods, and human health. However, the level of risks will depend on the location and existing forest management practices.
	Potential for severe flooding: In snowmelt-dominated watersheds, flooding usually results from heavy rain falling on melting snow, or from a rapid springtime warm-up leading to sudden snowmelt. In addition, climate models consistently show that precipitation will increasingly occur in more concentrated extreme events. These intense precipitation events may challenge current infrastructure for water management and flood control.
Ecological and wildlife resources: Potential effect of frost damage, negative effects on	**Increased frost-free season length**: Hot and moisture-stressed regions like the Southwest are projected to suffer from heat stress on plants and increased water demands for crops.

endangered species and ecological life.	Higher temperatures and more frost-free days during winter can lead to early bud burst or bloom of some perennial plants, resulting in frost damage when cold conditions occur in late spring. With higher winter temperatures, some agricultural pests can persist year-round, and new pests and diseases may become established. **Riverine habitat:** It is anticipated that changes to hydrology and climate may make it more difficult to achieve environmental flows to support endangered species. Projected increases in winter flooding and decreases in summer flows will affect marine ecological systems.
Other environmental and public health: Direct and indirect impact to the local economy and public health.	A warmer and drier climate could accelerate current trends of large transfers of irrigation water to urban areas, which would affect local agriculturally dependent economies. Increased temperatures can reduce air quality, because some of the key atmospheric chemical reactions proceed faster in warmer conditions. The outcome is that heat waves are often accompanied by increased ground-level ozone, which can cause respiratory distress. It has been reported that ozone has a variety of health effects, aggravates lung diseases such as asthma, and increases the risk of premature death from heart or lung disease. Heat stress has also been the leading weather-related cause of death and is a recurrent health problem for urban residents.

3. CLIMATE IMPACT ADAPTION STRATEGIES

Climate science and global climate modeling are associated with multiple sources of uncertainty. Commonly discussed uncertainties in climate models include unknown radiative forcing, system nonlinearity, dynamic social and economic changes, and unknown human effects and responses. Similarly, identification of possible future emission scenarios and selection of the representative global and regional climate model, and downscaling techniques are very complex and often unknown steps in climate modeling. Therefore, it is very challenging to predict the magnitude of climate change precisely for a specific location and time in the future despite extensive research in climate science and advancement in climate modelling capacity.

Planning for adaptation and mitigation measures to cope with and respond to climate change is a widely accepted norm in today's world. Planning for climate change adaptation and mitigation uses information about present and future climate to assess the suitability of current and planned practices, policies, and infrastructure in water and other sectors. Adaptation and mitigation planning efforts are sector-specific but are guided by some common critical questions. For example, how will future climatic and non-climatic conditions differ from those of the past? How do the expected changes influence current decisions? What are the risks of acting early and those of acting late? The overall objective of adaptation and mitigation planning, as synthesized in several publications, is to make recommendations about who should take what actions more often, less often, or differently, and with what resources (UKCIP, 2003; Hallegatte, 2008; Bierbaum et al., 2014; USEPA, 2015).

One of the best examples of climate adaptation initiatives in the western U.S. is the Drought Contingency Plans (DCPs) forwarded by the seven Colorado River Basin states and water entitlement holders and approved by Congress on March 19, 2019 (Reclamation, 2014). It was developed based on "The Colorado River Compact of 1922," which governs Colorado River water management. Under the compact, water supplies are divided equally between the Upper Basin and the Lower Basin. The need for the DCPS was realized after evaluation of the consumptive use in the basin, natural flows, and trend analysis of a long-term water supply and demand condition.

According to DCPs reporting (Reclamation, 2019), (1) "*The Upper Basin DCP would establish a Demand Management Program for the Upper Basin by authorizing storage of conserved water in Lake Powell. It also would establish 3,525 feet as the target operational level for Lake Powell and coordinate operations with other Upper Basin reservoirs so as to reduce the risk of Lake Powell's elevation falling below 3,490 feet (a point at which reduced hydropower generation and cutbacks to water users are possible)*".

(2) "*The Lower Basin DCP would require that when Lake Mead reaches predetermined elevations, Lower Basin states would forgo deliveries beyond the levels agreed to in 2007 (and includes for the first time cutbacks for California). It would also further incentivize voluntary conservation of water to be stored in Lake Mead and commit DOI to conserving 100,000 acre-feet of water per year to be left in the system. The agreement aims to avoid Lake Mead elevations falling below 1,020 feet".*

The basin has thus far avoided major impacts due to its significant storage capacity in two lakes (Lake Powell and Lake Mead), coupled with the fact that Upper Basin states have not fully developed their entitlement. However, the water storage level is dropping because of the drought (see Figure 18 for the critical water levels observed in Lake Mead). Earlier studies indicate that future water uses in the basin will be increased with increasing population and tribal water rights, and warn that Colorado River flows are unlikely to return to their 20th century average (Reclamation, 2014).

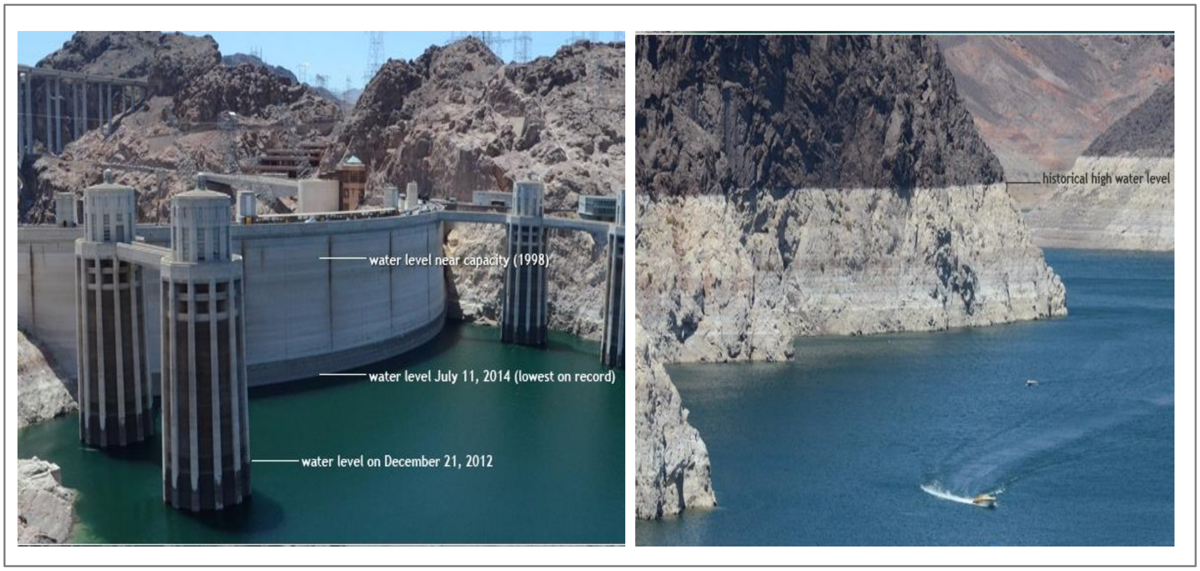

Figure 18: Critical water levels observed in Lake Mead: On July 11, 2014 the Lake Mead reservoir reached its lowest water level since the lake was first filled during the construction of the Hoover Dam in the 1930s. The lake's elevation was 1,081.77 feet, which is about 147.23 feet below capacity and about 133.99 feet below its last peak in 1998. Source: climate.gov, https://www.climate.gov/news-features/featured-images/western-drought-brings-lake-mead-lowest-level-it-was-built.

Some of the ongoing water resources planning and water conservation initiatives in Utah include drought planning, statewide water conservation goal setting, modeling integrated water systems, optimizing agricultural water demand, secondary water metering projects, and planning renovation of the aging reservoirs, dams, canals, and pumping structures. These measures could collectively help to preserve limited water resources and optimize water applications. Other ongoing adaption initiatives in the region, where Utah is actively contributing, include the 1992 Colorado River Compact and the Western Agency Support Team (WestFAST) (see, Bierbaum et al., 2014). The partnership between the Western States Water Council (WSWC) and 11 federal agencies created a work plan in 2011 to address three key areas: 1) climate change, 2) water availability, water use, and water reuse, and 3) water quality. The need for more collaborative and participatory approaches engaging water stakeholders has been recognized.

Adaptation planning is an iterative process of identifying projected impacts and challenges, assessing risks from these impacts, selecting and implementing adaptation options, and then revisiting assessments when new information is available or when additional capacity to implement options is in place. USEPA (2015) lists five main integrative steps for adaptation planning that could be applicable to water resources planning in Utah: (1) understand the projected impact and challenges, (2) identify thresholds for failure or damage, (3) assess risks, (4) determine adaptation options, and (5) implement and monitor.

4. SUMMARY AND RECOMMENDATIONS

The objective of this report was to present a brief summary of the historical observations and projected trends of major climate variables and their impacts on Utah's water resources. Utah historical temperature records from 1950 to 2017 show that annual mean temperatures in the state increased by about 2°F. Precipitation changes over the same period are comparatively small. Similar to the Southwest, the seasonality of precipitation varies substantially across Utah depending on exposure to the mid-latitude westerly storm track during the cool season, the monsoon circulation during the warm season, and elevation. SWE observations in Utah show a decreasing rate of snowpack over time, and the observed rates of change in southern Utah's SNOTEL stations are significantly higher than in the north. Reduced snowpack, earlier snow melting, and increased rain proportion of precipitation led to shifts in the timing of streamflow. Utah has already experienced multiple droughts, floods, and high summer heat events.

Most climate models suggest future strengthening of trends in climatic variables including temperature, precipitation, and snowpack in the western U.S. and Utah. Climate model projections indicate further increases in average temperatures by 3 to 6°F by 2060s and 4 to 10°F by the end of current century. The precipitation projections are uncertain, ranging from (-5) to 10% by the 2040s and a bit lower (-10) to (+5%) by the end of century. Future SWE values are uncertain but projected to be about 10 to 15% lower by the 2040s and up to 30% lower by the end of the current century. The compounded effects of changes in precipitation type, escalated warming and changes in snowmelt timing will lead to a shift in the timing of the spring runoff by one to three weeks by the 2040s and about four weeks by the end of century. Most climate variability studies indicate that more intense droughts and floods are expected in the future. The projected increase in the intensity of naturally occurring droughts will exacerbate the frequency and severity of wildfires.

The water cycle is dynamic and naturally variable. Every change in a climatic variable can potentially affect the water cycle, water supply, and water demand. The changing climate will have direct impacts on water resources by increasing water demand, increasing water losses by evapotranspiration, reducing snowpack, escalating snowmelt rates, changing the proportion of precipitation that falls as rain versus snow, and altering the frequency of extreme weather events, droughts, and floods. The compounded impacts of changing climate will be reflected in reduced streamflow, shifts in the timing of water supply, and increased demand for water. The observed records of the past show that rates of change and degrees of impacts are likely to continue but vary among regions and sectors (see Table 1).

Most climate studies and impact assessments agree on the mostly negative impacts of climate change, however there are uncertainties in predicting precisely temporally and spatially for any particular region. Climate adaptation and mitigation measures to cope with and respond to climate change must therefore be flexible, and have become widely accepted norms in today's world. Planning for adaptation and mitigation to climate change makes use of information about present and future climate change to assess the suitability of current and planned practices, policies, and infrastructure in water resources and sectors.

Some of the strategies applicable to combat the impact of the climate change in water sectors is summarized in Table 2. It is noted that summarized adaptation measures and strategies are based on the best practices and synthesized from the literature (e.g., Bierbaum et al., 2014; USEPA, 2015; Reclamation, 2016) that could be potentially applicable in Utah. Therefore, these are not exhaustive and should be considered as general guidance. It is recommended to undertake further detailed investigation on the tabulated impacts of climate change (Table 1) and to develop associated adaption strategies (Table 2).

Table 2: Potential adaptation and mitigation goals and strategies.

Goals	Potential strategies
A) Short term Goals	
Building adaptive capacity: system evaluation, performance metrics, options appraisal, and collaborative dialogue.	• Undertake continuous research on climate change, extreme events, climate variability, and impact analysis to understand the climatic conditions in a region and water sector. • Assess the hydrologic processes and water systems to quantify how hydrologic processes or restoration can amplify or absorb the effects of climate variability. • Assess climate vulnerability and impact from the perspective of the organizational goals, working partners, institutions, and supportive governance regulations, legislations, and guidance that are needed as a foundation for delivering adaptation actions.
Enhance climate adaptation and mitigation planning: connecting adaption and mitigation efforts.	• Incorporate climate change information into planning, policy and guidance to cope with climate impacts across several mission areas, including delivery of water and power and maintaining ecosystems. • Integrate flood management and modeling into land use planning. • Incorporate both climate adaptation and mitigation options during water resources planning and project development phases.
Expand information sharing	• Engage stakeholder to share knowledge, review challenges, and develop measures to respond to potential changes. The stakeholders could be federal, state, local, and community.

B) Long term Goals	
Increase water management flexibility: Decreasing water demand and increasing use efficiency.	• Manage water demand, conserve water, increase water delivery efficiency, generate new sources of supply, and identify opportunities to adapt reservoir operations. • Evaluate and encourage wastewater reuse and recycling practices. • Encourage the best agricultural practices and drought-resistant crops. • Improve management of irrigated agriculture, e.g., changing the cropping calendar, crop mix, irrigation method, and repair and maintenance of irrigation infrastructure. • Identify and remove invasive non-native vegetation from riparian areas. • Introduce new efficient technologies such as desalination, biotechnology, drip irrigation, and smart technologies to monitor water uses. • Expanded use of economic incentives to encourage water conservation through water pricing and water banking.
Improve infrastructure coping capacity	• Ensure the longevity of water infrastructure (e.g., reservoir sedimentation management, dam safety, pipes, canals condition assessment and renovations plan) and support climate resilient infrastructure • Develop a clear plan on major rehabilitation, maintenance, and re-engineering of existing systems such as dams, irrigation systems, canals, pumps, rivers, wetlands. • Build flood protection infrastructure systems and innovative approaches of disaster mitigation. • Update operation, monitoring, and regulation practices of existing systems to accommodate new uses or conditions (e.g., pollution control, climate change, population growth).

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