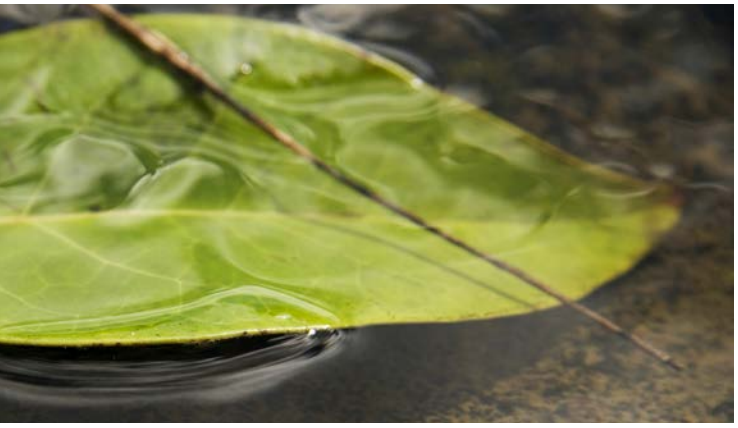

Recent US Climate Change and Hydrology Literature Applicable to US Army Corps of Engineers Missions

ARKANSAS, WHITE AND RED RIVERS REGION 11

FINAL

January 2015

USACE CLIMATE PREPAREDNESS AND RESILIENCE

REPORT DOCUMENTATION PAGE

Form Approved
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1. REPORT DATE *(DD-MM-YYYY)*
09-01-2015

2. REPORT TYPE
Civil Works Technical Series

3. DATES COVERED *(From - To)*
2014 - 2015

4. TITLE AND SUBTITLE
Recent US Climate Change and Hydrology Literature Applicable to US Army Corps of Engineers Missions - Arkansas, White and Red Rivers Region

5a. CONTRACT NUMBER
W912HQ-10-D-0004

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
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- Support from CDM Smith

5d. PROJECT NUMBER

5e. TASK NUMBER
147

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Directorate of Civil Works
US Army Corps of Engineers
Washington, DC

8. PERFORMING ORGANIZATION REPORT NUMBER
CWTS-2015-02

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Institute for Water Resources
7701 Telegraph Road (Casey Building)
Alexandria, Virginia 22315

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Available through National Technical Information Service, Operations Division
5285 Port Royal Road
Springfield, VA 22161

13. SUPPLEMENTARY NOTES

14. ABSTRACT
To help the US Army Corps of Engineers (USACE) staff in meeting the requirements of the 2011 and 2014 policy statements on climate change adaptation by the Assistant Secretary of the Army for Civil Works, the USACE Climate Change Adaptation Plans, and agency policy and guidance, this report presents concise and broadly-accessible summaries of the current climate change science with specific attention to USACE missions and operations. This report, focused on the Arkansas, White and Red Rivers Region, is part of a series of twenty one (21) regional climate syntheses prepared by the USACE under the leadership of the Response to Climate Change Program at the scale of 2-digit Hydrologic Unit Code (HUC) Water Resources Regions, across the continental United States, Alaska, Hawaii, and Puerto Rico. Each of these regional reports summarize observed and projected climate and hydrological patterns cited in reputable peer-reviewed literature and authoritative national and regional reports, and characterize climate threats to USACE business lines.

15. SUBJECT TERMS

Arkansas, White and Red Rivers	Observed Hydrology	Business Line
Water Resources Region 11	Projected Climate	Climate Vulnerability
Observed Climate	Projected Hydrology	Regional Climate Synthesis

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER *(Include area code)*
U	U	U	U		

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Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18
Adobe Professional 7.0

CLIMATE CHANGE AND HYDROLOGY LITERATURE SYNTHESIS FOR THE US ARMY CORPS OF ENGINEERS MISSIONS IN THE UNITED STATES

ARKANSAS, WHITE AND RED RIVERS REGION 11

January 9, 2015

CDM Smith
Contract # W912HQ-10-D-0004, Task Order 147

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Suggested Citation:

USACE (2015). Recent US Climate Change and Hydrology Literature Applicable to US Army Corps of Engineers Missions - Arkansas, White and Red Rivers Region 11. Civil Works Technical Report, CWTS 2015-02, USACE, Washington, DC

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Water Resources Region 11: Arkansas-White-Red Rivers

1. Introduction

US Army Corps of Engineers (USACE) staff are increasingly considering potential climate change impacts when undertaking long-term planning, setting priorities, and making decisions that affect resources, programs, policies, and operations, consistent with the 2011 and 2014 policy statements on climate change adaptation by the Assistant Secretary of the Army for Civil Works, the USACE Climate Change Adaptation Plans, and agency policy and guidance. USACE is undertaking its climate change preparedness and resilience planning and implementation in consultation with internal and external experts using the best available – and actionable – climate science and climate change information. This report represents one component of actionable science, in the form of concise and broadly-accessible summaries of the current science with specific attention to USACE missions and operations. This report is part of a series of twenty one (21) regional climate syntheses prepared by the USACE under the leadership of the *Response to Climate Change Program* at the scale of 2-digit U.S. Geological Survey (USGS) Hydrologic Unit Codes (HUC) across the continental United States, Alaska, Hawaii, and Puerto Rico. The twenty one Water Resources Regions included in this series of reports is shown in **Figure 1.1** along with USACE division boundaries. Each of these regional reports summarizes observed and projected climate and hydrological patterns cited in reputable peer-reviewed literature and authoritative national and regional reports, and characterizes climate threats to USACE business lines. They also provide context and linkage to other agency resources for climate resilience planning, such as sea level change calculation and coastal risk reduction resources, downscaled climate data for subregions, and watershed vulnerability assessment tools.

This report focuses on Water Resources Region 11, the Arkansas-White-Red Rivers, the boundaries for which are shown in **Figure 1.2**. The Albuquerque, Ft. Worth, Little Rock, and Tulsa USACE districts each include territory within Water Resources Region 11.

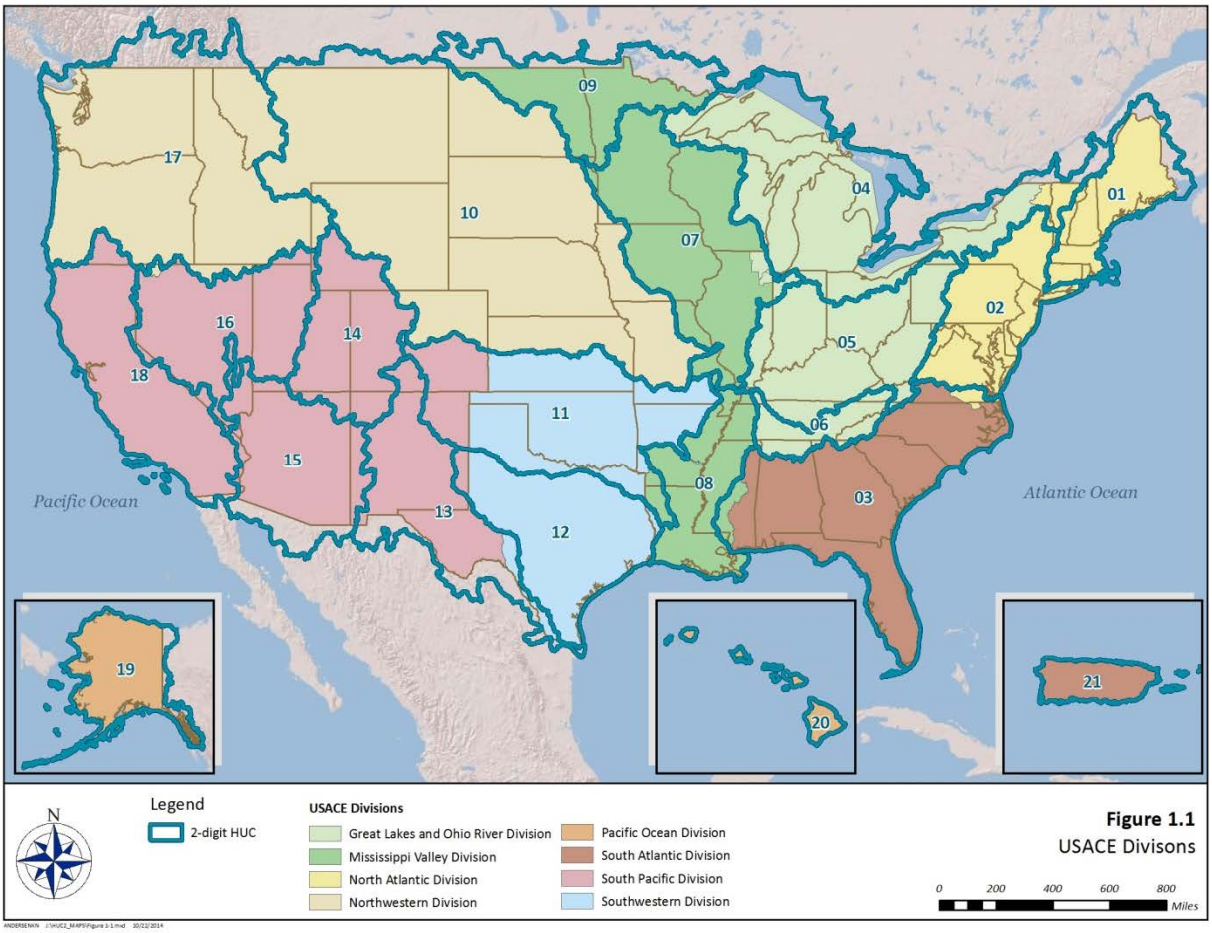

Figure 1.1. 2-digit Hydrologic Unit Code Boundaries for the Continental United States, Alaska, Hawaii, and Puerto Rico

Figure 1.2. Water Resources Region 11: Arkansas-White-Red Region Boundary.

1.1 A Note on the Water Resources Region Scale

USACE and other resource management agencies require reliable, science-based methods for incorporating climate change information into the assessments that support water resources decisions and actions. Such planning assessments must quantify projections of future climate and hydrology. One common practice is to begin by developing relationships between the currently observed climate and the projected future possible climate over the assessment region.

However, the numerical models producing these multiple projections of future possible climate were not designed to support these assessments for local-to-regional scale operations. This means that intervening steps have to be taken to correct obvious biases in the models' outputs and to make the outputs relevant at the scales where hydrologic resource assessments can take place. The commonly used name for these post-processing steps is "downscaling" because one step is using one or another method to spatially (and temporally) disaggregate or interpolate (or other) the results produced at the numerical climate models' native scale to the scale of the water resources assessment. The current generation of climate models, which includes the models used to generate some of the inputs described in this work, have a native scale on the order of one to two hundred kilometers on each side of the grids used to simulate climate for Earth, substantially too coarse for the watershed assessments needed to inform resource assessment questions and decisions.

On the other hand, these questions and decisions should not be addressed with model inputs at scales so fine that they impart false precision to the assessment. False precision would appear by suggesting that the driving climate model information can usefully be downscaled, by any method, to individual river reaches and particular project locations, for example.

The approach at USACE is to consider the questions in need of climate change information at the geospatial scale where the driving climate models retain the climate change signal. At present, USACE judges that the regional, sub-continental climate signals projected by the driving climate models are coherent and useful at the scale of the 2-digit HUC (Water Resources Region), and that confidence in the driving climate model outputs declines below the level of a reasonable trade-off between precision and accuracy for areas smaller than the watershed scale of the 4-digit HUC (Water Resources Subregion). Hence, these summaries group information at the Water Resources Region scale both to introduce relevant climate change literature and to support the vulnerability assessments USACE is conducting at the Water Resources Subregion scale. For Water Resources Region 11, both the 2-digit and 4-digit HUC boundaries are shown in Figure 1.2.

2. Observed Climate Trends

Observed climate trends within Water Resources Region 11 are presented in this section to generally characterize current, or past, climate in the study region. While the primary cause for global warming is attributed by the scientific community to human-induced increases in atmosphere levels of heat-trapping gases (Walsh et al., 2014), this section in not focused on attribution or cause (either natural or unnatural). Rather, it is specifically focused on the identification and detection of climate trends in the recent historical record. The interrelationships of Earth's climate systems are complex and influenced by multiple natural and

unnatural (i.e. anthropogenic greenhouse gas emissions) forcings. When additional detail is needed the reader is referred to the specific references cited, including the third National Climate Assessment (NCA) which includes not only regional assessments but also foundational resources related to climate science literacy.

The climate trends presented in this section are based on peer-reviewed literature on the subject of observed climate. To the extent possible, studies specific to Water Resources Region 11 or its sub-watersheds were relied upon. A focus is placed on identified primary variables including:

- mean temperature
- extreme temperatures
- average precipitation
- extreme precipitation events
- mean streamflow.

In addition to primary variables, peer-reviewed literature addressing climate change within the geographic region or inclusive of Water Resources Region 11 (fully or partially) revealed additional, secondary, climatic variables that have been studied such as the spring index (SI), drought indices, and soil moisture.

The results presented below indicate a mild upward trending for mean temperature, average precipitation, extreme precipitation events, and mean streamflow in the Arkansas-White-Red Region. Investigations into the observed trends of extreme temperatures were found to be less prevalent in the peer-reviewed literature. The limited literature indicates that maximum temperatures have remained relatively constant and the occurrence of minimum temperatures days was found to have increased slightly.

2.1. Temperature

Observed mean temperature trends specific to Water Resources Region 11 have not been reported widely in recent peer-reviewed literature; however, evaluation of trends across the United States that is inclusive of Water Resources Region 11 has been published. For example, Wang et al. evaluated historical climate trends for the entire continental United States from 1950 – 2000 (Wang et al., 2009). For the majority of the Water Resources Region 11, a slight to moderate warming trend during the spring months was observed. For the summer and fall a mild cooling trend is observed through the entire region. For winter, a slight cooling trend was observed in the upper and lower portion of the region, while the Water Resources Region 11's central area showed a slight warming in the winter. These results are summarized below (**Figure 2.1**) in addition to precipitation which is discussed in further detail in Section 2.2.

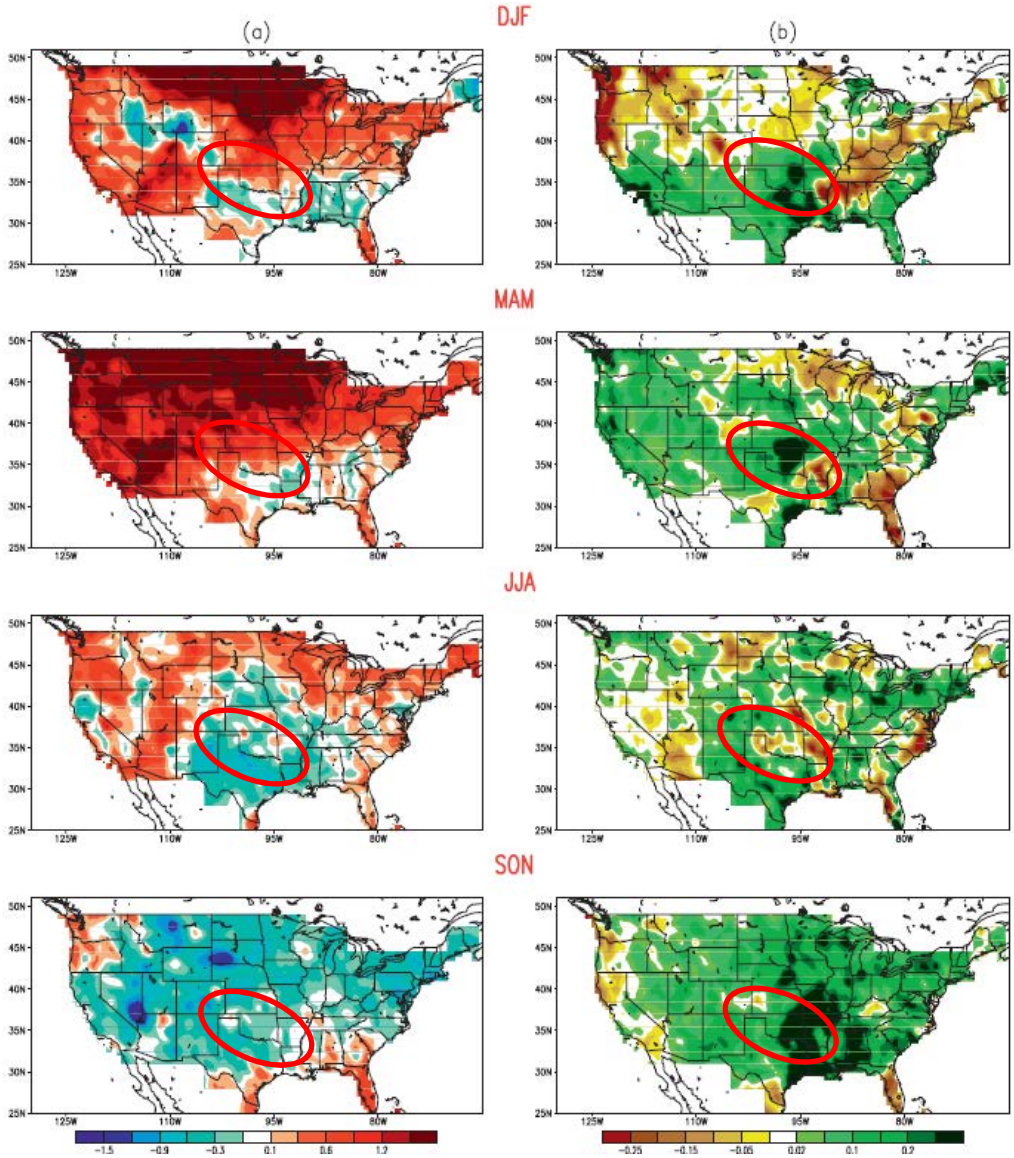

Figure 2.1. Linear trends in surface air temperature (a) and precipitation (b) over the United States, 1950 – 2000. The Water Resources Region 11 is within the red oval (Wang et al. 2009).

In addition to mean temperature, observed extreme temperatures have been evaluated by Grundstein and Dowd for the time period 1949 – 2010. In this study, 1-day extreme minimum and maximum apparent temperatures were evaluated for the entire United States (including Alaska and Hawaii). No trend was observed within the Water Resources Region 11for 1-day extreme maximum apparent temperatures; however, the frequency of days per decade for 1-day extreme minimum temperatures was found to be slightly increasing over the study period in the lower and central portions of Water Resources Region 11 (Oklahoma and Arkansas). Of note is that no trend was identified for the same parameter in an older but similar study that utilized a study period of 1949 – 1995 (Grundstein and Dowd, 2011). This indicates that the increasing trend in 1-day extreme minimum temperatures has emerged since 1995. Results from Grundstein and Dowd are summarized below (**Figure 2.2**).

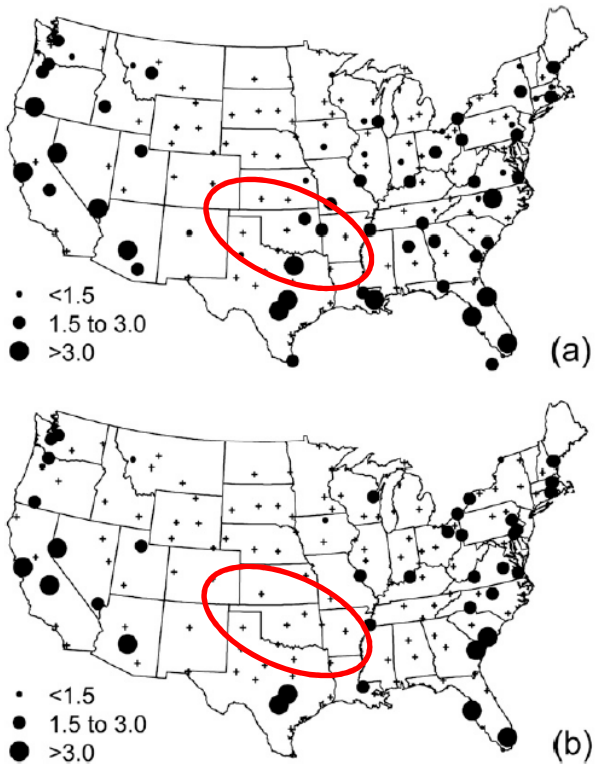

Figure 2.2. Trends, in days per decade (10 yr), in annual 1-day extreme minimum apparent temperature for (a) 1949-2010 (b) 1949-1995. The size of the circle represents the increase in the number of extreme heat days per decade. The Water Resources Region 11 is within the red oval (Grundstein and Dowd, 2011).

Key point: A general consensus amongst recent peer-reviewed literature indicates a mild upward trending for mean temperature; however this varies by season and location within the Water Resources Region 11. Peer-reviewed literature indicates that maximum temperatures have remained relatively constant and the occurrence of minimum temperatures days was found to have increased slightly.

2.2. Average Precipitation and Extreme Precipitation Events

Observed precipitation trends in Water Resources Region 11 have been widely reported on in peer-reviewed literature. Similar to observed temperature trends, the peer-reviewed literature reviewed for this report was largely inclusive of Water Resources Region 11 but not specific to the region. There is a large consensus among recent work that, overall, an increasing trend in precipitation for the Water Resources Region 11 has been identified over the time period 1895 to the present. McRoberts and Nielson-Gammon found positive linear trends in annual precipitation totals for the central and lower portions of Water Resources Region 11 on the order of 0 to 20%. However, a trend for the upper portion of Water Resources Region 11 that includes the Arkansas River headwaters was not identified (McRoberts and Nielsen-Gammon, 2011). The results of this study are shown below (**Figure 2.3**).

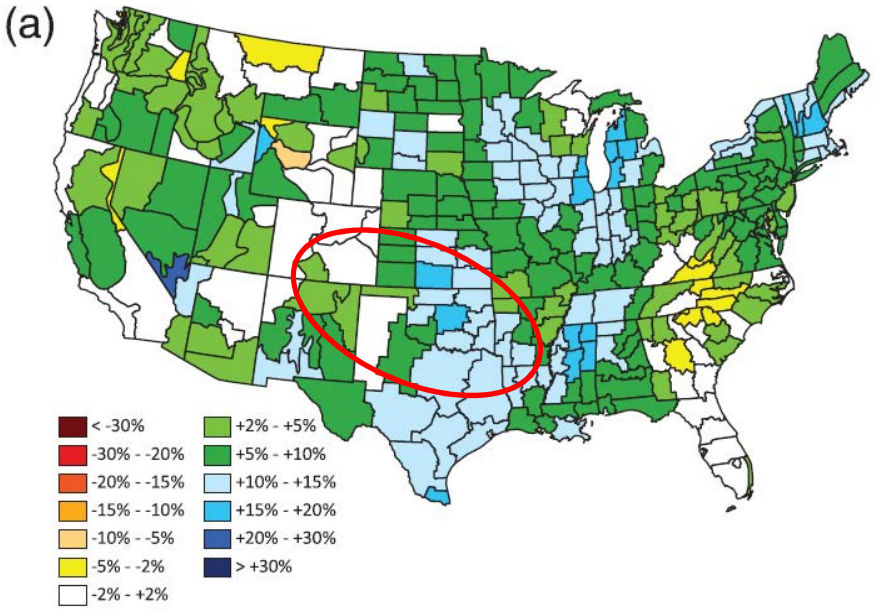

Figure 2.3. Linear Trends in Annual Precipitation, 1895 – 2009, Percent Change per Century. The Water Resources Region 11 is within the red oval (McRoberts and Nielsen-Gammon, 2011).

The increasing trend in precipitation reported by McRoberts and Nielsen-Gammon for the central and lower portion of the region confirmed what was previously reported in other peer-reviewed literature (Wang et al., 2009; Grundstein, 2009; Pryor et al, 2009). Wang et al. evaluated not just annual changes, but trends on a seasonal level. The mean annual precipitation trends identified in Water Resources Region 11 are also apparent at the seasonal level, but more predominant in the winter and spring (Wang et al., 2009) as shown in **Figure 2.1** in Section 2.1. A regionally focused study also found an increase in precipitation over a similar time period on the order of 6 percent to 20 percent for Oklahoma. (Garbrecht et al., 2004).

It has also been widely reported that the magnitude and duration of extreme precipitation events may be exceptionally sensitive to climate change. Analysis of historic trends in extreme precipitation events has been evaluated at the national level by Pryor et al. Review of this body of work for Water Resources Region 11 reveals definitively different trends depending upon location within the region. The upper portion of the region is observed to have slightly decreasing precipitation intensity (annual total / number of precipitation days) while the central and lower portion of the region has been observed to have slightly increased intensity (Pryor et al., 2009). The summary figure of this trend is shown below (**Figure 2.4**) for both 90th percentile daily precipitation totals and precipitation intensity.

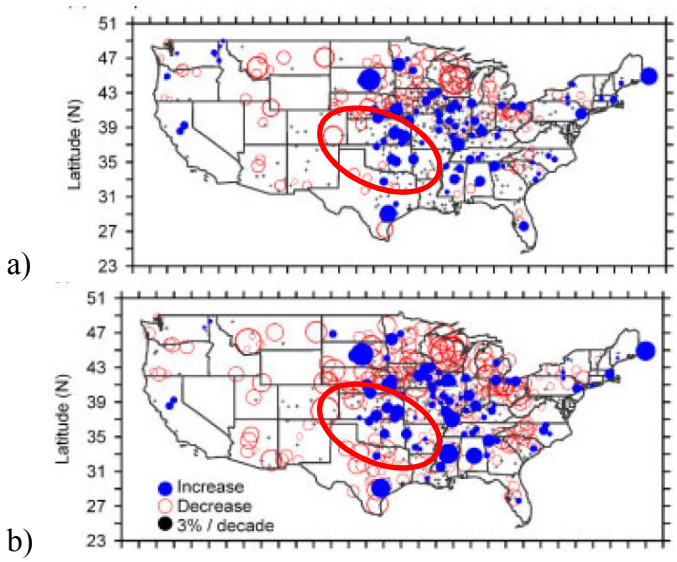

Figure 2.4. Historical precipitation trends (20th Century). a.) 90th percentile daily, b.) precipitation intensity (annual total / number of precipitation days). Note that blue dots indicate positive trend, red circles indicate negative trend, and symbol sizes are scaled to 3% change per decade. The Water Resources Region 11 is within the red oval (Pryor et al., 2009).

At a regional level, Wang and Zhang evaluated the frequency of the 20-year return maximum daily precipitation from 1949 to 1999. A comparison between the period 1977 to 1999 and 1949 to 1976 found that the frequency of the 20-year return level precipitation event increased between 50 percent and 100 percent for the Water Resources Region 11 as shown below (**Figure 2.5**) (Wang and Zhang, 2008). This confirmed the results of Madsen & Figdor in evaluating frequency of extreme precipitation events across the continental United States, though this earlier study found the increasing trend to be smaller in magnitude, approximately 24% across Water Resources Region 11 (Madsen and Figdor, 2007).

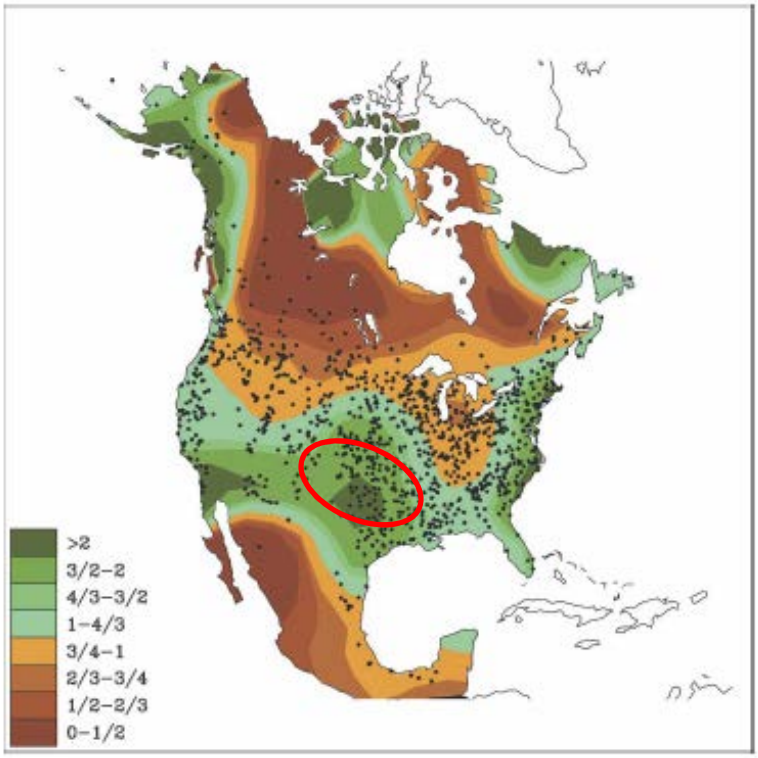

Figure 2.5. The risk of 20-yr return maximum daily precipitation computed from 1949-76 during 1977-99. A value of 2 indicates that the occurrence of daily precipitation at the 20-yr return level in 1949-76 has been doubled in 1977-99. Black dots show the locations of stations. The Water Resources Region 11 is within the red oval (Wang and Zhang, 2008).

Key Point: A general consensus amongst recent peer-reviewed literature indicates a mild upward trending for average precipitation and extreme precipitation events.

2.3. Hydrology

Observed streamflow trends have been evaluated at the Water Resources Region 11level by Kalra et al. (2008). The study utilized recorded streamflow data from 639 stations (unimpaired) to assess trends and step changes based on a study period of 1951 – 2002. Streamflow was evaluated based on water year and also seasonally for Autumn-Winter and Spring-Summer. For Water Resources Region 11 a predominant increasing trend was found for the water year and Autumn-Winter time intervals; however, no trend was identified for the Spring-Summer time period (Kalra et al., 2008). Similarly, runoff has been found to be increasing between 1948 and 2004 at a rate of approximately 140 mm per century for the lower portion of Water Resources Region 11 and 20 mm per century for the upper portion of the region (Qian et al., 2007). At the regional level, Garbrecht et al. (2004) found that streamflow in Oklahoma has increased between 20 percent and 150 percent.

Recent work has been completed utilizing the MOPEX (international Model Parameter Estimation Experiment) data set at the national level. The benefits of assessing streamflow based

on MOPEX is that it is more representative of recent hydrology (last half of the 20th century) than the commonly used Hydro-Climate Data Network (HCDN) data set (Xu et al., 2013). A study utilizing the MOPEX data set by Xu et al. (2013) found that the central and lower portion of Water Resources Region 11 had an increasing trend in streamflow as well as baseflow. The geographic extent of this study did not include the upper portion of Water Resources Region 11.

Key Point: A general consensus amongst recent peer-reviewed literature indicates an upward trending for average streamflow.

2.4. Observed Trends in Secondary Climate Variables

Secondary variables include those variables that are sensitive to the primary climate variables discussed in the preceding sections. These secondary variables include drought indices, soil moisture content, and the spring index, and the observed trends of these variables are consistent with the observed climate trends in the primary variables. For example, a slight increase in precipitation has been observed in the Water Resources Region 11 over the past half century. As a result drought indices have shown a slight decline (Chen et al., 2012; Cook et al., 2014) while soil moisture has been found to increase slightly (Grundstein, 2009). Additionally, the spring onset index is a function of temperature regimes but is related to plant growth. Schwartz et al. (2013) found that the majority of Water Resources Region 11 experienced a lag in initiation of the spring index; however, the upper portion of Water Resources Region 11 was shown to be earlier by about 4 days. These findings are consistent with the seasonal evaluation of observed mean temperature by Wang et al. (2009).

2.5. Summary of Observed Findings

Section 2 summarizes observed trends in primary and secondary climate variables in the Water Resources Region 11. Recent peer-reviewed literature indicates a mild upward trending for mean temperature, average precipitation, extreme precipitation events, and mean streamflow in the Arkansas-White-Red region. Investigations into the observed trends of extreme temperatures were found to be less prevalent in the peer-reviewed literature. The limited literature indicates that maximum temperatures have remained relatively constant and the occurrence of minimum temperatures days was found to have increased slightly. Observed trends in secondary variables such as drought indices, soil moisture contents, and the spring index were found to be agreement with the observed trends in primary variables.

3. Projected Climate Trends

While historical data is essential in understanding current and future climate, nonstationarity in the data (i.e. a changing climate) dictates the use of supplemental information in long term planning studies. In other words, the past may no longer be a good predictor of the future (Milly et al., 2008). Consequently, the scientific and engineering communities have begun using computer models of the Earth's atmosphere and associated thermodynamics to project future climate trends for use in water resources planning efforts. While significant uncertainties are inherent in these model projections, the models, termed global climate models (GCMs), are widely accepted as representing the best available science on the subject, and have proven highly

useful in planning as a supplement to historical data. A wealth of literature now exists on the use of GCMs across the globe.

This section summarizes projected climate trends, as projected by GCMs, within the Water Resources Region 11 identified in a review of recent peer-reviewed literature. The information presented should be considered an overview and, similar to Section 2 on observed climate trends, does not focus on attribution or causation of the projected climate trends or the causal relationships between climate variables. These relationships are complex and influenced by multiple natural and unnatural (i.e. anthropogenic greenhouse gas emissions) forcings that influence the Earth's climate system. Typical of projected climate studies, often specific (and sometimes multiple) greenhouse gas emission scenarios (or representative concentration pathways) are modeled by a single GCM (or ensemble of GCMs). The spectrum of scenarios offer a wide range of "climate futures" so each study's assumed emission scenario(s) are noted. When additional detail is needed, the reader is referred to the specific references cited, including the third National Climate Assessment (NCA) which includes not only regional assessments but also foundational resources related to climate science literacy, GCMs, and emission scenarios.

The USACE vulnerability assessments (https://corpsclimate.us/rccvar.cfm) rely on downscaled climate projection data and hydrologic simulations produced by USACE in conjunction with Lawrence Livermore National Laboratory, Bureau of Reclamation, U.S. Geological Survey, Climate Central, Scripps Oceanographic Institute and Santa Clara University, and others. The data are housed in the publicly accessible Downscaled Climate and Hydrology Projections website archive, hosted by Lawrence Livermore National Laboratory, which is meant to provide access to climate and hydrologic projections at spatial and temporal scales relevant to watershed or basin-scale water resources management decisions. These data, and the vulnerability assessments for which they provide a foundation, serve as supplements to the information about projected climate conditions provided in this report.

Results of this review indicate a strong consensus in the scientific literature that air temperatures will trend upwards over the next century in the Arkansas-White-Red region. In addition, a large consensus also exists regarding a sharp increase in maximum temperatures in the region. There is a general consensus in the reviewed literature that average precipitation will remain relatively constant but the occurrence of extreme precipitation events will increase. Also, there is general consensus that projected streamflow will decrease for portions of the Water Resources Region 11; however, projected trends are highly dependent on GCM selection.

3.1. Projected Mean Temperature and Extreme Temperatures

Mean temperature in Water Resources Region 11 is generally projected to increase over the next century, with the most significant increase coming in the latter half (Liu et al., 2012). Liu et al. (2012) evaluated the full suite of Couple Model Intercomparison Project, 3rd release (CMIP3, http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/) GCM projections for three different emission scenarios (A2, A1B, and B1). The study area included the south central portion of the United States, which includes the Water Resources Region 11 states of Texas, Oklahoma, Arkansas and Louisiana. The study found that an increase in average temperature in Water Resources Region 11 could range between 3.5 ºC and 5.0 ºC. A summary of the associated temperature modeling results for the entire study region can be found below (**Figure 3.1**). The projected increase in mean temperature by Liu et al (2012) confirmed earlier regional finding by

Zhang et al (2010) which projected an increase of 1.0 ºC in mean temperature in the central portion of Water Resources Region 11 (Texas and Oklahoma) from 2002 to 2050 for the A1B emissions scenario.

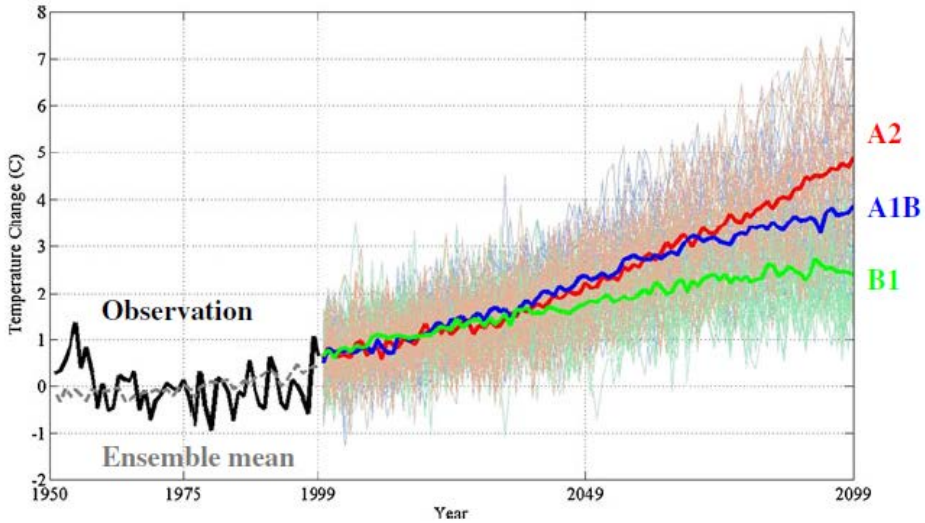

Figure 3.1. CMIP3 GCM Projections of Southern States Planning Region (Inset): Changes in Mean Annual Temperature. (Liu et al., 2012).

Liu et al. (2012) also evaluated projected seasonal changes in temperature. The first half of this century, 2000-2049, is projected to see the biggest changes in the Water Resources Region 11 during the winter and spring while the second half of this century, 2050-2099, is projected to see the largest increase in the summer and fall.

Extreme maximum temperatures are also generally expected to increase in Water Resources Region 11 (Kunkel et al., 2010; Scherer and Diffenbaugh, 2014). A recent study utilizing regional climate models for the entire United States projected that under high emissions scenarios that 3-day annual heat wave temperatures would increase between 3.5 ºC and 5.0 ºC. In addition to increasing temperature the frequency of heat wave days is projected to increase by up to an additional 50 days annually in the upper portion of the region and up to 80 days annually in the lower and central portions of the region (Kunkel et al., 2010). These results are summarized below (**Figure 3.2**). The projected increase in maximum temperature by Kunkel et al (2010) are in agreement with regional findings in Zhang et al (2010) which projected an increase of maximum temperatures between 1.0 ºC and 2.0 ºC in the central portion of Water Resources Region 11 (Texas and Oklahoma) from 2002 to 2050 for the A1B emissions scenario.

Zhang et al (2010) also reported an increasing trend in minimum temperature for the central portion of Water Resources Region 11 on the order of 2.0 ºC by 2050 (assuming A1B emissions). Relatedly, the National Climate Assessment's Chapter 20: Southwest (Garfin et al., 2014) reported an increase in the number of projected warm nights in central Water Resources Region 11 (Texas, Oklahoma, and Kansas) on the order of 35 to 45 days under both low (B1) and high (A2) emissions scenarios.

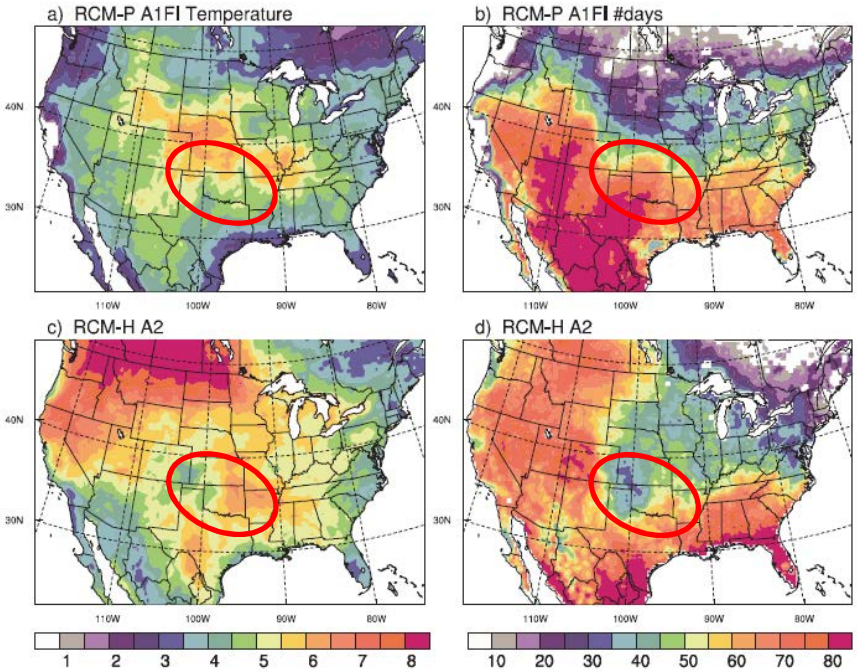

Figure 3.2. Projection of change in the (a),(c) average annual 3-day heat wave temperature (ºC) and (b), (d) average annual number of heat wave days. The Water Resources Region 11 is within the red oval (Kunkel et al., 2010).

Key point: A large consensus amongst recent peer-reviewed literature indicates a moderate upward trending for projected mean temperature and a significant upward trend for maximum temperature within the Water Resources Region 11.

3.2. Projected Average Precipitation and Extreme Precipitation Events

The southeastern United States, which is inclusive of the lower portion of Water Resources Region 11, is expected to have relatively consistent levels of total annual through the middle and end of the 21st century (Liu et al., 2012; Zhang et al., 2010). While the annual totals lack any significant trend at the regional level, a slight increase in annual precipitation totals between 10 and 40 mm per year is projected in major metro areas of Oklahoma City and Little Rock based on the mean of 16 GCMs (Liu et al., 2012). These results are highlighted below (**Figure 3.3** and **Figure 3.4**).

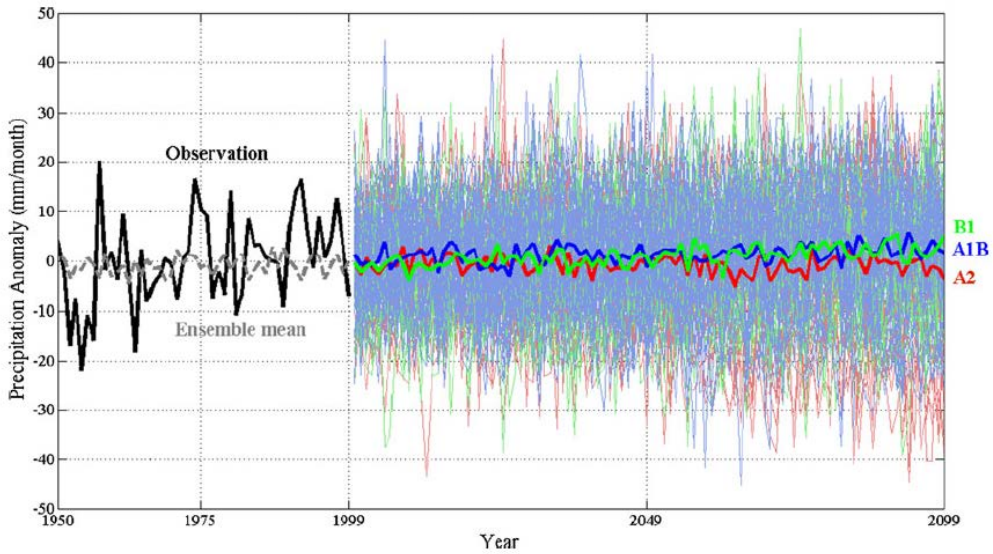

Figure 3.3. CMIP3 GCM Projections of Southern States Planning Region: total annual precipitation. Water Resources Region 11 is indicated by the red oval (Liu et al., 2012).

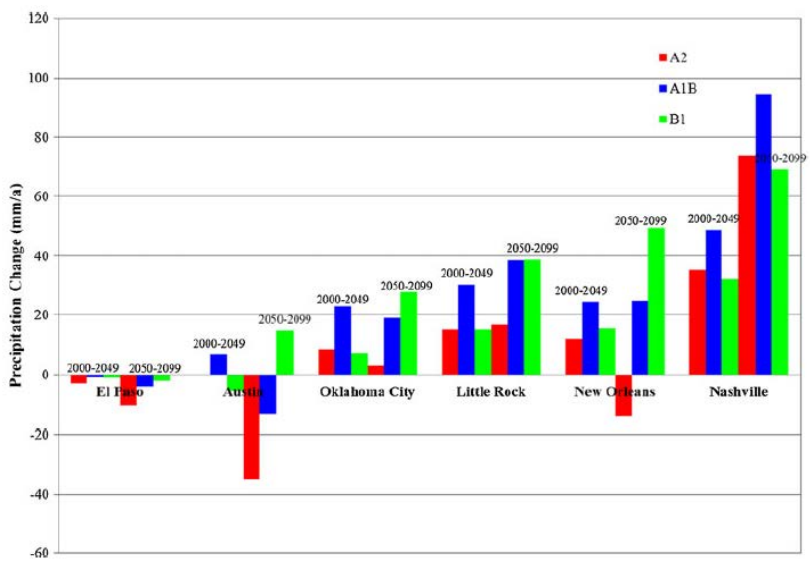

Figure 3.4. CMIP3 Ensemble Mean Projections of precipitation changes in 21st Century, compared to 1950 – 2000 historical period. Water Resources Region 11 is indicated by the red oval (Liu et al., 2012).

Additionally, while **Figure 3.3** does show a lack of any significant regional trend in annual precipitation totals it does show increased variability is projected with higher peak rainfall and lower minimum rainfall (Liu et al., 2012). Increases in projected 20-year return level precipitation events are also projected to increase in frequency on the order of 50 percent to 100 percent (Wang and Zhang, 2008), as shown below (**Figure 3.5)**. Additionally, the National Climate Assessment's Chapter 20: Southwest (Garfin et al., 2014) reported an increase in the number of consecutive dry days in central Water Resources Region 11 (Texas, Oklahoma, and Kansas) on the order of 2 to 4 days under both low (B1) and high (A2) emissions scenarios.

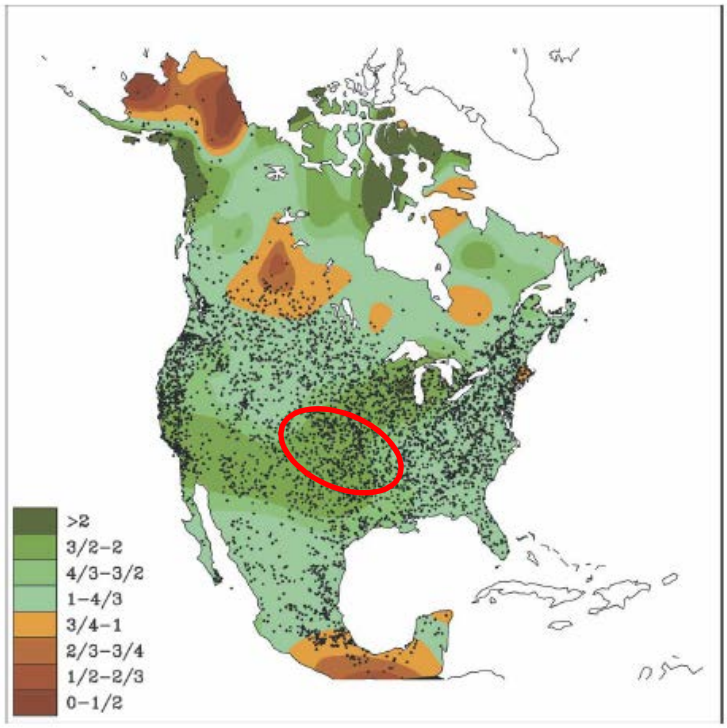

Figure 3.5. Projected risk of current 20-year 24-hour precipitation event occurring in 2070 compared to historical (1974). A value of 2 indicates this storm will be twice as likely in the future compared to the past. The Water Resources Region 11 is within the red oval (Wang and Zhang, 2008).

Key point: A general consensus amongst recent peer-reviewed literature indicates no change in projected annual precipitation levels within the Water Resources Region 11. However, there is consensus that the projected occurrence of extreme precipitation events will increase as well as the number of consecutive dry days.

3.3. Hydrology

A decreasing trend in streamflow in the Water Resources Region 11 is projected to occur throughout the next century under moderate to high emission scenarios (Döll and Zhang, 2010; Hagemann et al., 2013). This projected trend in changing streamflow is based on global studies and not regional or Water Resources Region level analyses. While generally a decrease in streamflow is projected, the magnitude and even whether streamflow will be increasing or decreasing, is dependent upon which GCM is utilized. For example, Hageman et al. (2013) evaluated trends in streamflow utilizing three different GCMs. On average, a projected decrease on the order of 20% was found for the Water Resources Region 11 but this varied across the three GCMs between a decrease in streamflow of 50% and an increase of 10%. Similarly, Brekke and Pruitt (2010) studied the projected change in runoff to seven reservoirs in Oklahoma. These authors found that, on an annual basis, projected change in runoff ranged from -50% to +30% depending upon assumptions related to GCM selection and weather generation technique.

The National Climate Assessment's Chapter 20: Southwest (Garfin et al., 2014) projects a decrease in snowpack for the western United States, including the Arkansas River headwaters.

Decreased snowpack, as measured by snow water equivalent (SWE), is strongly related to the amount of runoff and associated natural inflows to snowpack supplied rivers such as the Arkansas River headwaters (Garfin et al., 2014). Projected SWE for the Southwestern United States are summarized below (**Figure 3.6**). Each bar chart's size is proportional to amount of snowfall experienced by each state.

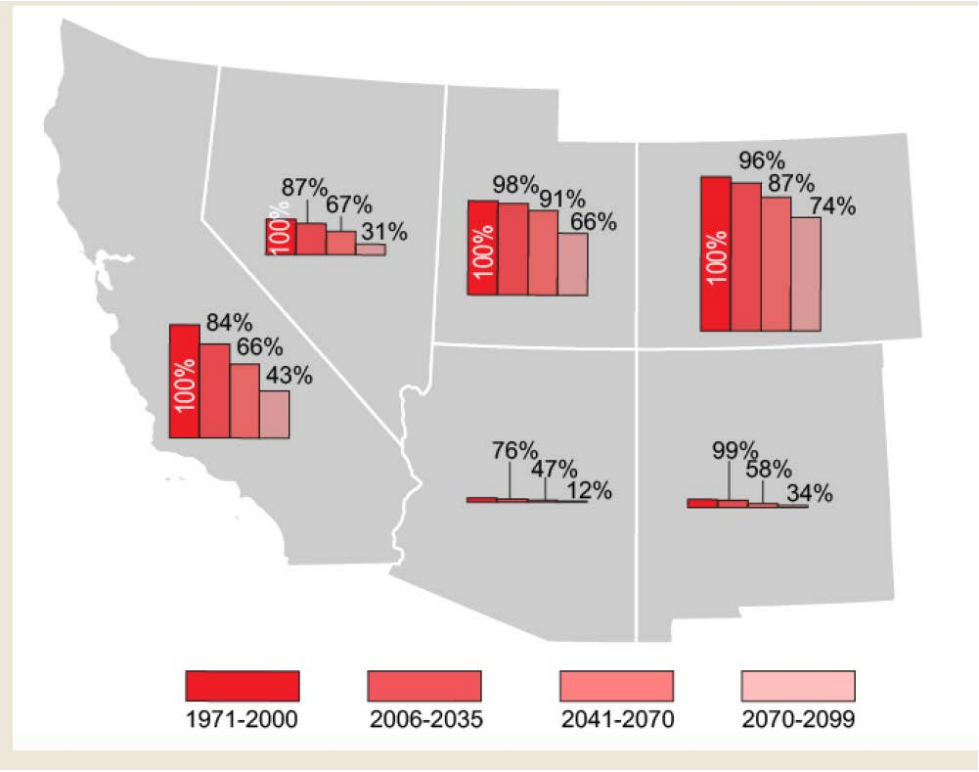

Figure 3.6. Projected snow water equivalent in the south western United Stated. A portion of the Water Resources Region 11 is located in southeastern Colorado (Garfin et al., 2014).

Key point: There is limited consensus that projected streamflow will decrease for portions of the Water Resources Region 11; however, projected trends are highly dependent on GCM selection.

3.4. Projected Trends in Secondary Climate Variables

Secondary variables include those variables that are sensitive to the primary climate variables discussed in the preceding sections. The projected trends of secondary climate variables found in the peer-reviewed literature include drought indices and soil moisture content. These variables are consistent with the projected climate trends in the primary variables. Specifically, multiple studies have found that drought indices or frequency of drought are projected to increase over the next century in the Water Resources Region 11 (Joetzjer et al., 2013; Liu et al., 2013). Furthermore, the Thornthwait climate classification of the lower Water Resources Region 11 is projected to change from *warm-dry* to *hot-dry* while the upper Water Resources Region 11 is projected to shift from *cool-semiarid* to *warm-semiarid* (Elguindi and Grundstein, 2013). A summary of the shift in climate classification is shown below (**Figure 3.7**). These projected

trends in drought indices and climate classification are consistent with an increasing trend in projected temperature and no projected trend in mean precipitation.

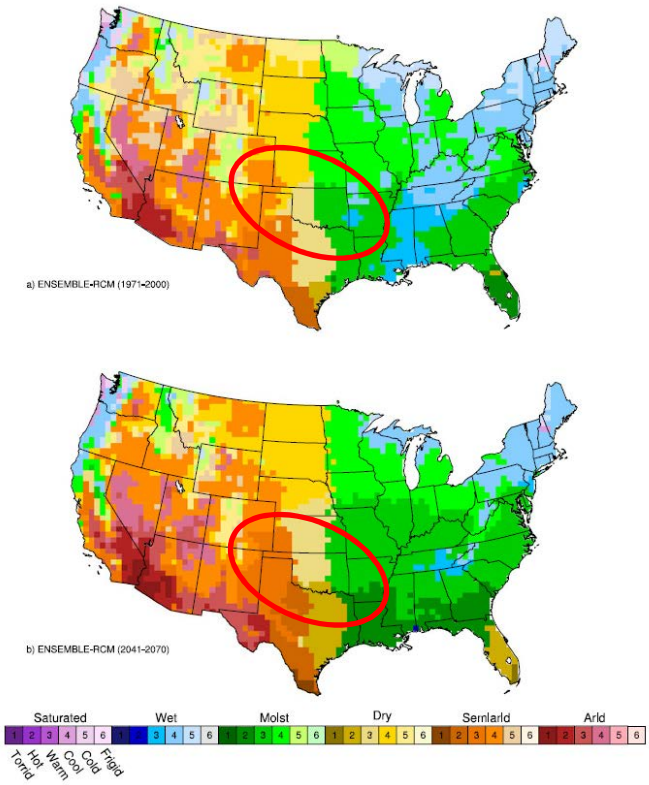

Fig. 3 Revised Thornthwaite climate types for the historical and future periods calculated from the bias-corrected MME-GCM

Figure 3.7. Revised Thornthwaite climate types for the historical and future periods. The Water Resources Region 11 is within the red oval (Elguindi and Grundstein, 2013).

3.5. Summary of Projection Climate Findings

Section 3 summarizes projected trends in primary and secondary climate variables in the Water Resources Region 11. The recent peer-reviewed literature indicates a strong consensus in the scientific literature that air temperatures will trend upwards over the next century in the Arkansas-White-Red Region. In addition, a large consensus also exists regarding a projected sharp increase in maximum temperatures in the region. There is a general consensus in the reviewed literature that projected average precipitation will remain relatively constant but the occurrence of extreme precipitation events will increase in the future. Also, there is a general consensus that projected streamflow will decrease for portion of the Water Resources Region 11; however, projected trends are highly dependent on GCM selection.

The trends and literary consensus of observed and projected primary variables noted above have been summarized for reference and comparison in the following figure (**Figure 3.8**).

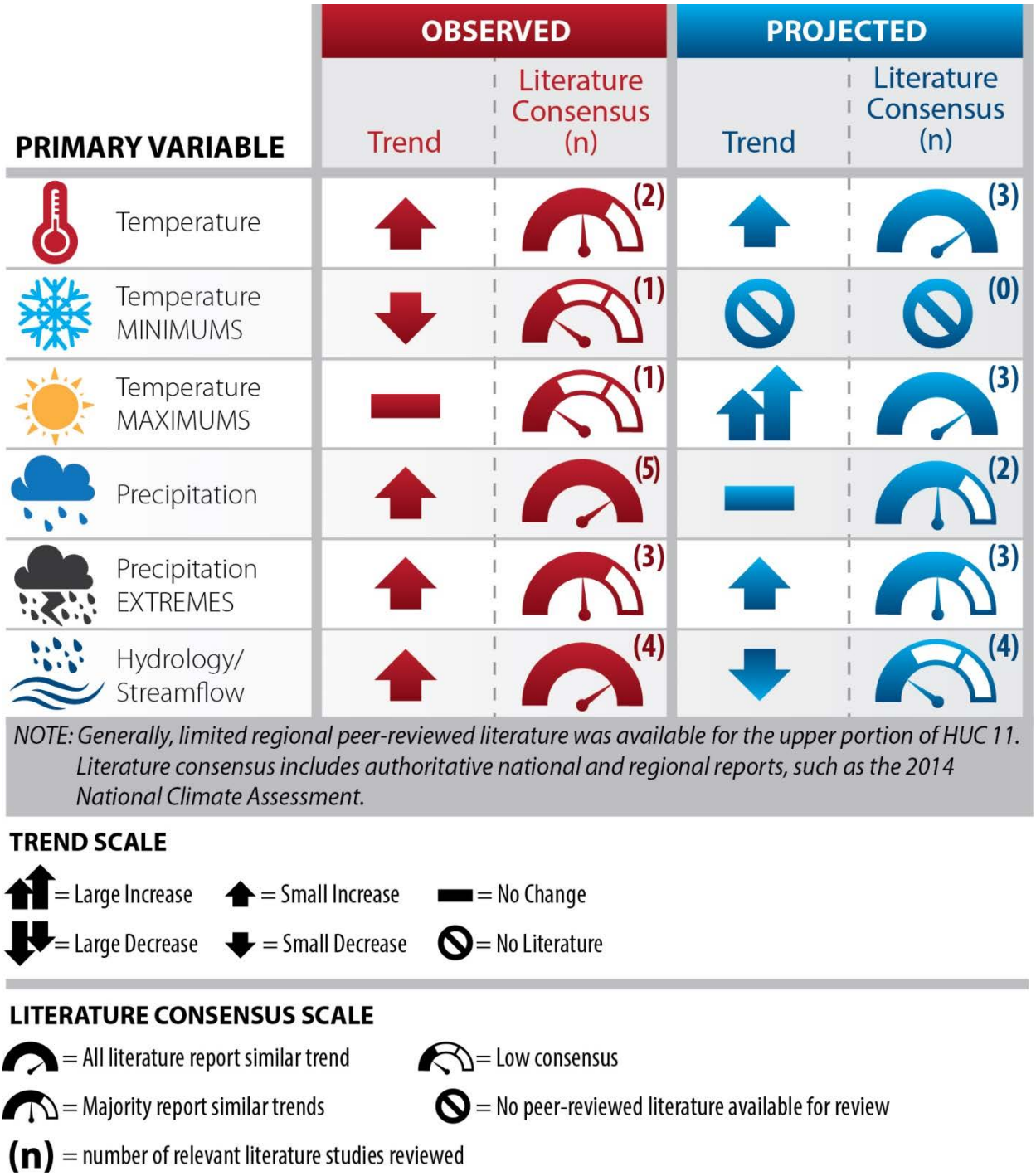

Figure 3.8. Summary Matrix of Observed and Projected Climate Trends and Literary Consensus.

4. Business Line Vulnerabilities

The Arkansas-White-Red Rivers Region encompasses a vast area in the central/south central region of the United States. The Arkansas, White, and Red Rivers are major tributaries to the Mississippi River. The headwaters of each span large areas of the Great Plains and are in Colorado, Arkansas, and Texas, respectively. As such, climate impacts to this area may be affected by climatic conditions beyond this given region. USACE recognizes the potential impacts of future climate considering the exposure and dependency of many of its projects on the natural environment. To assess the potential vulnerabilities that climate change may pose on USACE's missions, a set of primary USACE business lines were identified. They include:

- Navigation
- Flood Risk Management
- Water Supply
- Ecosystem Restoration
- Hydropower
- Recreation
- Emergency Management
- Regulatory
- Military Programs

Navigation is one of the primary missions of USACE in the Arkansas-White-Red Rivers Region. Millions of tons of cargo are transported on the McClellan-Kerr Arkansas Rivers annually, resulting in billions of dollars in cost and emissions savings associated with bulk shipment of goods on barges rather than by truck or rail. By the middle of the century, the frequency and intensity of large storm events and associated flooding are also expected to increase. In addition, the Arkansas-White-Red Rivers Region may experience increases in ambient air temperature and a broader range of extremes in water availability, which has implications for water levels and thus the ability for vessels to navigate and dock at ports.

The region has experienced several historic flooding events, which impacted urban centers and local communities, and inundated farmland. As a result, USACE implements flood risk management projects in the region include structural projects which maintain the flows in many of the river basins. Higher peak rainfalls and increased precipitation event frequency are predicted for the region. An increase in peak rainfall would cause increased runoff and may cause flash floods if the storms are intense. Flood risk management projects may be very important for reducing the residual flooding impacts due to extreme storm events, which are predicted to be more frequent and intense.

USACE also maintains and operates several fresh water supplies for aquifer replenishment for agricultural uses. The contrast between increasing mean air temperatures along with increased frequency and magnitude of heat waves, versus the increase, storm intensity and frequency will make managing competing water needs a challenge, especially when water demand is high and water supply is low.

USACE implements several ecosystem restoration projects in the Arkansas-White-Red Rivers Region, such as examining existing ecosystems, developing watershed management plans, performing restoration feasibility studies, executing comprehensive river restoration, and

preserving and maintaining natural habitats. Increased air temperatures and increased frequencies of drought, particularly in the winter and spring months by mid-century and then fall and summer months in the latter half of the century, will result in increased water temperatures. This may lead to water quality concerns, particularly for the dissolved oxygen levels, which are an important water quality parameter for aquatic life. Increased air temperatures are associated with the growth of nuisance algal blooms and influence wildlife and supporting food supplies.

Increased storm intensities coupled with prolonged periods of summer drought conditions in the Arkansas-White-Red Rivers region, may pose complications to planning for ecosystem needs and lead to variation in flows. This may be particularly true during dry years, when water demands for conflicting uses may outweigh water supply. During wet years, flooding may raise particular ecological concerns and may threaten ecosystems.

Hydropower is generated in the Arkansas-White-Red Rivers Region – primarily in the Southwestern Division in Oklahoma, North Texas, Missouri, and Arkansas. By the middle of the century, large storm events are expected to increase in the region, which may be beneficial for hydropower plants in the region, as flooding and increased river flows may lead to increased power generation. However, in extreme cases excess flooding may present some operational issues at these projects. Conversely, there may also be times during any given year where flows and reservoir levels are reduced due to high temperatures and drought conditions, which reduce the amount of power that may be generated by the hydropower plants.

Recreational facilities in the Arkansas-White-Red Rivers region offer several benefits to visitors as well as positive economic impacts. Increases in air temperature along extended heat waves in the summer months and the increased frequency of extreme storm events have the potential to decrease the number of visitors to USACE's recreational facilities. Periods of extreme high heat poses human health concerns and higher water temperatures can result in algal blooms and other water quality issues which may cause health risks for those involved in aquatic activities. Increased extreme storm events may make recreational activity difficult, dangerous, or impossible.

USACE has extraordinary capabilities to respond to natural disasters and other emergency situations throughout the country, and it is a top priority. There are designated emergency managers and assigned staff in each region and subregion that are able to quickly mobilize. Extreme storm events are capable of creating emergency situations in which USACE would be needed to provide assistance in the Arkansas-White-Red Rivers Region. These types of storms are capable of intense precipitation, winds, and storm surge in coastal areas. Since these may occur more frequently, USACE can expect an increased need for their assistance in disaster response and recovery.

USACE's regulatory mission has a serious commitment to protecting aquatic resources while allowing reasonable development. The climate projections may have indirect implications for permitting in the region, and may result from modifications in federal laws and guidance. This may spur stricter regulation or increase the permitting breadth and depth. While most of the permitting processes may not change, the volume and frequency of the permitting requirements may increase – thus increasing the permitting costs for projects.

In addition, USACE provides engineering, construction, real estate, environmental management, disaster response, and other support or consulting services for the Army, Air Force, other assigned U.S. Government agencies, and foreign governments. Environmental management services including rehabilitation of active and inactive military bases, formerly used defense sites, or areas that house excess munitions. Expected changes in climate may necessitate adjustments in rehabilitation approaches, engineering design parameters, and potential types of military construction/infrastructure projects that USACE may be asked to support.

USACE projects are varied, complex, and at times, encompass multiple business lines. The relationships among these business lines, with respect to impacts from climate change, are complicated with cascading effects. Such interrelationships must be recognized as an essential component of future planning efforts when considering the best methods or strategies to adapt. Figure 4.1 summarizes the projected climate trends and impacts on each of the USACE business lines.

CLIMATE VARIABLE	VULNERABILITY
Increased Ambient Temperatures	Increased ambient air temperatures throughout the century, and over the next century are expected to create the following vulnerabilities on the business lines in the region: • Loss of vegetation from increased periods of drought and reduced streamflows may have impacts on vegetation within the region, which is important for sediment stabilization in the watershed. Loss of non-drought resistant vegetation may result in an increase in sediment loading, potentially causing geomorphic changes in the tributaries to the river system. • Decrease in flows may result from periods of drought and reduced streamflow has implications for maintain water levels in the rivers. • Risk of wildfires during hot and dry conditions may cause an increased risk of wildfires, especially in heavily forested and dry areas. Flora and fauna that are not drought resistant can also be impacted by longer drought conditions, which may reduce opportunities for recreational wildlife viewing. **BUSINESS LINES IMPACTED:**
Increased Maximum Temperatures	Air temperatures are expected to increase 2-4°C in the latter half of the 21st century, especially in the summer months. This is expected to create the following vulnerabilities on business lines in the region: • Increased water temperatures leading to water quality concerns, particularly for the dissolved oxygen (DO) levels, growth of nuisance algal blooms and influence wildlife and supporting food supplies. • Increased evapotranspiration. • Human health risk increases from extended heat waves, impacting recreational visitors and increasing the need for emergency management. **BUSINESS LINES IMPACTED:**
Increased Storm Intensity and Frequency	Extreme storm events may become more intense and frequent over the coming century which are expected to influence the following vulnerabilities on business lines in the region: • Increased flows and runoff, which may carry pollutants to receiving water bodies, decreasing water quality. • Increased erosion with subsequent changes in sediment accumulation rates and creating water quality concerns. • Increased groundwater recharge rates, as residence times are shortened within areas where evapotranspiration takes place during high intensity events. • Increased flooding, which may have negative consequences for all infrastructure, habitats, and people in the area. **BUSINESS LINES IMPACTED:**
Streamflow Variability	The changes in streamflow may be positive or negative, depending on local conditions. This variability requires that multiple plausible streamflow futures be considered to adequately plan, design, and opearate projects and programs. **BUSINESS LINES IMPACTED:**

NOTE: The Regulatory and Military Program business lines may be impacted by all climate variables

= Navigation = Flood Risk Management = Ecosystem Restoration = Hydropower = Recreation = Water Supply = Emergency Management

Figure 4.1. Summary of Projected Climate Trends and Impacts on USACE Business Lines

Appendix A: References Climate/Hydrology Summary Table

References	Observed										Projected									
	Mean Temperature	Temperature Minimums	Temperature Maximums	Precipitation	Precipitation Extremes	Hydrology/Streamflow	Drought Indices	Soil Moisture	Spring Onset Index	Climate Classification	Mean Temperature	Temperature Minimums	Temperature Maximums	Precipitation	Precipitation Extremes	Hydrology/Streamflow	Drought Indices	Soil Moisture	Spring Onset Index	Climate Classification
Brekke and Pruitt (2010)																X				
Chen, G., Tian, H., Zhang, C., Liu, M., Ren, W., Zhu, W., . . . Lockaby, G. B. (2012)							X													
Cook, B. I., Smerdon, J. E., Seager, R., & Cook, E. R. (2014).							X													
Döll, P., & Zhang, J. (2010).																X				
Elguindi, N., & Grundstein, A. (2013).											X									X
Garbrecht, J., Van Liew, M., & Brown, G. (2004).				X		X														
Garfin, G. M., Franco, G., Blanco, H., Comrie, A. C., Gonzalez, T., Piechota, T., . . . Waskom, R. (Eds.). (2014).												X			X	X				
Grundstein, A. (2009).				X				X												
Grundstein, A., & Dowd, J. (2011).		X	X																	
Hagemann, S., Chen, C., Clark, D. B., Folwell, S., Gosling, S. N., Haddeland, I., . . . Wiltshire, A. J. (2013).																X				
Joetzjer, E., Douville, H., Delire, C., Ciais, P., Decharme, B., & Tyteca, S. (2013).																	X			
Kalra, A., Piechota, T., Davies, R., & Tootle, G. (2008).						X														
Kunkel, K. E., Liang, X.-Z., & Zhu, J. (2010).													X							
Liu, L., Hong, Y., Hocker, J. E., Shafer, M. A., Carter, L. M., Gourley, J. J., . . . Adhikari, P. (2012).	X										X			X	X					
Liu, Y., Goodrick, S. L., & Stanturf, J. A. (2013).																	X			
Madsen, T., & Figdor, E. (2007).					X															
McRoberts, D. B., & Nielsen-Gammon, J. W. (2011).				X																
Pryor, S. C., Howe, J. A., & Kunkel, K. E. (2009).				X	X															
Qian, T., Dai, A., & Trenberth, K. E. (2007).						X														
Scherer, M., & Diffenbaugh, N. (2014).													X							
Schwartz, M. D., Ault, T. R., & Betancourt, J. L. (2013).									X											
Wang, H., Schubert, S., Suarez, M., Chen, J., Hoerling, M., Kumar, A., & Pegion, P. (2009).	X			X																
Wang, J., & Zhang, X. (2008).					X										X					
Xu, X., Liu, W., Rafique, R., & Wang, K. (2013).						X														
Zhang, C., Tian, H., Wang, Y., Zeng, T., & Liu, Y. (2010).											X	X	X	X						

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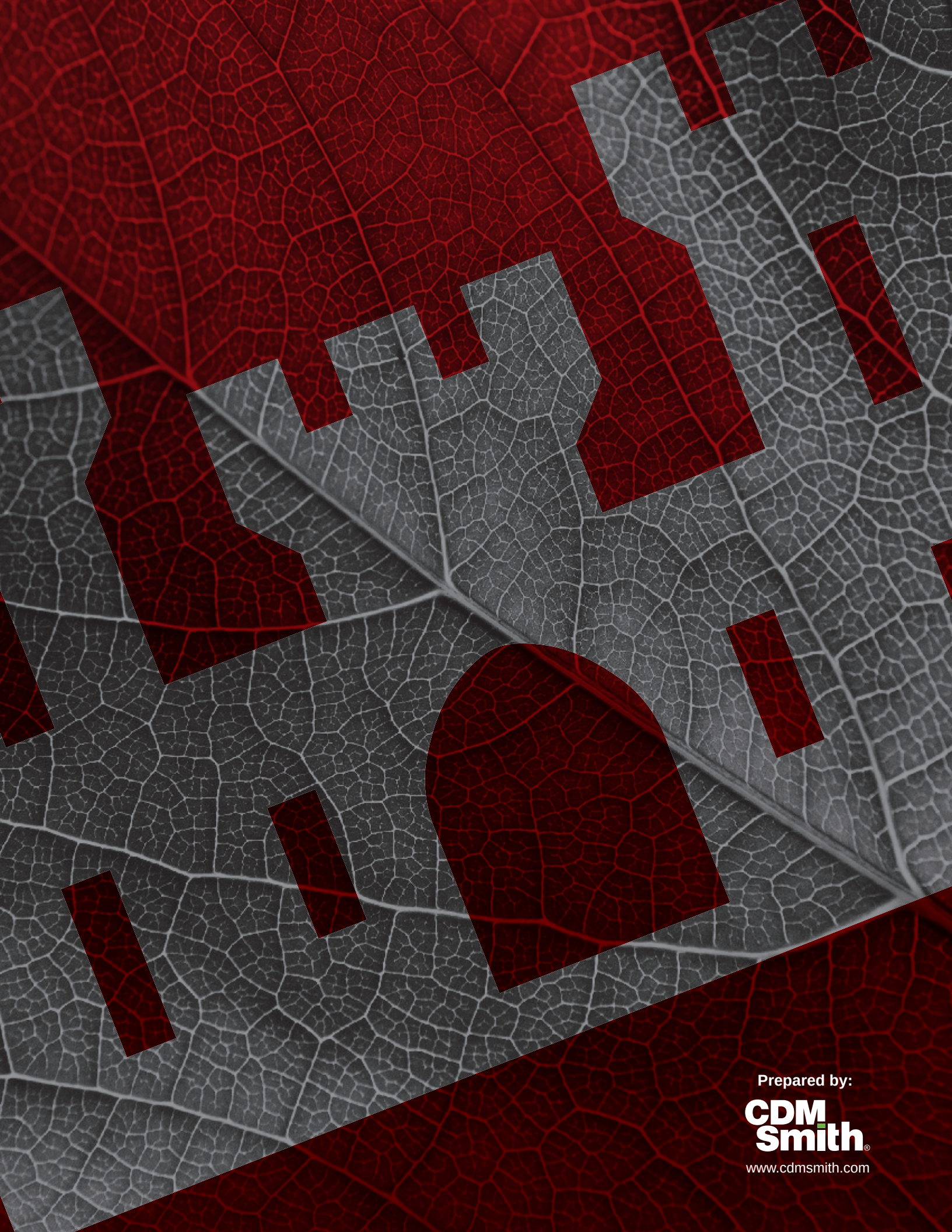

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