Drought in Texas: A Comparison of the 1950–1957 and 2010–2015 Droughts

February 2022

Cover photo, dust storm, Randall County, Texas March 2014. Credit A. Weinberg.

Executive Summary

This report examines two droughts that scorched Texas a half-century apart and explores their implications for water resources management in the state. Prior to the past decade, the 1950-1957 drought stood as the drought of record for all of Texas. It contributed to a major demographic transition, from a state rooted in farming and ranching to the largely urban Texas of the late 20th century and set the goalposts for water planners ever since. The 1950s drought lasted longer than the 2010-2014 drought in every climate division in the state, but by some measures the 2010-2014 drought was more severe. The 2010-2014 drought set new standards for the hottest and driest 12-month periods on record, dropped streamflow to new lows, and prompted widespread emergency actions to maintain water supplies. This report compiles a wide variety of data on the two droughts to document the meteorological conditions and their impacts on different sectors of the Texas economy. The authors evaluated how environmental conditions interacted with social, economic, and political systems to highlight how drought planning and drought response in Texas can be improved.

Measuring drought impacts

Drought impacts occur within a social framework. Social change over the half century between the 1950s and 2010-2014 droughts complicates direct comparison of drought impacts associated with the two events, as drought impacts are a product of both climatic factors and social factors. The social fabric of Texas changed dramatically between 1950 and 2010. The population tripled while simultaneously shifting from a rural agrarian economy to an urban, industrialized society. While population growth placed increasing demand on water resources, the relative decline of agriculture largely insulated most Texans from the effects of drought, which are felt first and hardest by those living closest to the land. Advances in agricultural technology, growth of crop insurance and other government farm support systems, and development of broader strategies for diversification and risk hedging by farm operators, together with extensive reservoir construction for municipal water supply, further mitigated the social and economic costs of the 2010-2014 drought in Texas.

In general, drought impacts are poorly tracked and consistent statistical resources and analytical methodologies for estimating drought costs at the state level are not available. The temporal and spatial extent of drought further complicates tracking impacts. Unlike flood events, droughts take place over years instead of days to weeks and may cover the entire state instead of some portion of a river basin. At this scale, business and market decisions adapt to drought conditions in a dynamic fashion, complicating efforts to attribute losses to drought. More systematic monitoring and reporting on drought impacts would help clarify how drought affects different sectors of society and how these effects change over time. Real-time monitoring and reporting systems would also help allocate drought response resources.

Meteorology of two droughts

Meteorological records show that the 1950s drought lasted significantly longer than the 2010-2014 drought, while 2011 was the most intense single year of drought on record in Texas. The measured drought duration depends on which index is used. As measured by the Standardized Precipitation Index (SPI), the 1950s drought lasted 80 months, from October 1950 through May 1957, while the Palmer Drought Severity Index (PDSI) measures 77 months of drought, from October 1950 through

February 1957. The 2010-2014 drought lasted 49 months as measured by the SPI, from February 2011 to March 2015, while the PDSI shows a 51-month duration, from August 2010 to November 2014. The peak intensity of the 2010-2014 drought was worse than in the 1950s drought, with a minimum PDSI of -8.06 in September 2011, compared to the 1956 minimum of -7.77 in September 1956.

Summertime temperatures and precipitation paint a similar picture of persistent drought in the 1950s versus intense drought in 2010-2014. The 1950s drought has four years ranking in the top 10 percent of the hottest, driest Texas summers. The 2010-2014 drought has only one summer in the top 10 percent, but 2011 ranks as far and away the hottest and driest summer on record for the state, with an average June, July, and August temperature more than 2.5 degrees Fahrenheit above the next hottest year.

Drought impacts on water resources

By some measures, streamflow reductions during the 2010-2014 drought were worse than those during the 1950s drought. Streamflow at unregulated index sites dropped further and faster during the 2010-2014 drought than in the 1950s drought, resulting in a larger cumulative streamflow deficit over the duration of the drought. The 10-million-acre-foot cumulative streamflow deficit measured at index sites during the 2010-2014 drought was 400,000 acre-feet greater than the total streamflow deficit during the 1950s drought, although the 1950s drought lasted almost two years longer.

Reservoirs in the eastern half of the state buffered downstream flows during the 2010-2014 drought, maintaining supplies to major urban centers and moderating damage to coastal bays and estuaries. Many reservoirs in the western half of the state were drawn down to record lows, necessitating emergency responses by state and local officials including water rights priority calls on the Brazos and other rivers and irrigation rights curtailment on the Lower Colorado. The Lower Colorado River Authority (LCRA) 2020 Water Management Plan determined the 2010-2014 to be the drought of record for the river basin. The minimum storage in these lakes would have been much lower if the LCRA had not curtailed irrigation water rights held by rice farmers in the Colorado River basin. Irrigation rights were not curtailed during the 1950s and contributed to the greater reservoir drawdown during that drought.

For a subset of six reservoirs that have been in operation during both the 1950s and 2010-2014 droughts, including lakes Buchanan, Brownwood, Kemp, Possum Kingdom, Red Bluff, and Travis, drawdown below 50 percent of capacity lasted longer in the 2010-2014 drought than in the 1950s, although the reservoirs reached a lower minimum storage during the 1950s drought. The total duration of drought conditions, as measured by the interval between the reservoirs reaching 100 percent of capacity, is similar for the two droughts.

Impacts on agricultural production

Drought impact is most readily measured by agricultural losses. The U. S. Department of Agriculture extensively documents agricultural production and, with the growth of federal crop insurance programs following the 1950s drought, has developed a system of rules defining how crop losses are defined and indemnified. Few other market sectors have specific rules on accounting for drought losses. Consequently, statistics summarizing drought losses are not typically collected outside the agricultural sector.

While drought remains costly for the agricultural sector, the overall impact on the state economy is lower now than in the 1950s, as fewer people are employed in agriculture and the relative prices of agricultural commodities have declined over time. In 2017 dollars, the agricultural costs of the 1950s drought totaled approximately $36 billion in direct losses. The direct costs of crop losses from the 1950s drought have been estimated at $3.0 billion dollars, excluding losses to ranchers. Based on the agricultural statistics service data, the authors estimate that livestock losses exceeded $1 billion dollars. Total losses to the state economy, including indirect and secondary effects, were undoubtedly much larger. In contrast to the $36 billion cost of the 1950s drought, the authors estimate direct agricultural losses during the 2011 to 2014 drought at $10 billion to $14 billion. This includes $7.62 billion in direct agricultural losses in 2011 alone (Fannin 2012). Additional direct agricultural losses for 2012 through 2014 estimated from U.S. Department of Agriculture statistics in this study totaled between $2.5 billion and $6.5 billion dollars. A separate estimate of the one-year total cost of drought to the Texas economy for 2011, including indirect and induced effects, totaled almost $17 billion dollars (Ziolkowska, 2016).

During the 1950s drought, limited federal assistance was available for relief efforts. In contrast, during the 2010-2014 drought, federal commodity insurance payments alone totaled more than $6.4 billion dollars. The social impact of the 1950s Texas drought was cushioned by the larger national economic expansion and trend of rural migration to urban areas. Socioeconomic impacts would have been much more severe if the drought had taken place during an economic downturn, as was the case with the 1930s Dustbowl.

Impacts on water supplies and planning

Small municipal water systems remain vulnerable to drought. During both the 1950s and 2010-2014 drought, numerous municipal water supply systems had to resort to emergency measures to bring new water supplies on line and keep the water running in their service areas. Most public water supply systems facing water shortages serve small communities and have limited resources. The most common source of new supply was groundwater. Reservoirs constructed following the 1950s drought ensured an adequate water supply for most larger urban areas during the 2010-2014 drought.

Major advances in water planning for Texas followed both droughts. The Texas Water Development Board (TWDB) was created in the aftermath of the 1950s drought, and during the 1960s a total of 49 new reservoirs with a combined storage capacity of more than 18 million acre-feet were constructed in Texas. During the 2010-2014 drought, Texans approved the State Water Implementation Fund for Texas (SWIFT) to fund water supply projects shown by the TWDB to meet projected state needs by 2060. These investments in planning and infrastructure currently serve to mitigate the effects of drought and reduce the risk of climate events leading to social disruption.

Long-term context for recent droughts

Long-term climate reconstructions based on tree-ring data show that the 1950s drought was one of the most intense by some measures over the last 600 years, although 'megadroughts' more severe and longer-lasting than either the 1950s drought or the 2010-2014 drought have occurred in the past and are likely to recur in the future. The climate reconstructions also show that the 20th century was anomalously wet compared to much of the previous millennium. Climate models of past megadroughts suggest that they are linked to persistent La Niña-like conditions in the tropical

Pacific Ocean, which paradoxically developed in response to overall warming trends. The models differ in predicting how greenhouse forcing will affect tropical ocean circulation patterns and associated drought in Texas but suggest caution in planning for drought in the 21st century.

Contents

Executive Summary E1

Measuring drought impacts E1

Meteorology of two droughts E1

Drought impacts on water resources E2

Impacts on agricultural production E2

Impacts on water supplies and planning E3

Long-term context for recent droughts E3

List of Figures ii

List of Tables iv

List of Acronyms v

1. Introduction 1

1.1 Definition of drought 1

1.2 Drought measurement 2

1.2.1 Historical droughts in Texas 4

1.2.2 Drought impacts 7

2.0 1950 – 1957 Drought 9

2.1 Meteorological record 9

2.2 Drought impact and drought response 12

2.2.1 Agricultural impact 13

2.2.2 Impact on municipal water supplies 21

2.2.3 Impacts on electric power and industrial facilities 26

2.2.4 Hydrological impacts 27

2.2.5 Environmental impacts 32

2.2.6 Impacts on state water planning and management 34

3.0 2010 - 2015 Drought 35

3.1 Meteorological record 35

3.2 Drought impact and drought response 37

3.2.1 Agricultural impacts 38

3.2.2 Hydrological impacts 44

3.2.3 Impacts on municipal water supplies 50

3.2.4 Impacts on industrial and commercial uses 53

3.2.5 Environmental impacts 56

3.2.6 Impacts on state water planning and management 59
4.0 Proxy records: a broader context for drought in Texas 61
4.1 Tree-ring data 61
4.2 Speleothems 64
5.0 Conclusions 67
6.0 References 69
Appendix A: Drought Indices and Indicators 78
Appendix A References 90

List of Figures

Figure 1-1. Palmer Drought Severity Index for Texas, 1895 to 2016 5
Figure 2-1. One-month and 12-month Standardized Precipitation Index for Texas, 1948-1958.. 10
Figure 2-2. June, July, August average statewide temperature, in degrees Fahrenheit, and total precipitation, in inches, 1895 to 2016.. 11
Figure 2-3. Statewide Palmer Drought Severity Index, September 1950 to April 1957. 11
Figure 2-4. Maps of Palmer Drought Severity Index by climate division, 1950 to 1957 12
Figure 2-5. Total agricultural production in Texas, 1949 to 1962.. 15
Figure 2-6. Number of cattle slaughtered and average live weight, 1949 to 1961. 16
Figure 2-7. Texas cattle and calf population and total herd value, 1948 to 1961 17
Figure 2-8. Texas sheep and lamb population and value, 1950 to 1959. 17
Figure 2-9. Texas wheat acreage planted and percent failure, 1947 to 1961. 18
Figure 2-10. Texas sorghum and wheat yields, 1947 to 1961 19
Figure 2-11. Texas cotton plantings and yield, 1947 to 1961.. 20
Figure 2-12. Texas grapefruit production, 1948 to 1960.. 20
Figure 2-13. Texas pecan production, 1949 to 1960 21
Figure 2-14. Accumulated runoff deficiency for water years 1952 to 1956 28
Figure 2-15. Data from 21 of the 29 streamflow index sites in Texas 29
Figure 2-16. Statewide reservoir storage and total conservation capacity, 1945 to 1960 31
Figure 2-17. Surface water and groundwater use for irrigation, 1937 to 1959 32
Figure 2-18. Areas of major soil damage due to wind erosion in 1936 and 1955-57 droughts 33
Figure 2-19. Reservoir construction and added storage capacity, by decade 34
Figure 3-1. Statewide 1-month and 12-month Standardized Precipitation Index, 2010 to 2015.. 36
Figure 3-2. Statewide Palmer Drought Severity Index, 2010 to 2015. 36
Figure 3-3. Weekly Drought Monitor for Texas, 2010 to 2015. 37
Figure 3-4. U.S. Drought Monitor maps, 2011 to 2014 38
Figure 3-5. 2011 Drought loss as a percent of average annual cash receipts from 2005 to 2009. 39
Figure 3-6. Value of crop production, livestock production, and commodity insurance payments in Texas, 2005 to 2015.. 40
Figure 3-7. Texas cattle and calf population and total herd value, 2005 to 2015. 41
Figure 3-8. Cattle killed and dumped by a rancher, Briscoe County, October 2013.. 42
Figure 3-9. Produced value and crop failure rates for upland cotton in Texas, 2005 to 2015.. 42
Figure 3-10. Produced value and crop failure rates for wheat in Texas, 2005 to 2015 43

Figure 3-11. Average daily and 90-day streamflow index values, 1950 to 2018. 45
Figure 3-12. Daily total streamflow deficits for the 1950s and 2010-2015 droughts for 21 of 29 unregulated index sites with records to 1950....45
Figure 3-13. Cumulative streamflow deficits for 1950s and 2010-2015 droughts, in acre-feet, based on daily records for 21 index sites. 46
Figure 3-14. Cumulative monthly deficit streamflow to the Gulf of Mexico with respect to the period of record median. 47
Figure 3-15. Texas statewide reservoir storage and capacity during the 2010-2015 drought....48
Figure 3-16. Total storage in six reservoirs during the 1950s and 2010-2015 droughts. 49
Figure 3-17. Statewide annual municipal water use and 12-month Standardized Precipitation Index, 2000 to 2015....52
Figure 3-18. Effect of drought on water main ruptures in San Antonio. 52
Figure 3-19. Map of the areas where junior surface water rights were curtailed from 2011, 2012, and 2013. 54
Figure 3-20. Median value of a four-bedroom Wichita Falls home, unemployment rate, and price of West Texas Intermediate crude oil for 2007 to 2017.. 56
Figure 3-21. Locations of the 31,453 reported wildfires in Texas during 2011 with responses by the Texas Fire Service and local fire departments. 57
Figure 4-1. Tree-ring reconstruction of Palmer Drought Severity Index for Texas, 1400 to 2005, showing annual and smoothed data.. 63
Figure 4-2. Natural Bridge Cavern, Texas speleothem chronology showing oxygen isotopes, strontium concentrations, carbon isotopes, and growth rate.. 66
Figure A-1. Keetch-Byrum Drought Index for January 2022 81
Figure A-2. Palmer Drought Severity Index dashboard for November 2021. 82
Figure A-3. Reservoir Storage Index by river basin and sub-basin for December 2021. 83
Figure A-4. Locations of streamflow index sites.. 84
Figure A-5. Precipitation data from the National Weather Service Advanced Hydrological Prediction Service, January 2022....86
Figure A-6. Evaporative Demand Drought Index display at Water Data for Texas....88
Figure A-7. Quick Drought Response Index display at Water Data for Texas....89

List of Tables

Table 1-1. Historical droughts with less than -4 Palmer drought severity index in at least three climate divisions of Texas. 6

Table 2-1. State-wide average annual precipitation and temperature, 1950-1957. 10

Table 2-2. Municipalities and water improvement districts provided with emergency water supplies during the 1950s drought. 22

Table 2-3. Municipalities using emergency sources of water supply as of July 1, 1953. 23

Table 2-4. Municipalities rationing water in 1953.. 25

Table 2-5. Reductions in storage from 1950 - 1956 at selected Texas reservoirs. 30

Table 3-1. Modeled economic effects of the 2011 drought on the Texas economy 39

Table 3-2. Twenty largest Texas wildfires in 2011.. 58

Table 3-3. Texas Southern Plains wildfire outbreaks in 2011. 59

Table 4-1. Longest-lasting droughts and most intense six -year periods of drought in Texas 64

Table A-1. Drought categories and index values used in Texas drought response. 78

Table A-2. Drought severity triggers for reservoirs within the Brazos River Authority service area 79

Table A-3. Streamflow index sites in Texas. 84

List of Acronyms

KBDI	Keetch-Bryam Drought Index
LCRA	Lower Colorado River Authority
NCEI	Nation Centers for Environmental Information
NOAA	National Oceanic and Atmospheric Administration
PDSI	Palmer Drought Severity Index
RSI	Reservoir Storage Index
SFI	Streamflow Index
SPI	Standard Precipitation Index
SPI-12	Twelve Monthly Standardized Precipitation Index
TWDB	Texas Water Development Board
USDA	United States Department of Agriculture

1. Introduction

This report evaluates the 2010-2014 Texas drought in the context of the 1950s drought, which is widely used for water planning purposes in the state. The authors examine the climatological conditions during both periods of drought, including the geographic distribution, intensity, and duration of precipitation, temperature, and soil moisture anomalies to better understand similarities and differences between the two droughts. The authors also explore the impacts of both droughts on the economy and natural resources of the state to better understand how drought planning, population growth, and economic diversification, among other factors, have changed the ways in which drought affected Texas over the 60-year interval between the two droughts.

This report draws on several previous reports generated in response to the 1950s and 2010-2014 droughts and a variety of primary data sources. The authors retrieved basic meteorological and climatological data presented in this report from the National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Information (NCEI), and the National Drought Mitigation Center. The authors also make use of the Texas State Climatologist's 2012 report detailing the initial year of the drought and comparing it to historical droughts in Texas. Data on drought impacts is derived from U.S. Department of Agriculture (USDA) annual agricultural statistics reports, several reports by the Texas Comptroller's office on the 2011 drought, reports by the U.S. Geological Survey and the Texas Water Commission, hydrological records maintained by the Texas Water Development Board (TWDB), and a variety of historical sources. The authors also reviewed the drought contingency plans prepared by Texas municipalities and river authorities to see how local units of government responded to the 2010-2014 drought.

The authors discuss how drought is defined and the different types of drought that are recognized. The authors describe the different measures of drought that are commonly used and the period of record on which these measures are based. The authors describe the record of droughts in Texas, as evidenced by historical observations and proxies such as tree-ring measurements, and how the drought impacts vary over time and between the different economic sectors and climate regions of the state. Finally, the authors discuss how drought factors into water planning in Texas at the state, regional, and local levels.

Because drought involves both social and climatic dimensions, comparing droughts necessarily involves a wide range of disciplines, including meteorology, hydrology, hydrogeology, economics, sociology, and history. Nace and Pulhkowski (1965) remind us that "The more highly developed and heavily populated an area is, the more water it requires and the greater the number of people who are adversely affected by water shortage. Owing to increase in water use, the margin between supply and demand is constantly narrowing, and the effect of a shortage may be more immediate and drastic now than it was formerly." This observation certainly holds true in comparing the 1950s and 2010-2014 droughts in Texas, where the state population increased from 7.8 million in 1950 to 25.2 million in 2010.

1.1 Definition of drought

Drought is defined most simply as "a prolonged period of abnormally low rainfall, leading to a shortage of water" (Lexico, 2017). Drought develops through the interplay between precipitation, evaporation, and heat on water supplies in the soil, rivers, lakes, aquifers, and their feedback on water demand, which leads to shortages of water for specific uses.

Because of this complexity, several types of drought are generally recognized: 1) meteorological drought, 2) hydrological drought, 3) agricultural drought, and 4) socioeconomic drought. The first three types of drought are defined by physical, hydro-meteorological, or biological indicators, while the fourth reflects drought impacts on society. Meteorological drought is defined simply in terms of the magnitude and duration of a precipitation shortfall. Agricultural drought occurs when precipitation shortages, higher evapotranspiration levels, and soil moisture deficits impact agricultural production, including irrigated and dryland crops, as well as livestock industries. Hydrological droughts occur when prolonged precipitation deficits deplete surface or groundwater water supplies and, like agricultural droughts, can be exacerbated by anomalies in other factors that affect evapotranspiration such as temperature, humidity, or wind. The relative timing of hydrological and agricultural droughts can vary depending on factors such as the prevalence of irrigated crops, the storage capacity of surface or groundwater reservoirs, and regulatory systems that prioritize certain user groups in times of shortage. Socioeconomic drought is driven by imbalances in the supply and demand of economic goods due to the physical characteristics of drought. Economic impacts include both direct effects, such as lost income from reduced crop yields, and secondary effects, such as reduced spending in rural communities. Social impacts can be health-related (physical and mental) and can be short-term or long-term. These known impacts support expanding the time periods and spatial scales that define drought to comprehensively account for the ripple of geophysical effects through social and economic systems (American Meteorological Society, 2013).

1.2 Drought measurement

There is no single measure of drought. Meteorologists, farmers, and hydrologists all have different ways of quantifying drought. Some are simple measurements of precipitation or stored water, for example, while others aggregate a variety of environmental measurements into a single statistic. In general, indicators are directly measurable quantities, while an index is a numerical aggregation of indicators.

Period of record, simply the period for which records are available, is a central concept for environmental measurements such as drought indicators and indices. Understanding both the normal range of variability and the extremes needed for planning in times of drought or flood is essential for effectively managing Texas water resources. Long periods of record help ensure that the full range of potential variability is known. Continuous environmental measurement records for Texas extend at most a bit over 100 years. Proxy records, such as measurements of tree rings and stalactite (speleothem) growth bands, suggest that much greater hydrological variability has occurred over millennial time scales than has been observed over the last 100 years. Such factors suggest that some caution is warranted in planning for the future based on the immediate past. As Lowry (1959) stated in the aftermath of the 1950s drought, “It is axiomatic in hydrology that with short periods of record, more severe floods and droughts will be experienced than any that have been observed.”

Stationarity is a related concept important for interpreting long term climate records. Stationarity involves the stability of both the measurement systems and the quantity being measured. Ward (2013) described in detail the history of hydrological measurements in Texas, particularly for precipitation and streamflow. In both cases, the measurement systems changed greatly over time as new measurement techniques were adopted and new sites were added to the monitoring networks, and some statistical manipulation is necessary to reconcile data across the period of record. For example, records for precipitation data by climate division are recalculated each time the division boundaries are changed. The NCEI uses sophisticated protocols to process historical measurements from individual stations and generate the daily gridded, quality-assured, period-of-record datasets that are the primary basis for climate analyses.

Stationarity also refers to the climate itself, in terms of precipitation, temperature, and other measurable quantities. Drought indicators based on relatively short periods of record may be inherently non-stationary. As Basara, Maybourn, Peirano, Tate, Brown, Hoey, and Smith (2013) note, "the past 30 years are typically used to define the climatology of normal temperatures and precipitation for a region. Because the last 30 years could have experienced significant pluvial conditions, as is the case throughout the Great Plains, it stands to reason that the past 30 years may not be representative of future precipitation patterns and drought conditions."

Over periods of centuries to millennia, the mean values of climate parameters have clearly varied and are unlikely to remain constant in the future. Human influences, including dam construction, urban development, and atmospheric carbon dioxide input may affect climate measures at local, regional, or global scales. Recognizing these changes may be important for future water resource management. If climate is stationary, then a longer period of record will be better to fully capture the range of variability. If climate is non-stationary, then the choice of the baseline period of record is a compromise between being "long enough to adequately define the reference conditions, but short enough to avoid errors due to underlying climatological trends" (Ward, 2013).

Perhaps the simplest measure of drought is the percent of normal precipitation, or the fraction of normal precipitation that occurs during a period of interest. The percentage of normal precipitation has some statistical limitations since precipitation values may not be normally distributed and their distribution may differ seasonally and/or regionally, limiting comparability across seasons or regions (Zargar, Sadiq, Naser, and Khan, 2011). Because the percent of normal precipitation is based solely on precipitation, it also fails to quantify the impact of additional variables, such as temperature, evapotranspiration, soil moisture, or streamflow on drought development, persistence, and mitigation.

Numerous indicators and indices have been developed to evaluate drought conditions at a variety of temporal and spatial scales. Each emphasizes different aspects of drought, and the choice of appropriate indicators and indices is a matter of perspective; an irrigation district may measure drought differently than a ranching community. Svoboda and Fuchs (2016) reviewed drought indicators and indices for the World Meteorological Society, evaluating 50 different measures of drought in terms of ease of use, input requirements, range of application, and strengths and weaknesses. Zargar, Sadiq, Naser, and Khan (2011) evaluated 74 drought indices out of the more than 150 described in the literature, reflecting a fundamental lack of any universal definition of drought, and the widely varying criteria for identifying drought conditions. Several recent Texas-specific studies have also examined drought monitoring practices. Quiring, Nielsen-Gammon, Srinivasan, Miller and Narasimhan (2007) studied drought monitoring and prediction tools to determine which are the most appropriate for monitoring moisture conditions at the local level in the state of Texas. Ward (2013) reviewed hydrological indices and triggers specifically for application to water management in Texas, with a detailed analysis of the formulation and application of the Standardized Precipitation Index, the Palmer Drought Severity Index, and the Standardized Runoff Index, among others.

This report focuses on five measures of drought that are used by the TWDB and the Texas Department of Emergency Management for drought response and planning. These include 1) the Keetch-Byram Drought Index, 2) the Palmer Drought Severity Index (PDSI), 3) the Reservoir Storage Index, 4) the Streamflow Index, and 5) the Standardized Precipitation Index (SPI). The U.S. Drought Monitor, which is a composite index, is also used for drought assessment and response in Texas.

More information on these drought measures is included in Appendix A.

Drought data is widely available on the internet. The TWDB Water Data for Texas webpage (waterdatafortexas.org/drought) provides links to current data for these and other drought monitoring resources. The monthly TWDB Texas Water Conditions Report (www.twdb.texas.gov/surfacewater/conditions/report/index.asp) summarizes data for selected reservoirs, streamflow sites, and groundwater wells. More data, maps, and tools for evaluating drought can be found on the U.S. Drought Portal webpage at www.drought.gov/drought/data-maps-tools. The TWDB also tracks drought impacts on surface water rights, groundwater levels, public water systems, and wildfires, among other factors. Links to data on these drought impacts can also be found on the Water Data for Texas webpage (https://www.waterdatafortexas.org/reservoirs/statewide).

1.2.1 Historical droughts in Texas

Drought is a regular component of the Texas landscape. It is unusual for all parts of the state to be completely free of drought. There has been at least one serious drought in some part of the state every decade of the 20th century (Texas State Historical Association, 2017a). The 1950s drought and the 2010-2014 drought stand apart from other historical droughts in terms of their intensity, duration, and statewide effect.

Because of their relatively long periods of record, the SPI and PDSI are best suited for comparing the 1950s and 2010-2014 drought events. Values for precipitation, SPI, and PDSI for all climate divisions of the United States and statewide are available through the National Climate Data Center for a period of record covering 1895 to present (NCEI, 2017a and 2017b). PDSI is based on precipitation, temperature, and modeled soil moisture. PDSI values run from -10 to +10 where a value of zero indicates normal conditions, +3 is considered abnormally wet conditions and -4 is considered severe drought. The PDSI record of climate conditions shows 30 separate intervals of moderate drought, with statewide monthly average PDSI exceeding -2, between 1895 and 2017 (Figure 1-1). Drought less than -2 PDSI occurs in 416 months, or 28.4 percent of the time. There have been 14 intervals of extreme drought during the instrumental record, when statewide monthly average drought has exceeded -4 PDSI, representing a total of 152 months, or 10.4 percent of the time.

There have been 12 historical droughts (1895 to 2017) in Texas that exceeded a -4 PDSI in at least three climate divisions. A 2012 report by the State Climatologist compared 2011 drought data to historical droughts in Texas using PDSI statistics (Nielson-Gammon, 2012). The results of this comparison, updated to include the full extent of the 2010-2015 drought, are shown in Table 1-1, which includes rows for each drought period and columns for each of the 10 climate divisions in the state. Values listed include the minimum monthly PDSI during the drought, the number of months below -4 PDSI, and the number of months below -2 PDSI. Overall records for each climate division are shown in bold. The start and end dates of drought periods vary by division, and drought conditions may start earlier or extend later than the overall dates indicated in the left-most column.

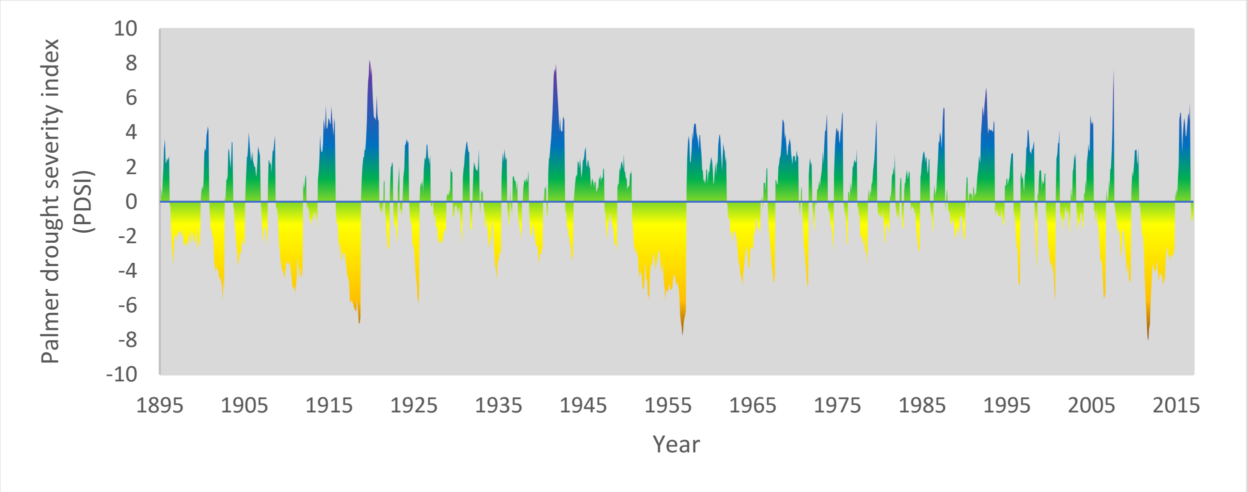


Figure 1-1. Palmer Drought Severity Index for Texas, 1895 to 2016. Data from the National Centers for Environmental Information, 2017a.

These PDSI statistics indicate that the 2010-2015 drought had the most severe one-month period on record in six of the ten climate divisions but had the longest duration below -4 PDSI in only two climate divisions. In contrast, the 1950s drought had the most severe single month on record in only 2 of the 10 climate divisions and had the longest duration below -4 PDSI in 7 of 10 climate divisions and had the longest duration below -2 PDSI in all 10 climate divisions.

Table 1-1. Historical droughts with less than -4 Palmer drought severity index (PDS) in at least three climate divisions of Texas. Values include minimum monthly PDSI, months below -4 PDSI, and months below -2 PDSI. Values in bold indicate all-time records. Adapted from Nielsen-Gammon, 2012; data from the National Centers for Environmental Information, 2017a.

Climate division	High Plains	Low Rolling Plains	North Central Texas	East Texas	Trans Pecos	Edwards Plateau	South Central Texas	Upper Coast	South Texas	Lower Valley
	1	2	3	4	5	6	7	8	9	10
1896-1902	-3.03 0 7	-3.73 0 14	-5.64 13 28	-3.36 0 36	-3.93 0 12	-4.05 1 26	-4.99 7 49	-3.52 0 25	-4.97 5 50	**-5.7** **38** 69
1908-1911	-3.69 0 12	-4.1 2 28	-5.97 25 54	-5.02 3 43	-4.21 5 24	-4.48 4 40	-4.31 2 35	-4.32 2 35	-4.39 1 38	-3.43 0 38
1915-1918	-3.9 0 20	-5.97 16 27	-6.11 12 22	-6.42 11 27	-4.58 4 29	-5.61 15 24	-6.13 21 35	**-7.0** **20** 31	-4.71 14 28	-4.51 5 26
1924-1925	-2.96 0 4	-3.26 0 5	-6.41 7 11	-6.2 9 14	-3.09 0 8	-3.95 0 9	-6.09 6 11	-5.20 6 12	-3.79 0 7	-2.51 0 3
1933-1935	-4.66 9 35	-4.42 1 16	-4.84 3 9	-3.55 0 6	-4.88 8 24	-4.51 2 17	-2.87 0 6	-2.90 0 7	-1.80 0 0	-1.76 0 0
1950-1957	-5.62 **19** **60**	-6.25 **25** **71**	**-6.82** **21** **70**	-5.09 9 **51**	-5.67 **24** **78**	-6.16 **39** **75**	**-6.68** **37** **64**	-5.72 13 **55**	-5.26 **17** **78**	-4.45 5 **77**
1961-1966	-3.89 0 21	-2.91 0 11	-3.95 0 14	-3.77 0 29	-2.87 0 25	-4.29 1 25	-4.80 5 28	-4.15 1 36	-3.71 0 27	-3.57 0 28
1966-1967	-3.31 0 7	-3.42 0 8	-4.61 3 8	-3.34 0 10	-2.55 0 1	-4.12 1 7	-4.73 2 7	-2.99 0 5	-3.62 0 3	-2.44 0 2
1970-1971	-3.33 0 10	-4.18 2 9	-4.41 1 5	-3.11 0 11	-2.8 0 5	-3.46 0 6	-5.01 3 7	-3.28 0 5	-3.68 0 5	-2.70 0 5
1999-2002	-3.88 0 4	-3.97 0 10	-3.76 0 11	-4.34 1 10	-4.93 4 51	-4.78 4 15	-4.39 2 13	-5.17 7 15	-4.12 1 18	-4.21 3 34
2005-2006	-4.58 2 7	-4.80 2 7	-4.93 4 14	-4.16 4 16	-3.72 0 4	-4.14 1 11	-5.23 8 13	-4.32 3 9	-4.73 4 15	-4.77 3 20
2010-2014	**-6.98** **19** 42	**-6.99** 17 44	-5.99 6 33	**-6.86** **11** 35	**-6.52** 13 43	**-6.39** 8 43	-6.21 13 44	-5.7 8 34	**-5.45** 11 40	-4.94 18 32

1.2.2 Drought impacts

Drought affects many different aspects of the economy and environment. Drought impacts may be immediate or delayed for months or years past the onset of drought, as effects propagate through networked systems connecting agriculture, manufacturing, finance, energy, municipal services, and natural resources. The great diversity of drought impacts, both in time and across economic sectors, complicates efforts to quantify or index the severity of drought impacts. As Ward (2013) notes, there is no direct, quantifiable correlation between any drought index value and its associated impact.

Drought impacts on agriculture are perhaps the most immediate and obvious. Crops may fail to reach harvest and livestock mortality may increase during drought. Even areas with irrigation supplies may experience increased watering costs, greater crop stress, and reduced yield. Agricultural impacts are generally well documented. The U.S. Department of Agriculture compiles statistics on agricultural production at the state level, providing a convenient means of comparison between drought events, although broader market forces often complicate efforts to quantify economic impacts related to drought. Agricultural impacts spread into the broader economy both through the input supply chain and the output food and fiber processing industries, although drought impacts may become less clearly defined in broad measures of economic activity in these linked industries, which tend to integrate production from national or international markets rather than a region experiencing drought.

Drought can impact a variety of industrial sectors where water is needed in large volumes for key processes. Some examples include steam-electrical power generation, chemical manufacturing, oil and gas drilling operations, and bottling and food processing. Water quality may be equally as important as water quantity for some processes. Demand management measures implemented during droughts may force industrial users to develop new water supplies or construct additional treatment and recycling systems, adding to their costs of production.

Electric power generation requires access to large volumes of water, making the power sector potentially vulnerable to drought. Water requirements vary greatly between different electricity generation and cooling technologies. Coal-fired and nuclear steam-electric units need more cooling water than natural gas combined cycle plants, while wind and photovoltaic solar do not need cooling water. Also, consumptive use by power generation is much smaller than the total volume of water that flows through the system, representing only about three percent of statewide water use; most of the water used by power plants is returned to lakes and rivers (Black and Veatch, 2013).

For power generation, the cost of water is usually dwarfed by operations, maintenance, and fuel costs. The problem is when water becomes unavailable or its use is restricted and generating units have to shut down or significantly de-rate or reduce their output. The National Pollutant Discharge Elimination System (NPDES) permit for each plant includes limits on the maximum discharge temperature and, in some cases, the instream temperature regime. To comply with these NPDES permits, all generators with these permits must monitor water temperatures at each plant and manage water releases to assist in meeting permit requirements. Nationally, it is not uncommon for generators to de-rate their coal-fired plants for some period each summer to meet NPDES permit requirements (Black and Veatch, 2013).

Drought also impacts municipal water supply customers as demand management measures are implemented. The biggest component of demand management typically involves curtailing outdoor watering, putting trees, shrubs, and lawns at risk during extended drought. Such measures impact quality of life and can lead to loss of real property value, both in terms of replacement costs for dead landscaping and in terms of reduced demand for property in drought-prone areas.

Drought impacts accrue over time as different parts of the hydrological system are affected and as the regional economy adjusts to drought conditions. The longer a drought persists, the more its impact is apparent. Farmers, ranchers, and businesses are reluctant to make long-term decisions in response to a drought that might break at any time, so it is tempting to put off drought responses for as long as possible. At the same time, the cost of response can increase over time during drought as resources become more scarce. Securing additional water rights, drilling new wells, and purchasing feed are all cheaper in wet years than during drought years.

2.0 1950 – 1957 Drought

The 1950s drought began in the late spring of 1949 in the lower valley, affected the western portions of the state by the fall, and covered nearly all Texas by the summer of 1951. The statewide annual precipitation in 1950 (Table 2-1) totaled just over 90 percent of normal and slipped to just under 75 percent of normal in 1951. The statewide total annual rainfall rebounded to almost 80 percent normal in 1952 and over 84 percent in 1953 before dropping to 66 percent normal in 1954. A relatively wet year in 1955, with over 81 percent normal precipitation, preceded the worst year of the drought, with just over 55 percent normal precipitation in 1956. Atmospheric circulation patterns during the drought tended to favor abnormally strong flow of dry polar air southward across the Great Plains and inhibited the northward movement of moist air from the Gulf of Mexico (McNab and Karl, 1989).

2.1 Meteorological record

The progress of the drought in terms of the Standardized Precipitation Index (SPI) is shown graphically in Figure 2-1. The 12-month SPI goes below zero in October 1950 and stays negative until June 1957, reaching its most negative point in November 1956. Relatively wet years in 1953 and 1955, with over 80 percent of normal rainfall state-wide (Table 2-2), eased drought conditions temporarily but did not break the drought.

The effects of decreased precipitation during the drought were increased by above normal temperatures, especially during the summer months (June, July, and August). The statewide average summer temperatures in 1951, 1952, 1953, 1954, and 1956 were among the twelve hottest since 1895 (Figure 2-2), with 1956 also being the second driest summer on record.

The statewide Palmer Drought Severity Index (PDSI) (Figure 2-3) generally tracks the SPI, first going negative in October 1950 and remaining below zero until March 1957, a total of 77 months in drought conditions. The PDSI reached a maximum negative value of -7.77 in September 1956, the 72nd month of the drought. Statewide, the PDSI remained below -2 for 75 consecutive months and was below -4 for a total of 48 months.

Statewide statistics mask regional variations in the intensity of the drought across Texas and into neighboring states. Maps showing the geographic range and intensity of the drought measured by monthly PDSI by climate division (Figure 2-4) show the first appearance of drought in the Lower Valley in September 1950. Drought spread, first into Central Texas in the spring of 1951, and then across the central, southern, and eastern parts of the state by August 1951, eventually extending through much of New Mexico and the Gulf states to the east of Texas. Drought conditions ameliorated across much of the state through the middle of 1952 but intensified across central Texas and the Edwards Plateau. In late 1952, the drought was most intense in central Texas, but extended north across much of the Great Plains and west across Montana, Idaho, and Washington states, and east from Texas into Alabama. In early 1953, drought was centered in the High Plains and along the Rio Grande Valley.

By the end of 1953, drought was centered in far west Texas, extending west through New Mexico, Arizona, and southern California, while a separate area of drought covered Missouri and the Ohio River basin. Through much of 1954, drought conditions improved in Texas while drought intensified in the Ohio basin. By December 1954, the area of Midwest drought shifted south, extending across the southern part of the US from South Carolina through Texas and across the

Great Plains in Oklahoma, Kansas, Colorado, and Wyoming. Rainfall during the summer of 1955 greatly reduced the area of drought, but in 1956 drought conditions spread south from Iowa and Missouri into Texas and west across New Mexico, Arizona, and Southern California, reaching a maximum extent and severity in the fall of 1956. Widespread rainfall in April 1957 greatly reduced the extent of drought across Texas, and by the end of 1957 Texas was virtually drought-free.

Table 2-1. State-wide average annual precipitation and temperature, 1950 to 1957. Data from National Centers for Environmental Information, 2017a.

	Precipitation (inches)	Percent normal precipitation	Temperature (degrees Fahrenheit)
30-year average	27.18	-------	64.8
1950	24.51	90.2	65.4
1951	20.35	74.9	65.3
1952	21.61	79.5	65.0
1953	22.85	84.1	65.8
1954	17.95	66.0	66.6
1955	22.11	81.4	65.2
1956	14.98	55.1	66.0
1957	35.78	131.7	64.6

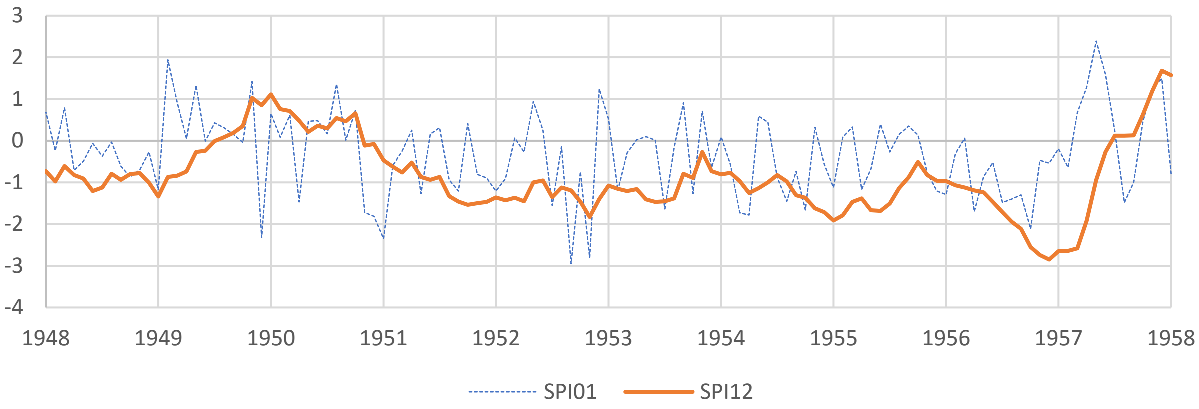


Figure 2-1. One-month and 12-month Standardized Precipitation Index for Texas, 1948-1958. Data from National Centers for Environmental Information, 2017a.

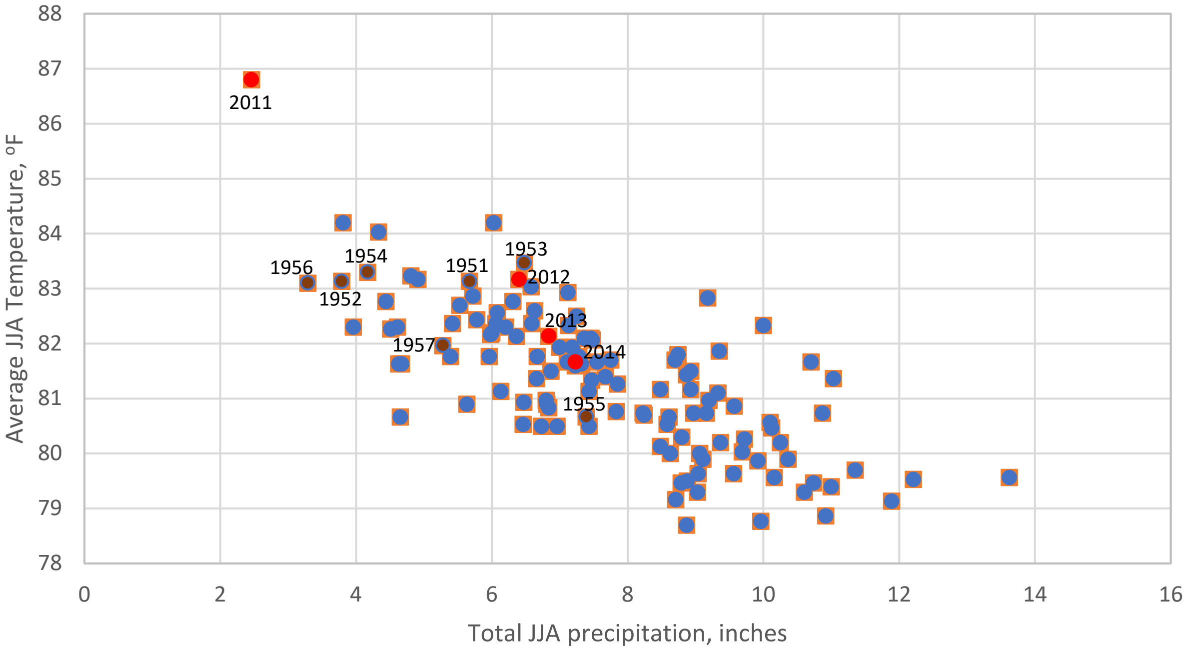


Figure 2-2. June, July, August average statewide temperature, in degrees Fahrenheit, and total precipitation, in inches, 1895 to 2016. Data points for the 1950s and 2010-2015 drought are labeled showing year of occurrence. Adapted from Nielsen-Gammon, 2012, with data from National Centers for Environmental Information, 2017a.

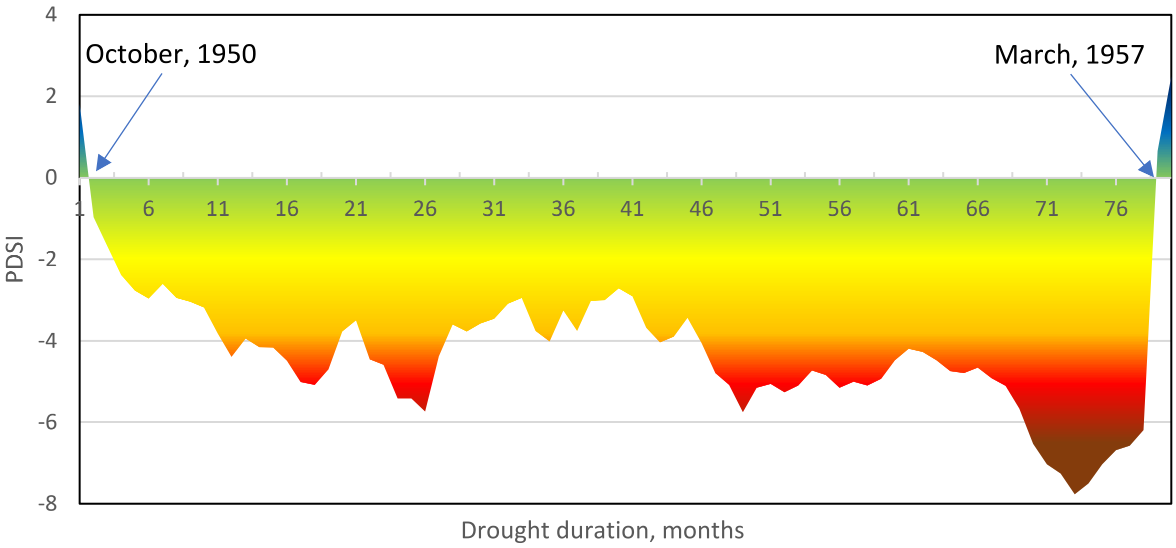


Figure 2-3. Statewide Palmer Drought Severity Index, September 1950 to April 1957. Data from National Centers for Environmental Information, 2017a.

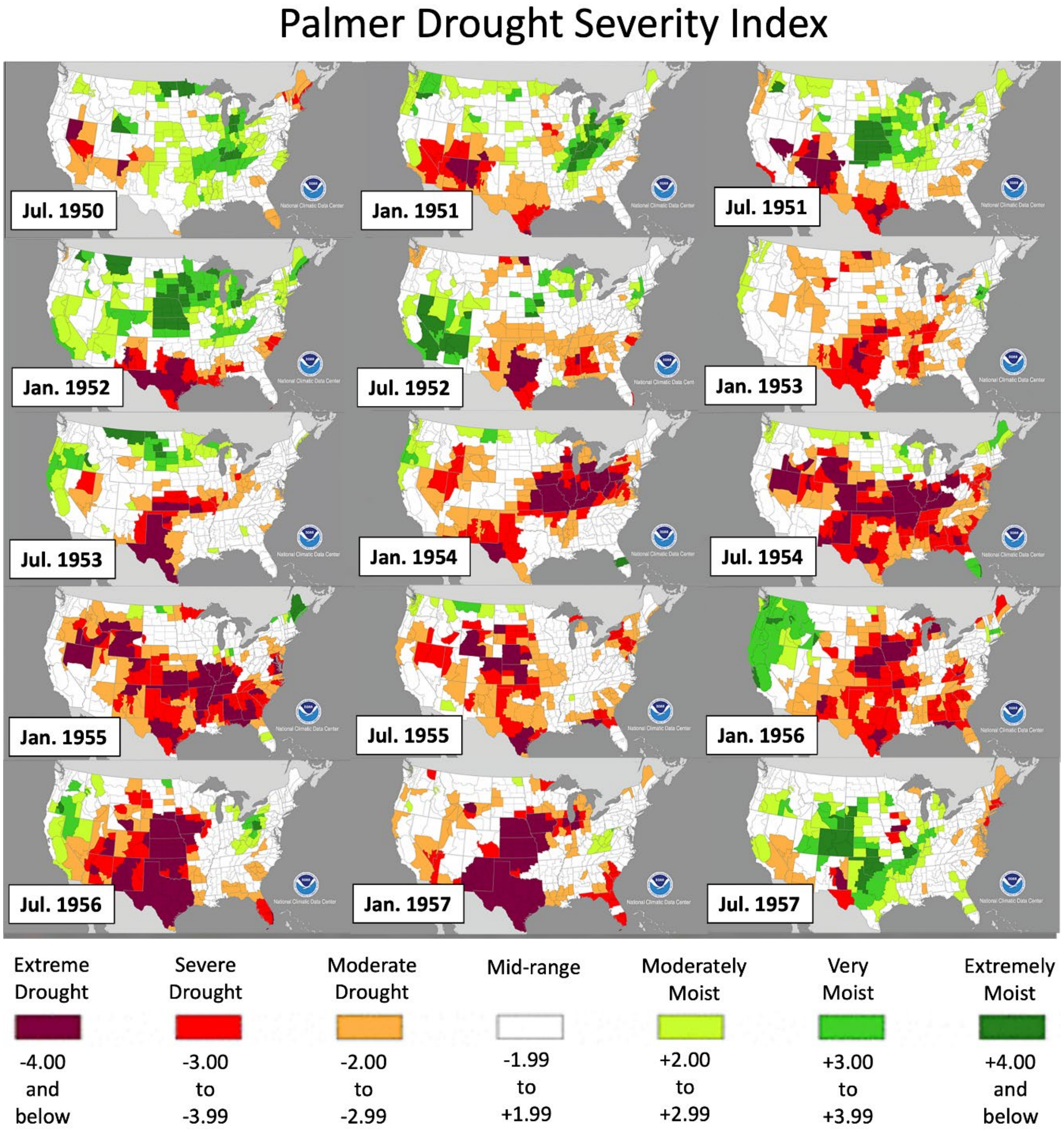


Figure 2-4. Maps of Palmer Drought Severity Index by climate division, 1950 to 1957. From National Centers for Environmental Information, 2017c.

2.2 Drought impact and drought response

For purposes of comparison between the 1950s drought and the recent 2010-2015 drought, this review focuses on specific sectors for which comparable data are available for both events. Agricultural losses are more directly attributable to drought than most other losses and are reasonably well documented through government statistics and contemporaneous reports. However, there has been relatively little research on the economic impact of the 1950s drought and there is no consensus estimate of the total economic impact of the drought. Robert L. Lowry, Jr.

produced *A Study of Droughts in Texas* for the Texas Board of Water Engineers in 1959, finding that "While the drought produced tremendous agricultural losses, its impact on the State's economy was less pronounced because of the industrial activity and expansion." Lowry (1959) estimated direct crop losses due to drought from 1950 through 1956 exceeded $3 billion, or over $27 billion in 2017 dollars (U.S. Bureau of Labor Statistics, 2017a). Figure 2-5 below shows the simplistic model developed by staff to show estimates of agricultural losses. The authors looked at drought impacts based on near-contemporary analyses, retrospective analyses, and government agricultural statistics. These assessments estimate agricultural losses during the 1950s drought at between $18 billion to $28 billion in 2017 dollars. Total losses to the state economy, including indirect and secondary effects, were undoubtedly much larger.

The 1950s drought occurred during a time of social transformation in Texas and the United States. These changes partially mask the impacts of the drought itself and confound econometric analysis of drought-related losses to Texas. In the previous decade, World War II pulled millions of young men and women off their farms and ranches and catalyzed industrial development to support the war effort. Farm mechanization, farm consolidation, rural electrification, new irrigation technologies, development of the agrichemical industry, and introduction of new crop varieties transformed rural economies in Texas and around the nation. Mechanization reduced labor requirements on farms and increased economies of scale while rising non-farm wages drew workers away from agriculture (Alston, James, Anderson, and Pardey, 2010), contributing to rural population losses, especially in areas with economically marginal farms and ranches. As a result, it is difficult to determine exactly how much the drought contributed to the economic and demographic changes in Texas during the 1950s, although the economic pressures it put on rural communities certainly accelerated many pre-existing trends.

2.2.1 Agricultural impact

Surprisingly little comprehensive accounting of drought impacts is available for the 1950s Texas drought. As Weiner, Pulwarty, and Ware (2016) note, the fundamental problem facing American agriculture of this era was overproduction. In this context, the 1950s drought was useful in that it tended to depress production of several major commodity crops, including wheat, cotton, and corn. Consequent price increases mitigated the effects of decreased production for many Texas farmers. Other large-scale external trends, including improved farm productivity, associated with mechanization and widespread adoption of chemical fertilizers, meant that overall national production of commodity crops continued to rise throughout the drought years as increases in states less impacted by drought more than made up for any losses in Texas and other drought-stricken areas. In the end, the net effects of weather and climate variation were largely overwhelmed in the aggregate by fluctuations of national policy and financial environments, and the 1950s drought received less national attention than the 1930s Dust Bowl and other climatological events of comparable severity (Weiner, Pulwarty, and Ware, 2016).

Even in agriculture, the drought was not entirely viewed as a negative force. Lowry (1959) found that "prolonged drought has stimulated irrigation development throughout Texas. The irrigated acreage in Texas has more than doubled in the past eight years." The Texas Almanac (1958-1959) echoes this position stating "despite the drouth, there was a continuation of trends of the last quarter century towards a sounder economic system of crop growing and livestock raising in Texas. In some ways, in fact, the pressures exerted by the drouth encouraged these trends." These trends include a decrease in the number of farms, a decrease in tenancy, and increases in acreage per farm and farm values. As the Almanac puts it, “The farming industry of Texas has been motorized, mobilized, and generally modernized” (Texas Almanac, 1958-1959).

The Texas Almanac (1958-1959) notes that “Texas’ basic crop growing industry, cotton, has undergone a change, shifting largely from its old base on the Blacklands to new, largely irrigated, acres in West and South Texas. The reverse has been the trend of the basic livestock industry, cattle raising, which has been shifting rapidly from west to east.” While state-wide statistics show “remarkable economic resistance to…drought”, these figures mask countless stories of individual loss and dispossession as economically marginal farms and ranches failed, and rural populations moved to urban centers. The Almanac contends that “a quarter of a century ago more than 100,000 Texas white and black sharecropper tenants had neither 40 acres nor a mule. Today the ‘average’ Texas farmer has 500 acres and a tractor.” While the Almanac implies great progress in the status of Texas farmers, the reality is that more than 90 percent of sharecroppers and 75 percent of all tenant farmers were forced out of farming during the 1950s drought. The only thing that spared this community the fate of the Okies in the Dust Bowl was the timing of the 1950s drought, which occurred during the post-war economic boom instead of during the Great Depression.

To the people who lived through it, the impact of the drought was perhaps clearer than it was to the economists. Texas Monthly reporter John Burnett (2012) collected stories of the 1950s drought from Texans who lived through it. One of the people Burnett interviewed, Charles Hagood, 59, who grew up in a ranch family that has had operations in West Texas since the 19th century, put it this way: *“*I grew up in Junction and then went into the banking business, and I would visit with men that I’d always known as carpenters, painters, merchants. When visiting with them in deeper detail, I’d find out that they had been ranchers until the drought. Just like my daddy. The drought drove us to town. And that happened all over West Texas—it drove people to town.”

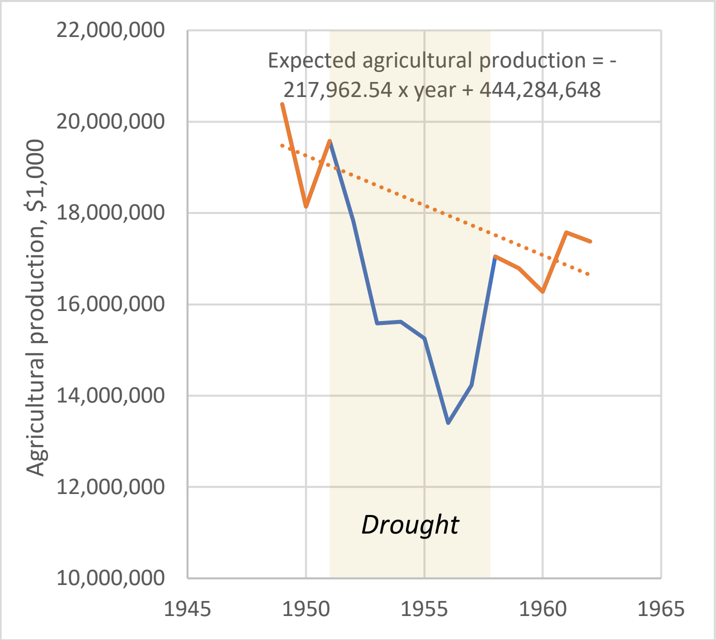
The Federal government provided small amounts of emergency assistance during the 1950s drought. Then Senator Lyndon B. Johnson travelled around the state in October 1953, writing “Drought and falling prices have put the farmer and rancher between a rock and a hard place. They need help.” (Johnson, 1953). Government payments to Texas farmers and ranchers amounted to a maximum of 6.5 percent of their total cash receipts in 1957, the worst year of the drought. Government payments averaged less than one percent of cash receipts between 1952 and 1955 (U.S. Department of Agriculture, 2017a). Lowry (1959) put the total amount of federal direct assistance to Texas agriculture at $61,814,600 over six years of drought, with over half of that aid ($33,142,700) coming in the 1956-1957 fiscal year. Nationwide, federal outlays for drought aid from mid-1953 through 1956 totaled $400 million, spread across the midwestern and southwestern states (Nace and Puhlkowski, 1965).

Agricultural producers had much less protection against losses incurred during the 1950s drought than today. From 1954 through 1956, federal drought relief totaled nearly $730 million, including distribution of surplus food, livestock feed, emergency credits and livestock loans, and price supports spread over at least a dozen states (Whilite, 1982). All-risk federal crop insurance was available on one or more crops in 818 counties across the U.S. as the drought ended in 1957. More than 330,000 producers were insured for crops including wheat, cotton, flax, corn, tobacco, soybeans, barley, oats, dry edible beans, peaches, and citrus fruit. Multiple-peril crop insurance was offered for the first time in 1956 with about 60 stock insurance companies in seven states participating. The 1956 multiple-peril crop insurance program got started late, and fewer than 100 policies were sold (Botts and Otte, 1958). Texas was not among the seven participating states.

Federal response to the drought also included the Soil Bank, created by Congress in 1956. The Soil Bank had two components. The Acreage Reserve Program was designed to immediately reduce production of six basic crops—wheat, corn, cotton, tobacco, rice, and peanuts—and ran for three crop years, from 1956 through 1958. The Conservation Reserve Program sought a long-term reduction in cropland acreage and continues to the present (USDA, 2017). Initially, the program tended to divert cropping from the lowest yielding acres, encouraging intensified crop production on the better land, with little net impact on production (Weiner and others, 2016). During the 1956-1957 Acreage Reserve Program, there were no restrictions on the use of non-contracted farmland, so a farmer could contract to reduce acreage of a target commodity crop, but increase acreage of other crops (Helms, 1985).

Agricultural losses to drought can be reasonably well documented using USDA statistical summaries and contemporaneous accounts. Lowry (1959) states that "An overall dollar-wise evaluation of all the possible effects on the economy has not been made," but he cites figures presented by the Texas Commissioner of Agriculture in an address in April 1955 stating: "We have lost a minimum of $2 billion during this natural disaster -- or one-fourth of our agricultural potential." Lowry also cited figures from the Commissioner of Agriculture, reported by the Houston Chronicle, on January 17, 1957, finding that the loss to farmers during 1956 was $750 million. Adding in losses for 1955, Lowry estimated that the value of lost crops from 1950 to 1956 exceeded $3 billion, not including losses to ranchers, or secondary and indirect losses to the broader state economy.

A highly simplified regression analysis of U.S. Department of Agriculture Economic Research Service statistics (Figure 2-5) suggests that agricultural production losses due to the drought totaled $17.75 billion. Total losses to the state economy, including indirect and secondary effects, were undoubtedly much larger.



	Forecast	Actual	Impact
1952	18,821,758	17,818,764	1,002,994
1953	18,603,795	15,582,296	3,021,499
1954	18,385,833	15,621,124	2,764,709
1955	18,167,870	15,255,182	2,912,688
1956	17,949,908	13,402,882	4,547,026
1957	17,731,945	14,230,755	3,501,190
		total impact	17,750,105

Values in $1,000

Figure 2-5. **Total agricultural production in Texas, 1949 to 1962. Dashed line shows expected production trend for non-drought years. Deviation from the trend is attributed to drought losses. Data from USDA Economic Research Service, 2017. Values in 2017 dollars.**

The authors estimate livestock losses to ranchers during the 1950s drought exceeded $1 billion (unadjusted) based on declines in total herd value. However, the decrease in herd value does not capture the operating losses each year for feed and labor. For this reason, total losses for producers were likely much larger than $1 billion. USDA statistics on the number of cattle slaughtered, average live weight, and gross income (Figure 2-6) show an increase of more than 500,000 in the number of cattle slaughtered between 1952 and 1953, as ranchers thinned out herds that the desiccated range could not support. The number of cattle brought to slaughter remained elevated through the drought, only returning to trend in 1958, as ranchers began restocking herds. At the same time, the average live weight of cattle brought to market declined from a high of 810 pounds per head in 1950 to a low of 770 pounds per head in 1953 because of poor feed conditions. With more and leaner cattle being brought to market, the gross income to farmers dropped more than 40 percent between 1951 and 1953, from $643,321,000 to $384,490,000. The Texas cattle and calf population (Figure 2-7) declined from more than 9.2 million at the start of the drought in 1951 to 8.5 million in 1955 as ranchers held on to as much of their herds as they could afford to feed. The population then plummeted to 6.5 million as the worst years of the drought hit in 1956 and early 1957 and did not recover to the pre-drought high until 1960. The total value of the Texas cattle herd dropped from $1.31 billion in 1951 to $430 million in 1957, representing by one measure a loss of nearly $885 million.

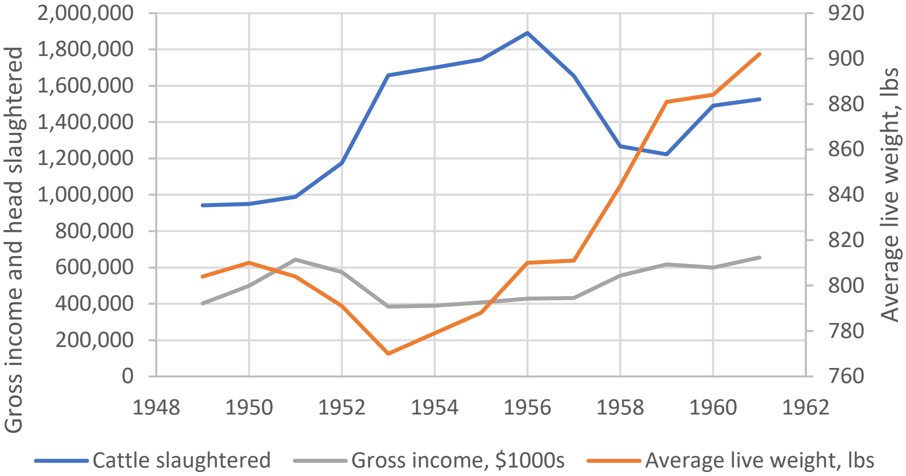


Figure 2-6. **Number of cattle slaughtered and average live weight, 1949 to 1961. Data from USDA, 2017a.**

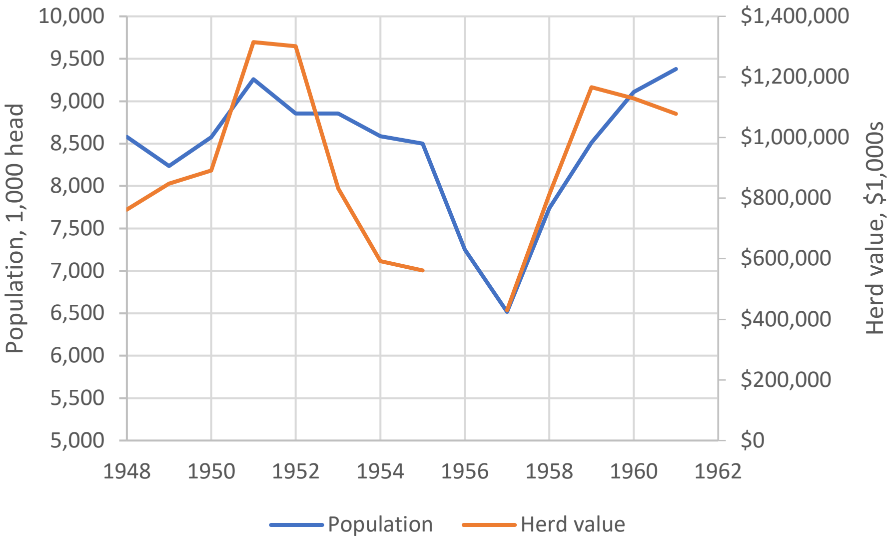


Figure 2-7. **Texas cattle and calf population and total herd value, 1948 to 1961 (herd value statistics missing for 1956). Data from USDA, 2017a.**

Stocks of sheep and goats were also severely impacted by the drought. Sheep and lamb flocks (Figure 2-8) decreased from a high of over 7 million head in 1951 to under 4.5 million in 1957. The market price per head dropped from $21.80 to $9.90 over the same period, resulting in a decline in the total value of the flock by more than $110 million. Gross income from sheep and lambs sold for slaughter spiked at over $40 million in 1952 as ranchers sold off herds at the beginning of the drought, but then held steady at about $20 million per year as ranchers maintained their stocks as best they could. The loss in value of hogs and pigs on farms likewise declined by almost $28 million. In total, the loss in value of all livestock held on farms declined by more than $1.0 billion for the duration the drought.

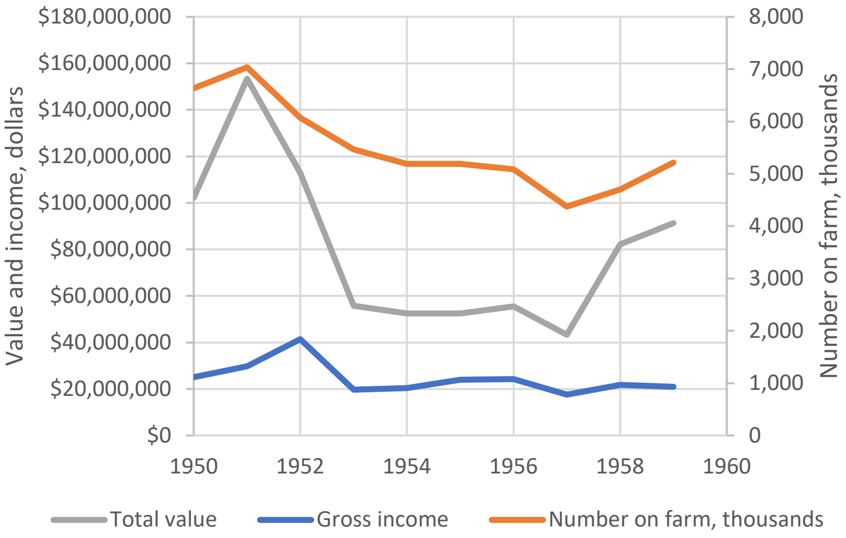


Figure 2-8. **Texas sheep and lamb population and value, 1950 to 1959. Data from USDA, 2017a.**

USDA statistics for wheat likewise reflect widespread drought conditions. The acreage of wheat planted and harvested both peaked in 1949, with over 7.5 million acres planted and about 7 million acres harvested (Figure 2-9). The acreage of wheat planted in 1950 declined to about 6 million acres, reflecting changes in agricultural markets, but the harvested acreage plummeted to less than 3 million acres with the initiation of drought conditions in wheat growing regions of the state, equating to a failure rate of over 50 percent. Wheat failures remained elevated through 1958, while the area planted to wheat decreased throughout the drought and remained low after the drought ended, suggesting long-term changes in the farm economy.

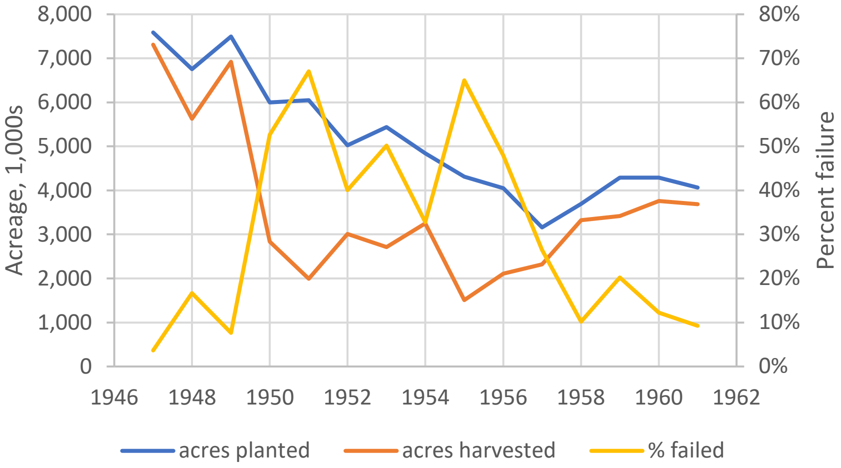


Figure 2-9. **Texas wheat acreage planted and percent failure, 1947 to 1961. Data from USDA, 2017a.**

Not all sectors of the farm economy were affected equally by the drought. For example, grain sorghum emerged as a major Texas crop during the 1950s through agricultural research, improved crop varieties, and irrigation development, even as drought conditions devastated other crops, like wheat. In the late 1940s, breeders succeeded in reducing the height of the sorghum plant, permitting harvesting with a combine. With the advent of drought and the spread of irrigation across the High Plains, farmers discovered the prolific nature of the crop when irrigated. USDA statistics (Figure 2-10) show that yields of sorghum dropped in the early years of the drought but had rebounded to pre-drought levels by 1955 while wheat yields remained flat until the drought broke in 1957. With the introduction of hybrid grain sorghum in 1957, average yields jumped to over 30 bushels per acre and continued to increase as improved varieties were bred (Texas State Historical Association, 2017a).

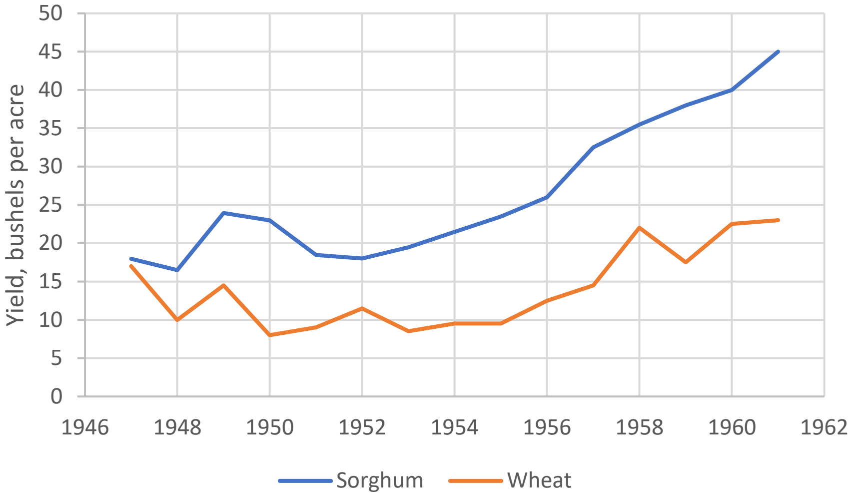


Figure 2-10. **Texas sorghum and wheat yields, 1947 to 1961. Data from USDA, 2017a.**

Cotton statistics also reflect a complex response to drought. Cotton was the number one cash crop in Texas, and before the drought the state had about 4,000 gins that processed over 6 million bales of cotton in 1949. Cotton was grown in the majority of Texas counties at the time, but especially in Central and East Texas on small family farms (Saffell, 2000). In response to the drought, the number of acres planted in cotton (Figure 2-11) dropped from over 12 million in 1951 to under 6 million in 1958. As the Texas Almanac (1958-1959) reports, the center of Texas cotton production shifted from the relatively small, unirrigated Blacklands farms to larger farms in the Southern High Plains. Farmers who could afford to invest in irrigation wells and equipment persisted, while many other farms failed. The combination of improved crop varieties and new irrigation technologies helped double cotton yields per acre during the drought; together with stable prices, these changes ensured good profits for producers with access to groundwater and financial resources. But even High Plains cotton farmers with good water supplies faced increased pumping costs because of the drought and a dropping water table. Lowry (1959) reported "Increased investment and a lengthened pumping season have raised the per-acre water cost from $7.06 in 1949 to $15.05 in 1954."

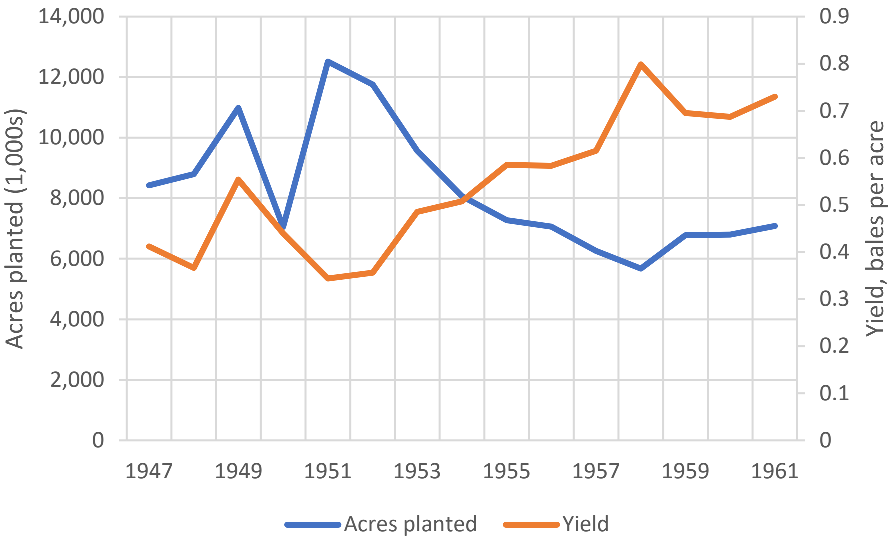


Figure 2-11. **Texas cotton plantings and yield, 1947 to 1961. Data from USDA, 2017a.**

In other cases, agricultural losses coincided with, but were not caused by, the drought. For example, USDA statistics for the Texas grapefruit industry (Figure 2-12) show over 10 million boxes of fruit shipped in 1948, but production drops essentially to zero after disastrous freezes in 1949 and 1951, which killed 7 million of the 9 million producing grapefruit and orange trees in Texas (Texas State Historical Association, 2017b). While not directly caused by drought, these freezes may be related to the same prevailing weather patterns promoting abnormally strong flow of dry polar air southward across the Great Plains and into southern Texas.

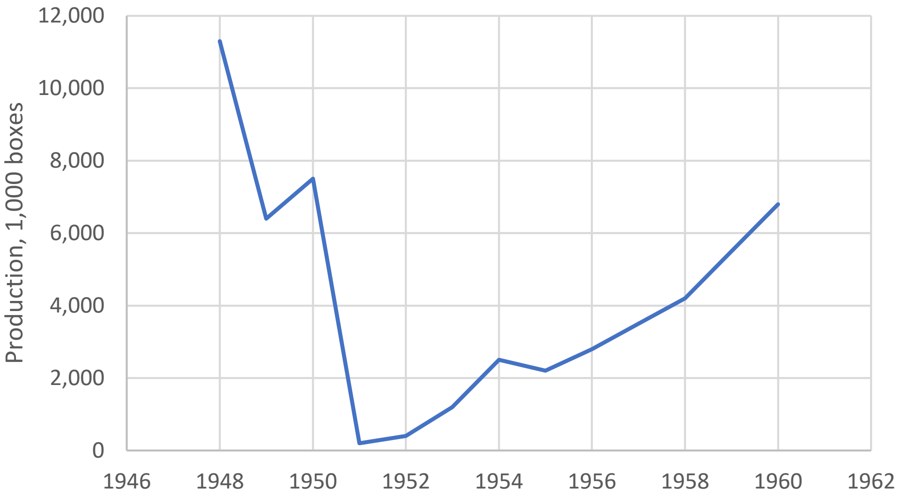


Figure 2-12. **Texas grapefruit production, 1948 to 1960. Data from USDA, 2017a.**

Texas pecan production (Figure 2-13) managed to hang on through the drought, perhaps because the deep-rooted trees tapped into shallow groundwater along the river bottoms. According to Hatfield (1965), the Kimble County Agricultural Agent, Vernon Jones, put the value of the 1955 pecan harvest at $250,000, saying “If it hadn’t been for pecans and goats there wouldn’t have been any income [in Kimble County] this year”.

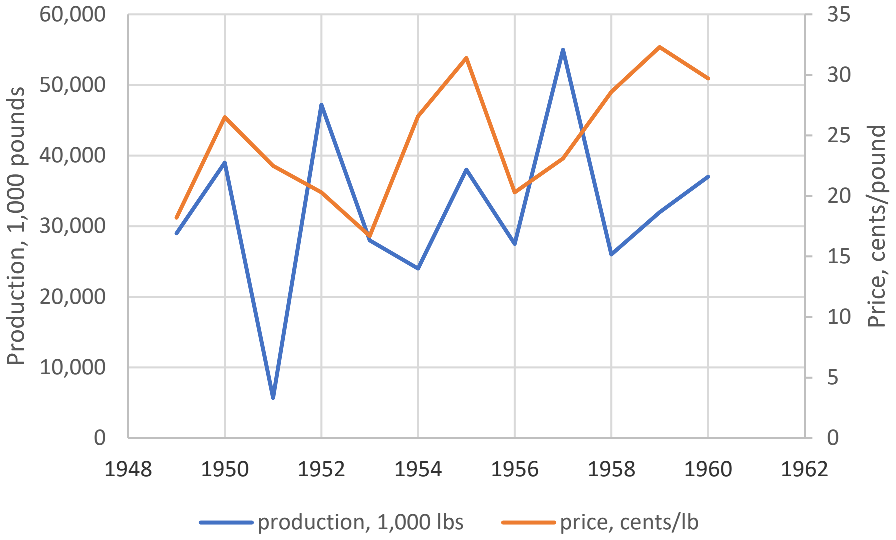


Figure 2-13. **Texas pecan production, 1949 to 1960. Data from USDA, 2017a.**

2.2.2 Impact on municipal water supplies

Numerous municipalities in Texas faced water shortages during the 1950s drought and were forced to develop emergency or alternative supplies. Little documentation of the costs incurred by local governments for these responses was found in the sources consulted for this report. Lowry (1959) cited a Texas Health Department statement from July 1, 1953, which listed 8 communities hauling water, 28 towns using emergency sources of supply, including most of the Rio Grande Valley, and 77 municipalities rationing water, including most urban areas in the Valley and major cities such as Corpus Christi, Houston, and San Antonio (Tables 2-2, 2-3, and 2-4). However, the statement does not provide any cost information. Hatfield (1964) provides costs for some drought responses by the City of Dallas from contemporary newspaper accounts, but no statewide data. In general, it is difficult to separate the direct costs of drought response from the costs incurred because of contemporaneous urban and suburban growth.

Table 2-2. Municipalities and water improvement districts provided with emergency water supplies during the 1950s drought. From Lowry, 1959.

	1951	1952	1953	1954	1955
Areas Provided New Water Systems	**17**	**23**	**29**	**23**	**41**
Areas Provided Additional Wells	**113**	**92**	**137**	**96**	**69**
Areas Provided Additional Ground or Elevated Water Storage Tanks	**27**	**-**	**32**	**70**	**56**
Areas Provided Additional Water Pumping Facilities	**30**	**-**	**19**	**49**	**23**
Areas Provided New or Expanded Surface-Water Treatment Plants	**22**	**51**	**25**	**-**	**13**

Although the City of Dallas is not on the list of municipalities using emergency water supplies or rationing water, it was one of the hardest hit cities in Texas because of rapid growth, the severity of the drought in that region, and the reluctance of city leadership to acknowledge a water problem that might discourage continued growth.

The rapid growth of the City of Dallas stretched water infrastructure even before the onset of the drought. By the mid-1940s, it was already clear that Lake Dallas was inadequate to supply the growing needs of the city, and construction of a new dam to expand the lake, later renamed Lewisville Lake, started in 1948. By the late summer of 1951, Dallas already had to truck water to newly annexed communities such as Pleasant Grove. Storage in the primary water supply reservoir for the city, Lake Dallas, fell to 11 percent of capacity (Texas State Library and Archives Commission, 2017). The dam was completed too late to help Dallas through the drought and the lake only began to fill as the drought broke in April 1957, finally reaching capacity in May 1957 (Hatfield, 1964). Compounding the water supply problem, Dallas had inadequate water treatment capacity—equipment for a new water treatment plant was held up by the onset of the Korean War.

Table 2-3. Municipalities using emergency sources of water supply as of July 1, 1953. From Lowry, 1959.

Alamo	Using large capacity wells which are privately owned
Anson	Developed 13 small wells
Brownsville	Drilled wells but water of poor quality
Byers	Pumping water 3.5 miles from spring to water treatment plant
Clyde	Lowering well pumps
Corpus Christi	Using wells located new Cambellton which discharge into Nueces River. Also planning to use industrial wells near Mathis.
Donna	Using large capacity wells which are privately owned
Edcouch	Using cannery wells and drilling city wells
Edinburg	Drilled emergency wells
Electra	Using 16 wells located approximately 8 miles from City. Planning to lay pipeline from dam to pump water into intake tower.
Elsa	Drilled emergency wells
Gordon	Laid emergency pipeline to town of Mingus. At present, a permanent line is being laid to Thurbar Lake, which is owned by the T&P Railroad.
Harlingen	Drilled emergency wells
Iowa Park	Using two shallow wells when use of new lake water is discontinued.
Jacksboro	Extended raw water intake line to deeper water
McAllen	Using cannery wells
Mercedes	Drilled emergency wells
Mission	Drilled emergency wells
New Castle	Hauled water from Graham, until recent rains, but may have to continue hauling operations
Olney	On June 29, City started using well producing salt water to furnish water to distribution system. Established central dispensing point for supplying drinking water.
Petrolia	Drilled shallow wells in Lake. Water pumped to treatment plant.
Pharr	Drilled emergency wells

Raymondville	Using cannery wells
Rotan	Using old gyp water well
San Benito	Drilled emergency wells
San Juan	Using privately owned wells
Sweetwater	Using wells near Roscoe
Weslaco	Using cannery wells
	*Data from State Health Department

In response to the drought, Dallas scrambled to secure new water supplies. The city increased water rates by 20 percent in August 1951 to cover $30 million in water and sewer improvements (Hatfield, 1964). In August 1952, the city began planning for Lake Lavon, 12,000-acre reservoir 22 miles northeast of Dallas on the East Fork of the Trinity River. Hatfield (1964) reports that the city of Dallas explored a wide variety of options for additional water during the winter of 1952-53. Dallas tried hiring the rainmaker Irving P. Krick, petitioning for rights to Red River water, and entering negotiations for more Trinity River supplies. The city secured rights to 158 billion gallons per year from the Elm Fork of the Trinity River and 78 million gallons per day of moderately saline water from the Red River, conveyed via the Elm Fork. Red River water started flowing in August 1953, with a salt content varying from 1,500 to 3,000 parts per million. The Red River supply proved insufficient to meet demand as the drought progressed. Despite a wet year in 1955, by July 1956 Dallas reservoirs stood at 18 percent of capacity, or less than half the volume in storage the previous year. In July 1956 the City of Dallas reached an agreement with the Sabine River Authority for an additional 160 million gallons per day of supply from the Iron Bridge Dam and continued looking for other sources of water supply (Hatfield, 1964).

Table 2-4. Municipalities rationing water in 1953. From Lowry, 1959.

Alamo	Cross Plains	Lake Worth	Quanah
Alamo Heights	Decatur	Laredo	Raymondville
Anson	Donna	Lipan	Rio Grande City
Amarillo	Dublin	Llano	Rio Hondo
Aspermont	Edcouch	Los Freznos	Roma
Benjamin	Edinburg	Matador	San Antonio
Blanco	Electra	Mathis	San Benito
Bowie	Elsa	McAllen	San Juan
Brady	Gonzales	Megargel	Slaton
Breckenridge	Gordon	Menard	Snyder
Bridgeport	Granbury	Mercedes	Spofford
Brownsville	Graham	Mission	Stephenville
Burkburnett	Harlingen	New Castle	Sweetwater
Byers	Harrold	Nocona	Throckmorton
Bynum	Holliday	Olney	Thorndale
Childress	Houston	Petrolia	Weatherford
Clyde	Iowa Park	Phillipe	Weslaco
Corpus Christi	Jacksboro	Port Isabel	Whichita Falls
Copperas Cove	Karnes City	Post	Zapata
Crane			

Note: Some rationing above due to inadequate distribution facilities in areas with rapidly expanding populations and water requirements rather than deficient supplies.

The salinity of Dallas city water increased from 40 parts per million to 850 parts per million as the city utilized water from the Red River to supplement supplies from Lake Dallas on an ‘emergency’ basis. The cost of adequately treating or softening the Red River water was deemed prohibitive, resulting in more diffuse costs to residents in terms of scale deposits in piping and damage to clothes and appliances (Hatfield, 1964).

Changes in quality of the water supply greatly increased the cost of water to consumers. Where residents were forced to rely on bottled water, Hatfield notes, “Good drinking water was now worth more than crude oil; water at 40 cents per gallon was 600 percent more valuable than oil.” The City of Kaufman passed water rates of up to $1,000 per 50,000 gallons, and the town of Hamlin provided water by railroad tank car for 60 cents per 100 gallons. The City of De Soto, south of Dallas, installed coin operated water meters at rates of 10 cents per hundred gallons.

In the 1950s, effective demand management programs were not well known. Increased drought resulted in increased water consumption, rather than conservation. Dallas water consumption rose from 85 million gallons per day in July 1953 to 135 million gallons per day in July 1954. When daily use hit 160 million gallons per day on July 24, 1954, or nearly 300 gallons per day per capita, the city enacted an alternate day sprinkling ordinance with $200 penalties with little effect. Hatfield (1964) reports that "Limited water restrictions not enforced by law enforcement or the courts had the psychological effect of causing people to use more water than usual." Hatfield notes observations by Harold Harles, San Antonio City Water Works Production Manager, saying, "many residents began watering their lawns at one minute past midnight on their designated day and continued straight through the 24-hour day until the following midnight," in response to alternate day watering ordinances. When the ordinance was repealed on June 3, 1954, the city saw an immediate decline in water consumption.

Lack of clear messaging and political transparency also exacerbated the drought impact. Local officials struggled to balance the demands of drought response and urban growth. Without adequate plans in place prior to the drought, many water supply and demand management efforts were too little, too late. Hatfield (1964) reports that Charles K. Foster, a member of the Dallas County Health Board during the drought, "believes the truth of the Dallas water crisis of the 1950s will never be known as closed sessions of the City Council and clever manipulation of the data leaves largely obscured much of the direct evidence that might induce industries to place their investments elsewhere." Colonel Herbert D. Vogel of U.S. Army Corps of Engineers gave an address in August 1953, stating "Dallas has no water problem" just after the emergency Red River supplies began flowing (Hatfield, 1964).

2.2.3 Impacts on electric power and industrial facilities

Electric power production is affected by drought both through reduced flow at hydropower facilities and reduced cooling capacity at steam-electric generating stations. Lowry (1959) cited figures showing the hydro-power production at the Possum Kingdom Dam was nearly 40 percent below design capacity during the 1950s drought, with a minimum of 24 percent capacity in 1952. Hydroelectric power production at Lower Colorado River Authority (LCRA) Buchanan, Inks, Mansfield, and Tom Miller dams averaged less than 54 percent of pre-drought totals between 1950 and 1956. The 1950s drought did not constrain development of steam-electric power. Lowry (1959) stated, "…the effect of this on the economy of the State was not large because steam-electric generating facilities were available to handle the increased load requirements." Overall, steam-electric generation rose from 17,087 million kilowatt-hours in 1950 to 41,788 million kilowatt-hours in 1956 (Hatfield, 1964), overwhelming any deficits in hydropower production.

Determining state-wide industrial impacts is beyond the scope of this report. There are few reports of drought impact on industrial production and reported costs to one business may show up as added revenue to another. Lowry (1959) reported that "…industries which had sufficient reservoir storage were not too seriously affected economically by the recent drought…. Plants dependent upon the natural flow of this stream continued their operations in spite of this loss of spring flow and the absence of flood runoff. However, emergency measures such as the construction of recirculating water systems were required to keep the plants in operation." In other instances, alternate sources were made available to meet industrial demands. The U.S. Army Corps of Engineers made emergency releases of water from Belton Reservoir in December 1956 to provide water for the Dow Chemical Company. The Alcoa plant in Rockdale, which was constructed in 1952 without planning for its water needs, was saved when the Missouri Pacific Railroad granted its entire water supply to the city of Rockdale, since it no longer needed water rights initially secured to supply its steam engines (Hatfield, 1964). Small businesses may have been more seriously affected by the drought. Hatfield (1964) cites news reports on the difficulties facing ice plants, bottlers, laundries, and nursery and garden supply businesses due to the poor quality of Dallas city water during the drought. Other businesses got a surprise boost from the drought; Hatfield reports that "November of 1956 became the biggest month in history for Dallas automobile radiator repairmen, as brackish water broke down cooling systems."

2.2.4 Hydrological impacts

As the 1950s drought progressed, hydrological systems were affected as well as agricultural production. Data on streamflow and reservoir storage are discussed in this section.

2.2.4.1 Streamflow

Discharge in unregulated streams in Texas dropped to new record lows during the drought. The minimum discharge of Rio Grande near Del Rio was 519 cubic feet per second in 1953, by far the lowest flow on record at that time. Further downstream, at Laredo, the river went completely dry for the first time in June 1953 (Nace and Pluhowski, 1965). A year later, Hurricane Alice dropped up to 34 inches of rain across the watersheds of the Pecos and Devils rivers and in northern Mexico (Von Zuben, Hayes, and Anderson, 1957). The resulting runoff produced an 86-foot wall of water on the Pecos River (Del Rio Chamber of Commerce, 2017) and record floods on the lower Rio Grande, but the area of the heavy downpours was so localized that it did little to alleviate the statewide drought.

U.S. Geological Survey streamflow records indicate that streamflow remained deficient in most areas of the state for the entire period of the drought, although some gaging stations had short periods of average to greater than average flow between longer periods of deficient flow (Paulson, Chase, Roberts, and Moody, 1991). Nace and Pluhowski (1959) found that the accumulated runoff deficiency for water years 1952 through 1956 exceeded 300 percent of the median annual runoff volume across a broad area of central Texas and exceeded 200 percent of the median in all areas except extreme east and far west Texas (Figure 2-14).

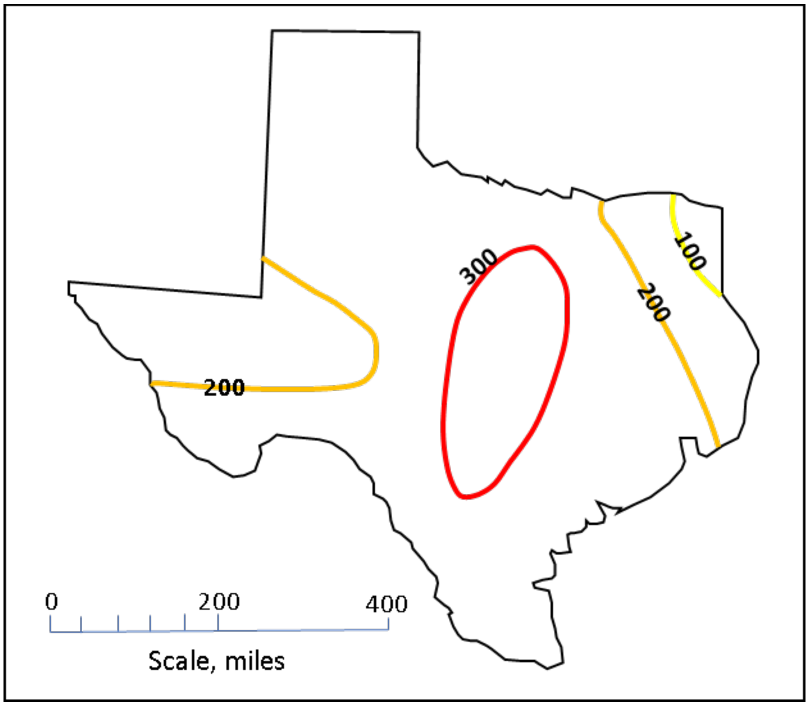


Figure 2-14. **Accumulated runoff deficiency for water years 1952 to 1956, in percent departure from the median. Adapted from Nace and Pluhowski, 1959.**

The authors used daily data from the 21 of 29 streamflow index sites that have records back to at least 1950 to track the streamflow deficit over time (TWDB, 2018a). The daily streamflow deficit is calculated as the difference between the 365-day moving average of the sum of the 21 daily streamflow values and the period of record (1945 to 2017) average of the daily sum, which equals 4,653 cubic feet per second (Figure 2-15). The deficit period for the 1950s drought began on February 6, 1951 and ended on May 29, 1957. The most extreme streamflow deficit occurred on March 10, 1957, when total streamflow was less than 20 percent of the long-term average. The cumulative streamflow deficit for the 21 sites over the duration of the drought totaled over 9.6 million acre-feet. U.S. Geological Survey runoff data for the entire state put the streamflow deficit for 1951 through 1956 at over 119 million acre-feet. Streamflow in 1956, the worst year, ran more than 29 million acre-feet below normal (U.S. Geological Survey, 2017).

2.2.4.2 Reservoir storage

Lowry (1959) reported a reduction in storage of nearly 2.5 million acre-feet during the 1950 to 1956 drought for nine reservoirs for which records are available, as detailed in Table 2-5.

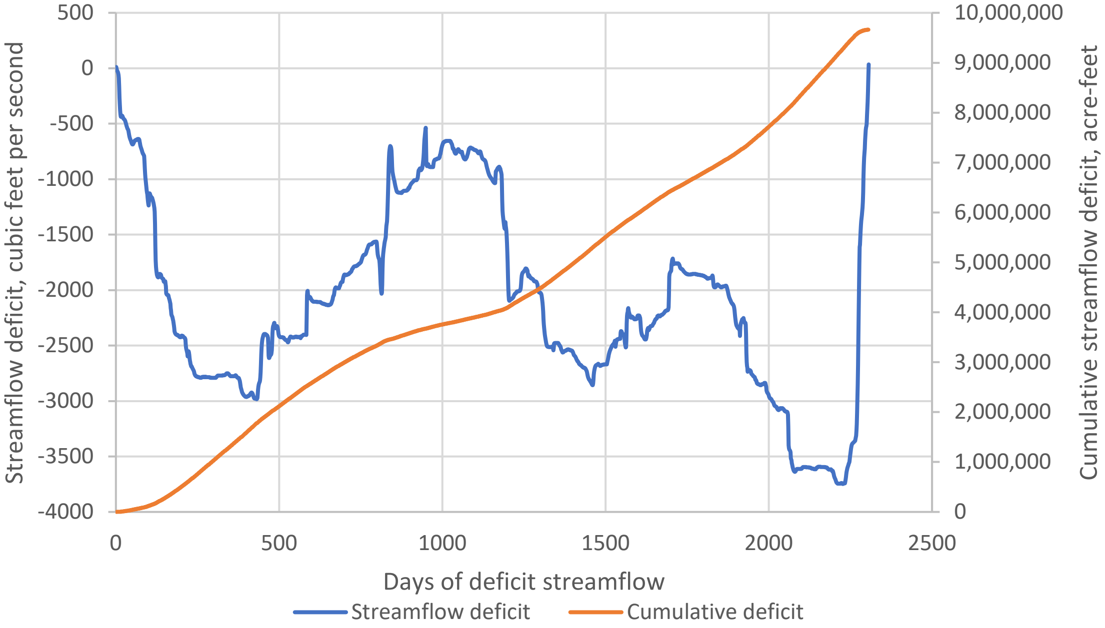


Figure 2-15. **Data from 21 of the 29 streamflow index sites in Texas with records dating to 1950 were used to evaluate streamflow deficits during the drought. The streamflow deficit is calculated as the difference between the 365-day moving average of the sum of the daily values and the period of record average of the daily sum. The deficit period for the 1950s drought began on February 6, 1951 and ended on May 29, 1957. Data from TWDB, 2018a.**

Table 2-5. Reductions in storage from 1950 to 1956 at selected Texas reservoirs. From Lowry, 1959.

Drought	Reservoir	Max. Storage Preceding*	Drought Month	Min. Storage Preceding*	Drought Month	Difference in Storage*
1950-1956	Bridgeport	317.7	Jul. 1950	7.5	Sep. 1956	-310.2
	Eagle Mountain	220.6	Jul. 1950	65.1	Sep. 1956	-155.5
	Lake Dallas	211.6	Aug. 1950	21.5	Sep. 1956	-190.1
	Medina	48.2	Jun. 1949	2.2	Dec. 1954	-46.0
	Possum Kingdom	698.2	Jul. 1950	275.1	Apr. 1953	-423.1
	Buchanan	998.9	Apr. 1949	409.4	Feb. 1952	-589.5
	Lake Travis	966.0	Jun. 1949	337.0	Jun. 1952	-629.0
	Brownwood	133.8	Jun. 1951	90.5	Feb. 1953	-43.3
	Red Bluff	115.0	Feb. 1950	14.4	Sep. 1952	-100.6
						**In thousand acre-feet.*

Statewide reservoir storage data (TWDB, 2017d) indicate a decline in storage, as a percent of conservation capacity, from over 80 percent in June 1949 to a low of 29.1 percent in September 1952. Rainfall and runoff in late 1952 and 1953 increased reservoir storage even as new reservoir construction boosted the overall conservation capacity from 3.8 million acre-feet in 1950 to 7.9 million acre-feet by the beginning of 1955 (Figure 2-16).

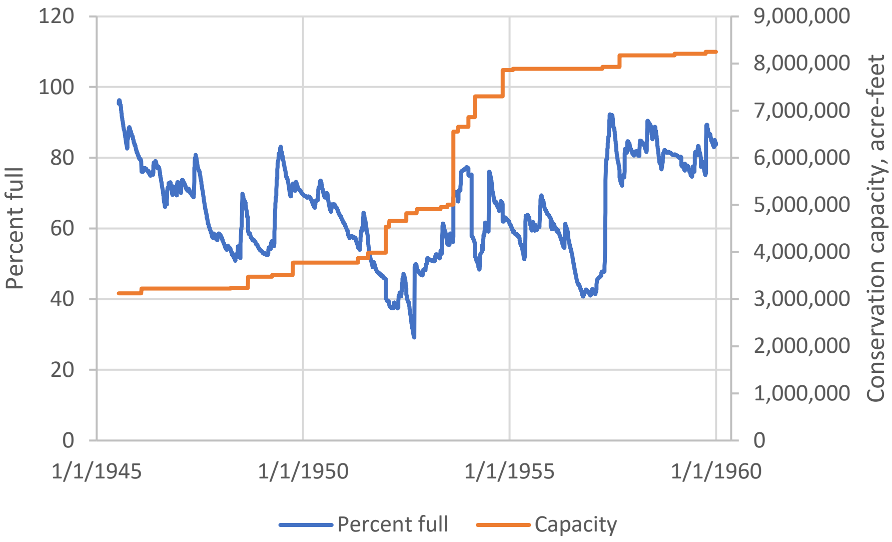


Figure 2-16. **Statewide reservoir storage and total conservation capacity, 1945 to 1960. Storage reached a low of 29.1 percent capacity on September 10, 1952. Almost 4.5 million acre-feet of new reservoir capacity was brought on line during the 1950s. Data from TWDB, 2017d.**

Nace and Pluhowski (1965) observed generally declining water levels during drought, because of both reduced recharge and increased pumping. Therefore, the amount of groundwater depletion caused directly by drought is difficult to determine. Irrigation in many areas of Texas increased sharply beginning around 1940 with the advent of improved pumping technology. For example, in the High Plains region, 300,000 acres were irrigated in 1940 and 2,900,000 acres in 1953. Drought further increased the demand for irrigation water, and the result was increased pumping and a general lowering of water levels throughout the High Plains. Municipal use of groundwater also increased in many parts of the state, as cities drilled new wells, deepened old wells, and increased pumping rates to meet demand. Statewide, groundwater usage for irrigation increased from 3.08 million acre-feet in 1950 to 10.4 million acre-feet in 1956 (TWDB, 2017a). A total of 48 million acre-feet of groundwater was used for irrigation between 1950 and 1957, most of which was withdrawn from the Ogallala Aquifer and resulted in a net loss of storage. Surface water use for irrigation continued to rise during the early years of the drought, as reservoirs were drawn down, before dropping sharply from the 1954 high of 6.75 million acre-feet to a low of 2.8 million acre-feet in 1957 (Figure 2-17).

While groundwater provided irrigators in the High Plains ample supplies during the drought, water shortages limited irrigation use in some other regions dependent on surface water. Lowry (1959) reported water shortages in the Lower Rio Grande Valley increased from 30 days in 1947 to 109 days in 1948, 122 days in 1950, 193 days in 1951, 365 days in 1952, and 140 days in 1953. The El Paso County Unit of the Rio Grande Project experienced deficient water supplies from 1951 through 1956. During these years, the allotment of water per acre was as little as 0.13 acre-feet per acre, less than five percent of the regular 3.0 acre-feet per acre allotment. The most severe shortages occurred in the Red Bluff Water Power Control District near Pecos where a 100 percent shortage occurred in 1953 (Lowry, 1959). In contrast, the Possum Kingdom reservoir continued releases for downstream agriculture and the Lower Colorado River Authority maintained releases from Lakes Buchanan and Travis for downstream rice farmers.

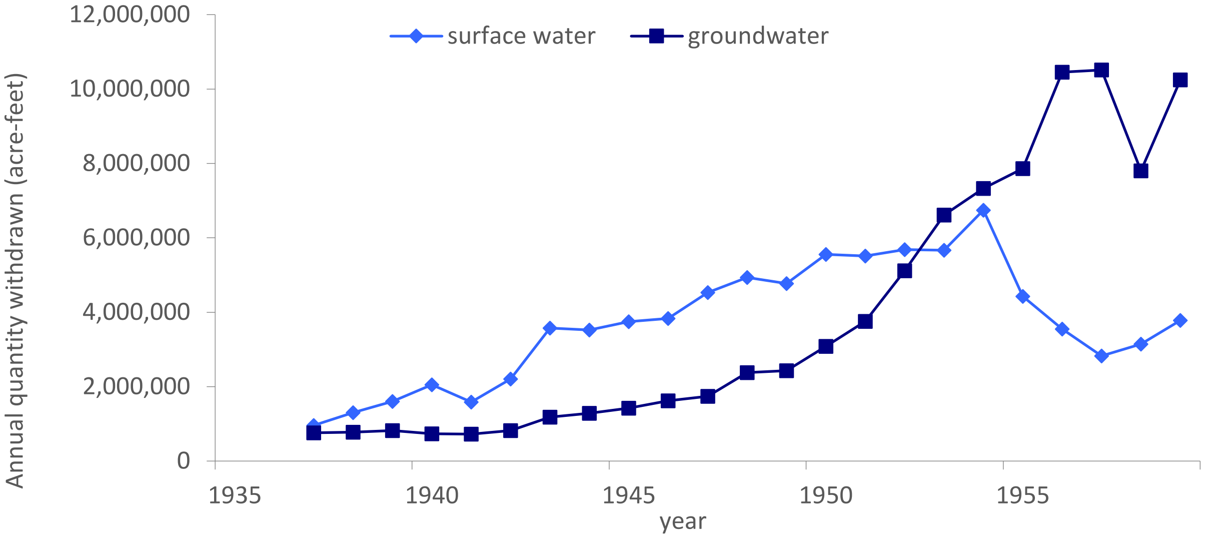


Figure 2-17. **Surface water and groundwater use for irrigation, 1937 to 1959. Data from TWDB, 2017a.**

2.2.5 Environmental impacts

Lowry (1959) and Young (1956) noted that deterioration of forage and vegetative cover during the drought resulted in less available food and fewer sheltered areas for wildlife as well as domestic livestock, particularly in heavily foraged areas. These conditions resulted in smaller game populations, poorer hunting prospects, and increased vulnerability to erosion.

Drought in west Texas can bring dust storms and soil loss. Data on wind damage are somewhat contradictory, making it difficult to understand direct impacts. Soil conservation methods practiced during the 1950s drought largely prevented the return of dust storms of the same magnitude as those experienced during the 1930s Dust Bowl (Texas State Library and Archives Commission, 2017). Nace and Pluhowski (1965) produced a map of the areas affected by wind erosion, (Figure 2-18) indicating that during the 1950s drought dust storms were largely confined to the High Plains, while dusting associated with the 1930s drought affected almost two-thirds of the state. Their report cites figures for crop acreage damaged by wind erosion in Texas between 1955 and 1958, including 1.9 million acres in 1954-55, 2.7 million acres in 1955-56, 1.8 million acres in 1956-57, and 397,000 acres in 1957-58. Muehlbeier (1958) estimated 10 million to 15 million acres across the Great Plains were damaged by wind each year from 1954 through 1956, with one million to five million acres of crops destroyed, commenting that “Although the dust storms were more awesome in the 1930s than in the 1950s, the acreage damaged was about equal in the two periods.” Local witnesses of the 1950s dust storms recall them being “as bad as or even worse than those of the Dust Bowl years” (Burnett, 2012).

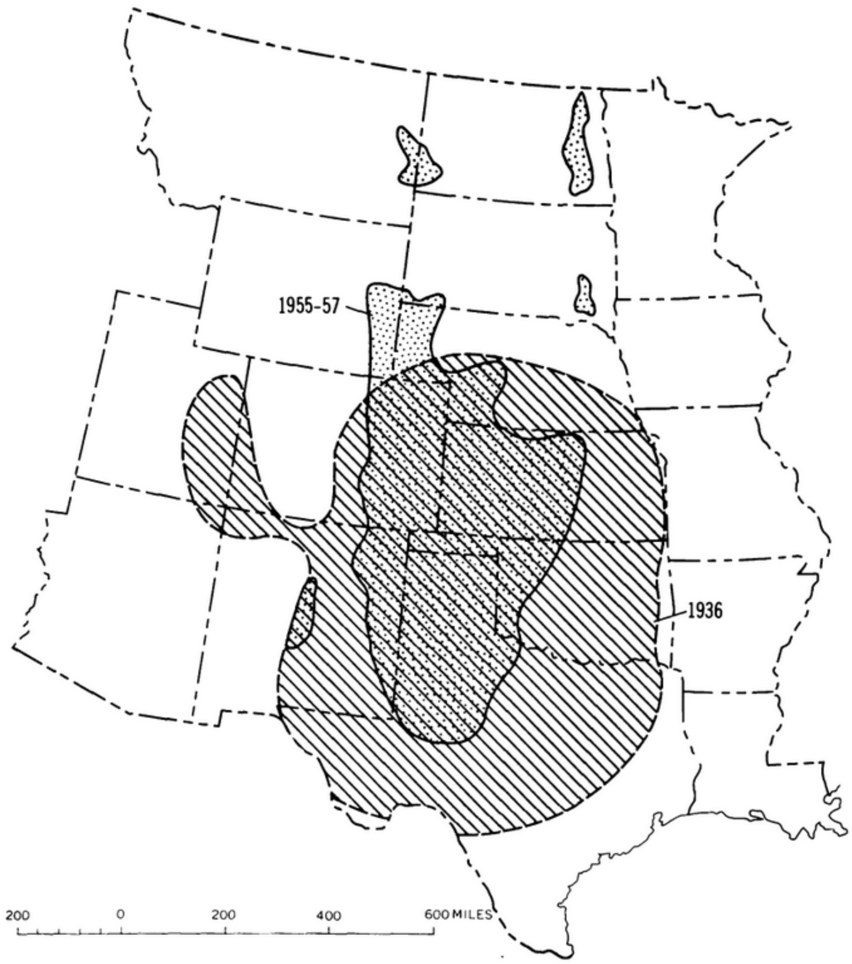


Figure 2-18. Areas of major soil damage due to wind erosion in 1936 and 1955-57 droughts. From Nace and Puhlowski, 1965.

2.2.6 Impacts on state water planning and management

Reservoir construction boomed in the wake of the 1950s drought (Figure 2-19). The Water Planning Act of 1957 enacted the first statewide plan for developing, conserving, and using Texas water. The legislation created the Texas Water Development Board to forecast water supply needs and administer a $200-million water development fund for constructing new reservoirs in Texas. The law authorized the Texas Board of Water Engineers (now the Texas Water Development Board) to create plans to meet the needs of the forecast. The first plan, delivered in 1961, provided for construction of 45 new major reservoirs (Texas State Library and Archives Commission, 2017).

The severe municipal and agricultural water shortages in the Lower Rio Grande Valley also led to two major lawsuits that resulted in significant changes to Texas water law. Texas courts established a dual system of water rights, which included elements of both the Spanish riparian water law and a prior appropriations system, in 1889. The case *State v. Valmont Plantations* resulted in abandonment of the dual system, resulting in a single state licensing system for surface water rights (Harrington and Lacewell, 2015).

The case of *State v. Hidalgo County Water Control & Improvement District No. 18*, otherwise known as the *Valley Water* case, began during the drought in the 1950s and took more than thirty years to resolve. It involved roughly 3,000 parties and cost an estimated $10 million in court costs and attorney's fees (Jarvis, 2014). The *Valley Water* case resulted in a watermaster system to administer available water in the Lower Rio Grande, including Falcon Reservoir. The court rejected time priorities for water rights on the Lower Rio Grande, observing that the existing appropriative rights were to divert from a free-flowing stream, whereas the Lower Rio Grande had been transformed to a controlled stream by dams built by the federal government.

The *Valley Water* decision also prioritized water for domestic, municipal, and industrial use relative to irrigation rights and created two classes of irrigation rights. Class A rights could be proven through a Spanish-Mexican grant or prior appropriation. Class B rights were given to claimants with a 'history of diversion' from the river. Class A rights receive 1.7 times the allocation for Class B rights during times of shortage (Jarvis, 2014).

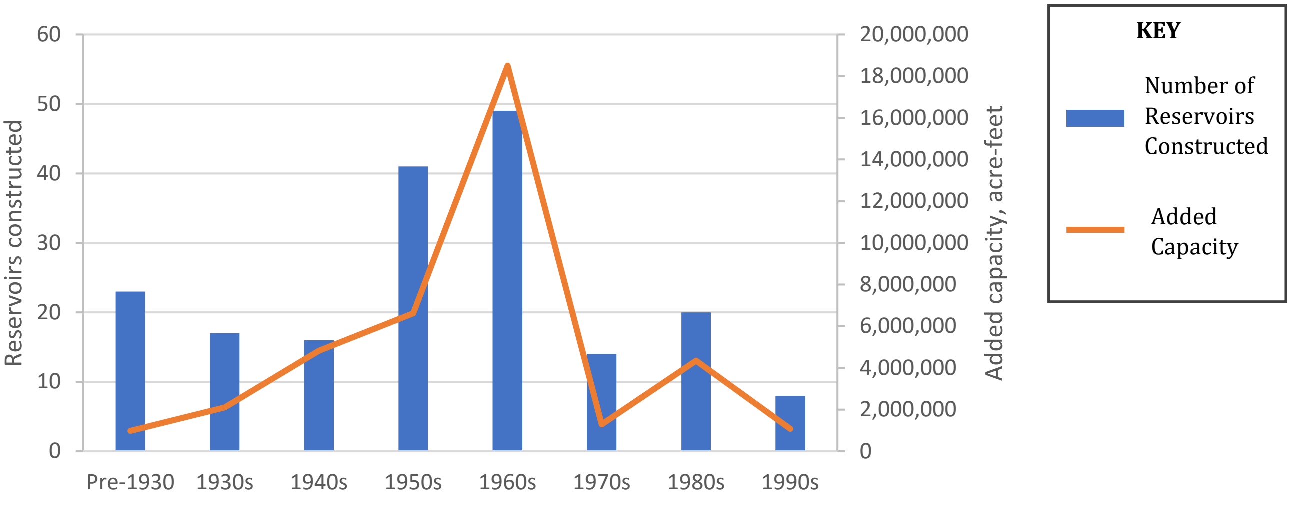


Figure 2-19. Reservoir construction and added storage capacity, by decade, showing the boom in reservoir construction in the 1950s and 1960s. Source: Texas Almanac, 2017.

3.0 2010 - 2015 Drought

Across much of Texas, 2010 started out as a wet year, before turning abruptly drier in the late fall as a La Niña weather pattern developed. The dry conditions continued into the spring, and the drought intensified quickly with rainfall far below the normal level. Both temperature and evapotranspiration were far above normal through the summer of 2011. In large areas of the state, the grass never greened up in the spring and pastures remained dead and brown. Governor Rick Perry issued an emergency disaster proclamation on July 5, 2011, covering 188 counties in Texas, and renewed the proclamation on January 25, 2013. Grass and fine fuel left over from 2010 growth dried out and fueled widespread wildfires during 2011. Since 2000, the longest duration of drought in Texas lasted 271 weeks, beginning on May 4, 2010 and ending on July 7, 2015 (US Drought Monitor 2020). For purposes of this report, the authors consider the 2011 drought to have lasted from May 2010 to July 2015.

At the peak of the drought, in October 2011, 88 percent of the state was classified as in extreme drought by the Texas Drought Monitor. Near-normal rainfall in late 2011 eased drought conditions, but soil moisture and streamflow deficits persisted across much of the state until flooding rains in May 2015.

In the half century between the 1950s drought and the 2010-2015 drought, the economy and demographics of Texas have changed enormously, altering both the impact of the drought and the drought response. The population of Texas stood at 7.7million in 1950; in 2010 it was 25.1million (U.S. Census Bureau, 2012). The per capita personal income, in 2014 dollars, grew from $1,392 in 1950 to $46,310 in 2014 (Federal Reserve Bank of St. Louis, 2017).

3.1 Meteorological record

John Nielsen-Gammon, the Texas State Climatologist, describes the evolution of the drought in detail in his report *The 2011 Texas Drought* (Nielsen-Gammon, 2012). Nielsen-Gammon notes, "While Texas was already in serious drought at the end of February 2011, the upcoming months were disastrous for farmers and ranchers. If ample rain had begun in March, the most serious drought impacts might have been limited to the winter wheat crop and excess winter-feeding costs for ranchers. Instead, the opposite happened. March 2011 was the driest March on record for the state of Texas as a whole."

The 1-month and 12-month standardized precipitation indices for Texas (Figure 3-1) show the rapid onset of drought in early 2011, following wet conditions in the fall of 2010. Near-normal rainfall over much of the state in late 2011 briefly brought the 12-month SPI above zero in November 2012, but lower-intensity drought returned and persisted until March 2015, as measured by the SPI-12.

Other drought indices show a continuous progression of drought from late 2010 until late 2014 or early 2015. The PDSI (Figure 3-2) shows 51 consecutive months of drought, starting in August 2010 and ending in November 2014. The Texas Drought Monitor (Figure 3-3) shows small areas of drought developing through the summer of 2011, with drought intensifying and spreading rapidly in October 2011 and persisting through May 2015, for a total duration of 55 months. U.S. Drought Monitor data shows the geographic distribution of drought in the U.S. between January 2011 and

July 2014 (Figure 3-4), highlighting the rapid onset in 2011, centered in Texas, and the spread to the Midwest and West in following years.

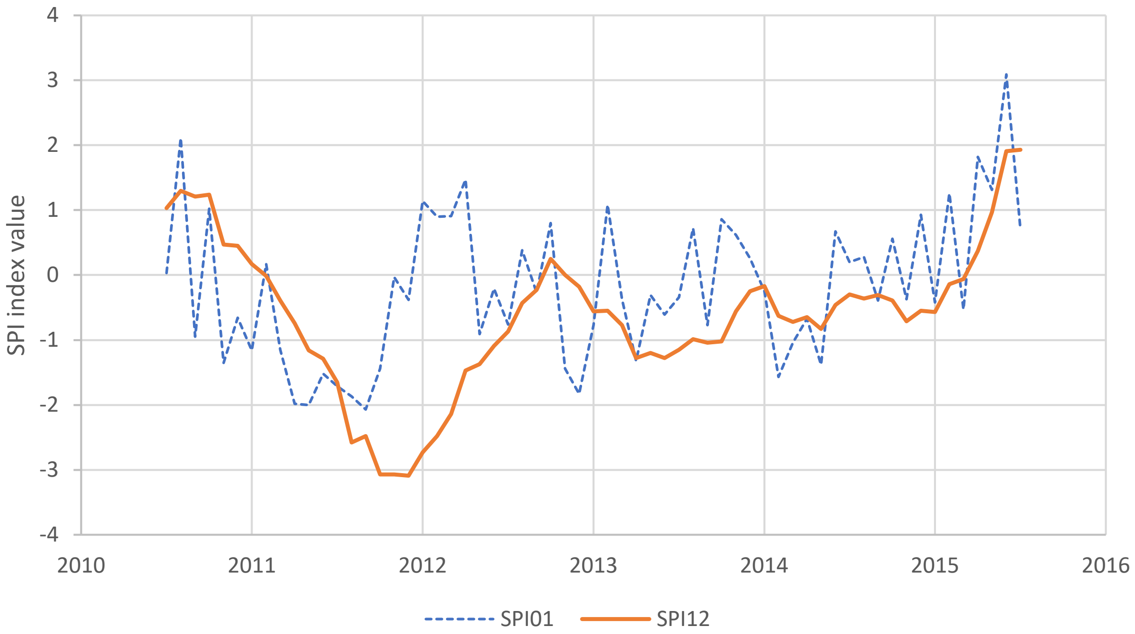


Figure 3-1. **Statewide 1-month and 12-month Standardized Precipitation Index, June 2010 to June 2015. Data from National Centers for Environmental Information, 2017a.**

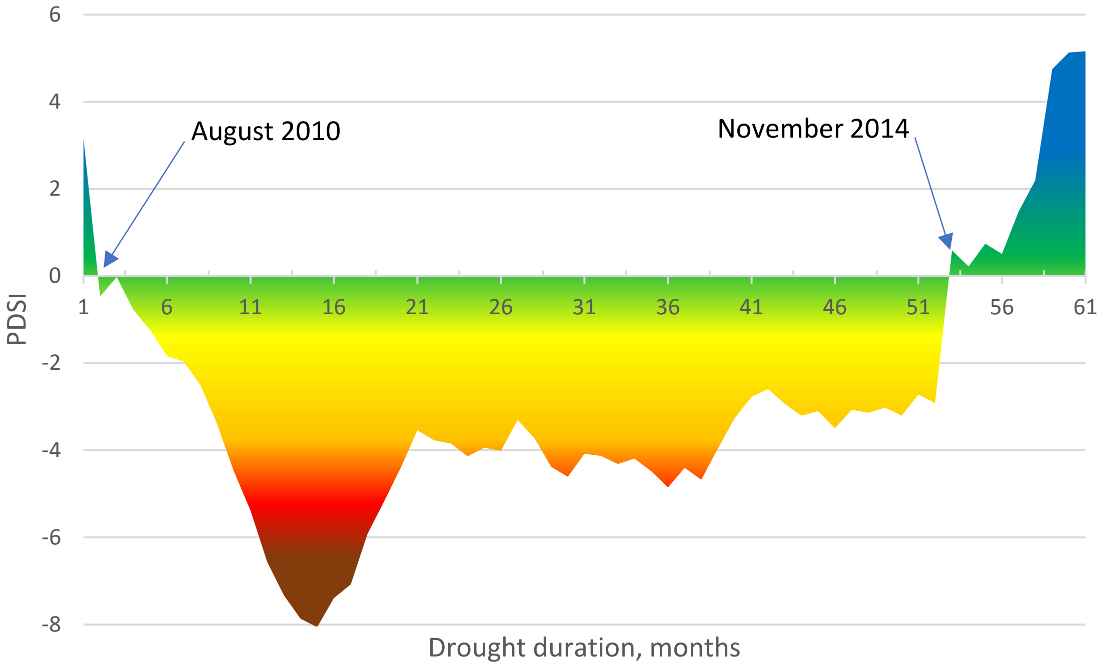


Figure 3-2. **Statewide Palmer Drought Severity Index, July 2010 to July 2015. Data from National Centers for Environmental Information, 2017a.**

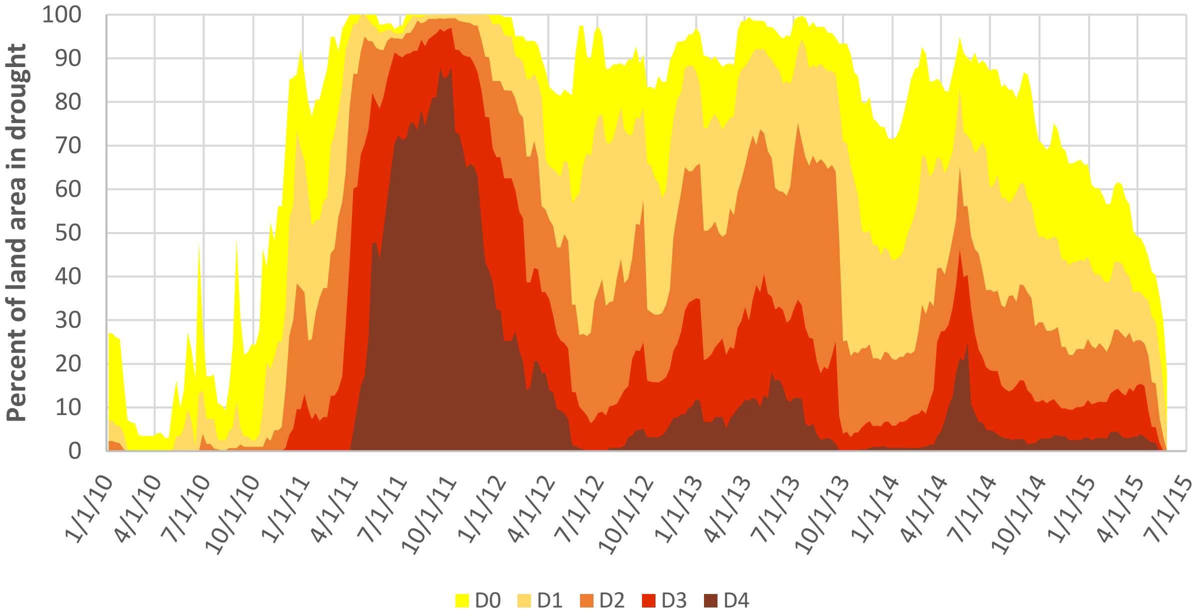


Figure 3-3. **Weekly Drought Monitor for Texas, 2010 to 2015. Data from National Drought Monitor, 2017.**

3.2 Drought impact and drought response

The extreme drought conditions in 2011 cost Texas agriculture nearly $17 billion. Three additional years of more moderate drought added at least another $3 billion in costs. Municipal water supply systems around the state were stretched to the limit, and many were forced to implement drought contingency plans and secure new water sources as reservoirs dried up and groundwater levels dropped below pump inlets. At least one industrial plant on the Brazos river was forced to make a seniority call to restrict junior water rights to maintain operations. Wide-spread impacts on electrical power production facilities were avoided, but the power sector did not entirely escape the effects of the drought: arcing from powerlines was responsible for igniting some of the wildfires that were the signature environmental impact of the 2010-2015 drought.

State policy responses to the 2010-2015 drought included additions of a chapter on drought and drought response to the State Water Plan. During the drought, in 2013, voters approved Proposition 6, a constitutional amendment that used $2 billion from the State's 'rainy day fund' to create the State Water Implementation Fund for Texas (SWIFT) and the State Water Implementation Revenue Fund for Texas (SWIRFT) programs. Under TWDB management, these funds were intended to leverage up to $50 billion in water projects identified in the state water plan. The SWIFT program helps communities develop cost-effective water supplies by providing low-interest loans, extended repayment terms, deferral of loan repayments, and incremental repurchase terms. Through Fiscal Year 2020, SWIFT has committed over $8.87billion for projects across Texas (TWDB, 2020).

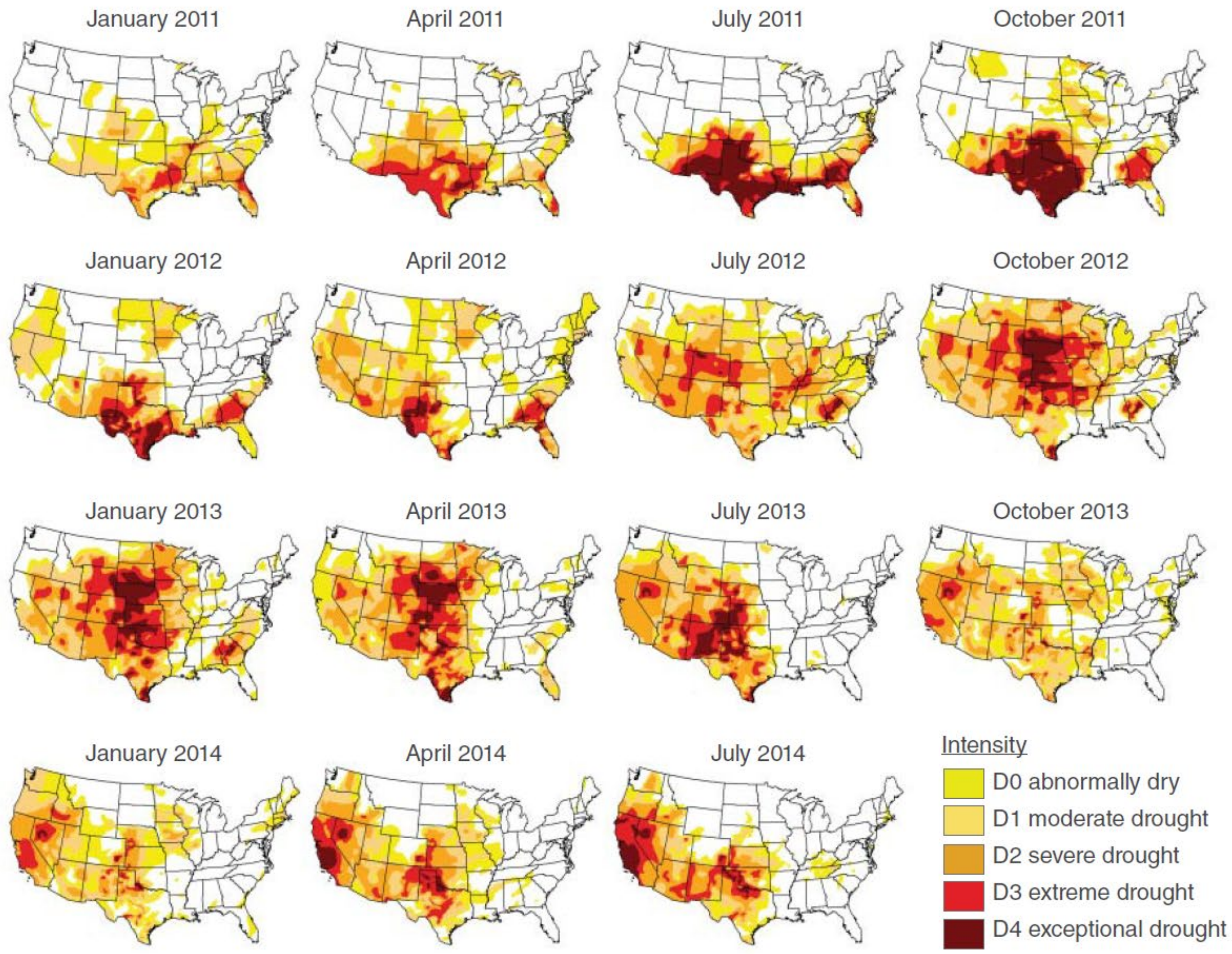


Figure 3-4. U.S. Drought Monitor maps, January 2011 to July 2014. From Svoboda, 2017.

3.2.1 Agricultural impacts

Direct agricultural impacts of the drought in 2011 are estimated at over $7.6 billion. The total direct, indirect, and induced economic effects for that year are estimated to have cost the Texas economy nearly $17 billion. Agricultural data for 2012 through 2014 reviewed for this report suggest that there were at least another $6.5 billion in direct drought-related losses through 2014. The methods used to arrive at these estimates are discussed in detail below.

Only 57 percent of planted crop acreage in Texas was harvested in 2011—meaning 43 percent of acreage was abandoned due to crop failure. The 2011 abandonment rates were 28 percent for corn, 45 percent for soybeans, and 59 percent for cotton, resulting in crop production decreases of 55 percent, 69 percent, and 55 percent, respectively (Kerr, 2012). Anderson, Welch, and Robinson (2012) evaluated the economic impacts of these crop losses. Losses from the 7.1 million acres planted in cotton, valued at the USDA's projected price of 91 cents per pound, added up to $2.2 billion. The authors note that the 10-year average total value of cotton lint and cottonseed production in Texas is $1.8 billion; Texas cotton growers lost more market income in 2011 than they would normally make for an entire cotton crop (Figure 3-5). The Comptroller's Office estimated agricultural losses from the 2011 drought totaling $314 million in wheat, $736 million in corn, $385 million in sorghum, $750 million in hay, $3.23 billion in livestock, and $824 million direct losses in commercial timber, leading to a $7.6 billion economic impact to agricultural production in Texas (Combs, 2014).

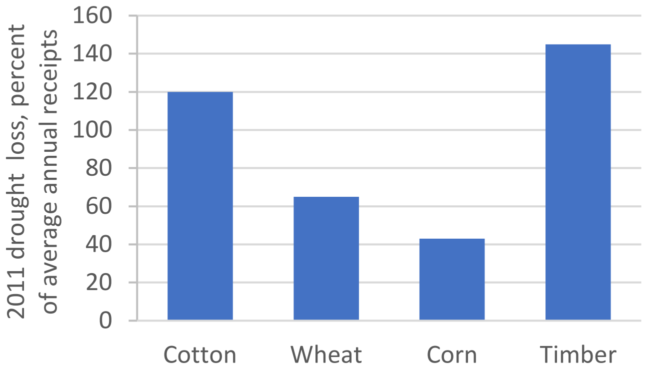


Figure 3-5. **2011 Drought loss as a percent of average annual cash receipts from 2005 to 2009. Adapted from Anderson, Welch and Robinson, 2012.**

Guerrero (2012) estimated the total impact of the $7.62 billion agricultural production loss in 2011 to represent an estimated $12.5 billion loss to the overall Texas economy. Ziolkowska (2016) used economic models to evaluate the impacts of drought losses through direct effects on livestock, cotton, sorghum, wheat, corn, hay, and timber production, indirect effects on other related sectors providing materials and production factors for the agricultural sector, and induced effects on household incomes due to losses in the agricultural sector. Ziolkowska modeled production flows between different sectors of the Texas economy, generating four measures of economic activity: industry output, value added, labor income, and employment, reflecting changes as a result of the 2011 drought. Ziolkowska's results indicate an overall loss of more than 166,000 Texas jobs, $3 billion in labor income, and $6.7 billion in value added, totaling nearly $17 billion in lost output for the state (Table 3-1). These impacts on the Texas economy are only for the first, and most severe, year of the drought and represent static market conditions relative to base conditions in 2010. Other models that account for market dynamics are needed to account for spillover effects on prices and consumption, especially for multi-year drought events.

Table 3-1. **Modeled economic effects of the 2011 drought on the Texas economy. Adapted from Ziolkowska, 2016.**

Impact type	Employment (number of jobs)	Labor income (billion$)	Value added (billion $)	Output (billion $)
Direct effect	106,437	$0.6	$2	$8.2
Indirect effect	42,305	$1.5	$3.2	$6.3
Induced effect	18,152	$0.7	$1.4	$2.3
Total effect	**166,895**	**$3**	**$6.7**	**$16.9**

Agricultural losses for subsequent years of the drought have not previously been compiled in published sources. A review of the USDA annual agricultural statistics indicates that substantial losses continued in 2012, 2013, and 2014. Preliminary figures on agricultural production for the remainder of the drought total as much as $6.5 billion, including $850 million losses in cattle, $3.1 billion losses in cotton, $1.1 billion losses in wheat, $725 million losses in corn, and $734 million losses in sorghum. Econometric modeling of the effects of lost agricultural production on the broader Texas economy is beyond the scope of this report, but it is plausible that there were relatively large indirect and induced effects of the drought in 2012, 2013, and 2014 as continued weakness in the agricultural economy forced related industries to make economic adjustments.

Drought losses to Texas farmers and ranchers from the 2010-2015 drought were substantially buffered by federal insurance payments, providing a sharp contrast to the meager federal response during the 1950s drought. Widespread participation in federal commodity insurance programs helped maintain farm incomes during the 2010-2015 drought (Figure 3-6). Federal commodity insurance payments from 2011 through 2014 totaled $6.44 billion (USDA Economic Research Service, 2017). Federal payments in 2011 totaled over $2.37 billion, or more than 45 percent of the total value of crop production for that year. Texas producers received over 25 percent of total national payments by the federal commodity insurance programs in 2011.

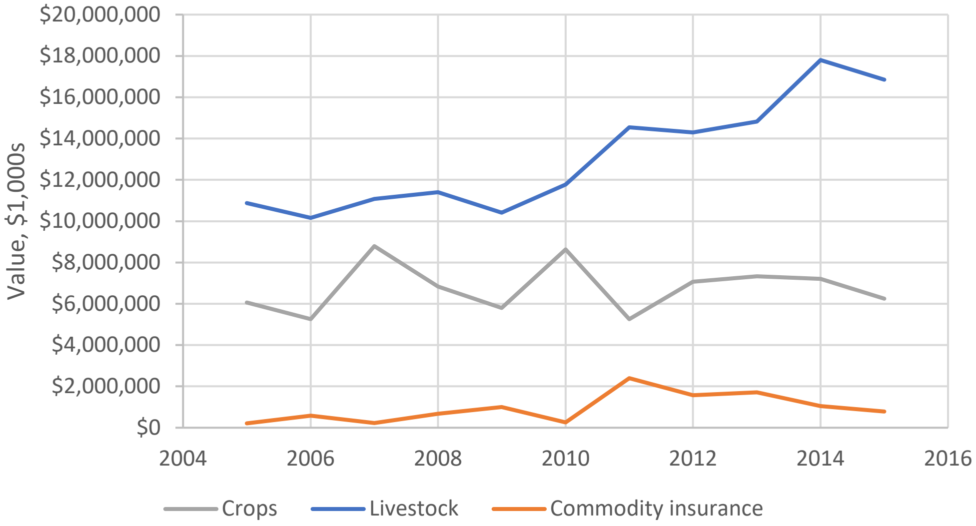


Figure 3-6. **Value of crop production, livestock production, and commodity insurance payments in Texas, 2005 to 2015. Data from USDA Economic Research Service, 2017.**

3.2.1.1 Livestock

The Texas population of cattle and calves declined from 13.3 million in 2011 to 11.9 million in 2012 and continued to drop slowly through the remainder of the drought, reaching a low of 11.1 million in 2014 as ranchers thinned their herds because of poor feed conditions or moved cattle to other states (Figure 3-7). The total value of the 800,000 head of cattle lost between 2011 and 2014 is over $850 million at the average 2012-2014 price of $1,067 per head. Rangeland was also seriously affected by the drought. The Texas Water Resources Institute quoted Dr. Ron Sosebee, professor emeritus with Texas Tech University's Department of Natural Resources Management and a 40-year expert on the effects of Texas' droughts, saying "The pastures and the rangeland look, I want to say like the dead of winter, but it really looks worse than that. Auction barns in Abilene, Coleman and that central part of West Texas have been running 48 hours straight selling cattle—people are bringing them in to just get rid of them" (Texas Water Resources Institute, 2011).

Paradoxically, USDA statistics show that the minimum total value of the Texas cattle herd was $10.1 billion in 2010, when the price per head bottomed out at $760. As drought conditions reduced supplies and the market tightened, the price per head rose to $1,010 in 2012 and $1,530 in 2015. These price fluctuations stabilized the total value of the herd at about $12 billion between 2011 and 2014. The total value of Texas cattle jumped to almost $18 billion in 2015 as the herd size started to rebound and prices per head remained strong.

Reduced herd sizes and sharply increased feed costs created real hardship for Texas ranching and associated industries, despite any paper increase in herd value. With little grass in the pastures and feed prices skyrocketing, more than one rancher simply shot and dumped calves that they could no longer afford to raise and were not worth the price of transport (Figure 3-8). Facing a tight cattle supply following two years of drought, the agricultural firm Cargill, one of seven major meatpackers in the Panhandle region, announced on January 17, 2013 that it would close its beef processing facility in Plainview, Texas effective at the close of business, on February 1, 2013, taking with it over 2,000 jobs.

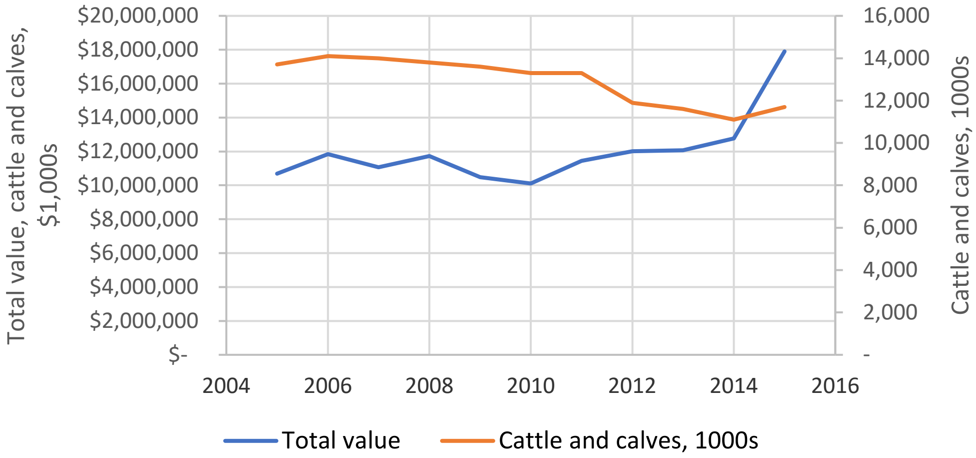


Figure 3-7. **Texas cattle and calf population and total herd value, 2005 to 2015. Data from USDA National Agricultural Statistics Service, 2017b.**

Cargill's news release stated, "…we were compelled to make a decision that would reduce the strain created on our beef business by the reduced cattle supply. The U.S. cattle herd is at its lowest level since 1952. Increased feed costs resulting from the prolonged drought, combined with herd liquidations by cattle ranchers, are severely and adversely contributing to the challenging business conditions we face as an industry" (Cargill, 2013). Texas AgriLife Extension Service economist Steve Amosson found that Cargill represented about 38 percent of all industrial output in Hale County and its pullout was projected to cause more than $1 billion in losses for the region (Oliver, 2013).

Figure 3-8. Cattle killed and dumped by a rancher, Briscoe County, October 2013. Photo by A. Weinberg.

3.2.1.2 Crop production

Following a bumper crop of cotton in 2010 and anticipating continued strong prices driven by international demand, Texas farmers planted over 7.5 million acres of cotton in 2011, more than 2 million acres above the average for 2005 to 2010. As the drought intensified in 2011, cotton production plummeted in 2011, with a 62 percent failure rate and a 55 percent drop in produced value (Figure 3-9).

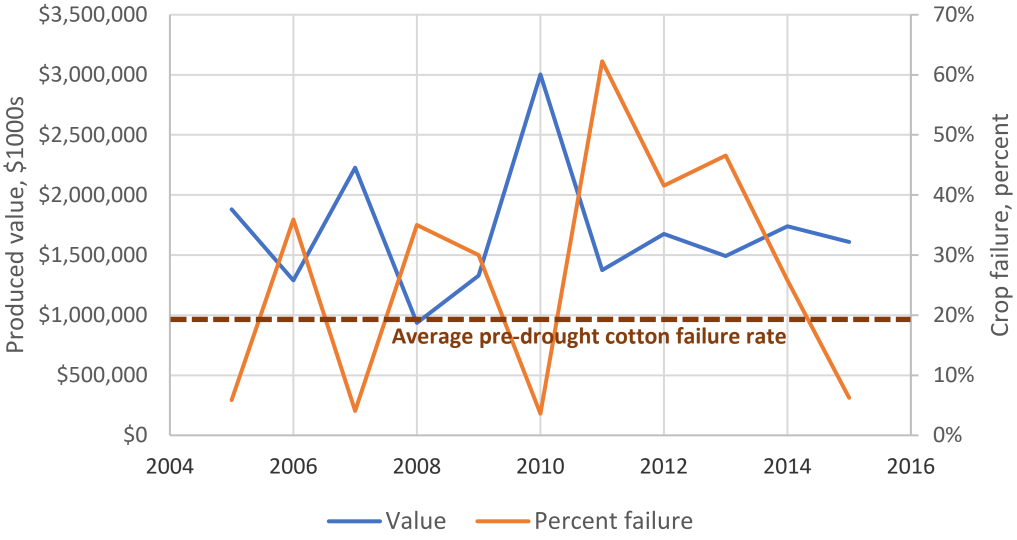


Figure 3-9. Produced value and crop failure rates for upland cotton in Texas, 2005 to 2015. Data from USDA National Agricultural Statistics Service, 2017.

In the face of these crop losses and continuing drought, many farmers, especially dry-land farmers, re-evaluated their planting choices; the acreage planted with cotton in the 2012 through 2015 growing seasons dropped to 5.8 million acres, close to the 2005 through 2010 average of 5.4 million acres, but well below the 2011 total. The failure rate remained elevated in 2012, 2013, and 2014, averaging 44 percent compared to less than 20 percent for 2005 through 2010. If cotton losses are calculated as the product of failed acres, average annual yield, and average annual price, losses for 2012 through 2014 total $3.01 billion dollars. According to this method of accounting, the 2011 cotton loss is $2.3 billion, which matches estimates by Combs (2012). Alternatively, if costs are based on the additional 24 percent loss above average failure rates, the drought impact totals $1.2 billion in lost cotton production value at the average 2012 to 2014 price.

Wheat harvests in Texas are highly variable. Wheat is largely grown as a dryland crop and is therefore more vulnerable to drought. Growers often utilize wheat acreage for cool-season pasture before bringing the grain crop to harvest but may decide to terminate the wheat before harvest depending on weather and market conditions.

Texas wheat harvests were impacted by drought in 2006, 2009, and 2011 through 2014. The 2006 crop outlook was rated 'the worst in history' by the Eagle Land and Livestock Post in Bryan, Texas (2006); a 2006 National Agricultural Statistics Service crop progress report rated only 5 percent of the Texas crop in good condition and none excellent (USDA, 2006). In wet years, an average of 60 percent of the planted acreage is brought to harvest for grain, as opposed to 36 percent in 2011 and an average of 42 percent for 2012, 2013, and 2014 (Figure 3-10). The 18 percent reduction in wheat acreage brought to harvest for 2012 to 2014 resulted in lost production value of over $270 million for that period. If drought costs are calculated for 50 percent of failed wheat acres at average yield and price per year, the 2012 to 2014 total loss amounts to $1.1 billion.

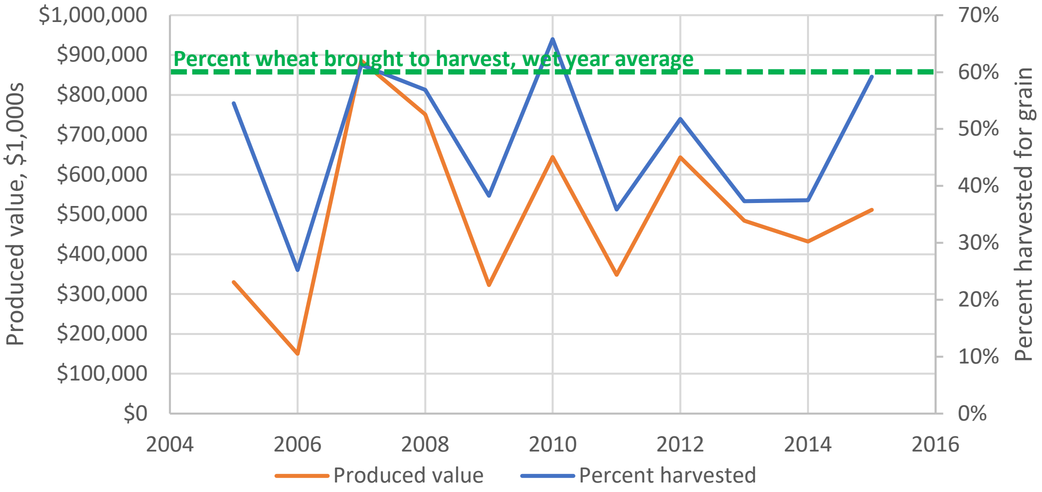


Figure 3-10. **Produced value and crop failure rates for wheat in Texas, 2005 to 2015. Data from USDA National Agricultural Statistics Service, 2017.**

Corn is grown under a mix of dryland and irrigated production systems in Texas. The 2011 crop yielded only 91 bushels per acre, down from 145 bushels per acre in 2010, and over 28 percent of the acreage planted was not brought to harvest. The 2012 and 2013 crops had failure rates of 16 and 17 percent of the planted acreage, above the wet year average of 9.5 percent failure. The lost production value for these two years is $198 million, based on the $2.8 billion in total produced value of corn in 2012 and 2013. The 2014 corn harvest had near average yield and failure rates. If corn losses are calculated as the product of failed acreage, annual yield, and average annual price, the losses for 2012 through 2014 total $725 million.

Agricultural response to the 2010-2015 drought was constrained by limitations on irrigation capacity. Groundwater depletion since the 1950s, especially in the Ogallala Aquifer, has reduced the capacity of irrigation wells. Crop yield declines as maximum daily irrigation rates are reduced because the farmer is unable to satisfy the full crop water requirement throughout the growing season, leading to increasing soil moisture deficits and resultant reductions in final crop yields. Many farmers have drilled additional wells to supply each center-pivot, increasing their production costs, but still face declining well yields over time. In other regions of the state, the availability of surface water supplies for irrigation has been constrained by urban growth. For example, rice farmers along the Lower Colorado River were denied irrigation water for the first time during the 2010-2015 drought. In contrast to the 1950s drought, where increased irrigation allowed some farmers to maintain production, these limits on irrigation reduced the agricultural sector's ability to adapt to the recent drought.

Uncertainty in drought forecasting limits farmers' ability to adapt to drought and minimize their losses. Farmers can adapt by reducing planted acreage so that available water can be used to bring at least a partial crop to harvest, but that requires either advance knowledge of future drought or abandonment of some already planted crops as drought conditions develop (Foster, Bronzovic, and Butler, 2015).

3.2.2 Hydrological impacts

The 2010-2015 drought severely impacted hydrological systems in Texas. Record low runoff in 2011 was followed by persistent below-normal rainfall in much of the state, causing rivers and streams to recover slowly, lagging far behind normal until May 2015. By some measures, streamflow reductions during the 2010-2015 drought were worse than during the 1950s drought, although the increased reservoir capacity, especially in the eastern half of the state, helped maintain water supplies to major urban centers and sustained minimum downstream baseflows, mitigating damage to coastal ecosystems. Many reservoirs in the western half of the state were drawn down to record lows, necessitating emergency responses by state and local officials.

3.2.2.1 Streamflow

Different measures of streamflow are appropriate for monitoring and responding to different aspects of drought. Fish and other sensitive riparian wildlife need minimum flows maintained every day to survive, while reservoir managers are more focused on longer-term trends in streamflow. For purposes of this report, the authors focus on statewide aggregate streamflow measurements at both unregulated index sites and at the Gulf Coast and evaluate streamflow deficits both in terms of percentile reductions in flow and in terms of volumetric measures.

Streamflow at the 21 of 29 unregulated index sites with measurements dating back to 1950 dropped further during the 2010-2015 drought than in the 1950s drought and by some measures resulted in a larger cumulative streamflow deficit over the duration of the drought. Although the minimum daily average streamflow index value occurred in October 1956, low flows were much more consistent during the 2010-2015 drought (Figure 3-11). Texas streamflow for April through June 2010 was the lowest in U.S. Geological Survey records dating to 1930 (USGS, 2012), and the 90-day average of streamflow remained below the 50th percentile for 1,652 days, from November 3, 2010 until May 12, 2015.

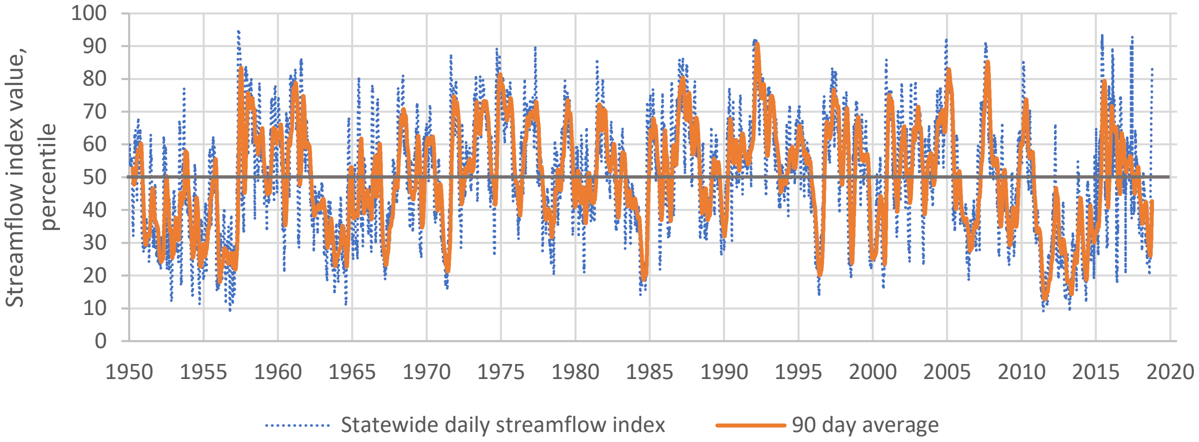


Figure 3-11. **Average daily and 90-day streamflow index values, 1950 to 2018. Data from TWDB, 2018a.**

The authors calculated a volumetric streamflow deficit (Figure 3-12) as the difference between the 365-day moving average of the sum of the 21 daily streamflow measurements and the period of record average of the daily sum. The deficit period for the 1950s drought lasted 2,302 days, from February 6, 1951 to May 29, 1957. The deficit period for the 2010-2015 drought by this measure lasted 1,658 days from January 9, 2010 to May 5, 2015. Although the 1950s drought lasted 644 days longer than the 2010-2015 drought, the cumulative streamflow deficit for the 2010-2015 drought was greater, totaling 9.96 million acre-feet compared to 9.66 million acre-feet.

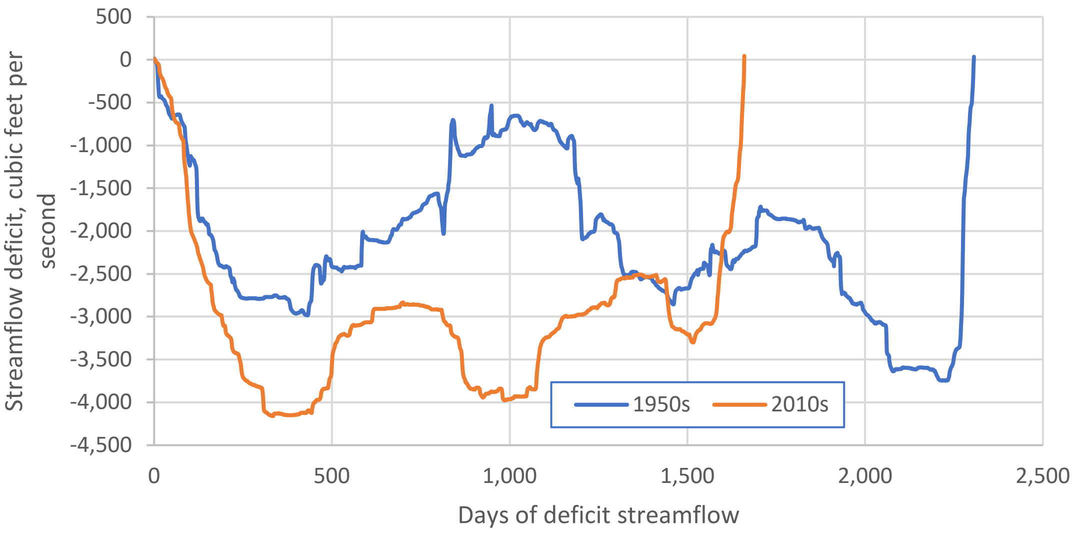


Figure 3-12. **Daily total streamflow deficits for the 1950s and 2010-2015 droughts for 21 of 29 unregulated index sites with records to 1950. Data from TWDB, 2018a.**

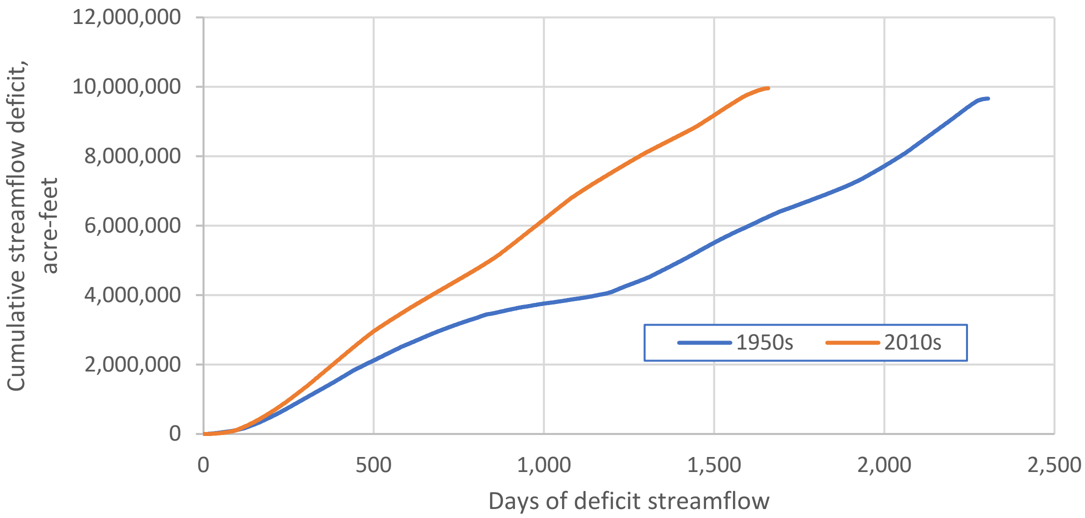


Figure 3-13. Cumulative streamflow deficits for 1950s and 2010-2015 droughts, in acre-feet, based on daily records for 21 index sites, as described above. Data from TWDB, 2018a.

Reservoir releases helped maintain streamflow during the 2010-2015 drought. Data on statewide runoff from the U.S. Geological Survey (2017) and gaged river flows at the Gulf of Mexico (TWDB, 2017c) complement the streamflow data from the index sites. Total annual runoff in 2011 was 6.84 million acre-feet, the lowest on record. The minimum runoff during the 1950s drought was 9.98 million acre-feet in 1956. Monthly gaged freshwater inflows to the Gulf of Mexico during the 1950s and 2010-2015 droughts (Figure 3-14) reflect the influence of reservoirs constructed throughout Texas in the wake of the 1950s drought. In contrast to the streamflow index sites, which are typically located in the upper portions of the drainage basins, above any dams, flows at the Gulf include releases from reservoirs in the basin and groundwater discharge along gaining reaches of the stream network. These additional sources of flow to the Gulf buffered the extreme reductions in runoff in 2011, although dams also limited the flow at the coast during relatively wetter intervals in 2012 as reservoirs re-filled. Overall, dams reduced the streamflow deficit at the Gulf for the 2010-2015 drought in comparison to the deficit at the unregulated index sites. As a result, total freshwater flows to the Gulf declined more during the 1950s drought than during the 2010-2015 drought.

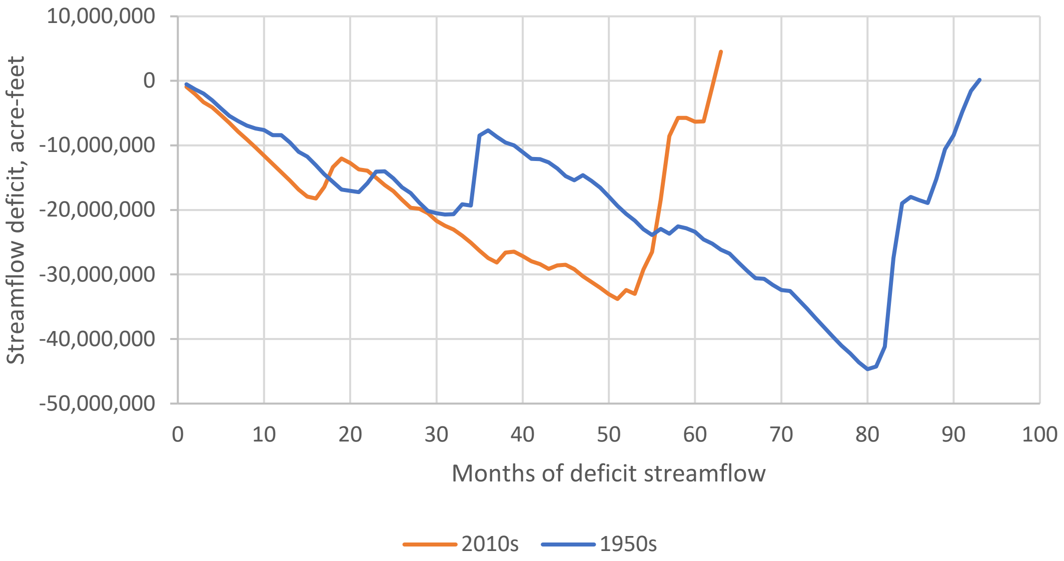


Figure 3-14. **Cumulative monthly deficit streamflow to the Gulf of Mexico with respect to the period of record median, in acre-feet. Data from TWDB, 2017c.**

The Texas Commission on Environmental Quality (TCEQ) Water Availability Models (WAMs), used to assess water supplies under drought conditions, show the 1950s drought to be the most severe on record, but the models need to be updated. In 2017 testimony to the Texas House Natural Resources Committee, L'Oreal Stepney, the TCEQ Deputy Director for the Office of Water, stated "Some basins have exhibited signals indicating the potential for a new basin-wide drought of record. However, whether it is a new drought of record or not will not be known until there is an extension of the naturalized flow data for the basin. Except for the Colorado River Basin, the naturalized flows across the state have not been updated to add more data since their original development. In response to extended severe drought conditions in the Colorado River Basin, the authors extended the naturalized flows in the Colorado WAM to consider the streamflow conditions through 2013. However, after examining data from 1940 through 2013, the TCEQ found that the 1950's drought was still the limiting factor in looking at water availability in the Colorado River Basin" (Stepney, 2017).

Streamflow measurements integrate many aspects of landscape response to drought but may not capture the total effects of drought in all parts of the state. Streamflow depletion during the 2010-2015 drought was a product of extreme desiccation of surface soils in surrounding watersheds, depletion of shallow groundwater that typically contributes to baseflow, increased evapotranspiration by riparian vegetation, and direct evaporation in response to high temperatures and low humidity. But in areas with few perennial streams, such as the Panhandle, or under severe drought when streams go dry, streamflow is a poor measure of drought impact. Long, Scanlon, Longuevergne, Sun, Fernando, and Save (2013) used Gravity Recovery and Climate Experiment (GRACE) satellite data to estimate the total change in water storage during the 2011 drought, including reservoir storage, stored soil moisture, and groundwater storage. They documented a depletion in total storage of 62.3 ± 17.7 cubic kilometers in September 2011, with soil moisture loss representing the largest component of the total depletion.

Changes in climate, land use, and agricultural practices since the 1950s may have also contributed to the steeper declines in streamflow observed during the 2010-2015 drought. The Canadian River Municipal Water Authority (CRMWA) cites the spread of salt-cedar as a factor in declining streamflow in the Canadian River (CRMWA, 2017). Brauer and others (2015) found that a decrease in the frequency of precipitation events greater than 50 millimeters was responsible for declines in runoff to the Canadian River.

3.2.2.2 Reservoir storage

Texas had far more reservoir storage capacity available during the 2010-2015 drought than was available during the 1950s drought. There were also better plans in place to allocate water during drought periods to preserve availability for critical needs, thus mitigating the drought impact on municipal and industrial users in many parts of the state.

Between the high point in April 2010 and the low in December 2011, reservoir storage dropped almost 10 million acre-feet statewide, which was more than the total storage available during the 1950s drought (Figure 3-15). In just 250 days, between March and November 2011, total storage declined by over 8,000,000 acre-feet, or nearly 22 percent of state-wide capacity. Despite the enormous reduction, statewide reservoir storage never dropped below 58 percent of total capacity during the drought, in contrast to the 1950s drought, when the state reached a low of less than 30 percent total capacity remaining in storage in September 1952.

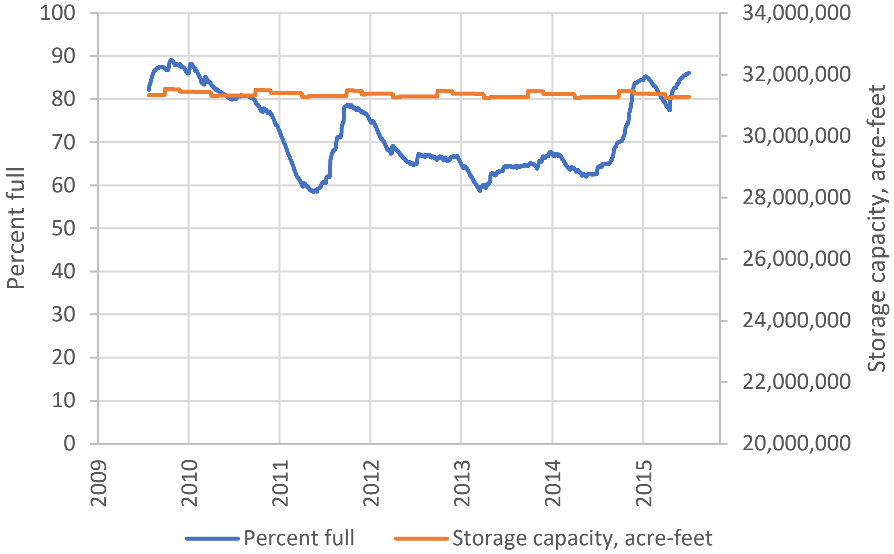


Figure 3-15. Texas statewide reservoir storage and capacity during the 2010-2015 drought. Data from TWDB, 2017d.

Regionally, many reservoirs were reduced much further than the statewide average, especially in west Texas. Lake Meredith bottomed out at zero percent storage from May 2011 through June 2014. Lake O.H. Ivie stood at less than 11 percent capacity in May 2014. For a subset of six reservoirs that had been in operation during both the 1950s and 2010-2015 droughts -- including lakes Buchanan, Brownwood, Kemp, Possum Kingdom, Red Bluff, and Travis -- reduction below 50 percent of capacity (about 1,500,000 acre-feet) lasted longer in the 2010-2015 drought than in the 1950s (Figure 3-16). However, these reservoirs reached a lower minimum storage during the 1950s drought.

The minimum storage in these lakes would have been much lower if not for LCRA management decisions to curtail irrigation water rights held by rice farmers in the Colorado River Basin, who hold interruptible rights to almost 368,000 acre-feet per year of water from lakes Buchanan and Travis. At the beginning of 2012, combined storage in these lakes was under 740,000 acre-feet. The LCRA petitioned the TCEQ for approval of emergency relief measures to limit irrigation releases, and these measures were approved on December 7, 2011. The LCRA curtailed most irrigation rights on March 1, 2012, when the combined storage of the lakes failed to reach 850,000 acre-feet (LCRA, 2012). Becky Motal, the LCRA General Manager at that time, noted, "This is the first time in history that downstream farmers will not receive all the water they need from LCRA," in contrast to the 1950s drought, when irrigation releases were maintained. Irrigation rights were also curtailed in 2013 and 2014 under emergency orders approved by the Texas Commission on Environmental Quality (TCEQ, 2014a). The lakes reached a minimum stored volume of 637,123 acre-feet on September 19, 2013, and the combined storage of the two lakes did not reach 850,000 acre-feet again until May 23, 2015.

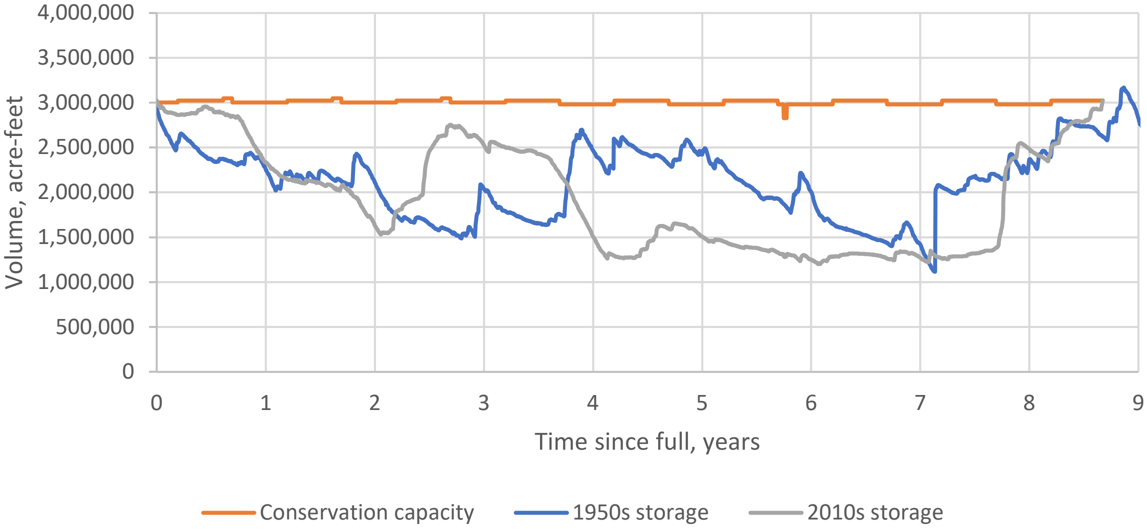


Figure 3-16. **Total storage in six reservoirs during the 1950s and 2010-2015 droughts, in acre-feet. Total storage for lakes Buchanan, Brownwood, Kemp, Possum Kingdom, Red Bluff, and Travis is shown for periods from the date when the lakes were last full to when they reached capacity again, starting on July 26, 1945 for the 1950s drought and on August 23, 2007 for the 2010-2015 drought. Data from TWDB, 2017d.**

The LCRA 2020 Water Management Plan includes amendments which allow for more flexibility in allocating interruptible stored water based on projected conditions for each crop season (LCRA, 2020a). The LCRA 2020 plan attempts to balance drought risks against its obligations to its customers and the public. The LCRA acknowledges how important it is “to be able to identify a drought potentially worse than the drought of record while the drought is still in progress,” and that “timely action under a drought potentially worse than the drought of record can lessen the need for more restrictive demand reductions and the resulting consequences of more severe water supply shortages" (LCRA, 2020a). Waiting until the firm yield cannot be sustained may reduce the ability of demand reduction measures to possibly avert a severe shortage and limit the potential to run out of water. The 2020 plan allows the LCRA to use models to look ahead at likely future conditions and retains criteria of less than 600,000 acre-feet of storage, inflows below drought of record, and a 24-month drought duration to define a drought of record (LCRA 2020b). Storage of 600,000 acre-feet represents nearly three and a half years of average firm water demand from the lakes, but evaporation losses, which average over 150,000 acre-feet per year (Texas Living Waters, 2014), could reduce the life of 600,000 acre-feet of storage to less than two years.

3.2.3 Impacts on municipal water supplies

Cities and towns across Texas activated drought contingency plans as streamflow and reservoir levels dropped during the 2010-2015 drought. While only a few small systems ran out of water, many more water supply managers had to resort to emergency plans to bring new water supplies on line and to keep their systems running. The most common source of new supply was groundwater (TWDB, 2017b). As water shortages developed during the 2010-2015 drought, the TCEQ issued new rules in September 2013; requiring public water utilities and entities from which the utilities obtain wholesale water service to report when they have less than 180 days water supply remaining (TWDB, 2017b). A total of 110 public water systems were listed on the TCEQ High Priority Water System List (also known as the 180-day list) from 2011 through 2015, with as many as 58 on the list at any one time (TWDB, 2017b). The 58 systems on the 180-day list as of February 20, 2015 ranged in size from the City of Mineral Wells (2010 population of 16,800) to the Twin Buttes water system, serving a population of 44. Of those systems, 37 relied primarily on surface water supplies while 21 used groundwater sources. The most common strategy for resolving shortages, adopted by 36 of the systems, was to drill new wells. Other strategies included constructing new interconnections (seven systems) and increasing surface water treatment capacity (six systems).

While most of the water systems on the 180-day list represented small communities, the City of Wichita Falls, with a population of over 100,000, was placed on the list in February 2013 as reservoir levels dropped to record lows. Wichita Falls is in an area without abundant groundwater resources and has too large a population for feasible alternatives such as trucking in water. In response to local drought conditions, Wichita Falls tried several innovative water supply strategies, including cloud seeding, evaporation suppression, and water reuse, all on an accelerated schedule.

The city implemented a comprehensive cloud seeding project in the spring of 2014 at a cost of $300,000 and sought joint participation from other entities that could benefit from a cloud seeding operation to offset a portion of the expense (City of Wichita Falls, 2014). In July 2014, the city also hired a company called Flexible Solutions to apply a white powder product, known as WaterSavr, to Lake Arrowhead at a cost of $400,000. The company claimed that the product would save the city hundreds of millions of gallons of water by reducing evaporation from the lake (Satija, 2014). TWDB analysis of the evaporation suppression project suggests that the Watersavr application reduced evaporation by about 15 percent over the 10-week period that it was applied (Wentzel and Solis, 2015). The benefits of cloud-seeding and evaporation suppression proved difficult to quantify, and the strategies were ultimately not pursued long-term.

In contrast, direct potable reuse put an easily measurable quantity of water back into the city supplies every day at a reasonable cost. In July 2014, the City of Wichita Falls began operating an emergency direct potable reuse facility. The city conveyed wastewater effluent through a 12-mile, above-ground pipeline, treated it in an existing treatment plant, and produced 5 million gallons per day of water that was stored in a holding lagoon and then blended with surface water supplies from existing sources (TWDB, 2016a). The entire process of permitting and building the system was completed at "'lightning speed" in just 27 months, according to the utility operations manager, Daniel Nix (Espinola, 2016). The direct potable reuse system was online for 12 months before conversion to an indirect potable reuse system, which costs less to operate and produces more water (Espinola, 2016).

The Canadian River Municipal Water Authority (CRMWA) provides another example of drought planning and adaptation. Lake Meredith was intended as the primary water supply for the CRMWA service area, which includes Amarillo, Lubbock, and several smaller High Plains communities. The water level in Lake Meredith peaked at almost 80 percent full in August 1999. In January 2004, it stood at under 20 percent of capacity, and fell to zero percent full in May 2011. But nobody's tap went dry. Faced with declining flows on the Canadian River over many years, CRMWA had ample time to plan and develop alternate water supplies, ultimately acquiring rights for 69,000 acre-feet of groundwater per year from 42,765 acres of rangeland. Phase 1 of the John C. Williams aqueduct and wellfield project began operations in December 2001, with two additional wells added in 2008. As Lake Meredith continued to decline, CRMWA acquired additional water rights in Gray, Hutchinson, Roberts, and Wheeler counties. Wells and pipelines were built in these areas and came into service in 2010 and 2011, just as drought hit Texas (CRMWA, 2017b).

Municipal water use restrictions were widely adopted during the 2010-2015 drought and appear to have been successful in reducing demand. Water consumption per capita per day generally increased from 2010 to 2011 in response to dry conditions, reflecting normal use patterns before drought restrictions were put in place. As water use restrictions were progressively tightened in 2012, 2013, and 2014, water use dropped. For example, Wichita Falls summer water consumption dropped by more than half, from an average of nearly 50 million gallons a day down to 17 million gallons per day by June 2014 (Hargrove, 2014). Per capita per day water use in Austin dropped from 162 gallons in 2011 to 142 gallons in 2012, 135 gallons in 2013, 124 gallons in 2014, and 122 gallons in 2015 (City of Austin, 2017). San Antonio water use varied within a smaller range, from 149 gallons per capita per day in 2011 to 134 gallons per capita per day in 2013 (Mills and Martinez, 2015). The TWDB's water use summary estimates (Figure 3-17) show a similar pattern, with a generally declining trend in average municipal daily per capita water use from 2000 to 2015 and steeper declines following the onset of drought conditions in 2011. Since 2000, Texas municipal water use has trended downwards, with an average decline of almost 2.3 gallons per capita per day each year. After the onset of the most recent drought in 2011, the average daily municipal water use in Texas dropped almost 22 percent, from 173 gallons per capita per day in 2011 to 136 gallons per capita per day in 2014.

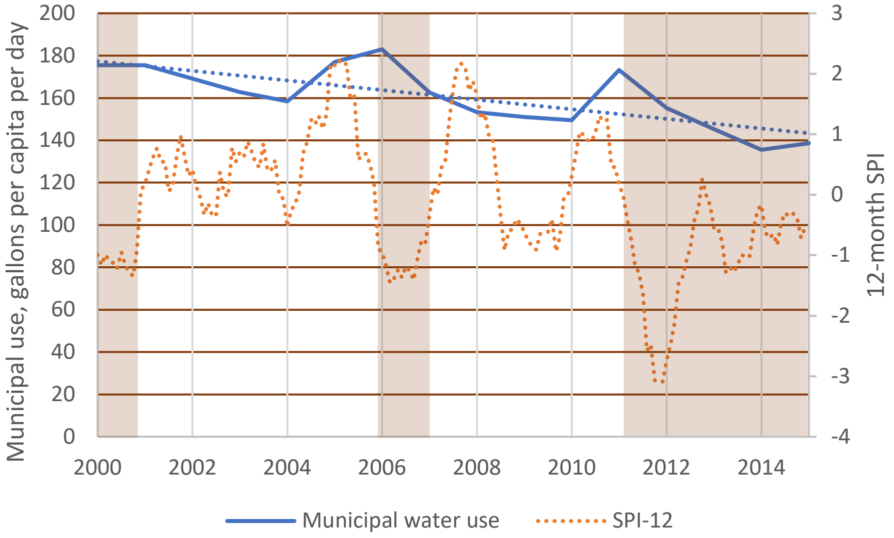


Figure 3-17. **Statewide annual municipal water use and 12-month Standardized Precipitation Index (SPI), 2000 to 2015. Shading indicates drought periods. Data from TWDB, 2017a and NCEI, 2017b.**

Drought has other effects on the operations of municipal utilities beyond water use restrictions. Drought can cause soil movement, especially in parts of the state with vertisol soils, which are found in a broad arc through central and north Texas and in parts of the coastal plain. Soil movement can cause damage to foundations, roadways, and buried utilities. Dry years can have anomalously high rates of failure for buried pipes, as illustrated by Figure 3-18, which shows the annual frequency of water main breaks in San Antonio in relationship to yearly total precipitation. Spikes in main breaks correlate with dry years in 2006, 2009, and 2011, with drought year breaks occurring at double the rate of wet years (Mills and Martinez, 2014).

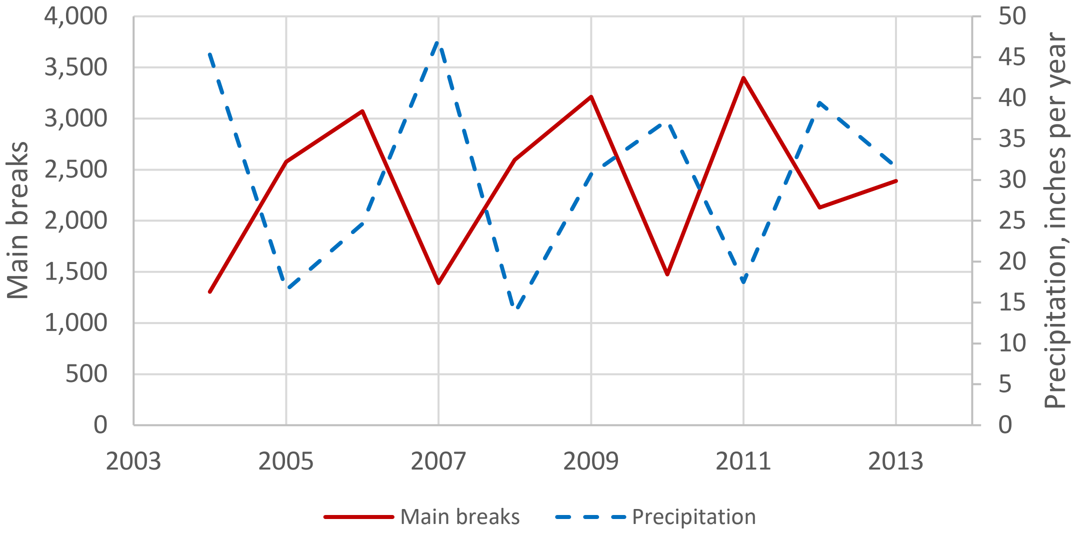


Figure 3-18. **Effect of drought on water main ruptures in San Antonio. Data from Mills and Martinez, 2014.**

Drought can also impact a municipality's ability to withdraw water from reservoirs. When reservoir levels are low due to water use and evaporation, the water level can fall below the intake pipe. This issue impacted several communities in Texas during the 2010-2015 drought. For example, in January of 2014 the Windthorst Water Supply Corporation in Archer County was awarded $350,000 in Emergency Disaster Relief Funds from the Texas Department of Agriculture so the water utility could lower its surface water intake pipe (TCEQ 2014b). Additionally, in February of 2012 the City of Emory in Rain County utilized a floating barge and submersible pumps to access deeper water in Lake Tawakoni as water levels had fallen below the permanent surface water intake (TCEQ 2015).

3.2.4 Impacts on industrial and commercial uses

Industrial water systems are not centrally tracked to the extent that municipal systems are, so the extent to which industrial users were forced to find alternative water supplies is unknown. At least one industrial system invoked its water rights seniority to maintain its water supply, forcing systems holding more junior rights to adapt or secure other water supplies through the marketplace. Large industrial systems, such as the electrical power generators, generally avoided serious disruptions in operations, reflecting the relatively low cost of water as an input for most industries.

During the 2010-2015 drought, streamflow in several basins was inadequate to meet all permitted uses and senior rights holders petitioned the TCEQ to curtail water use by those holding more junior water rights. The priority call affecting the largest area and most users was on the Brazos River (Figure 3-19). Dow Chemical Corporation made priority calls to the TCEQ in 2011, 2012, and 2013 to maintain the water supply at their facility on the Gulf Coast in Freeport. On November 19, 2012, over 700 water rights junior to Dow Chemical's 1942 rights to 150,000 acre-feet per year were curtailed, excluding rights for municipal use, power generation, and domestic use (TCEQ, 2017b).

Other priority calls affected smaller areas and fewer water rights. Certain non-municipal diversions with priority dates of 1900 or later were suspended due to multiple priority calls on surface water from domestic and livestock water users in the San Saba River watershed (TCEQ, 2017b). Water rights on the San Saba River were first curtailed on August 8, 2011 (TCEQ, 2017b). The TCEQ again suspended several San Saba water rights in August 2013 after receiving a priority call for domestic and livestock use. Neches River rights were suspended following priority calls by the Lower Neches Valley Authority on November 10, 2011 and January 23, 2012. A priority call was made for the Llano River watershed on July 5, 2011 and was rescinded October 26, 2011. The same situation occurred on the Little Sandy Creek watershed on January 4, 2012 and was rescinded February 16, 2012.

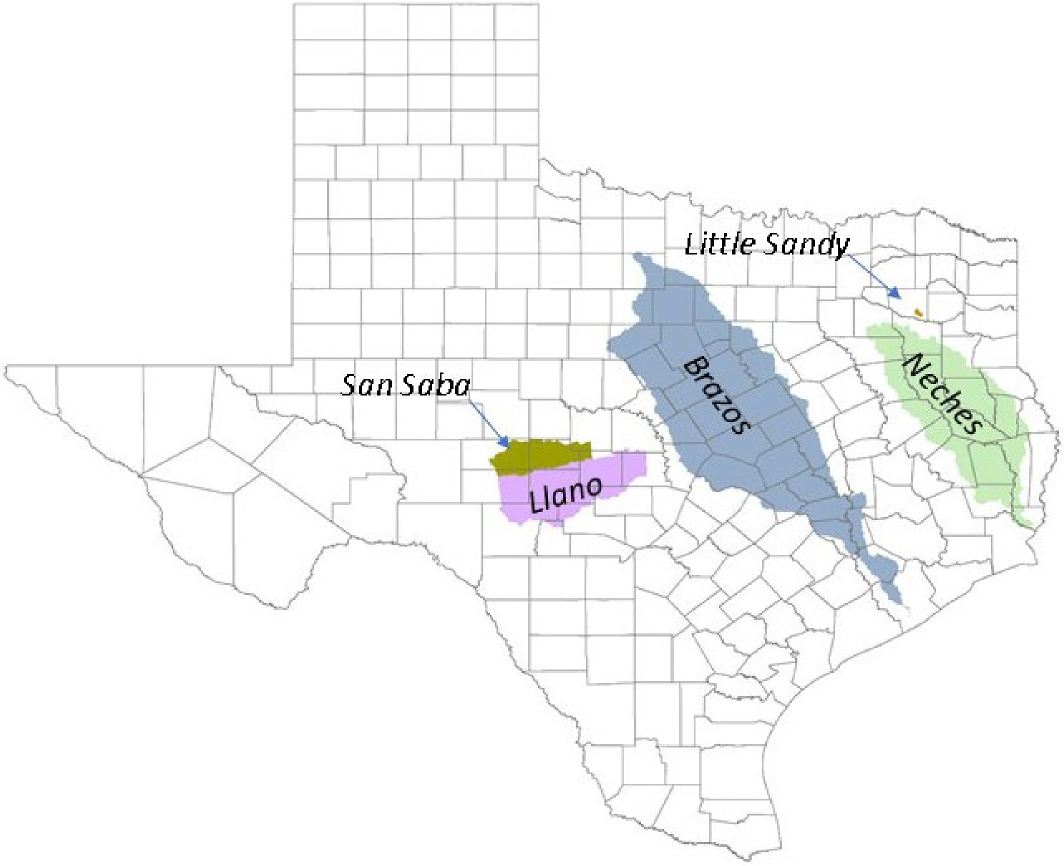


Figure 3-19. **Map of the areas where junior surface water rights were curtailed in 2011, 2012, and 2013. From TCEQ, 2017b.**

3.2.4.1 Electric power production

Electric power generation was not significantly disrupted by the 2010-2015 drought. A 2013 drought analysis conducted for the Electric Reliability Council of Texas (ERCOT) concludes that "survey data provided by the generators and the actual unit history from 2011 have shown that most generators were prepared for or had contingency plans for a single-year severe drought such as experienced in 2011. The more complex issue for generators in Texas appears to be a multi-year drought when water storage is further diminished" (Black and Veatch, 2013).

In a 2011 report for Argonne National Laboratory, Harto and Yan concluded that up to 25 percent of the thermal electric generating capacity in Texas was at risk during drought. The modeled drought was defined as the 10th percentile of the annual average stream flow over the 109-year period of record for streamflow, which they calculate as equaling an annual streamflow of 6.6 million acre-feet into the Gulf of Mexico, or about 30 percent of normal. They stress that the 25 percent loss of capacity represents the amount of replacement generation or load reduction that would be required if no reserve capacity were available and no mitigation actions were taken. The fact that minimal disruption occurred in 2011, when streamflow totals represented only 18.6 percent of the average, demonstrates that ERCOT and Texas power producers had effective drought plans in place.

Following the 2010-2015 drought, ERCOT developed a drought risk monitoring tool to screen for potential drought-related impacts to generation resources (ERCOT, 2017). The tool predicts whether water supplies used by generation resources in the ERCOT region are at risk of reaching levels requiring closer monitoring over the next 6 to 18 months, based on the most recent reservoir and lake levels from the TWDB and historical trends in water usage. Reports are available at www.ercot.com/gridinfo/resource.

3.2.4.2 Real estate

The authors examined data on real estate prices in Wichita Falls to determine if drought conditions had measurable impacts on the real estate market in one of the areas hit hardest by drought. Drought and uncertainty about future water supplies are real issues for residents of many Texas cities. Loss of valuable landscaping during a drought imposes real costs on residents. Water system upgrades motivated by drought bring the prospect of higher water bills in the future. The authors examined how these ongoing and expected future costs might be incorporated in real estate valuation as another way of measuring the impact of drought events in Texas. Focus was placed on Wichita Falls because of the state and national news coverage that their drought response actions received. Also, Wichita Falls is the largest metropolitan area that was on the 180-day list during the drought and is therefore more likely to exhibit drought impacts on aggregate economic indicators than the small communities that make up the bulk of the list.

Local news reports suggest that drought had a significant effect on real estate. A 2016 special report looking back on the drought by Deanna Watson of the Wichita Falls Times Record News quotes the owner of Hirschi Realtors as saying “In the 12 months since May of last year, our market has experienced a 12-13 percent increase in units and dollar volume sold, along with an increase in values of 2-3 percent. Demand for existing homes continues to grow while listing inventory continues to marginally shrink, and homes are selling at a faster pace” (Watson, 2016). Ted Buss of the Times Record News quotes Ed Holcomb, North Texas Home Builders Association president, as saying "The drought was a killer for our industry. Even when it ended a lot of people elected to sit tight. We are now getting back to normal for consumer confidence for building, remodeling, and moving up to another home" (Buss, 2016). And Danielle Malagarie, from News Channel 6, spoke with Denny Bishop, the owner of the Bishop Realtor Group, who said home sales in the area were up 17 percent in Wichita Falls for the first quarter of 2016 (Malagarie, 2016).

Economic statistics suggest that oil prices and unemployment are much stronger drivers of local real estate values than drought. Data from the real estate website Zillow (2017) show some depression in local real estate values generally coincide with the duration of the drought. But real estate values started dropping before the drought began, in response to a severe recession associated with nationwide collapse of real estate markets and precipitous drops in oil prices. Employment data for the Wichita Falls area (Bureau of Labor Statistics, 2017b) indicate that the 2010 decrease in home values lagged six to seven months behind a local rise in unemployment, which peaked in July 2009 (Figure 3-20).

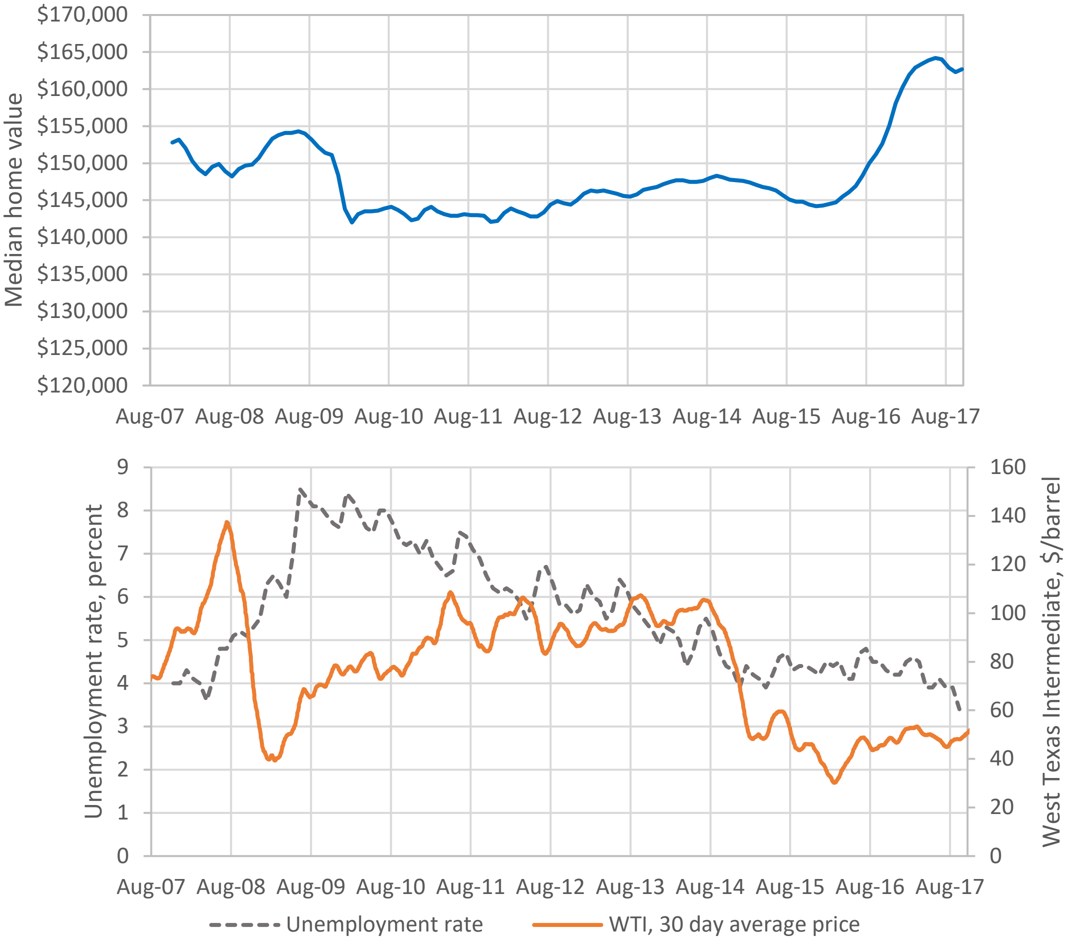


Figure 3-20. Median value of a four-bedroom Wichita Falls home (top), unemployment rate, and price of West Texas Intermediate crude oil (bottom) for 2007 to 2017. Data from Zillow, 2017; Bureau of Labor Statistics, 2017b; and FRED Economic Research, 2017.

The peak in unemployment lagged approximately six months behind the market for West Texas Intermediate crude oil, which dropped from a high of over $130 per barrel in August 2008 to under $40 per barrel in January 2009 (FRED Economic Research, 2017). The Wichita Falls general business index, compiled by John E. Martinez for the Wichita Falls regional economic outlook report, shows that growth during the drought from 2011 through 2013 met or exceeded the long-term trend before tailing off below trend in 2014 (Martinez, 2014). Thus, any connection between drought conditions and aggregate regional economic performance remains tenuous at best.

3.2.5 Environmental impacts

Wildland fires were the signature environmental impact of the 2010-2015 drought. Dry conditions, high fuel loads, low humidity, and strong winds contributed to numerous wildfire outbreaks in 2011. A total of 31,453 wildfires occurred during the year, burning over 4 million acres, and destroying 2,947 homes across virtually all areas of the state (Figure 3-21). February, April, June, and September were peak months during the 2011 wildfire season (Texas A&M Forest Service, 2011). In 2011, there was over $1 billion of reported property loss due to fire, an increase of 103 percent from the previous year. Outside and other types of fires increased 51 percent over 2010; structure fires were up 15 percent, while vehicle fires were unchanged. Almost half of the dollar loss of property occurred during the September 2011 wildfire outbreak, which included the Bastrop Complex fire, with $454 million in losses. The 20 largest fires during 2011 are listed in Table 3-2.

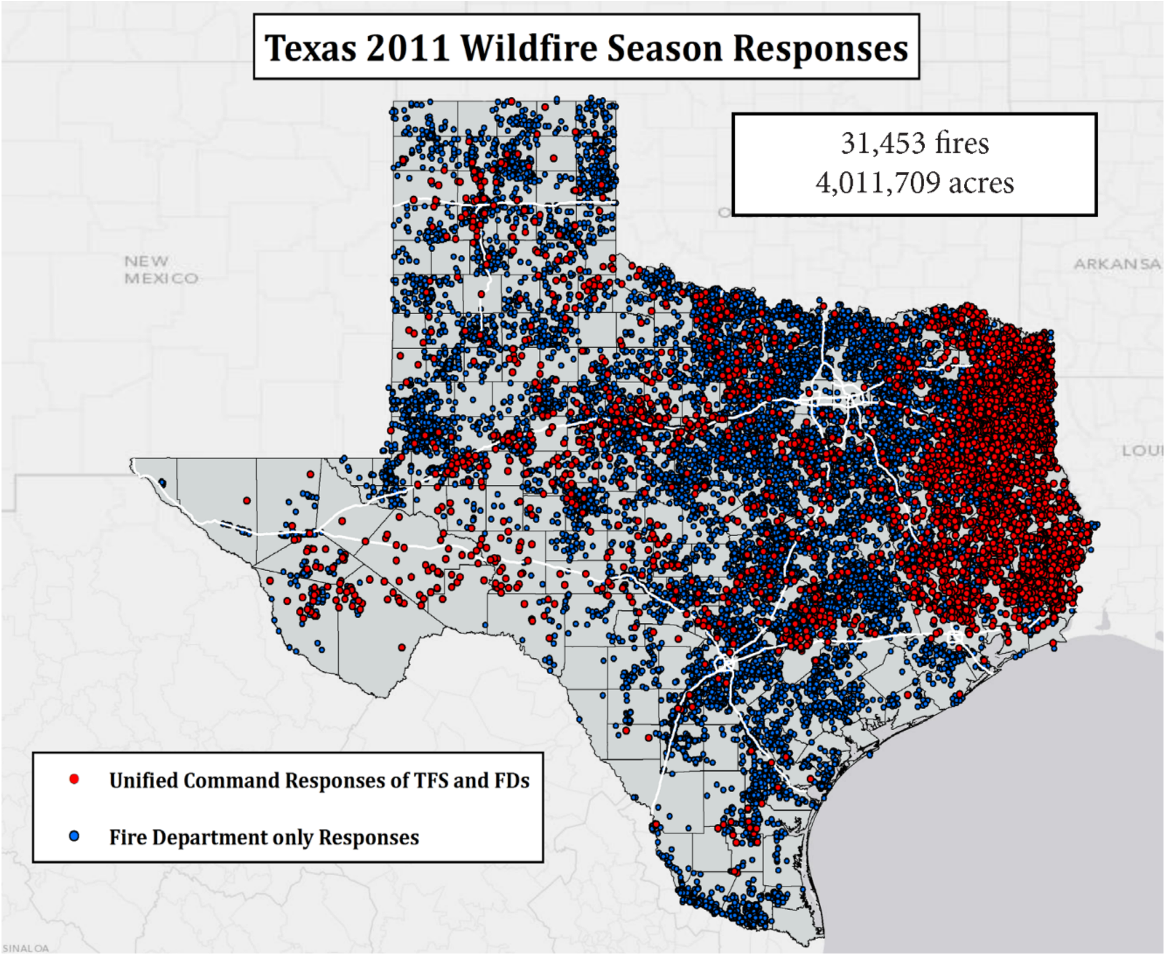


Figure 3-21. **Locations of the 31,453 reported wildfires in Texas during 2011 with responses by the Texas Fire Service (TFS) and local fire departments (FD). From Texas A&M Forest Service, 2011.**

Overall, 13 civilian fatalities, 85 civilian injuries, 133 fire service injuries, and property losses estimated at $494,130,059 resulted from wildfires in 2011. Fires caused by electrical distribution systems were responsible for the greatest share of these losses, causing $400,322,809 out of the total damage from wildfires in 2011 while representing only 0.8 percent of all fires of this type (State Fire Marshall, 2012). Power lines downed by Tropical Storm Lee, which brought strong dry winds to central Texas, contributed to the 430 wildfires reported on September 4, 2011 (Texas A&M Forest Service, 2011).

Table 3-2. Twenty largest Texas wildfires in 2011. From Nielsen-Gammon, 2012.

Fire	Primary county affected	Date started	Area burned, acres	Homes lost
Matador West	Motely	2/27/2011	41,000	2
Tom	Adams	2/27/2011	65,000	0
Swenson	Stonewall	4/6/2011	122,500	2
Killough	Garza	4/9/2011	32,000	1
Roper	Brewster	4/9/2011	41,000	0
Crawford Ranch	Moore	4/9/2011	35,096	0
Possum Kingdom	Palo Pinto	4/9/2011	126,734	168
Rockhouse	Jeff Davis	4/9/2011	314,444	23
Wildcat	Coke	4/10/2011	159,308	0
Cooper Mountain Ranch	Kent	4/11/2011	162,625	4
Pierce/Sutton	Crockett	4/11/2011	30,814	0
Cannon Complex	Pecos	4/11/2011	63,427	0
Frying Pan	Andrews	4/14/2011	80,907	0
Deaton Cole	Val Verde	4/25/2011	175,000	0
Dickens Complex	Dickens	5/7/2011	89,200	0
Schwartz	Brewster	5/7/2011	84,000	0
Iron Mountain	Brewster	5/9/2011	89,400	0
White Hat	Nolan	6/20/2011	72,473	0
Bastrop complex	Bastrop	9/4/2011	32,400	166
Bear Creek	Cass	9/4/2011	41,050	92

Some of the largest wildfires during the 2011 fire season were associated with Southern Plains wildfire outbreaks, in which 1,255 fires consumed more than 1.2 million acres in just nine days (Table 3-3). Southern Plains wildfire outbreaks are characterized by strong westerly or southwesterly surface winds, high velocity jet-stream winds aloft, extremely low relative humidity, and above average temperatures coming together to produce extremely critical fire weather conditions.

Table 3-3. Texas Southern Plains wildfire outbreaks in 2011. In nine days, 1,255 fires burned over 1.2 million acres, killed two people and destroyed over 700 structures in the High Plains area. From State Fire Marshall, 2012.

Wildfires in Texas Southern Plains 2011				
Event Date	Wildfires	Acres	Fatalities	Structures Destroyed
27 Feb	197	262,434	0	132
22 March	105	12,556	0	4
03 April	112	19,883	0	11
09 April	144	582,615	1	361
14 April	76	85,287	0	3
15 April	270	50,321	1	58
26 April	82	50,235	0	56
24 May	100	127,732	0	16
20 June	169	86,966	0	64
Total				
Events	**Wildfires**	**Acres**	**Fatalities**	**Structures Destroyed**
9 Days	**1,255**	**1,278,029**	**2**	**705**

In addition to the devastating wildland fires, considered to be the signature environmental impact of the 2010-2015 drought, wildlife throughout Texas were also negatively affected. Poor pasture conditions led to smaller numbers of whitetail deer, quail, pheasants, and other game species. Declining water levels and warmer water temperatures in lakes and streams affected fish populations. Lower freshwater inflows to coastal bays and estuaries, especially the lack of seasonal flood flows, reduced the biological productivity of these important marine ecosystems. However, environmental releases from reservoirs and return flows from municipal systems maintained some level of streamflow to the bays and estuaries, limiting the environmental impact of the drought on these systems.

3.2.6 Impacts on state water planning and management

The most significant change in Texas water management in the wake of the 2010-2015 drought was the creation of the State Water Implementation Fund for Texas (SWIFT) in 2013. While SWIFT is not explicitly a response to the 2010-2015 drought, drought conditions in 2013 clearly contributed to a sense of urgency and helped ensure support for the program by the Texas Legislature and the public. Prior to the 83rd Legislative Session in 2013, the 2012 State Water Plan identified the need for nine million acre-feet per year of new water supplies by 2060 at a projected cost of $53 billion. House Bill 4 from the 83rd Texas Legislature established SWIFT as a revolving fund for financing those water projects included in the state water plan and changed the composition of the TWDB's Board from six, part-time members to three full-time members. SWIFT was funded under House Bill 1025 which appropriated $2 billion from the Economic Stabilization Fund to SWIFT, contingent upon voter approval. These measures were considered by voters on the November 2013 ballot as a constitutional amendment under Proposition 6, which was approved by more than 73 percent of the vote. The TWDB adopted rules implementing SWIFT on November 6, 2014. Through Fiscal Year 2020, the TWDB committed over $8.87 billion for projects across Texas through the SWIFT program (TWDB, 2020).

The overwhelming support for SWIFT resulted from a confluence of events, including the ongoing drought, the state budget surplus available at that time in the wake of record high oil prices, and support from key leadership in the Texas Legislature (Rochelle, 2015). Proposition 6 also received broad support because it specified that portions of the funding be devoted to conservation measures and rural water supplies. As Laura Huffman, Texas state director of the Nature Conservancy at the time, said "This bold action — by both voters today and state leaders during the last legislative session — is reminiscent of the sweeping response our state made during the drought of record in the 1950s. What is different, however, is the strong emphasis on water conservation and the critical role it will play in enabling Texas to prosper and ensuring the viability of our lakes, rivers, aquifers, and coastal bays" (Ramsey and Satija, 2013).

The 2010-2015 drought also prompted changes in the state water planning process. Section 358.3 (1) of the Texas Administrative Code was modified to require regional water plans to include a chapter with information on drought preparation and response. In 2013, Senate Bill 662 was passed, expanding membership of the Drought Preparedness Council by adding representatives from the Public Utility Commission of Texas and ERCOT. In the state water plan, discussion of drought was promoted from a few paragraphs in the Texas climate section of the 2012 State Water Plan to a separate chapter focusing on drought and drought response in Texas in the 2017 State Water Plan.

The Texas Department of Emergency Management substantially updated the drought annex to the State of Texas Emergency Management Plan in December 2016. The revised drought annex expands the 2012 document from 9 pages of text to over 50 pages, reflecting an increased awareness of drought hazards following the 2010-2015 drought. The 2016 Drought Annex details the roles and responsibilities of various units of government in responding to drought according to severity, outlines emergency functions used in response to drought, and establishes lines of coordination. The drought annex also provides resource support checklists for potentially affected sectors, including public health, animals and agriculture, firefighting, energy, public works and utilities, volunteer management, and drought recovery (TDEM, 2016).

4.0 Proxy records: a broader context for drought in Texas

Proxy records are indirect measurements of past climate which can be used to extend the period of record for instrumental observations. Proxy records include measurements of annual tree growth rings, the size and isotope concentrations of annual bands in cave formations, ice cores, and a variety of other indicators. Proxy records can provide an assessment of the likelihood of droughts worse than the drought of record, informing plans for the future.

Tree-ring data for the last millennium indicate megadroughts in the western U.S. that lasted from decades to centuries. Tree-ring data for Texas since the year 1400 show at least five droughts that lasted more than twice as long as the 1950s drought, with one drought that lasted 26 years and was more intense than the 1950s drought. These reconstructions also suggest that our instrumental record of climate is based on a century of anomalously wet conditions and may not be truly representative of "normal" in the longer-term. Climate models based on these reconstructions show a linkage between drought in the southwestern U.S. and La Niña-like conditions in the tropical Pacific that are associated with generally warming conditions. These models differ as to how increased greenhouse forcing will affect the prevalence and intensity of drought in the future. Speleothems, or cave formations, preserve information on Texas climate stretching back tens of thousands of years, but the duration and intensity of individual drought events is difficult to discern from the available data.

4.1 Tree-ring data

Tree rings are the best-documented and most widely accepted proxy record used to reconstruct drought chronologies in the U.S. prior to the historical record. Cook, Meko, Stahle, and Cleaveland (1999) developed a 2 degrees latitude by 3 degrees longitude grid of summer drought reconstructions for the continental U.S. based on 425 annual tree-ring chronologies. Cook, Seager, Heim, Vose, Herweijer, and Woodhouse (2010) extended that work, using 1,845 irregularly-spaced North American tree-ring chronologies to reconstruct 2,000-year PDSI chronologies at 11,396 grid points at a one-half degree spacing, creating the Living Blended Drought Atlas (LBDA) (Cook, 2017). Gille, Wahl, Vose, and Cook (2017) recalibrated the data from Cook and others (2010) to incorporate an improved climate dataset for the continental U.S. and to remove bias, creating the LBDA Version 2. Cleaveland, Votteler, Stahle, Casteel, and Banner (2011) used several new tree-ring chronologies based on measurements in south central Texas to examine Texas drought since the year 1500.

Tree-ring chronologies have several limitations. Tree-ring data are problematic for some parts of Texas, such as the High Plains, which is not naturally forested, and Central Texas, where records based on post oak tree rings only extend to 1648; gridded data for these areas are typically extrapolated from sites with dissimilar climate, such as mountain areas of West Texas or New Mexico (Cleaveland and others, 2011). Because tree growth is seasonal, tree-ring data are typically calibrated to June-July-August average PDSI values for each year and may not accurately represent rainfall events outside the growing season, for example from fall tropical storms (Cleaveland and others, 2011). Also, tree rings are less reliable climate indicators under wet conditions when tree growth is limited by factors other than water availability.

Drought reconstructions based on LBDA data have been used to evaluate the distribution of drought in time and space over the last 1,000 years. Herweijer, Seager, Cook, and Emile-Geay (2007) and Cook, Seager, Cane, and Stahle (2007) have found megadroughts took place in the western U.S. during a 400-year period in the early to middle second millennium AD, with droughts in the southwestern U.S. linked to cool La Niña conditions in the tropical eastern Pacific. Cleaveland and others (2011) found that these megadroughts were not as intense in Central Texas as in other parts of the western U.S., although several droughts of the past were longer and/or more intense than the 1950s drought.

For this report, the authors analyzed data from the 260 Texas grid-points in the LBDA Version 2 (Gille and others, 2017). Figure 4-1 presents a reconstruction of the PDSI for Texas from 1400 to 2005, the most recent data available, using the average value of Texas tree-ring data, showing both the annual index values (dashed line) and smoothed values (filled and shaded curve). The authors used a single exponential smoothing algorithm (NIST, 2017) with a smoothing constant of 0.5 to reduce annual variability and highlight multi-year trends.

The duration of droughts is difficult to quantify in such reconstructions owing to the complexity of drought variability over a region as large as Texas and because inter-annual variability tends to punctuate otherwise dry multi-year intervals with occasional wet years (Cook and others, 2010). Different smoothing algorithms or smoothing constants can have a pronounced effect on the estimated duration and severity of drought events. The exponential smoothing constant of 0.5 used to generate Figure 4-1 results in an estimated duration of the 1950s drought of six years, or 72 months, close to the 77-month duration given by the instrumental PDSI values and the 80-month duration for the 12-month SPI. In contrast, an exponential smoothing value of 0.3 overestimates the duration for the 1950s drought at nine years, or 108 months. Subsequent discussion references tree-ring PDSI values smoothed with a constant of 0.5.

The tree-ring records clearly show the severity of the 1950s drought, but also suggest that more severe, longer-lasting droughts occurred in the past. The longest-lasting drought documented in the tree-ring records for Texas stretched for 26 consecutive years from 1435 to 1460, with an average PDSI for that period of -0.85. It was also more intense than the 1950s drought. During the most severe six-year period of that drought, from 1453 to 1458, the PDSI averaged -1.84, compared to the 1952 to 1957 average of -1.62. Table 4-1 lists the five longest droughts and the five most intense six-year periods of drought from the Texas tree-ring data. The years from 1952 to 1957 recorded the second-most intense six-year period of drought but are nowhere near the top in terms of drought duration. These results are consistent with the conclusions of Cleaveland and others (2011), confirming that droughts more intense than the 1950s drought have occurred in the past in Texas, although the megadroughts seen in the western U.S. were not as intense locally.

The authors' analysis of Texas tree-ring data suggests that the historical period from about 1900 through 2005 was considerably wetter than earlier periods, in contrast to the finding of Cleaveland and others (2011), that the 20th century record was not anomalously wet or dry. The PDSI value for 1400 through 1600 was -0.385, compared to the 1900 to 2005 average of +0.152. This result is consistent with the conclusions of Cook and others (2007), that past climate in western North America was significantly drier than today.

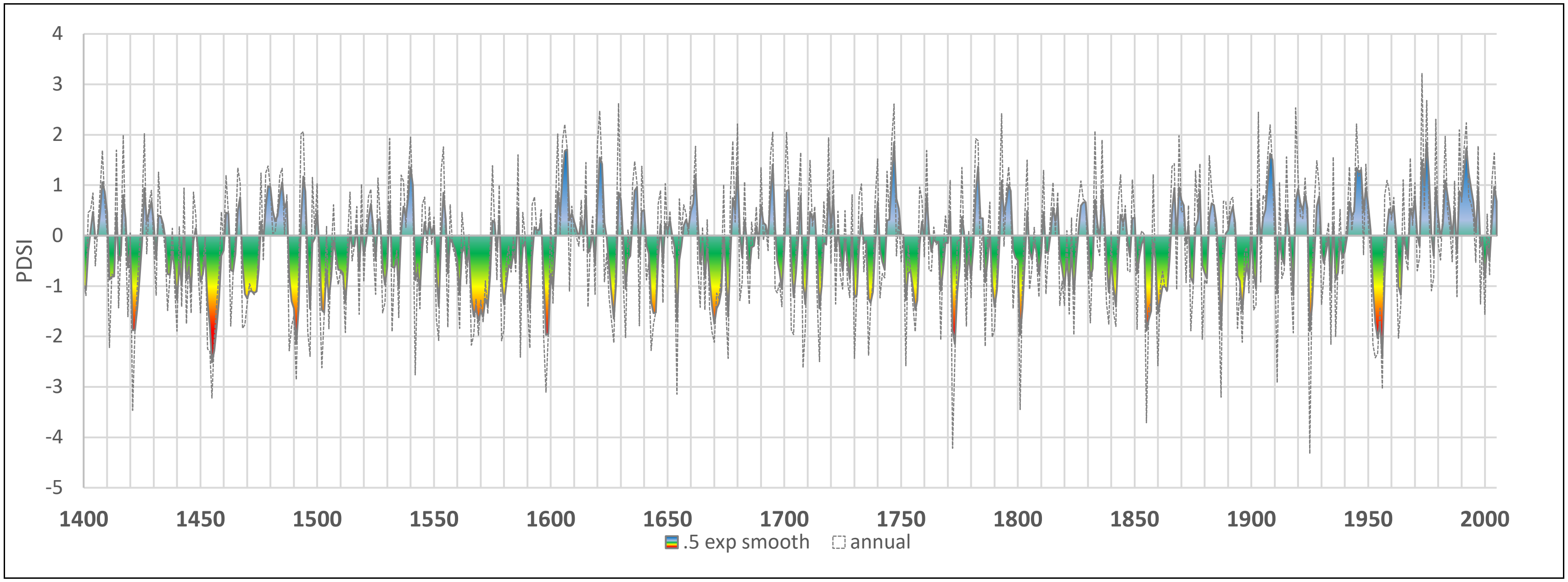


Figure 4-1. **Tree-ring reconstruction of Palmer Drought Severity Index for Texas, 1400 to 2005, showing annual and smoothed data. Annual values represent averages of 260 Texas Living Blended Drought Atlas grid points. Data from Cook and others, 2010.**

Table 4-1. Longest-lasting droughts and most intense six-year periods of drought in Texas, 1400 to 2005.

Drought duration			6-year drought intensity	
Dates	Duration (years)	Average PDSI	Dates	Average PDSI
1435-1460	26	-0.85	1453-1458	-1.84
1556-1574	19	-0.88	1952-1957	-1.62
1851-1865	15	-0.90	1567-1572	-1.51
1664-1671	14	-0.90	1668-1673	-1.31
1501-1513	13	-0.82	1855-1860	-1.20

Whether future conditions revert to a drier norm remains uncertain. Cook and others (2007) find an association between past megadroughts and persistent La Niña-like conditions in the tropical Pacific, which are characterized by anomalously cold water in the eastern tropical Pacific. Paradoxically, these La Niña-like conditions are associated with an overall warming climate during the Medieval period (roughly AD 900 to 1300); increased heating creates stronger temperature gradients and stronger trade winds, driving an increase in upwelling cold water in the eastern tropical Pacific. Results from climate models reviewed by Cook and others (2007) differ as to how the tropical Pacific will respond to future greenhouse forcing. Further research on potential long-term changes in hydrological conditions is needed.

Researchers are continually trying to push climate reconstructions further back in time, but older records tend to have poor spatial resolution and can be harder to interpret. Cook and others (2010) find evidence for widespread megadroughts lasting for several decades in the western U.S. during the medieval climate anomaly, but tree-ring data in some climate regions of Texas are sparse prior to about 1400, limiting our ability to evaluate drought in Texas before that time.

4.2 Speleothems

Climate reconstructions based on cave formations have the potential to extend our record of drought in Texas back much further in time, but current interpretations outline broad changes in the 'normal' climate over time and are not detailed enough to distinguish individual periods of drought. Stalactites and stalagmites, also known as speleothems, form as groundwater percolates through caves and precipitates calcite. Many speleothems have quasi-annual growth bands, superficially resembling tree growth rings. The growth bands can be dated using high-precision thermal-ionization mass spectrometer techniques, while automated micro-scale analyses generate detailed data on compositional changes between bands (Musgrove, Banner, Mack, Combs, James, Cheng, and Edwards, 2001). Speleothem chronologies can cover tens of thousands of years, but speleothem paleoclimatology is challenging, as multiple processes may obscure or efface the original climatic signal (Lachinet, 2009).

Speleothems capture information on several climatic variables, reflecting a complex site-specific network of processes in the atmosphere, soil, groundwater, and cave environments. The growth rates of speleothems are influenced by the abundance of water, among other factors. Under wet conditions speleothems typically grow faster. But if the cave is totally flooded growth stops, and changes in cave ventilation can affect the carbon dioxide content of the cave air, which also regulates speleothem growth rates. Isotope analyses of the growth rings can provide information on prevailing temperature, moisture sources, and vegetation. But independent lines of evidence from background studies on local and regional hydrology and climate are needed to sort out the balance between these factors as well as other processes that can influence isotope distributions, such as changing seasonality or varying atmospheric sources of precipitation (Lachinet, 2009). The Texas climate is particularly challenging for speleothem interpretation because precipitation can come from several different sources, including the Gulf of Mexico, the tropical Pacific, and northern Pacific storm tracks, each of which carry different oxygen isotope signatures (Wong, Banner, and Musgrove, 2015). Trace element concentrations and strontium isotopes can record additional evidence on moisture conditions and water-rock interactions (Musgrove and Banner, 2004; Wong and Breeker, 2015), but they can also be influenced by local geology, hydrogeology, and soil processes.

A high-resolution analysis of a speleothem from Natural Bridge Cavern in Central Texas (Figure 4-2) covering the mid- to late-Holocene (modern to 7,000 years before present) illustrates the complexity of reconstructing past climate from such records. There is a hiatus in speleothem growth from 1,600 to 300 years before present, spanning most of the tree-ring record for North America, that may indicate drier conditions during that interval, but could also reflect changes in ventilation or water flow-paths in the cave that have little to do with broader climate fluctuations. The oxygen isotope records show a 1,500-year periodicity of unknown origin, possibly linked to ocean circulation patterns and changing moisture sources. Carbon isotopes show a broad shift at about 5,000 years before present that is probably linked to ecosystem changes, as deeper soil and more extensive forest cover developed in Central Texas. None of these chemical or isotopic variations can be directly related to specific measures of past drought intensity or duration. Speleothems are an area of active research. More detailed regional and temporal patterns will likely emerge as more high-resolution records become available, improving our understanding of how climate has changed in the past. Speleothems have potential as indicators of long-term changes in the intensity and frequency of drought, but are currently of limited use for identifying individual drought events and quantifying their severity.

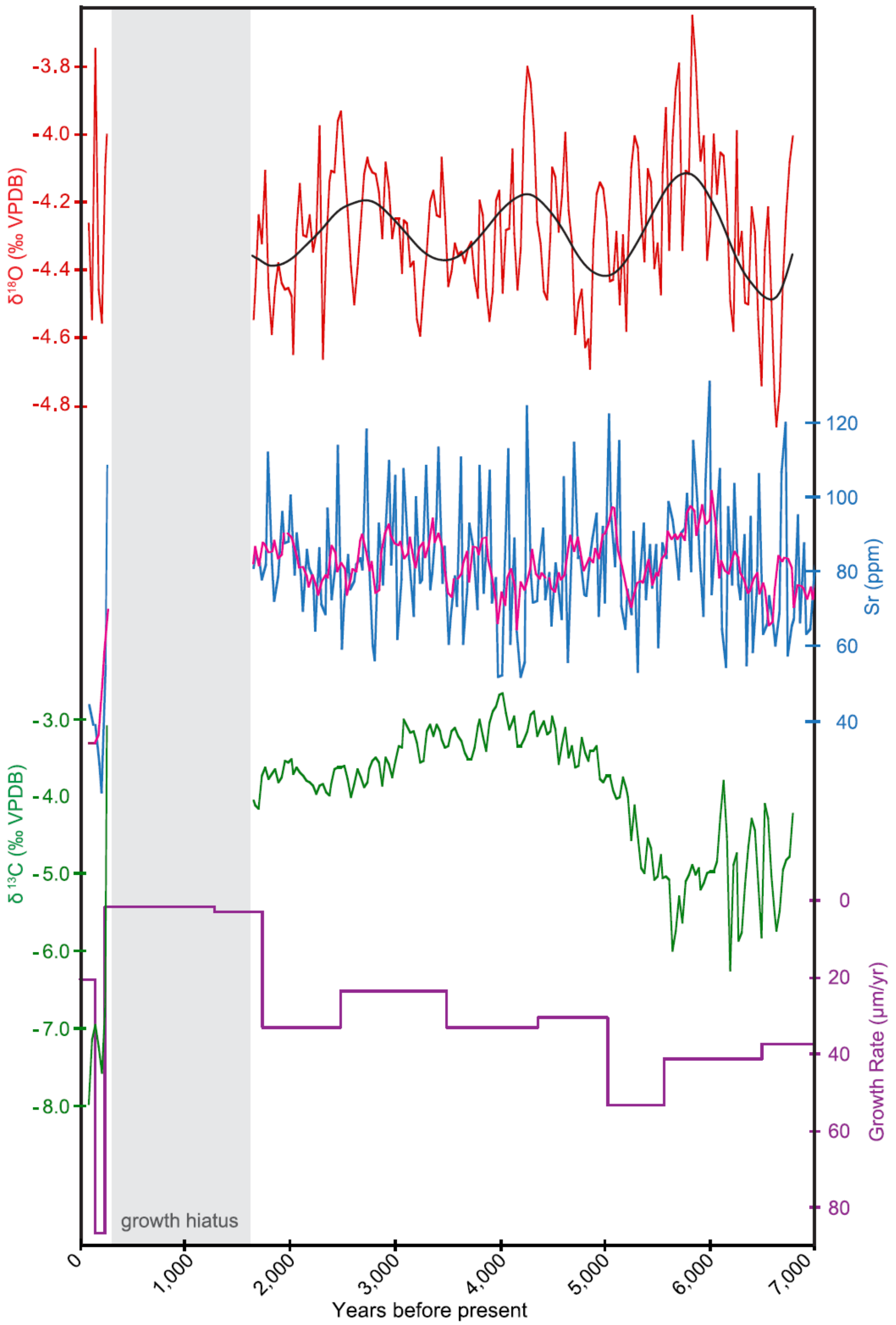


Figure 4-2. **Natural Bridge Cavern, Texas speleothem chronology showing oxygen isotopes (red), strontium concentrations (blue), carbon isotopes (green), and growth rate (purple). The 1,500-year leading component of variability (black) of the oxygen isotope time series, accounts for 25% of the variation. Pink curve (5-point smooth of the 30-yr Sr concentration) shows lower frequency variability. Growth rate axis is inverted. From Wong, Banner, and Musgrove, 2015.**

5.0 Conclusions

Because of its extended duration, the 1950s drought remains the most severe for Texas within the period of historical records. The 2010-2015 drought included the most severe 12-month period of drought on record, with the highest summer temperatures, the highest 12-month average temperature, and the lowest 12-month total precipitation on record for the state, while the streamflow deficit exceeded that for the 1950s drought. A combination of moderating drought conditions in 2012 through 2014 and the conservation and adaptation measures that were implemented prevented depletion of water supplies in major metropolitan areas below the crisis levels reached in the 1950s drought, but many localities were forced to take emergency measures to secure additional water supplies.

Accounting of drought impacts is uncertain at best and is especially problematic when comparing events taking place over a half-century apart. Drought is not a discrete event like a flood or storm. Impacts accrue over time and need to be tracked and reassessed to ascertain the total impact. But after drought breaks, often in a flood, the interest in tracking drought impacts may quickly diminish. No comprehensive accounting of the costs of the 1950s drought has ever been completed, and though a flurry of reports on the costs of the 2010-2015 drought were issued in 2012, costs associated with the remaining years of the drought have received minimal attention. There does not appear to be any accepted statistical dataset or methodology to assess drought impacts outside of the agricultural sector, and even in agriculture simple accounting models based on static markets are inadequate for evaluating the total, multi-year costs of droughts. Additionally, non-agricultural costs are seldom included in estimates of drought impacts because costs outside the agricultural sector are difficult to link directly to drought conditions.

Social change over the half century between the 1950s and 2010-2015 droughts further complicates direct comparison of drought impacts associated with the two events. Factors including a shift from rural to urban lifestyles, industrialization and technological advances, growth of crop insurance and other government farm support systems, and development of broader strategies for diversification and risk hedging by farm operators, together with extensive reservoir construction, mitigated the social and economic costs of the 2010-2015 drought in Texas in comparison to the 1950s drought.

More systematic monitoring and reporting of drought impacts would help address these issues, clarifying how drought events affect different sectors of society and how the effects change over time. Monitoring and reporting systems for drought impacts could help allocate drought response resources and could improve tracking of long-term impacts on the Texas economy, comparable to what is currently tracked in the agricultural sector.

Variability in demand for water means reductions in water supply during drought do not immediately impact the economy to the extent one might predict based on simple models. Farmers need to be good businesspeople to stay on the land. They adapt and hedge as best they can, and net farm income does not show the full extent of predicted losses. Costs in other sectors can be even harder to quantify. For example, costs to households for lawns and landscaping are not tracked in any official database, and a newly xeriscaped lawn may save money over time. Additionally, costs to businesses for development of additional water supplies or increased water treatment are not aggregated in official documents and may drive adoption of improved processes and equipment. The quality of life added by a century-old shade tree is not readily accounted for by its value as lumber products, and the cost to remove a shade tree killed by drought may not show up until months or years after the drought is over.

The specter of major reservoirs running dry and large cities rationing water are real risks in Texas. More than one reservoir effectively went dry during the 2010-2015 drought. For example, Lake Meredith went dry, but the Panhandle cities kept going. Planning and investment can make situations tolerable that might otherwise be disastrous.

6.0 References

Alston J.M., James J.S., Andersen M.A., Pardey P.G., 2010, A Brief History of U.S. Agriculture. In: Persistence Pays. Natural Resource Management and Policy, vol 34. Springer, New York, NY, link.springer.com/chapter/10.1007/978-1-4419-0658-8_2

American Meteorological Society, 2013, Drought, an information statement of the American Meteorological Society, www.ametsoc.org/ams/index.cfm/about-ams/ams-statements/statements-of-the-ams-in-force/drought/

Anderson, D.P., Welch, J.M. and Robinson, J., 2012, Agricultural Impacts of Texas's Driest Year on Record, Agricultural & Applied Economics Association, Choices, 3rd Quarter 2012, Vol. 27, No. 3, ageconsearch.umn.edu/bitstream/137449/2/cmsarticle_248.pdf

Basara, J.B., Maybourn, J.N., Peirano, C.M., Tate, J.E., Brown, P.J., Hoey, J.D., and Smith, B.R., 2013, "Drought and Associated Impacts in the Great Plains of the United States—A Review." International Journal of Geosciences, 2013, vol. 4, pp. 72-81.

Black and Veatch, 2013, Draft water use and availability in the ERCOT region: Drought analysis, www.ercot.com/content/committees/other/lts/keydocs/2013/ERCOT_Water_Use_and_Availablility_-_DrtRpt_1DF.pdf

Botts, R.R. and Otte. R.C., 1958, Insurance against losses on farms, in *Land, the yearbook of agriculture, 1958,* pp. 230-239.-U.S. Department of Agriculture publication, archive.org/details/yoa1958/page/n293

Brauer, D., Baumhardt, R.L., Gitz, D., Gowda, P., and Mahan, J., 2015; Characterization of trends in reservoir storage, streamflow, and precipitation in the Canadian River watershed in New Mexico and Texas, Lake and Reservoir Management, Vol 31No. 1, pp 64-79.

Burnett, J., 2012, When the sky ran dry. Texas Monthly, www.texasmonthly.com/articles/when-the-sky-ran-dry/

Buss, T., 2016, "Drought's end brings rainbow of opportunity for home builders, buyers," Times Record News, February 28, 2016, archive.timesrecordnews.com/special/imagine-wichita-falls/quality-of-life/droughts-end-brings-rainbow-of-opportunity-for-home-builders-buyers-2a2de87a-1dc6-4136-e053-0100007f-371001941.html

Cargill, 2013, Cargill to idle Plainview, Texas, beef processing plant; dwindling cattle supply cited, news release, www.cargill.com/news/releases/2013/NA3070552.jsp

City of Austin, 2017, Austin Water 2016-2017 Approved Budget, www.austintexas.gov/edims/document.cfm?id=277813

City of Wichita Falls, 2014, Frequently asked questions about Wichita Falls water 2014, www.wichitafallstx.gov/DocumentCenter/View/20379

Cleaveland, M.K., Votteler, T.H., Stahle, D.K., Casteel, R.C., and Banner, J.L., 2011, Extended chronology of drought in south central, southeastern and west Texas, Texas Water Resources Institute, Texas Water Journal, Vol. 2, No. 1, pp. 54–96; journals.tdl.org/twj/index.php/twj/article/view/2049

Combs, S., 2014, Texas Water Report: Going deeper for the solution, www.nacubo.org/-/media/Nacubo/Documents/BusinessPolicyAreas/WaterReportTexas.ashx?la=en&hash=2430CAB76190FD20C7D3DC4D251C7C2D31159107

Cook, E.R., Meko, D.M., Stahle, D.W., and Cleaveland. M.K., 1999. Drought reconstructions for the continental United States. Journal of Climate, 12:1145-1162.

Cook, E.R., Seager, R., Cane, M.A., and Stahle, D.W., 2007, North American drought: reconstructions, causes, and consequences, Earth-Science Reviews, Vol. 81 (2007) pp. 93–134.

Cook, E. R., Seager, R., Heim, R. R., Vose, R. S., Herweijer, C., and Woodhouse, C. W. ,2010, Megadroughts in North America: Placing IPCC projections of hydroclimatic change in a long-term paleoclimate context. Journal of Quaternary Science, 25(1), 48-61.

Cook, E.R. and National Center for Atmospheric Research Staff (Eds), 2017, The Climate Data Guide: Drought atlases from tree rings, climatedataguide.ucar.edu/climate-data/drought-atlases-tree-rings

Canadian River Municipal Water Authority (CRMWA), 2017a. Lake Meredith: Frequently asked questions, www.crmwa.com/FAQ

Canadian River Municipal Water Authority (CRMWA), 2017b, John C. Williams Aqueduct & Wellfield – Phase I & II, www.crmwa.com/john-c-williams-aqueduct-wellfield-phase-i-ii

Del Rio Chamber of Commerce, 2017, The great Acuna flood, www.drchamber.com/The-Great-Acuna-Flood

Eagle Land and Livestock Post, 2006, Historic losses facing Texas' wheat industry, May 15, 2006, www.theeagle.com/landandlivestockpost/historic-losses-facing-texas-wheat-industry/article_6740461a-68e9-5f50-8c8d-ead6f43b3495.html

Electric Reliability Council of Texas (ERCOT), 2017, Resource adequacy 2016: Drought risk, www.ercot.com/gridinfo/resource/2016

Espinola, A., 2016, How one utility won public support for potable reuse, American Water Works Association legislation and regulation news, www.awwa.org/AWWA-Articles/how-one-utility-won-public-support-for-potable-reuse

Fannin, B., 2012, Updated 2011 Texas agricultural drought losses total $7.62 billion, AgriLife Today Texas A&M University, agrilifetoday.tamu.edu/2012/03/21/updated-2011-texas-agricultural-drought-losses-total-7-62-billion/

Federal Reserve Bank of St. Louis, 2017; Per capita personal income in Texas, fred.stlouisfed.org/series/TXPCPI

Foster, T., Brozovic, N., and Butler, A.P., 2015, Why well yield matters for managing agricultural drought risk, Weather and Climate Extremes, V. 10, Part A, December 2015, pp. 11-19.

FRED Economic Research, 2017a, Crude Oil Prices: West Texas Intermediate (WTI) - Cushing, Oklahoma, Federal Reserve Bank of St. Louis, fred.stlouisfed.org/series/DCOILWTICO

Gille, E.P., Wahl, E.R., Vose, R.S., and Cook, E.R., 2017, Living Blended Drought Atlas (LBDA) Version 2 - recalibrated reconstruction of United States Summer PMDI over the last 2000 years, www.ncdc.noaa.gov/paleo-search/study/22454

Guerrero, B., 2012, The impact of agricultural drought losses on the Texas economy, 2011, Texas Agrilife Extension briefing paper, updated 4/2/2012, agecoext.tamu.edu/wp-content/uploads/2013/07/BriefingPaper09-01-11.pdf

Hargrove, B., 2014, "The effluent society: In the midst of an unprecedented drought, Wichita Falls is turning to a once unthinkable source to slake its thirst." Texas Monthly, June 2014, www.texasmonthly.com/politics/the-effluent-society/

Harrington, P., and Lacewell, R., 2015, Impacts of Institutions on Water Conservation Incentives in the Texas Rio Grande Valley; Texas Water Resources Institute Technical Report TR-481, September 2015, twri.tamu.edu/publications/technical-reports/2015-technical-reports/tr-481-impacts-of-institutions-on-water-conservation-incentives-in-the-texas-rio-grande-valley/

Harto, C.B. and Yan, Y.E., 2011, Analysis of drought impacts on electricity production in the western and Texas interconnections of the United States, Environmental Science Division, Argonne National Laboratory, report ANL/EVS/R-11/14, www.osti.gov/biblio/1035461-analysis-drought-impacts-electricity-production-western-texas-interconnections-united-states

Hatfield, T.M., 1965, "The Texas drought of 1950-1956," MA thesis, the University of Texas at Austin, 179 pp.

Helms, J.D., 1985, Brief history of the USDA soil bank program, www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1045666.pdf

Herweijer, C., Seager, R., Cook, E.R., and Emile-Geay, J., 2007, North American droughts of the last millennium from a gridded network of tree-ring data, Journal of Climate, vol. 20, pp. 1353 – 1376, journals.ametsoc.org/doi/full/10.1175/JCLI4042.1

Jarvis, G., 2014, Historical Development of Texas Surface Water Law: Background of the Appropriation and Permitting System and Management of Surface Water Resources, glennjarvis.com/water-rights-adjudication/3_Hist_Devlpmnt_TX_Surf_Wtr_Law.pdf

Johnson, L.B., [Washington News Letter from Lyndon B. Johnson - 1953-10-12], periodical, October 12, 1953; (texashistory.unt.edu/ark:/67531/metapth249179/: accessed November 9, 2017), University of North Texas Libraries, The Portal to Texas History, texashistory.unt.edu; crediting Houston Metropolitan Research Center at Houston Public Library.

Kerr, E., 2012, Brutal drought depresses agriculture, thwarting U.S. and Texas economies, in *Southwest Economy*, Federal Reserve Bank of Dallas, Fourth Quarter 2012, www.dallasfed.org/~/media/documents/research/swe/2012/swe1204c.pdf

Lachinet, M.S., 2009, Climatic and environmental controls on speleothem oxygen-isotope values, Quaternary Science Reviews, vol. 28, pp. 412–432, www.sciencedirect.com/science/article/abs/pii/S0277379108003119

Lower Colorado River Authority (LCRA), 2012; Most downstream farmers will go without Highland Lakes water this year, press release dated March 02, 2012 10:35 AM.

Lower Colorado River Authority (LCRA), 2020a; Lakes Buchanan and Travis water management plan and drought contingency plans, www.lcra.org/water/water-supply-planning/water-management-plan-for-lower-colorado-river-basin

Lower Colorado River Authority (LCRA), 2020b; Appendix A: Technical Papers, A-7 Proposed Methodology for identifying a Drought Potentially Worse Than the Drought of Record, www.lcra.org/water/water-supply-planning/water-management-plan-for-lower-colorado-river-basin

Lexico, 2021, Definition of drought, www.lexico.com/en/definition/drought

Long, D., Scanlon, B.R., Longuevergne, L., Sun, A.Y., Fernando, N., and Save, H., 2013, GRACE satellite monitoring of large depletion in water storage in response to the 2011 drought in Texas, Geophysical Research Letters, Vol. 40, No. 13, pp. 3395-3401.

Lowry, R.L., 1959. A study of droughts in Texas; Texas Board of Water Engineers Bulletin 5914, www.twdb.texas.gov/publications/reports/bulletins/doc/B5914/B5914.pdf

McNab, A.L., and Karl, T.R., 1989, Climate and droughts, in Paulson, R.W., Chase, E.B., Roberts, R.S., and Moody, D.W., Compilers, National Water Summary 1988-89 Floods and Droughts: Hydrology, US Geological Survey Water Supply Paper 2375, pp. 89-98.

Malagarie, D., 2016, “Wichita Falls housing market springs into 2016,” KAUZ news, May 2, 2016, www.newschannel6now.com/story/31870659/wichita-falls-housing-market-springs-into-2016

Martinez, J.E., 2014, State of the local economy, fourth quarter 2014, msutexas.edu/Assets/documents/academics/business/center/Q4-2014/State-of-Local-Economy-Q4-2014.pdf

Mills, S., and Martinez, F., 2014, San Antonio Water System 2013 stats book.

Mills, S., and Martinez, F., 2015, San Antonio Water System 2014 stats book.

Muehlbeier, J., 1958, Land-use problems in the Great Plains, in *Land: The Yearbook of Agriculture, 1958*, U.S. Department of Agriculture, pp. 161-166, archive.org/stream/yoa1958#page/n231/ mode/2up

Musgrove, M., Banner, J.L., Mack, L.E., Combs, D.M., James, E.W., Cheng, H., and Edwards, R.L., 2001, Geochronology of late Pleistocene to Holocene speleothems from central Texas: Implications for regional paleoclimate, GSA Bulletin vol. 113, no. 12, pp. 1532-1543.

Musgrove, M., and Banner, J.L., 2004, Controls on the spatial and temporal variability of vadose dripwater geochemistry; Edwards aquifer, central Texas: Geochimica et Cosmochimica Acta, v. 68, p. 1007–1020.

Nace, R. L., and Pluhowski, E. J., 1965, Drought of the 1950's with Special Reference to the Midcontinent, USGS Water Supply Paper 1804, 93 pp.

National Centers for Environmental Information (NCEI), 2017a, Divisional temperature-precipitation-drought data, ftp.ncdc.noaa.gov/pub/data/cirs/climdiv/

National Centers for Environmental Information (NCEI), 2017b, Tool for retrieval of national, regional, state, and divisional data, www7.ncdc.noaa.gov/CDO/CDODivisionalSelect.jsp#

National Centers for Environmental Information (NCEI), 2017c, Historical Palmer drought indices, www.ncdc.noaa.gov/temp-and-precip/drought/historical-palmers/

National Drought Mitigation Center, 2017, Climate Division Standardized Precipitation Index (SPI), drought.unl.edu/droughtmonitoring/SPI/Maps.aspx

National Drought Monitor, 2017, Data download, comprehensive statistics, droughtmonitor.unl.edu/Data/DataDownload/ComprehensiveStatistics.aspx

National Institute of Standards and Technology (NIST), 2017, Single exponential smoothing, Engineering Statistics Handbook, section 6.4.3.1., www.itl.nist.gov/div898/handbook

Nielsen-Gammon, J.W., 2012, The 2011 Texas drought; Texas Water Journal vol. 3, no. 1, pp. 59-95.

Oliver, R., 2013, "Drought takes big bite out of beef industry ," part 4 of 4 in special feature "Running Dry," San Antonio Express News, www.expressnews.com/news/item/Ranchers-have-a-beef-with-Mother-Nature-24069.php

Palmer, W.C., 1965, Meteorological Drought; U.S. Weather Bureau Office of Climatology Research Paper No. 45.

Paulson, R.W., Chase, E.B., Roberts, R.S., and Moody, D.W., Compilers, 1991, National Water Summary 1988-89--Hydrologic Events and Floods and Droughts: U.S. Geological Survey Water-Supply Paper 2375.

Quiring, S., Nielsen-Gammon, J.W., Srinivasan, R., Miller, T. and Narasimhan, B., 2012, Drought monitoring index for Texas; contract report to TWDB, www.twdb.texas.gov/publications/reports/contracted_reports/doc/2005483028_drought_index.pdf

Ramsey, R. and Satija, N., 2013, "All nine constitutional amendments approved," Texas Tribune, November 6, 2013, www.texastribune.org/2013/11/06/election-results-headline/

Rochelle, M.C. , 2015, A water session: Highlights from the 83rd Texas Legislature, presentation to the North Central Texas AWWA Drinking Water Seminar, www.lglawfirm.com/wp-content/uploads/2015/09/A-Water-Session.pdf

Saffell, C.L. 2000, When did King Cotton move his throne (and has it moved back)? Agricultural Historical Society vol 74, no. 2, ppp.293-308, www.jstor.org/stable/3744853

Satija, N. 2014, Four Guys on a Boat Set Out to Tackle a Texas-Sized Water Problem, Texas Tribune, July 30, 2014, www.texastribune.org/2014/07/30/four-guys-and-boat-tackle-texas-sized-water-proble/

State Fire Marshall, 2012, Fires in Texas, 2011 annual fire statistics.

Stepney, L., 2017, 'Texas Commission on Environmental Quality Select Water Issues,' Testimony to House Natural Resources Committee Hearing – March 1, 2017

Svoboda, M., 2017, Drought Monitor maps for Texas, droughtmonitor.unl.edu/Maps/MapArchive.aspx

Svoboda, M. and Fuchs, B.A., 2016, Handbook of Drought Indicators and Indices, Integrated Drought Management Tools and Guidelines Series 2; World Meteorological Organization and Global Water Partnership Integrated Drought Management Program, publication No. 1173, 52 p.

Texas Almanac, 1958-1959, University of North Texas Libraries, The Portal to Texas History, texashistory.unt.edu; crediting Texas State Historical Association; p. 215, texashistory.unt.edu/ark:/67531/metapth117139/m1/217/

Texas Almanac online, Lakes and Reservoirs, texasalmanac.com/topics/environment/lakes-and-reservoirs

Texas A&M Forest Service, 2011, Texas Wildfires: Common Denominators of Home Destruction, tfsweb.tamu.edu/uploadedFiles/TFSMain/Preparing_for_Wildfires/Prepare_Your_Home_for_Wildfires/Contact_Us/2011%20Texas%20Wildfires.pdf

Texas Commission on Environmental Quality (TCEQ), 2014a, LCRA Executive Order EO-072414, www.tceq.texas.gov/assets/public/agency/lcra/LCRA-EO-072414.pdf

Texas Commission on Environmental Quality (TCEQ), 2014b, Public Drinking Water Section Water Supply Division Weekly Drought Report January 17, 2014. Available upon request.

Texas Commission on Environmental Quality (TCEQ), 2015, Public Drinking Water Section Water Supply Division Weekly Drought Report June 6, 2015. Available upon request.

Texas Commission on Environmental Quality (TCEQ), 2017a. Priority Calls: Claiming Water Rights, www.tceq.texas.gov/response/drought/claiming-water-rights

Texas Commission on Environmental Quality (TCEQ), 2017b. Brazos, San Saba, Neches River and Little Sandy Creek priority calls, www.tceq.texas.gov/response/drought/priority.html, www.tceq.texas.gov/response/drought/sansaba-priority.html, www.tceq.texas.gov/response/drought/neches-priority.html, and www.tceq.texas.gov/assets/public/response/drought/littlesandy-priority

Texas Department of Emergency Management (TDEM), 2016, Drought Annex, State of Texas Emergency Management Plan, waterdatafortexas.org/drought/twdb-reports/state_of_texas_drought_annex_2016.pdf

Texas Living Waters, 2014, Evaporation – a loss for humans and wildlife in Texas, texaslivingwaters.org/evaporation-loss-humans-wildlife-texas/

Texas State Historical Association, 2017a. Agriculture, tshaonline.org/handbook/online/articles/ama01

Texas State Historical Association, 2017b, Citrus fruit culture, tshaonline.org/handbook/online/articles/afc01

Texas State Library and Archives Commission, 2017, “Confronting Extreme Drought,” www.tsl.texas.gov/lobbyexhibits/water-extreme

Texas Water Development Board (TWDB), 2016a, Water Reuse, www.twdb.texas.gov/publications/shells/WaterReuse.pdf

Texas Water Development Board (TWDB), 2016b, State Water Implementation Fund for Texas (SWIFT), www.twdb.texas.gov/publications/shells/swift_info_sheet.pdf?d=7026.275000000001

Texas Water Development Board (TWDB), 2017a. Water use summary estimates, www.twdb.texas.gov/waterplanning/waterusesurvey/estimates/index.asp

Texas Water Development Board (TWDB), 2017b, 2017 State Water Plan, Chapter 3, Drought and Drought Response in Texas, www.twdb.texas.gov/waterplanning/swp/2017/chapters/03-SWP17-DROUGHT.pdf

Texas Water Development Board (TWDB), 2017c, Coastal Hydrology – monthly freshwater inflows to major estuaries, www.twdb.texas.gov/surfacewater/bays/coastal_hydrology/index.asp

Texas Water Development Board (TWDB), 2017d, Water Data for Texas, www.waterdatafortexas.org/reservoirs/statewide

Texas Water Development Board (TWDB), 2018a, Streamflow (daily), waterdatafortexas.org/drought/streamflow/daily

Texas Water Development Board (TWDB), 2018b, State Water Implementation Fund for Texas (SWIFT), www.twdb.texas.gov/publications/shells/swift_info_sheet.pdf

Texas Water Development Board (TWDB), 2020, 2020 Biennial Report on the Use of the State Water Implementation Fund for Texas, Report for the 87th Texas Legislature,

www.twdb.texas.gov/publications/reports/special_legislative_reports/index.asp

Texas Water Resources Institute (TWRI), 2011, The grass isn’t greener on the other side: Drought’s effects on waterbodies, crops, livestock, energy, consumers and pocketbooks, TX H_2O newsletter, fall, 2011.

U.S. Bureau of Labor Statistics, 2017a, Consumer price index inflation calculator, data.bls.gov/cgi-bin/cpicalc.pl?cost1=1&year1=195501&year2=201710

U.S. Bureau of Labor Statistics, 2017b, Local Area Unemployment Statistics, Wichita Falls, TX Metropolitan Statistical Area, data.bls.gov/timeseries/LAUMT484866000000004?amp%253bdata_tool=XGtable&output_view=data&include_graphs=true

U.S. Census Bureau, 2012, Texas: 2010, Population and Housing Unit Counts, www.census.gov/prod/cen2010/cph-2-45.pdf

U.S. Department of Agriculture (USDA), 2017, Conservation reserve program, https://www.fsa.usda.gov/programs-and-services/conservation-programs/conservation-reserve-program/

U.S. Department of Agriculture (USDA), National Agricultural Statistics Service, 2006, Crop progress report , April 24, 2006, www.nass.usda.gov/Charts_and_Maps/Crop_Progress_&_Condition/index.php

U.S. Department of Agriculture (USDA), National Agricultural Statistics Service, 2017, Agricultural Statistics, Annual, www.nass.usda.gov

U.S. Department of Agriculture (USDA), Economic Research Service, 2017, Value added to the U.S. economy by the agricultural sector, 2010-2017, data.ers.usda.gov/reports.aspx?ID=17830#P207fbc3692bf4ea1a04285fd969e954c_2_110iT0R0x43

U.S. Geological Survey (USGS), 2012, Streamflow of 2011 - Water Year Summary, USGS Fact Sheet 2012-3085, waterwatch.usgs.gov/2011summary/

U.S. Geological Survey (USGS), 2017, WaterWatch, Table of computed runoff by water-year for Texas, waterwatch.usgs.gov/index.php?r=tx&id=statesum

Von Zuben, F.J., Hayes, G.R., and Anderson, E.C., 1957, Public health disaster aid in the Rio Grande flood of 1954, Public Health Reports 1957; vol. 72, no. 11, pp. 1009–1017.

Ward, G.H., 2013, Hydrological indices and triggers and their application to hydrometeorological monitoring and water management in Texas; University of Texas at Austin Center for Research in Water Resources, contract no. 0904830964, www.twdb.texas.gov/publications/reports/contracted_reports/doc/0904830964_hydrological.pdf

Watson, D., 2016, "Faith, hope rewarded after rains," Wichita Falls Times Record News, June 1, 2016, archive.timesrecordnews.com/special/lifeline/faith-hope-rewarded-after-rains-33c1ae40-70b9-1a8b-e053-0100007f2717--381453871.html

Weiner, J.D., Pulwarty, R.S., and Ware, D., 2016, "Bite without bark: How the socioeconomic context of the 1950s U.S. drought minimized responses to a multiyear extreme climate event," Weather and Climate Extremes 11, pp. 80–94.

Wentzel, M. and Solis, R.S., 2015, Evaluation of Evaporation Suppression Tests on Lake Arrowhead, Texas, Texas Water Development Board Analysis Paper 15-1, www.twdb.texas.gov/publications/reports/technical_notes/doc/TechnicalNote15-01.pdf

Wilhite, D.A., 1982, Government response to drought in the United States, with particular reference to the Great Plains; Journal of Climate and Applied Meteorology, Vol 22, January 1983, pp. 40-50.

Wong, C.I., Banner, J.L., and Musgrove, M., 2015, Holocene climate variability in Texas, U.S.A.: an integration of existing paleoclimate data and modeling with a new high-resolution speleothem record, Quaternary Science Reviews (2015) 1-19.

Wong, C.I. and Breeker, D.O., 2015, Advancements in the use of speleothems as climate archives, Quaternary Science Reviews, vol. 127, pp. 1-18, dx.doi.org/10.1016/j.quascirev.2015.07.019

Young, V.A., 1956, The effect of the 1949-1954 drought on the ranges of Texas, Journal of Range Management, Vol. 9, No. 3 (May, 1956), pp. 139-142, Society for Range Management, www.jstor.org/stable/3894235

Zargar, A., Sadiq, R., Naser, B., and Khan, F.I., 2011. A review of drought indices, Environ. Rev. 19: 333–349.

Zillow, 2017, Zillow Data, www.zillow.com/research/data/

Ziolkowska, J. R., 2016, Socio-Economic Implications of Drought in the Agricultural Sector and the State Economy, Economies 2016, vol. 4, no. 3, 11 p., www.mdpi.com/2227-7099/4/3/19/htm

Appendix A: Drought Indices and Indicators

The TWDB and the Texas Department of Emergency Management use five measures of drought for drought response and planning under the Drought Annex to the State Drought Preparedness Plan (TWDB, 2017a). These include 1) the Keetch-Byram Drought Index, 2) the Palmer Drought Severity Index (PDSI), 3) the Reservoir Storage Index, 4) the Streamflow Index, and 5) the Standardized Precipitation Index (SPI). Table A-1 lists the index values used to define drought categories and drought response in Texas. The U.S. Drought Monitor, which is a composite index, is also used for drought assessment and for informing drought response in Texas. The TWDB also utilizes the Evaporative Demand Drought Index (EDDI) and the Quick Drought Response Index (QuickDRI) as additional drought indicators to monitor whether conditions are favorable for the onset and intensification of drought (using the EDDI), and to monitor near-term impacts on vegetation conditions (using the QuickDRI).

Drought data are widely available on the internet. The TWDB Water Data for Texas webpage (waterdatafortexas.org/drought) provides links to current data for drought monitoring resources. The monthly TWDB Texas Water Conditions Report (www.twdb.texas.gov/surfacewater/conditions/report/index.asp) summarizes data for selected reservoirs, streamflow sites, and groundwater wells. More data, maps, and tools for evaluating drought can be found on the U.S. Drought Portal webpage (www.drought.gov/drought/data-maps-tools).

The TWDB also tracks drought impacts on surface water rights, groundwater levels, public water systems, and wildfires, among others. Links to data on these drought impacts can also be found on the TWDB Water Data for Texas webpage (TWDB, 2022).

Table A-1. Drought categories and index values used in Texas drought response. From Texas Department of Emergency Management, 2016.

Index	Normal to wet	D0 Abnormally dry	D1 Moderate drought	D2 Severe drought	D3 Extreme drought	D4 Exceptional drought
KBDI	0-300	300-400	400-500	500-600	600-700	700-800
PDSI	-0.99 to >4.00	-1.0 to -1.9	-2.00 to -2.99	-3.0 to -3.99	-4.0 to -4.9	< = -5.0
RSI	> = 70%	60-70%	40-60%	20-40%	10-20%	0-10%
SFI	> = 30%	20-30%	15-20%	10-15%	5-10%	< 5%
SPI	-0.49 to >2.0	-0.5 to -0.7	-0.80 to -1.29	-1.30 to -1.59	-1.60 to -1.99	<-2.0

Drought triggers can vary between different entities. An example of the use of drought triggers can be found in Table A-2 below. This example from the Brazos River Authority Drought Contingency Plan shows triggers for Stages 1 - 4 of drought. The triggers are based on specific water storage volumes, surface elevation, or reservoir drawdown for the reservoirs within the Brazos River Authority service area.

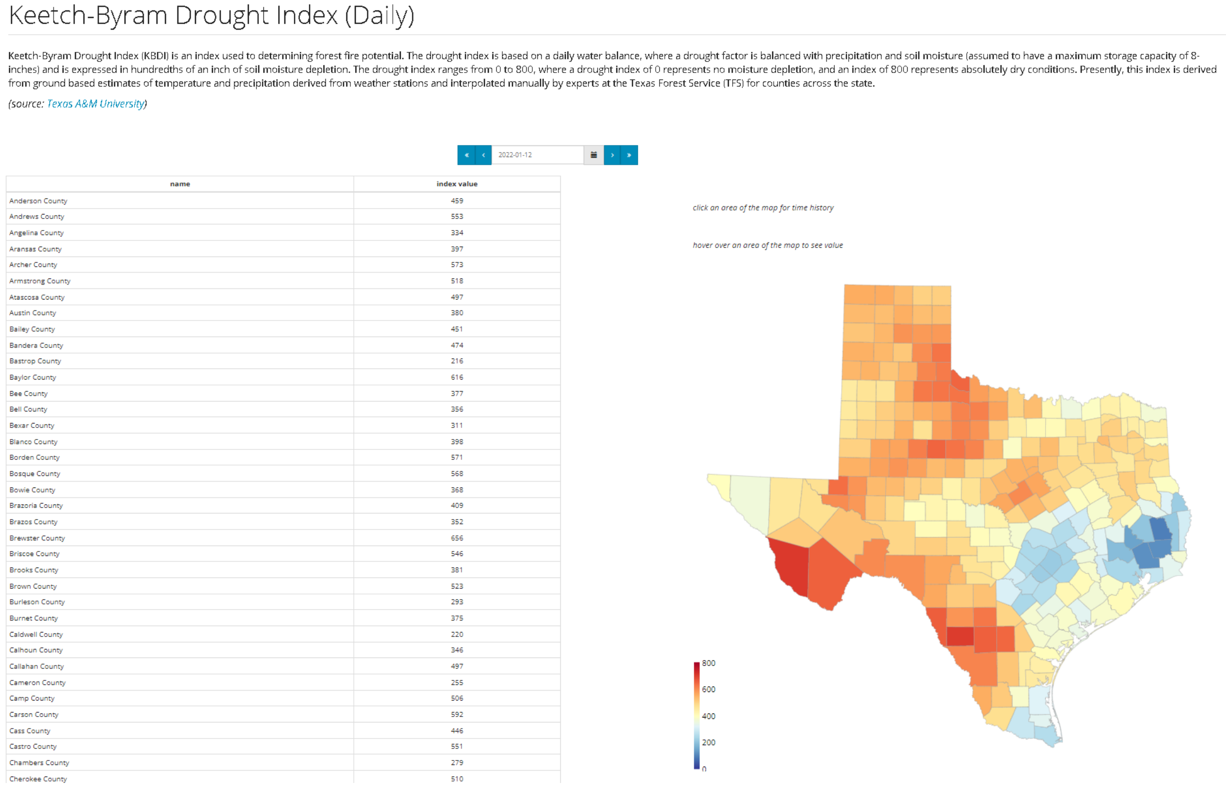
Table A-2. **Drought severity triggers for reservoirs within the Brazos River Authority service area. From the Brazos River Authority Drought Contingency Plan, 2019.**

Drought Severity Triggers[1]			
Status	**Surface Elevation[4]**	**Water Storage[4]**	**Reservoir Drawdown**
	(ft msl)	**(acre-feet)**	**(ft)**
Lake Aquilla			
Top of Conservation (full)	537.5	43,293	0
Stage 1 Drought Watch	533.6	32,253	3.9
Stage 2 Drought Warning	530.5	25,189	7.0
Stage 3 Drought Emergency	526.8	18,125	10.7
Stage 4 Pro-rata Curtailment	523.7	13,436	13.8
Lake Belton			
Top of Conservation (full)	594	432,631	0
Stage 1 Drought Watch	588.1	363,410	5.9
Stage 2 Drought Warning	578.7	268,231	15.3
Stage 3 Drought Emergency	566.3	173,052	27.7
Stage 4 Pro-rata Curtailment	550.2	86,526	43.8
Lake Granger			
Top of Conservation (full)	504	51,822	0
Stage 1 Drought Watch	501.8	43,116	2.2
Stage 2 Drought Warning	498.4	31,935	5.6
Stage 3 Drought Emergency	494.1	20,754	9.9
Stage 4 Pro-rata Curtailment	490.0	12,956	14
Lake Limestone			
Top of Conservation (full)	363	203,780	0
Stage 1 Drought Watch	357.6	142,646	5.4
Stage 2 Drought Warning	354.8	115,136	8.2
Stage 3 Drought Emergency	351.5	87,625	11.5
Stage 4 Pro-rata Curtailment	346.9	56,927	16.1
Lake Proctor			
Top of Conservation (full)	1162	54,762	0
Stage 1 Drought Watch	1,158.2	38,388	3.8
Stage 2 Drought Warning	1,156.1	31,297	5.9
Stage 3 Drought Emergency	1,153.3	24,206	8.7
Stage 4 Pro-rata Curtailment	1,150.1	16,976	11.9
Lake Somerville			
Top of Conservation (full)	238	150,293	0
Stage 1 Drought Watch	234.9	117,229	3.1
Stage 2 Drought Warning	231.8	88,673	6.2
Stage 3 Drought Emergency	228.2	60,117	9.8
Stage 4 Pro-rata Curtailment	223.9	30,059	14.8

Drought Severity Triggers[1] Continued			
Status	**Surface Elevation[2]**	**Water Storage[2]**	**Reservoir Drawdown**
	(ft msl)	**(acre-feet)**	**(ft)**
Lake Possum Kingdom, Lake Granbury, Lake Whitney[3]			
Top of Conservation (full)	N/A[4]	724,022[5]	N/A[4]
Stage 1 Drought Watch	N/A[4]	564,737[5]	N/A[4]
Stage 2 Drought Warning	N/A[4]	427,173[5]	N/A[4]
Stage 3 Drought Emergency	N/A[4]	289,609[5]	N/A[4]
Stage 4 Pro-rata Curtailment	N/A[4]	144,804[5]	N/A[4]
Lake Georgetown, Lake Stillhouse Hollow			
Top of Conservation (full)	N/A[4]	267,949[6]	N/A[4]
Stage 1 Drought Watch	N/A[4]	222,398[6]	N/A[4]
Stage 2 Drought Warning	N/A[4]	164,789[6]	N/A[4]
Stage 3 Drought Emergency	N/A[4]	107,180[6]	N/A[4]
Stage 4 Pro-rata Curtailment	N/A[4]	53,590[6]	N/A[4]
Brazos River Authority System			
Top of Conservation (full)	N/A[4]	1,928,552	N/A[4]
Stage 1 Drought Watch	N/A[4]	1,524,177	N/A[4]
Stage 2 Drought Warning	N/A[4]	1,152,423	N/A[4]
Stage 3 Drought Emergency	N/A[4]	780,668	N/A[4]
Stage 4 Pro-rata Curtailment	N/A[4]	415,273	N/A[4]

1. Triggers were derived using a water availability tool specifically developed to simulate the BRA water supplysystem. Assumptions for developing the triggers include:
    - Estimated year 2030 sedimentation conditions and 2030 demands;
    - Previous 3 year (2015 through 2017) average return flows;
    - Operation of Lake Whitney hydropower;
    - Excluded water rights above Possum Kingdom Lake; and
    - included required environmental flow releases and assumed leakage through the dams
2. Elevation-Capacity Tables are contained in Appendix E.
3. In deriving the triggers, balancing factors established in the Possum Kingdom-Granbury Water ManagementStudy were incorporated.
4. Surface elevation and reservoir drawdown are not applicable because reservoirs are operated as a system. Their combined storage is a better drought indicator than individual elevations because elevations in each reservoir can be influenced by other reservoirs within the system. For example, water can be transferred fromLake Stillhouse Hollow to Lake Georgetown through a pipeline that connects the two lakes. Stillhouse Hollowcould be completely full while Lake Georgetown was 15 feet low, or Georgetown could be completely full withStillhouse Hollow being 2.5 feet low, and in both cases, the collective capacity of the reservoirs is 94% full. Using combined storage instead of individual reservoir elevations for the trigger levels allows the operation of the pipeline to be taken into account.
5. Storages shown are for the combined conservation pool storage volume of Lakes Possum Kingdom, Granbury, and Whitney; BRA storage in Lake Whitney is limited to 51,987 acre-feet.
6. Storages shown are for the combined conservation pool storage volume of Lakes Stillhouse Hollow and Georgetown.

The Keetch-Byram Drought Index (KBDI) (Figure A-1) is used to determine forest fire potential. The index, developed in 1968, is based on daily water balance, temperature, precipitation, and soil moisture (Keetch and Byram, 1968). The TWDB Water Data for Texas website (TWDB, 2022) provides access to daily county-level data from January 1, 2009 to present. The Texas Weather Connection at Texas A&M publishes daily maps of the KDBI with a 4-kilometer grid resolution and county averages at twc.tamu.edu/kbdi.



Keetch-Byram Drought Index (Daily)

Keetch-Byram Drought Index (KBDI) is an index used to determining forest fire potential. The drought index is based on a daily water balance, where a drought factor is balanced with precipitation and soil moisture (assumed to have a maximum storage capacity of 8-inches) and is expressed in hundredths of an inch of soil moisture depletion. The drought index ranges from 0 to 800, where a drought index of 0 represents no moisture depletion, and an index of 800 represents absolutely dry conditions. Presently, this index is derived from ground based estimates of temperature and precipitation derived from weather stations and interpolated manually by experts at the Texas Forest Service (TFS) for counties across the state.

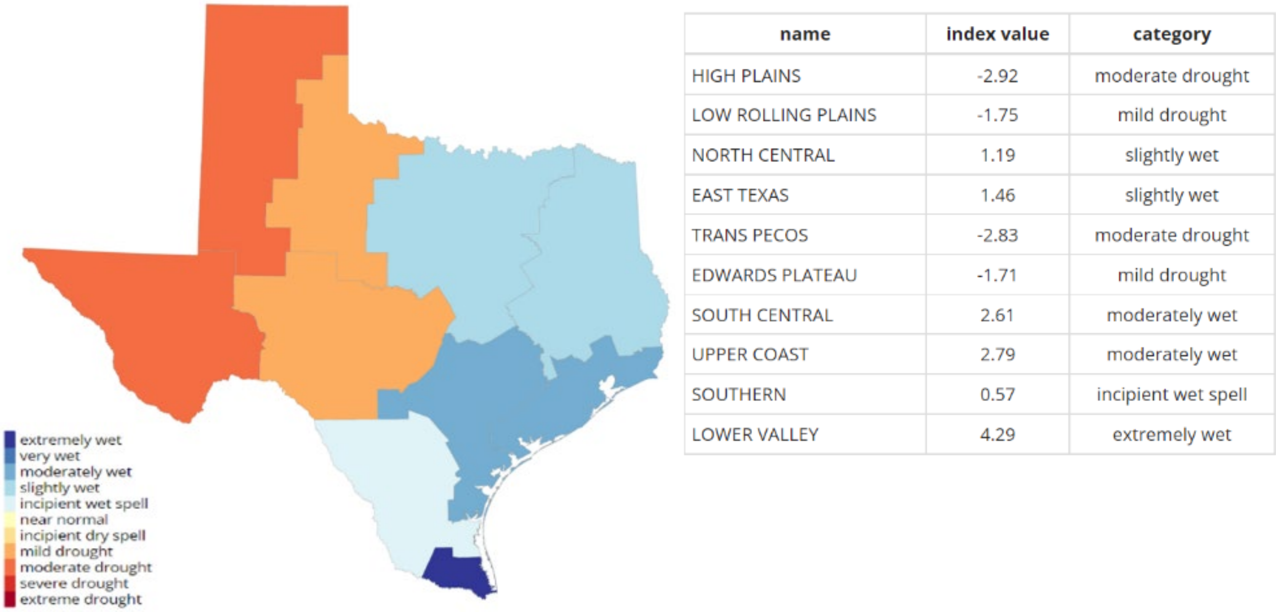
(source: Texas A&M University)

2022-01-12

name	index value
Anderson County	459
Andrews County	553
Angelina County	334
Aransas County	397
Archer County	573
Armstrong County	518
Atascosa County	497
Austin County	380
Bailey County	451
Bandera County	474
Bastrop County	216
Baylor County	616
Bee County	377
Bell County	356
Bexar County	311
Blanco County	398
Borden County	571
Bosque County	568
Bowie County	368
Brazoria County	409
Brazos County	352
Brewster County	656
Briscoe County	546
Brooks County	381
Brown County	523
Burleson County	293
Burnet County	375
Caldwell County	220
Calhoun County	346
Callahan County	497
Cameron County	255
Camp County	506
Carson County	592
Cass County	446
Castro County	551
Chambers County	279
Cherokee County	510

Figure A-1. Keetch-Byrum Drought Index for January 2022. From Water Data for Texas, 2022.

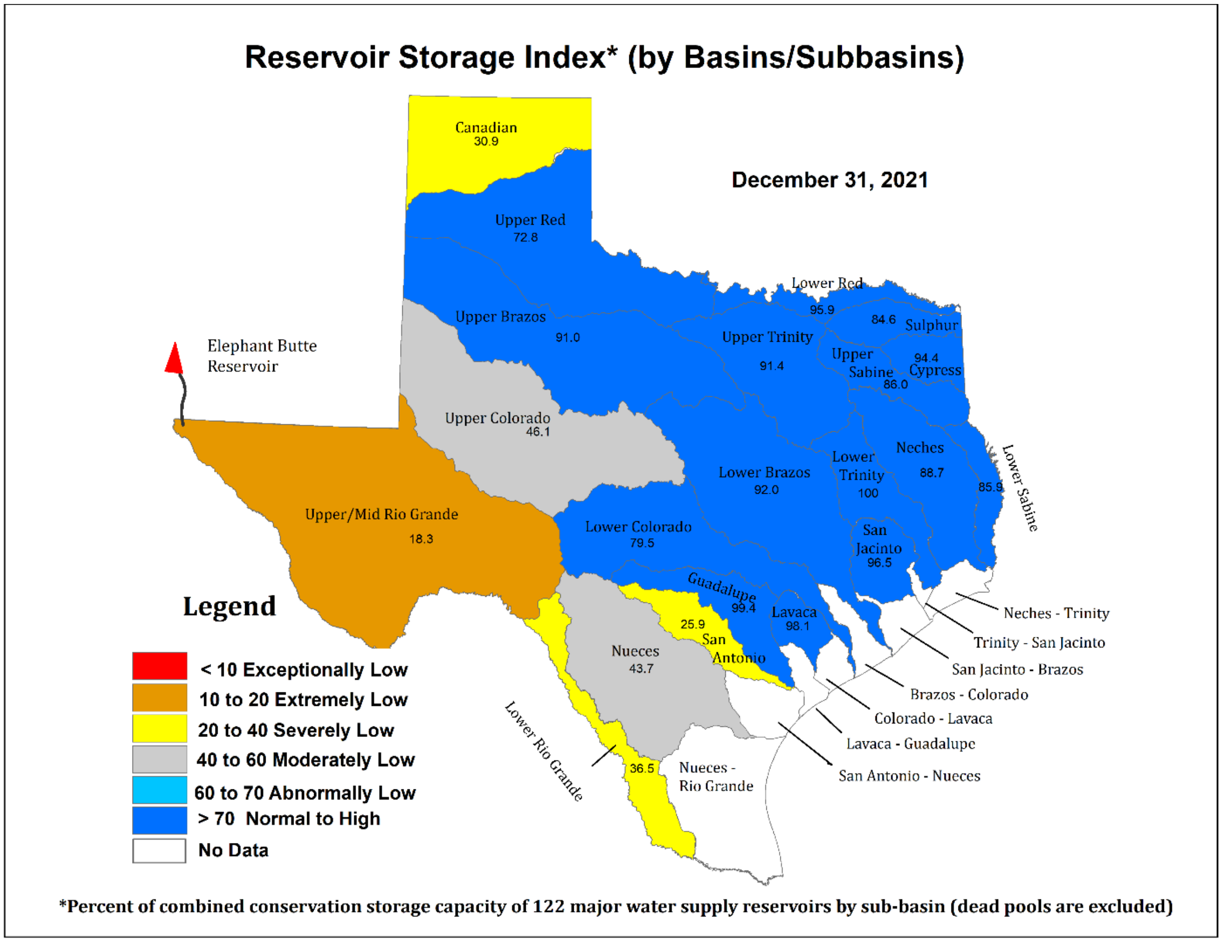
The Palmer Drought Severity Index (PDSI) (Palmer, 1965) is primarily used to reflect long-term drought, on the order of months to years, and is most accurate for non-irrigated cropland (Figure A-2). The PDSI is calculated weekly and monthly. The PDSI is a standardized index that spans -10 (dry) to +10 (wet). It incorporates antecedent and current moisture supply from precipitation and demand from potential evapotranspiration into a hydrological accounting system that includes a 2-layer bucket-type model for soil moisture calculations. Monthly PDSI values do not capture droughts on time scales less than about 12 months. Several different versions of the PDSI are in use, depending on whether the index is calibrated to local conditions instead of using the fixed coefficients originally proposed by Palmer and how evapotranspiration is calculated for the index (Dai, 2017). Alley (1984) notes that the PDSI uses rather arbitrary rules to quantify drought intensity and drought duration, which can cause the index to show abrupt transitions between drought and non-drought periods.



name	index value	category
HIGH PLAINS	-2.92	moderate drought
LOW ROLLING PLAINS	-1.75	mild drought
NORTH CENTRAL	1.19	slightly wet
EAST TEXAS	1.46	slightly wet
TRANS PECOS	-2.83	moderate drought
EDWARDS PLATEAU	-1.71	mild drought
SOUTH CENTRAL	2.61	moderately wet
UPPER COAST	2.79	moderately wet
SOUTHERN	0.57	incipient wet spell
LOWER VALLEY	4.29	extremely wet

Figure A-2. **Palmer Drought Severity Index dashboard for November 2021. From Water Data for Texas, 2022.**

The Reservoir Storage Index (RSI) (Figure A-3) is used to display how much combined water is available in the state's major water supply reservoirs in each river basin and sub-basin. The RSI compares current data from active U.S. Geological Survey (USGS) and U.S. Army Corps of Engineers (USACE) gauges at 109 major water supply reservoirs or lakes with their normal storage or 'conservation storage capacity', which is the volume between dead pool elevation and the conservation pool elevation. The RSI is expressed as a percentage. RSI values do not represent a fixed volume of water or fraction of demand because of changes in the total available reservoir capacity and water usage over time. Current and historical reservoir storage data for Texas are available through the TWDB at the Water Data for Texas webpage (TWDB, 2022). The RSI an important tool used by the TWDB to measure and monitor hydrological drought.


Reservoir Storage Index* (by Basins/Subbasins)

December 31, 2021

*Percent of combined conservation storage capacity of 122 major water supply reservoirs by sub-basin (dead pools are excluded)

Figure A-3. **Reservoir Storage Index by river basin and sub-basin for December 2021.**

The Stream Flow Index (SFI) is also used to measure drought conditions and water quality and helps with calculating impact estimates. The SFI is derived from average daily stream flow data collected from the 29 reference stream stations (Figure A-4 and Table A-3). These reference stations were chosen because they are minimally impacted by development and are representative of conditions across the state. At each station, a 30-day moving average flow is calculated from historical mean daily flow rate records. For each day, the average flow for the preceding 30-days is presented as a percentage of the historical average flow for that calendar day. Periods of record for discharge measurements at the 29 stations range from 50 to 102 years, with a median length of record of 78 years, although daily discharge data may be available for much shorter periods of record. Streamflow index sites have relatively small contributing areas, with a median of 827 square miles. Index sites are generally in upstream areas because dam construction and other development along waterways has changed streamflow patterns over time, complicating interpretation of discharge data in downstream areas. Lowry (1959) notes that "streamflow records are obtained under historical runoff conditions, i.e., the records reflect the watershed uses and conditions at the time measurements were made. Streamflow records obtained for previous conditions must be corrected when additional development takes place on drainage areas above the gaging stations." Areas with minimal development are specifically selected as streamflow index sites so that data from these sites remains comparable throughout the period of record.

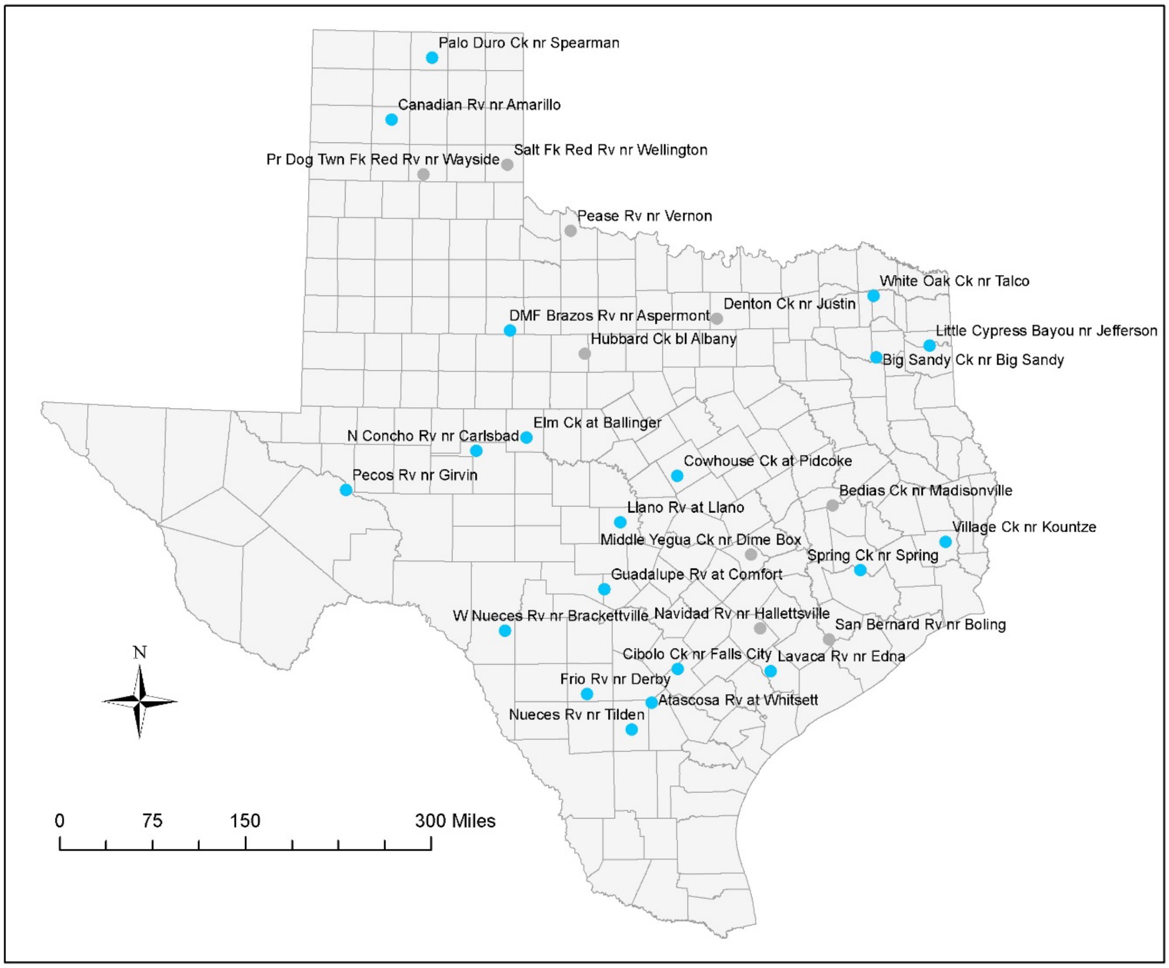


Figure A-4. Locations of streamflow index sites. Records for sites shown with grey symbols do not extend back to 1950.

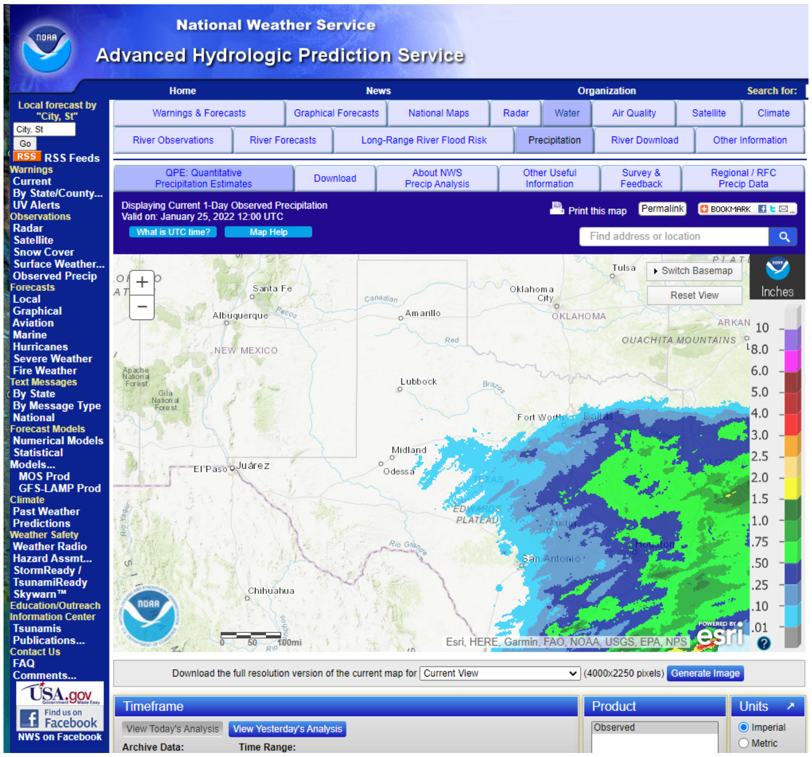
Table A-3. Streamflow index sites in Texas. Sites with data for both 1950s and 2010-2015 drought shown in bold. Data from TWDB, 2022.

Site name	River basin	Site ID	Drainage area (square miles)	Period of record (years)
Atascosa Rv at Whitsett, TX	Nueces	8208000	1171	85.45
Bedias Ck nr Madisonville, TX	Trinity	8065800	321	50.07
Big Sandy Ck nr Big Sandy, TX	Sabine	8019500	231	78.71
Canadian Rv nr Amarillo, TX	Canadian	7227500	19,445	79.59
Cibolo Ck nr Falls City, TX	San Antonio	8186000	827	87.09
Cowhouse Ck at Pidcoke, TX	Brazos	8101000	455	7967.08
Denton Ck nr Justin, TX	Trinity	8053500	400	68.08

DMF Brazos Rv nr Aspermont, TX	Brazos	8080500	1620	93.85
Elm Ck at Ballinger, TX	Colorado	8127000	450	85.59
Frio Rv nr Derby, TX	Nueces	8205500	3429	102.27
Guadalupe Rv at Comfort, TX	Guadalupe	8167000	1371	78.42
Hubbard Ck bl Albany, TX	Brazos	8086212	613	51.07
Lavaca Rv nr Edna, TX	Lavaca	8164000	817	79.22
Little Cypress Bayou nr Jefferson, TX	Cypress	7346070	675	71.42
Llano Rv at Llano, TX	Colorado	8151500	4192	78.13
Middle Yegua Ck nr Dime Box, TX	Brazos	8109700	236	55.24
N Concho Rv nr Carlsbad, TX	Colorado	8134000	1191	93.60
Navidad Rv nr Hallettsville, TX	Lavaca	8164300	332	56.07
Nueces Rv nr Tilden, TX	Nueces	8194500	8093	74.92
Palo Duro Ck nr Spearman, TX	Arkansas	7233500	1076	72.25
Pease Rv nr Vernon, TX	Red	7308200	3488	57.91
Pecos Rv nr Girvin, TX	Rio Grande	8446500	37300	78.17
Pr Dog Twn Fk Red Rv nr Wayside, TX	Red	7297910	3754	50.07
Salt Fk Red Rv nr Wellington, TX	Red	7300000	1941	65.39
San Bernard Rv nr Boling, TX	San Bernard	8117500	727	63.50
Spring Ck nr Spring, TX	San Jacinto	8068500	409	78.59
Village Ck nr Kountze, TX	Neches	8041500	860	93.43
W Nueces Rv nr Brackettville, TX	Nueces	8190500	694	78.10
White Oak Ck nr Talco, TX	Sulphur	7343500	494	67.91

Precipitation data are available in a variety of formats from the National Weather Service Advanced Hydrological Prediction Service (water.weather.gov/precip/), including precipitation amounts and departure from normal precipitation (Figure A-5) for periods ranging from one week to one year.

The Standard Precipitation Index (SPI) (McKee, Doesken, and Kleist, 1993) can be used to monitor conditions on a variety of time scales, typically between one month and one year. This temporal flexibility allows the SPI to be useful in both short-term agricultural and long-term hydrological applications (National Drought Mitigation Center, 2017). In 2009, WMO recommended the SPI as the main meteorological drought index for monitoring and tracking meteorological drought conditions (Hayes, Svoboda, Wall, and Widhalm, 2011). The SPI is the accepted index for characterizing drought in Texas (TWDB, 2017a). The SPI is based on the probability of recording a given amount of precipitation. The probabilities are standardized so that an index of zero indicates the median precipitation amount (half of the historical precipitation amounts are below the median, and half are above the median). The index is negative for drought and positive for wet conditions. As the dry or wet conditions become more severe, the index becomes more negative or positive. The SPI is useful for comparing drought conditions between locations with different climate norms because the index values express the departure from median conditions at each location. Related indices, such as the standardized precipitation-evapotranspiration index (SPEI), build on the SPI by accounting for factors such as evaporative stresses (Vicente-Serrano, Beguria, and Lopez-Moreno, 2010).



Displaying Current 1-Day Observed Precipitation
Valid on: January 25, 2022 12:00 UTC

Download the full resolution version of the current map for Current View (4000x2250 pixels)

Product: Observed

Figure A-5. **Precipitation data from the National Weather Service Advanced Hydrological Prediction Service, January 2022**

Most common measures of drought do not fully capture the scale and severity of hydrological drought, especially for river basins where reservoirs regulate flows or in areas where groundwater aquifers are the dominant source of water supply. The U.S. Drought Monitor is an alternative measure that more fully captures these dimensions of hydrological drought.

The U.S. Drought Monitor issues a weekly map of drought conditions produced jointly by the National Oceanic and Atmospheric Administration, the U.S. Department of Agriculture, and the National Drought Mitigation Center at the University of Nebraska-Lincoln. The map is based on measured weather, hydrologic, and soil conditions as well as reported impacts and observations from more than 350 contributors around the country. The Drought Monitor map is not a strictly quantitative product; it represents a blend of science and expert judgement provided by the community of drought observers. The U.S. Drought Monitor was established in 1999, and the period of record for drought monitor data only extends from 2000 to the present. Consequently, the drought monitor cannot be used to compare recent droughts with the 1950s drought. It is mentioned in this report because of its importance in evaluating drought impacts in future droughts.

The U.S. Drought Monitor is widely used for allocating drought relief. The U.S. Department of Agriculture's Farm Service Agency uses the U.S. Drought Monitor to target relief through the Livestock Forage Disaster Program, the Livestock Assistance Grant Program, and the Non-Fat Dry Milk Program. The Internal Revenue Service also uses the U.S. Drought Monitor to determine the replacement period for livestock sold because of drought. As part of its response to the drought of 2012, the U.S. Department of Agriculture streamlined the process for disaster declarations, making declarations nearly automatic for counties shown by the Drought Monitor to be in severe drought for eight consecutive weeks (U.S. Drought Monitor, 2017). Additionally, the U.S. Drought Monitor is used by the Texas Drought Preparedness Council to develop drought proclamation recommendations for the governor. Inclusion in state drought proclamations makes counties eligible for certain agricultural insurance programs and eases restrictions on the transportation of hay bales needed for supplemental feeding programs.

The Evaporative Demand Drought Index (EDDI, Figure A-6) is an experimental drought monitoring and early warning guidance tool. It examines how anomalous the atmospheric evaporative demand (E_0), also known as "the thirst of the atmosphere", is for a given location and across a time period of interest. EDDI is multi-scalar, meaning that this period—or "timescale"—can vary to capture drying dynamics that themselves operate at different timescales; we generate EDDI at 1-week through 12-month timescales. EDDI categories correspond the US Drought Monitor categories and range from 100% (driest) to 0% (wettest). https://waterdatafortexas.org/drought/evaporative-demand-drought-index, (https://www.esrl.noaa.gov/psd/eddi/).

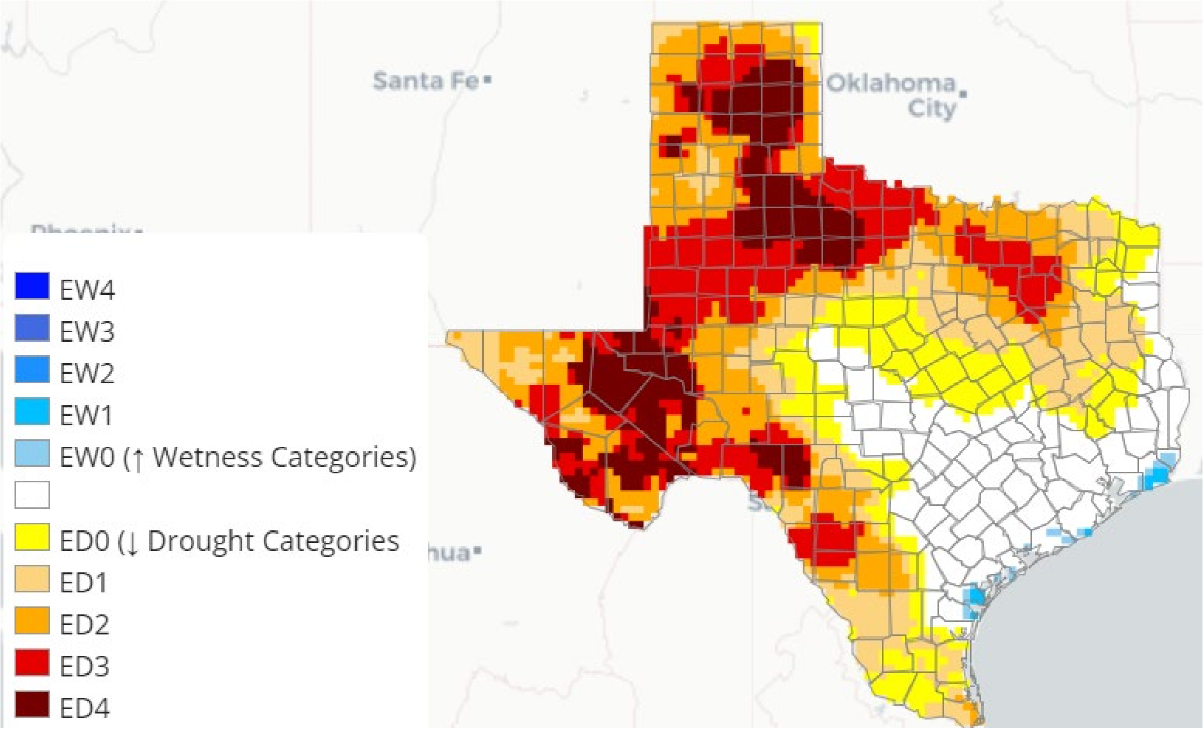


Figure A-6. **Evaporative Demand Drought Index (EDDI) display at Water Data for Texas, November 2021**

QuickDRI (Figure A-7) is a drought index that is designed to detect rapid-onset, “flash drought” events. It is an indicator of short-term dryness of the landscape. It combines several hydrologic and vegetation-related indicators commonly used for drought monitoring. (https://waterdatafortexas.org/drought/quick-drought-response-index)

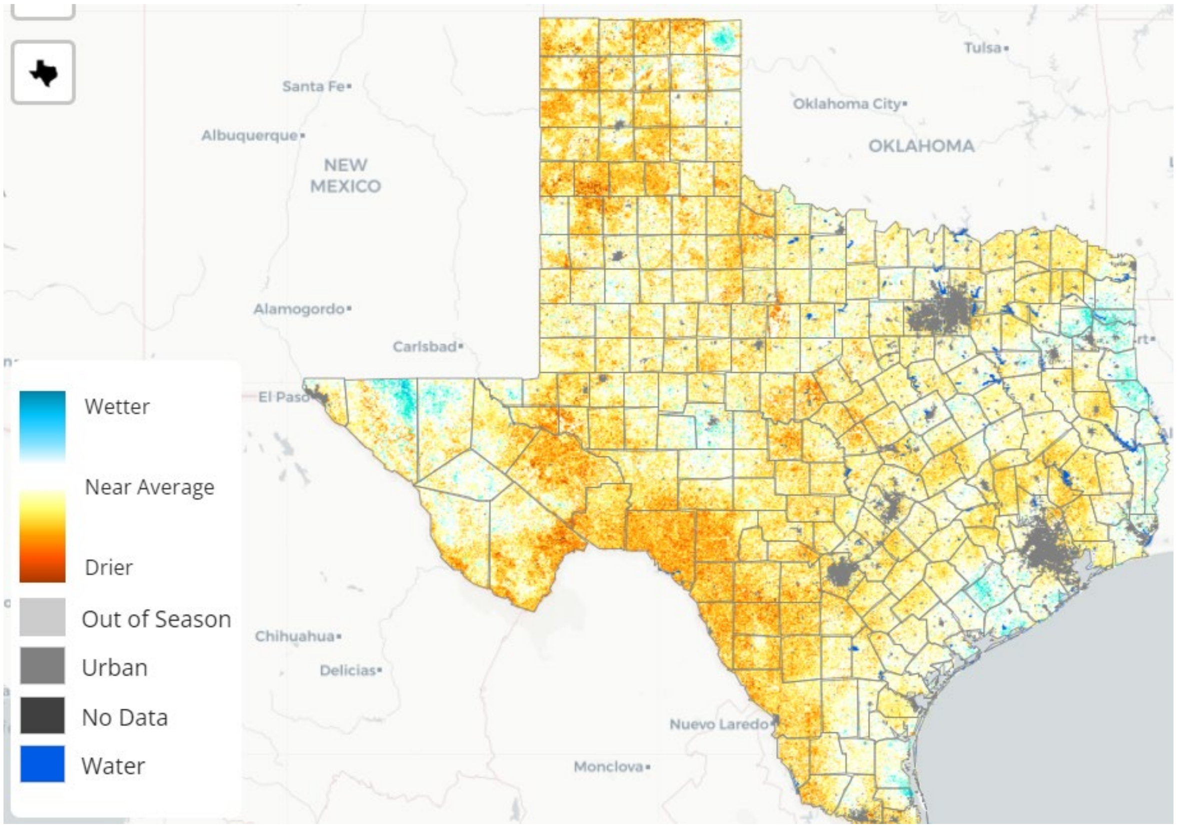


Figure A-7 Quick Drought Response Index display at Water Data for Texas, November 2021

Appendix A References

Alley, W.M., 1984, The Palmer Drought Severity Index: limitations and assumptions,

Journal of Climate and Applied Meteorology, Vol. 23, pp. 1100-1109.

Brazos River Authority, 2019, Drought Contingency Plan, https://brazos.org/Portals/0/drought/DCP-2019.pdf

Dai, A. and National Center for Atmospheric Research Staff (Eds), 2017, The Climate Data Guide: Palmer Drought Severity Index (PDSI), climatedataguide.ucar.edu/climate-data/palmer-drought-severity-index-pdsi

Hayes, M., Svoboda, M., Wall, N., and Widhalm, M., 2011, The Lincoln declaration on drought indices: Universal meteorological drought index recommended, Drought Mitigation Center Faculty Publications. 14. digitalcommons.unl.edu/droughtfacpub/14

Lowry, R.L., 1959. A study of droughts in Texas; Texas Board of Water Engineers Bulletin 5914, www.twdb.texas.gov/publications/reports/bulletins/doc/B5914/B5914.pdf

Keech, J.J. and Byram, G.M., 1968, A drought index for forest fire control, U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station, Research Paper SE-38. 35 p, www.srs.fs.usda.gov/pubs/rp/rp_se038.pdf

McKee, T.B., Doesken, N.J. and Kleist, J., 1993, The relationship of drought frequency and duration to time scales, Eighth Conference on Applied Climatology, 17-22 January 1993, Anaheim, California, www.droughtmanagement.info/literature/AMS_Relationship_Drought_Frequency_Duration_Time_Scales_1993.pdf

National Drought Mitigation Center, 2017, Climate Division Standardized Precipitation Index (SPI), drought.unl.edu/droughtmonitoring/SPI/Maps.aspx

Palmer, W.C., 1965, Meteorological Drought, U.S. Weather Bureau Office of Climatology Research Paper No. 45.

Texas Department of Emergency Management, 2016, Drought Annex, State of Texas Emergency Management Plan, waterdatafortexas.org/drought/twdb-reports/state_of_texas_drought_annex_2016.pdf

(TWDB) Texas Water Development Board, 2017a, 2017 State Water Plan, Chapter 3, Drought and drought response in Texas, www.twdb.texas.gov/waterplanning/swp/2017/chapters/03-SWP17-DROUGHT.pdf

(TWDB) Texas Water Development Board, 2022, Water Data for Texas, waterdatafortexas.org

U.S. Drought Monitor, 2017, About U.S. Drought Monitor, droughtmonitor.unl.edu/About.aspx.

Vicente-Serrano, S.M., Beguria, S., and Lopez-Moreno, J.I., 2010, A multiscalar drought index sensitive to global warming: the standardized precipitation evapotranspiration index, Journal of Climate, Vol. 23, No. 7, pp1696-1718.