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An online, peer-reviewed journal
published in cooperation with the
Texas Water Resources Institute

TEXAS WATER JOURNAL

2011

Volume 2, Number 1

TEXAS WATER JOURNAL

Volume 2, Number 1
2011
ISSN 2160-5319

texaswaterjournal.org

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Texas Water Resources Institute
Texas Water Journal
Volume 2, Number 1, Pages 1–22, August 2011

Statistical relations of precipitation and stream runoff for El Niño and La Niña periods, Texas Hill Country

Raymond M. Slade Jr.[1] *, T. Edwin Chow[2]

Abstract: The Texas Hill Country is threatened by devastating long-duration droughts and short-duration floods, either of which can occur at any time. In Central Texas, El Niño and La Niña conditions each occur about one-quarter of the time. Long-term precipitation data for the area reveal that greater rainfall generally occurs during La Niña periods for summer months but greater rainfall typically occurs during El Niño periods for other months. Annual streamflow peaks cannot be attributed to El Niño or La Niña conditions, but typically occur during the hurricane season (June through November), especially for the largest peaks. Additionally, El Niño period runoff volumes exceed those during La Niña at all runoff-gaged streams in the area. For the streams in the northern part of the Hill Country, El Niño period runoff only slightly exceeds La Niña period runoff. However, for the streams in the southern part of the area, El Niño period runoff greatly exceeds La Niña period runoff.

Keywords: El Niño-Southern Oscillation, Texas Hill Country, floods, drought

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Citation: RM Slade, TE Chow. 2011. Statistical relations of precipitation and stream runoff for El Niño and La Niña periods, Texas Hill Country. Texas Water Journal. 2(1):1-22. Available from: https://doi.org/10.21423/twj.v2i1.3665.

INTRODUCTION

The primary source of all surface water and groundwater in the Texas Hill Country is surface water runoff from precipitation within the area. Without sufficient storm runoff, the entire Hill Country region would be without water over time. However, the area is subject to droughts that are extreme in nature and duration. Data records document that almost all stream reaches and most springs are dry in the Hill Country during some droughts. As a result, substantial declines in groundwater levels occur during droughts and many hundreds, if not thousands, of wells become dry during severe droughts. The area is also subjected to frequent catastrophic flooding due to extreme rainfall rates, some of which represent world record rates. The Hill Country area typically is threatened by long-duration droughts or short-duration floods, either of which can occur at any time.

Climate anomalies associated with flood and droughts can be attributed to the regional ocean temperature phenomena commonly known as El Niño and La Niña. In addition to their influence in the short-term or cyclic variation of precipitation and temperature, El Niño and La Niña periods also have direct impact on streamflow as well. Significant impact of El Niño and La Niña periods on precipitation and streamflow has been reported around the globe, including Australia (Chiew et al. 1998), China (Zhang et al. 2007), Columbia (Gutiérrez and Dracup 2001), Nepal (Shrestha and Kostaschuk 2005), and the United States (Piechota et al. 1997). The effect of climate change associated with El Niño and La Niña also extends to ecosystems (Tolan 2007), wildlife population (Deslippe et al. 2001), and human economy as well (Chen et al. 2001). The purpose of this study is to investigate the relations of precipitation and streamflow for El Niño, La Niña, or neither (other) periods in the Texas Hill Country.

Definition of El Niño and La Niña

Short-term or cyclic variations in precipitation have been attributed to El Niño, which has been labeled as a dominant source of annual climate variability around the world (Trenberth 1997). The meaning of the term, however, has evolved over the years. Originally, the term El Niño applied to an annual weak warm ocean current that ran southward around the coast of Peru and Ecuador about Christmas time (Niño is Spanish for "the boy Christ-child") and subsequently became associated with large ecology-changing warmings that occur every few years. The large warmings, however, are related to extensive anomalous ocean warming, and it is this Pacific basinwide phenomenon that forms the links with the anomalous global climate patterns.

The atmospheric component tied to El Niño is the Southern Oscillation. The term ENSO (El Niño-Southern Oscillation) represents the phenomenon where the atmosphere and ocean collaborate together. La Niña corresponds to the cold phase of ENSO while El Niño represents the warm phase of ENSO and corresponds to basinwide warming in the eastern and central tropical Pacific.

Many scientists, such as the Scientific Committee for Ocean Research working group (SCOR 1983), have attempted to provide a quantitative definition for occurrences and event intensities of El Niño based on coastal data, while others have attempted to define it based on data for the tropical Pacific (Kiladis and van Loon 1988). Most of the definitions are based on variations or standard deviations of the sea surface temperature (SST). However, the definitions include various statistical analyses of temperatures for a subjective number of sites and durations. A single definition has not been accepted by the scientific community, thus identified conditions and periods for occurrences of El Niño and La Niña differ among scientists.

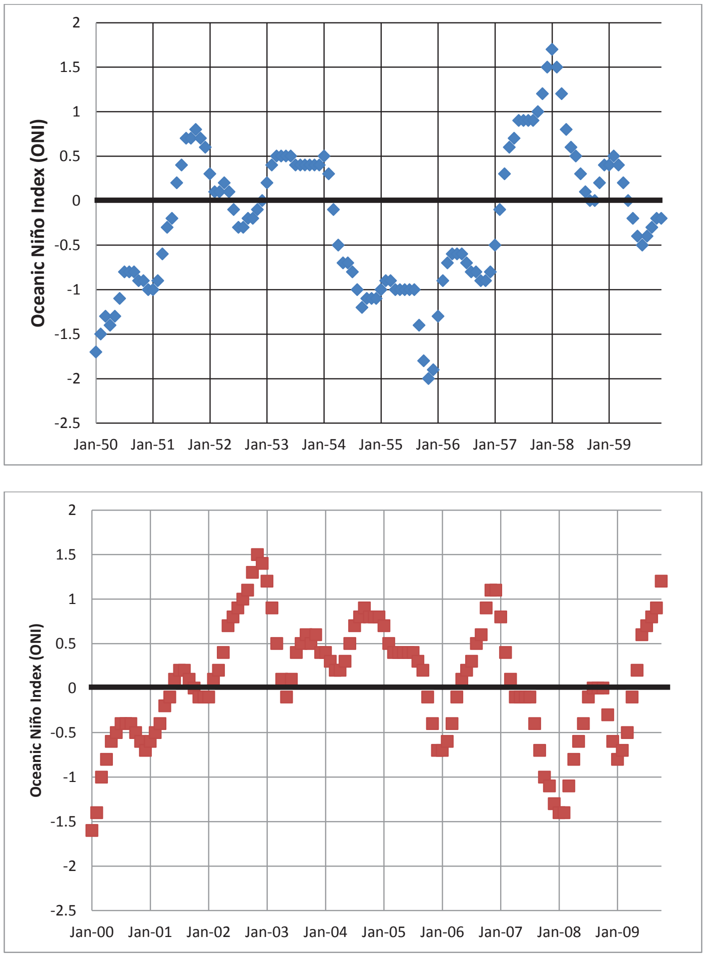


Fig. 1. The monthly Oceanic Niña Indices (ONI) of Niño 3.4 region during 1950s and 2000s.

Indices

The definitions of El Niño and La Niña have varied (Trenberth 2001). Among many definitions, indices such as Southern Oscillation Index (SOI) and Trans-Niño Index (TNI) have been developed to identify conditions and time periods for El Niño and La Niña as identified by the National Center for Atmospheric Research (NCAR 2010). In this study, El Niño and La Niña periods are based on National Oceanographic and Atmospheric Administration's (NOAA) operational definitions as described below (2010):

- NOAA's operational definitions of El Niño and La Niña conditions are based upon the Oceanic Niño Index [ONI]. The ONI is defined as the 3-month running means of SST anomalies in the Niño 3.4 region [i.e. 5°N–5°S in latitude and 120°–170°W in longitude]. The anomalies are derived from the 1971–2000 SST climatology.
- The Niño 3.4 anomalies may be thought of as representing the average equatorial SSTs across the Pacific from about the dateline to the South American coast.
- To be classified as a full-fledged El Niño and La Niña episode, the ONI must exceed +0.5 [El Niño] or -0.5 [La Niña] for at least five consecutive months.

By using this definition, El Niño and La Niña periods are provided in Table 1. Additionally, monthly Niño 3.4 indices (conditions) for a longer period (since 1871) are provided at the NCAR (2008) and used in this article to document El Niño and La Niña conditions for historic flood peaks at several streamflow gaging sites in the Hill Country area. A graph showing the indices for the 1950s and 2000s decades is presented in Fig. 1.

IMPACTS OF EL NIÑO AND LA NIÑA IN THE SOUTHWEST UNITED STATES

Weather

The Pacific jet stream controls much of the temperature and precipitation variations across the United States, and the position of the jet stream over the United States changes between El Niño and La Niña conditions (Fig. 2). Many sources concluded that precipitation and streamflows in western North America respond to ENSO with a pattern of dry El Niños in the Northwest and wet El Niños in the Southwest (Cayan and Webb 1992, Kahya and Dracup 1993, 1994) and (Dettinger et al. 2000). When ENSO creates warm tropical Pacific conditions, there is an increase in the frequency of days with high precipitation and streamflow during the cool season in the Southwest. Under these conditions, in contrast, the cool season in the Northwest is characterized by a decrease in the frequency of days with high precipitation and streamflow. The opposite pattern is recorded for conditions of cool tropical Pacific conditions (Reynolds et al. 2003).

The Western Regional Climate Center (WRCC 1998) concluded that the La Niña climate signal seems more reliable than the El Niño signal, especially in the Southwest where El Niño generally brings wet weather to the West in winter. It further stated that La Niña brings dry winters to the Southwest, and there are no exceptions during the past 65 years. During El Niño conditions, the period of October through March tends to be wetter than usual in a swath extending from southern California eastward across Arizona, southern Nevada and Utah, New Mexico, and into Texas. There are more rainy days and more rain per rainy day. El Niño winters can be two to three times wetter than La Niña winters in this region (WRCC 1998). The success of these analyses suggested that general forecasts of the effects of El Niño on the Southwest can be made several months in advance, at least with respect to predictions of higher frequency of rainy days and greater streamflows than during La Niña or nonevent years.

However, in the spring, weak frontal systems can cause substantial rainfall in Texas. During the summer and fall, large storms are caused by rainfall associated with tropical storms or hurricanes moving inland from the Gulf of Mexico and originating in the Atlantic Ocean. Hurricane season of the Atlantic typically occurs from June 1 through November 30. Many studies have found that La Niña periods provide a greater number and greater intensity for hurricanes in the Atlantic. For example, the International Research Institute for Climate and Society (IRICS 2007) documented the ENSO condition for every intense Atlantic hurricane from 1950 through 2001 and found that only in two El Niño years (out of 12 years) were there more intense Atlantic hurricanes than the historical average, while in La Niña years this happened in eight years (out of 12 years). In El Niño years, there is a reduction in the probability of U.S. landfalling hurricanes, and it is also less likely for major hurricanes to make landfall in the United States in an El Niño year (Bove et al. 1998).

The above studies suggest, for Texas at least, that greater rainfall typically is associated with El Niño periods during cooler months (December through May) but is associated with La Niña periods during hurricane season (June through November). Many websites are dedicated to data and information regarding El Niño and its effect on the weather and streamflow in the United States. A list of selected websites identified as pertinent to this article are presented in Table 2.

Stream Runoff

Several reports have documented the impacts of El Niño

Table 1. Periods for El Niño and La Niña conditions.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Year	**DJF**	**JFM**	**FMA**	**MAM**	**AMJ**	**MJJ**	**JJA**	**JAS**	**ASO**	**SON**	**OND**	**NDJ**
1950	-1.7	-1.5	-1.3	-1.4	-1.3	-1.1	-0.8	-0.8	-0.8	-0.9	-0.9	-1
1951	-1	-0.9	-0.6	-0.3	-0.2	0.2	0.4	0.7	0.7	0.8	0.7	0.6
1952	0.3	0.1	0.1	0.2	0.1	-0.1	-0.3	-0.3	-0.2	-0.2	-0.1	0
1953	0.2	0.4	0.5	0.5	0.5	0.5	0.4	0.4	0.4	0.4	0.4	0.4
1954	0.5	0.3	-0.1	-0.5	-0.7	-0.7	-0.8	-1	-1.2	-1.1	-1.1	-1.1
1955	-1	-0.9	-0.9	-1	-1	-1	-1	-1	-1.4	-1.8	-2	-1.9
1956	-1.3	-0.9	-0.7	-0.6	-0.6	-0.6	-0.7	-0.8	-0.8	-0.9	-0.9	-0.8
1957	-0.5	-0.1	0.3	0.6	0.7	0.9	0.9	0.9	0.9	1	1.2	1.5
1958	1.7	1.5	1.2	0.8	0.6	0.5	0.3	0.1	0	0	0.2	0.4
1959	0.4	0.5	0.4	0.2	0	-0.2	-0.4	-0.5	-0.4	-0.3	-0.2	-0.2
1960	-0.3	-0.3	-0.3	-0.2	-0.2	-0.2	-0.1	0	-0.1	-0.2	-0.2	-0.2
1961	-0.2	-0.2	-0.2	-0.1	0.1	0.2	0	-0.3	-0.6	-0.6	-0.5	-0.4
1962	-0.4	-0.4	-0.4	-0.5	-0.4	-0.4	-0.3	-0.3	-0.5	-0.6	-0.7	-0.7
1963	-0.6	-0.3	0	0.1	0.1	0.3	0.6	0.8	0.9	0.9	1	1
1964	0.8	0.4	-0.1	-0.5	-0.8	-0.8	-0.9	-1	-1.1	-1.2	-1.2	-1
1965	-0.8	-0.4	-0.2	0	0.3	0.6	1	1.2	1.4	1.5	1.6	1.5
1966	1.2	1	0.8	0.5	0.2	0.2	0.2	0	-0.2	-0.2	-0.3	-0.3
1967	-0.4	-0.4	-0.6	-0.5	-0.3	0	0	-0.2	-0.4	-0.5	-0.4	-0.5
1968	-0.7	-0.9	-0.8	-0.7	-0.3	0	0.3	0.4	0.3	0.4	0.7	0.9
1969	1	1	0.9	0.7	0.6	0.5	0.4	0.4	0.6	0.7	0.8	0.7
1970	0.5	0.3	0.2	0.1	0	-0.3	-0.6	-0.8	-0.9	-0.8	-0.9	-1.1
1971	-1.3	-1.3	-1.1	-0.9	-0.8	-0.8	-0.8	-0.8	-0.8	-0.9	-1	-0.9
1972	-0.7	-0.4	0	0.2	0.5	0.8	1	1.3	1.5	1.8	2	2.1
1973	1.8	1.2	0.5	-0.1	-0.6	-0.9	-1.1	-1.3	-1.4	-1.7	-2	-2.1
1974	-1.9	-1.7	-1.3	-1.1	-0.9	-0.8	-0.6	-0.5	-0.5	-0.7	-0.9	-0.7
1975	-0.6	-0.6	-0.7	-0.8	-0.9	-1.1	-1.2	-1.3	-1.5	-1.6	-1.7	-1.7
1976	-1.6	-1.2	-0.8	-0.6	-0.5	-0.2	0.1	0.3	0.5	0.7	0.8	0.7
1977	0.6	0.5	0.2	0.2	0.2	0.4	0.4	0.4	0.5	0.6	0.7	0.7
1978	0.7	0.4	0	-0.3	-0.4	-0.4	-0.4	-0.4	-0.4	-0.3	-0.2	-0.1
1979	-0.1	0	0.1	0.1	0.1	-0.1	0	0.1	0.3	0.4	0.5	0.5
1980	0.5	0.3	0.2	0.2	0.3	0.3	0.2	0	-0.1	-0.1	0	-0.1
1981	-0.3	-0.5	-0.5	-0.4	-0.3	-0.3	-0.4	-0.4	-0.3	-0.2	-0.1	-0.1
1982	0	0.1	0.1	0.3	0.6	0.7	0.7	1	1.5	1.9	2.2	2.3
1983	2.3	2	1.5	1.2	1	0.6	0.2	-0.2	-0.6	-0.8	-0.9	-0.7
1984	-0.4	-0.2	-0.2	-0.3	-0.5	-0.4	-0.3	-0.2	-0.3	-0.6	-0.9	-1.1
1985	-0.9	-0.8	-0.7	-0.7	-0.7	-0.6	-0.5	-0.5	-0.5	-0.4	-0.3	-0.4
1986	-0.5	-0.4	-0.2	-0.2	-0.1	0	0.3	0.5	0.7	0.9	1.1	1.2
1987	1.2	1.3	1.2	1.1	1	1.2	1.4	1.6	1.6	1.5	1.3	1.1
1988	0.7	0.5	0.1	-0.2	-0.7	-1.2	-1.3	-1.2	-1.3	-1.6	-1.9	-1.9
1989	-1.7	-1.5	-1.1	-0.8	-0.6	-0.4	-0.3	-0.3	-0.3	-0.3	-0.2	-0.1

Table 1. Continued

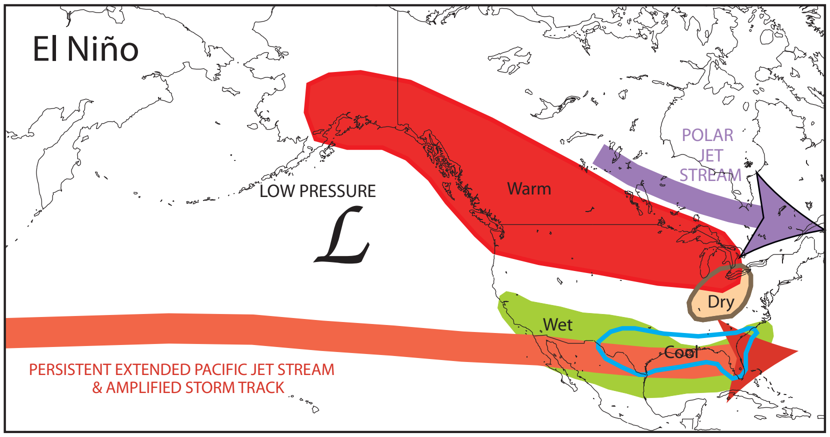
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Year	**DJF**	**JFM**	**FMA**	**MAM**	**AMJ**	**MJJ**	**JJA**	**JAS**	**ASO**	**SON**	**OND**	**NDJ**
1990	0.1	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.3	0.4
1991	0.4	0.3	0.3	0.4	0.6	0.8	1	0.9	0.9	1	1.4	1.6
1992	1.8	1.6	1.5	1.4	1.2	0.8	0.5	0.2	0	-0.1	0	0.2
1993	0.3	0.4	0.6	0.7	0.8	0.7	0.4	0.4	0.4	0.4	0.3	0.2
1994	0.2	0.2	0.3	0.4	0.5	0.5	0.6	0.6	0.7	0.9	1.2	1.3
1995	1.2	0.9	0.7	0.4	0.3	0.2	0	-0.2	-0.5	-0.6	-0.7	-0.7
1996	-0.7	-0.7	-0.5	-0.3	-0.1	-0.1	0	-0.1	-0.1	-0.2	-0.3	-0.4
1997	-0.4	-0.3	0	0.4	0.8	1.3	1.7	2	2.2	2.4	2.5	2.5
1998	2.3	1.9	1.5	1	0.5	0	-0.5	-0.8	-1	-1.1	-1.3	-1.4
1999	-1.4	-1.2	-0.9	-0.8	-0.8	-0.8	-0.9	-0.9	-1	-1.1	-1.3	-1.6
2000	-1.6	-1.4	-1	-0.8	-0.6	-0.5	-0.4	-0.4	-0.4	-0.5	-0.6	-0.7
2001	-0.6	-0.5	-0.4	-0.2	-0.1	0.1	0.2	0.2	0.1	0	-0.1	-0.1
2002	-0.1	0.1	0.2	0.4	0.7	0.8	0.9	1	1.1	1.3	1.5	1.4
2003	1.2	0.9	0.5	0.1	-0.1	0.1	0.4	0.5	0.6	0.5	0.6	0.4
2004	0.4	0.3	0.2	0.2	0.3	0.5	0.7	0.8	0.9	0.8	0.8	0.8
2005	0.7	0.5	0.4	0.4	0.4	0.4	0.4	0.3	0.2	-0.1	-0.4	-0.7
2006	-0.7	-0.6	-0.4	-0.1	0.1	0.2	0.3	0.5	0.6	0.9	1.1	1.1
2007	0.8	0.4	0.1	-0.1	-0.1	-0.1	-0.1	-0.4	-0.7	-1	-1.1	-1.3
2008	-1.4	-1.4	-1.1	-0.8	-0.6	-0.4	-0.1	0	0	0	-0.3	-0.6
2009	-0.8	-0.7	-0.5	-0.1	0.2	0.6	0.7	0.8	0.9	1.2	1.5	1.8

Description: Warm (red) and cold (blue) episodes based on a threshold of +/- 0.5 ºC for the Oceanic Niño Index (ONI) [3-month running mean of ERSST.v3b SST anomalies in the Niño 3.4 region (5°N-5°S, 120°-170°W)], based on the 1971-2000 base period. The 3-month means are based on the month and its previous and prior month as shown in the second row of the table. For historical purposes, cold and warm episodes (blue and red colored numbers) are defined when the threshold is met for a minimum of 5 consecutive over-lapping seasons. (Source: cpc.noaa.gov)

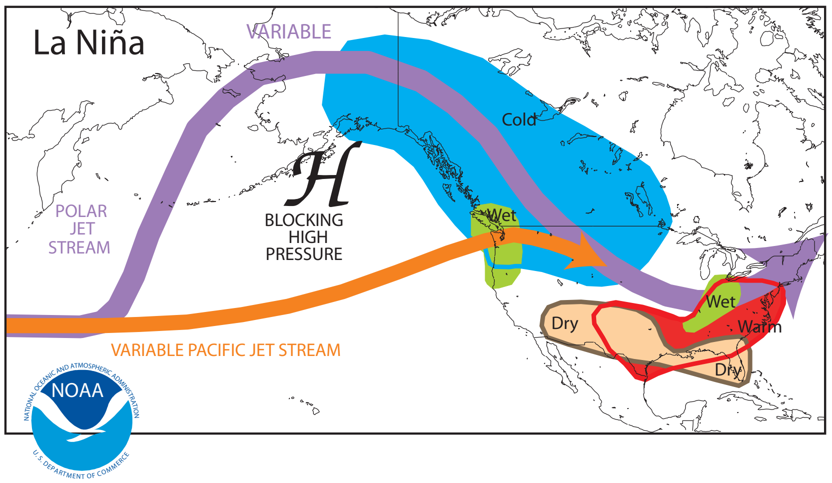
on floods in the southwestern United States. Piechota et al. (1979) analyzed flood data for 79 streamflow gaging stations in the western half of the United States and found eight regions for which flood peaks tend to co-vary with El Niño periods. None of the gaging stations for this study was in Texas, but one of the regions represents eastern New Mexico adjacent to Texas. However, the WRCC concluded most of the major flood episodes on mainstem rivers have occurred during El Niño in southern California, Arizona, southern Nevada, New Mexico, and southern Utah. Ely and others (1993) documented and determined the ages of 251 floods during the past about 8,000 years in 19 river basins in the southwestern United States. These data indicate that intervals of flooding are correlated with periods of cool, moist climate and frequent El Niño events.

A U.S. Geological Survey (USGS) report documented discharges for design floods in the Southwest exceeding the 2-year event to be greater for El Niño periods than for La Niña periods (Reynolds et al. 2003). However, only two streamflow sites in Arizona were analyzed by the study so the effect of El Niño on floods for other sites is unknown. Additionally, the studies above generally included southern California, Arizona, southern Nevada, southern Utah, and New Mexico. However, none of the studies represents Texas. Studies analyzing the effects of ENSO on flooding in Texas could not be found.

Previous studies suggested that the severity and frequency of floods appears to co-vary with El Niño. Trenberth and Hoar (1996) suggested that global warming could increase the effect of El Niño, which could cause increases in winter flooding. In the southwestern United States, floods are caused by three distinct sources—by snowmelt, by rain on snow, and by rain only. Floods caused by rain on snow or rain only tend to have larger magnitudes than do floods caused only by snowmelt. Many of the snowmelt floods are associated with snow that occurred in winters prior to the floods. However, snowmelt is not a major cause of flooding in Texas. As discussed in the pre-



During El Niño, the Pacific Jet Stream travels over the southern United States and typically delivers above average rainfall to the Southwest, including Texas, especially during winter months.



During La Niña, the Pacific Jet Stream travels over the northern United States, thus Texas typically has less than average rainfall.

Fig. 2. Conceptual model of movement of the Pacific jet stream over the United States during El Niño and La Niña conditions. (NOAA 2005)

vious section, in the summer and fall, large storms are caused by rainfall associated with tropical storms or hurricanes moving inland from the Gulf of Mexico; such activity is the cause for substantial flooding in Texas and especially the Hill Country.

Many studies have investigated individual large floods and concluded that El Niño conditions caused the flooding. For example, Brakenridge (2009) blamed the floods that occurred throughout much of south and central Texas in 1997 and 1998 on El Niño. Many studies of individual storms have concluded likewise. However, there are exceptions regarding the hypothesized association between El Niño and large-scale flooding in Texas. For example, the widespread and severe flooding in August 1978 in Texas occurred during La Niña conditions (Table 1). Some studies reported the strength of El Niño periods to be associated with the largest floods; however, little data has been identified to substantiate such claims.

METHODOLOGY

The purpose of this article is to examine the statistical relations of precipitation and annual peak streamflow discharges and runoff volumes that occurred during El Niño and La Niña periods in the Texas Hill Country.

Approach

The USGS operates streamflow-gaging stations throughout the nation with many in the Texas Hill Country. Data[1] from these stations were used herein to analyze the annual flood peaks and monthly mean streamflow discharges over time.

[1] *These data are presented online at http://nwis.waterdata.usgs.gov/tx/nwis/peak and at http://waterdata.usgs.gov/tx/nwis/monthly/?referred_module=sw.*

Table 2. Selected websites presenting data and information pertinent to El Niño.

Agency	Description	URL
NOAA	El Niño research, observations, impacts, forecast, education, and information	http://www.elnino.noaa.gov/
	El Niño Theme Page—access to distributed information	http://www.pmel.noaa.gov/tao/elnino/nino-home.html
	What is El Niño?	http://www.pmel.noaa.gov/tao/elNino/el-Nino-story.html
	El Niño impacts on the United States and North America	http://www.pmel.noaa.gov/tao/elNino/impacts.html#part5b
NWS	Climate forecasts based on El Niño	http://www.cpc.noaa.gov/products/analysis_monitoring/lanina/
	Oceanic Niño index	http://www.cpc.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml
	Enso impacts on Texas	http://www.cpc.ncep.noaa.gov/products/predictions/threats2/enso/el-nino/tx_bar.html
WRCC	Information on the effects of Niño on the Western United States	http://www.wrcc.dri.edu/enso/enso.html
USGS	El Niño Information regarding floods, landslides, and costal hazards	http://elnino.wr.usgs.gov/

Periods for El Niño and La Niña are presented in Table 1. The approach for the analyses in this paper is summarized as follows:

1. Based on January 1950 through September 2009 monthly precipitation data representing the entire Hill Country area, calculate the mean precipitation depth for each of the twelve months during each ENSO period (El Niño, La Niña, and other period).
2. Identify all streamflow gaging stations in the Hill Country with unregulated flow and data from January 1950 through September 2009 (Fig. 3). Unregulated flow represents that not controlled by major reservoirs that would impact the timing and discharges of runoff.
3. Identify the ENSO period for each annual peak discharge in all qualified streamflow stations.
4. Calculate the number of annual peaks and the mean value for the annual peak discharge during each ENSO period for each qualified station.
5. Calculate the mean streamflow discharge during each ENSO period for each qualified station.
6. Calculate the mean streamflow discharge of the four seasons—winter, spring, summer, and fall—during each ENSO period for each qualified station.

In addition, for four of the streamflow stations with the longest database of annual peak discharges, the ENSO indices were documented for the largest annual peak discharges; the results of this analysis also is reported herein. The objective of this analysis is to determine if the largest Hill Country peaks are associated with either ENSO condition.

Description of the Study Area

The Texas Hill Country is an indigenous term applied to a region of Central Texas (Fig. 3). The area is within a semiarid region and features tall rugged hills that consist of thin layers of soil lying on top of mostly limestone or granite. Austin and San Antonio, respectively, are located at the northeastern and southeastern boundaries of the area, which represent the eastern portion of the Edwards Plateau and the easternmost region of the American Southwest. It is bounded by the Balcones Escarpment on the east and the Llano Uplift to the west and north. The terrain is punctuated by a large number of limestone or granite rocks and boulders and a thin layer of topsoil, which makes the region very dry and prone to flash flooding. The Texas Hill Country is also home to several native southwestern types of vegetation, such as various yucca, prickly pear cactus, mountain *cedar* (*Juniperus ashei*), and Texas live oak.

Because of its karst topography, the Hill County contains many caves, some of which are extensive in size and have been developed for public exploration. Also, hundreds of springs exist in the area, many of which provide base flow for the streams crossing the landscape. The Hill Country contains the headwaters for several major Texas streams, including the San Saba, Llano, Guadalupe, San Antonio, Frio, Medina, and Nueces rivers.

Much information and data regarding the physical and water resource characteristics of the Hill Country are presented on the web by the Hill Country Alliance (2010). Seventeen streamflow stations met the criteria for inclusion in this study; the location for each station is presented in Fig. 3.

Precipitation

The mean annual precipitation varies from about 22 inches per year in the western part of the area to about 32 inches in the eastern part (Slade 2008). One source for precipitation is water from the eastern Pacific Ocean, which is carried into the area from the southwest by tropical continental air masses. However, the principal source of moisture is the Gulf of Mexico, brought into the area from southerly winds. The hills and associated elevation increases along the north and west sides of the Balcones Escarpment assist in the uplifting of air masses and the formation of storms. Many large thunderstorms form in the Hill Country along the escarpment, where they can stall and produce extreme precipitation depths during a few hours or few days (Slade and Patton 2003, Fig. 2). Many of the largest storms in the state have occurred in this area, some of which represent world record rates for durations of 48 hours or less (Slade and Patton 2003, Fig. 3). Many storms in the Hill Country area have produced rainfall rates in excess of those identified as 100- and even 500-year events.

However, because of the semiarid nature of the area, droughts can be substantial in duration and areal extent. During droughts, annual precipitation in the area can be one-third or less of the mean annual precipitation. Also, the few storms that occur during droughts often produce little precipitation and are separated by long durations; therefore, little, if any, runoff occurs and most of the precipitation is lost as evaporation and transpiration from soil moisture.

Runoff

Mean annual runoff ranges from slightly less than 1 inch per year in the west to slightly more than 5 inches in the eastern part of the area (Slade 2008). However, most of the runoff in

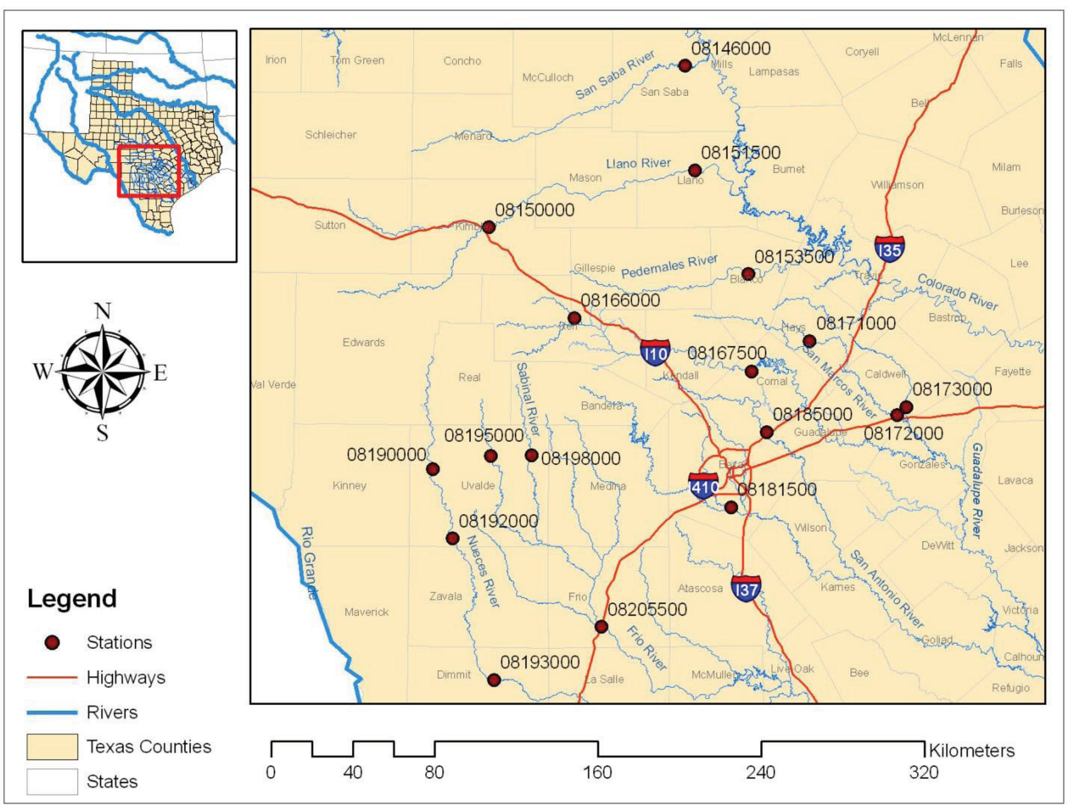


Fig. 3. Locations of streamflow-gaging stations used for analyses.

the area is associated with a few major storms each year. For example, for the station Nueces River near Asherton, Texas, the mean flow for the period analyzed in this paper is 187 ft^3/s. However, an analysis of the daily-mean discharges for this station and period reveals that the daily-mean discharge exceeds this value only 15% of the time. Additionally, the median (50 percentile) flow is only 0.40 ft^3/s and no flow occurs 40% of the time for this station. Such flow characteristics are typical for Hill Country streams, which have zero or very low base flow most of the time. Exceptions to this characterization represent streams with base flows sustained by major springs; however, most of the major springs in the Hill Country area discharge from the Edwards Aquifer, which lies along the southern and eastern boundary on the downstream side of the Hill Country.

Because of the limited basin sizes and steep slopes in the Hill Country area, the time of concentration for most stream reaches in the Hill Country is about or less than 48 hours. Therefore, many extreme storms in the area produce extreme flash floods and/or flood peaks, some of which greatly exceed those of 100-year events. Peak discharges up to about four times greater than the 100-year peak discharge have been documented in the area (Asquith and Slade 1995). The State of Texas has more annual flood deaths and flood damage costs than any other state (Frech 2010) with many of those deaths and much of the damages in the Hill Country. A report documenting storm and flood information, data, and photographs for all known major floods in the area and Texas was prepared by Slade and Patton (2003).

RESULTS/FINDINGS

Precipitation Analyses

Precipitation data used to represent the Hill Country are from the Texas Water Development Board (TWDB 2005). The data analyzed are monthly precipitation values (1950 through 2009) representing each one-degree quadrangle for four quadrangles that overlay the majority of the Hill Country. The quadrangles numbered 708, 709, 808, and 809 represent an area between latitude lines of 29° and 31° and between longitude lines of -98° to -100° degrees. The mean precipitation value for each month was calculated based on the data for each of the four quads.

A summary of the findings for the precipitation analyses is presented in Table 3. For the monthly analyses, the table shows monthly precipitation depths to be comparable for El Niño and La Niña periods for two of the three summer months. August precipitation for La Niña periods exceeds that for El Niño periods. However, for all other months, El Niño precipitation exceeds or greatly exceeds La Niña precipitation, especially during December and February, during which El Niño precipitation is more than double than that of La Niña precipitation. For the "other period" (during which neither El Niño nor La Niña occurred) precipitation was less than that for the entire period for each of the 12 months. The largest precipitation deficit for the other period from mean precipitation of entire period occurs in December (22%) and January (20%).

Based on the seasonal precipitation analyses, with the exception for summer months, Table 3 shows El Niño precipitation to exceed La Niña precipitation for all other seasons. Summer precipitation is comparable between El Niño and La Niña periods. The monthly and seasonal analyses show that La Niña precipitation is comparable to that for the entire "other period" (i.e. neither El Niño nor La Niña).

Another observation from this analysis represents the durations for the ENSO periods. Based on the 60-year period, only ten El Niño periods occurred during March and only eight El Niño periods occurred during April. The seasonal analyses documented that few El Niño periods (31) occurred during spring; about 50% more La Niña periods (46) occurred in that season. The seasonal analyses also showed that the number of El Niño and La Niña periods is comparable for other seasons.

Due to limited samples for the ENSO periods (i.e. the number of monthly precipitation data values), statistical tests were performed for the aggregated seasonal data. Normality tests, including skewness, kurtosis, Kolmogorov-Smirnov and Shapiro-Wilk tests, indicated that, except for the spring season El Niño period, the seasonal precipitation data were not normally distributed. Therefore, the Kruskal-Wallis test, a nonparametric equivalent of one-way analysis of variance (ANOVA), was performed on the seasonal precipitation data. This test revealed no significant differences of precipitation among the ENSO periods for each season except during the winter ($\chi^2 = 18.81$, $p < 0.01$, $df = 2$). To explore the specific difference among the ENSO periods, Mann-Whitney tests revealed that El Niño was significantly different from La Niña ($Z = -3.98$, $n_1 = 48$, $n_2 = 55$, $p < 0.01$) and other period ($Z = -3.59$, $n_1 = 48$, $n_2 = 76$, $p < 0.01$) during the winter season. Despite no overall significant difference as indicated by the Kruskal-Wallis test in the spring ($\chi^2 = 4.72$, $p = 0.09$, $df = 2$), the Mann-Whitney test reported that the El Niño was significantly different from La Niña during the spring ($Z = -2.05$, $n_1 = 31$, $n_2 = 46$, $p < 0.05$) and the fall ($Z = -2.21$, $n_1 = 54$, $n_2 = 53$, $p < 0.05$).

Annual Flood Peak Analyses

A summary of the findings for the annual flood peak analyses is presented in Table 4. The table shows that the number of annual peaks that occur during El Niño periods and La Niña

Table 3. Summary for statistical comparisons of monthly mean precipitation for ENSO periods. (Note: For percentages, negative sign indicates given value to be less than value for entire period and no sign indicates given value to exceed value for entire period.)

Month	Monthly mean precipitation (inches)				Number of months				Difference in precipitation between entire period and (%)		
	Entire Period	El Niño	La Niña	Other	Entire Period	El Niño	La Niña	Other	El Niño	La Niña	Other
January	1.41	1.88	1.33	1.12	60	17	20	23	34%	-6%	-20%
February	1.77	2.66	1.31	1.63	60	13	16	31	51%	-26%	-8%
March	1.82	2.25	1.40	1.89	60	10	15	35	23%	-23%	3%
April	2.38	2.69	2.22	2.39	60	8	15	37	13%	-7%	0%
May	3.65	4.56	3.34	3.44	60	13	16	31	25%	-9%	-6%
June	3.25	4.24	3.02	2.88	60	15	13	32	30%	-7%	-11%
July	2.11	2.19	2.08	2.09	60	13	14	33	4%	-1%	-1%
August	2.42	1.72	3.12	2.44	60	15	14	31	-29%	29%	1%
September	3.20	3.24	3.06	3.27	60	18	17	25	1%	-5%	2%
October	3.17	3.92	3.02	2.71	60	18	18	24	24%	-5%	-14%
November	1.92	2.39	1.52	1.86	59	18	18	23	25%	-21%	-3%
December	1.48	2.28	1.11	1.15	59	18	19	22	54%	-25%	-22%
Annual Total	28.58	34.01	26.52	26.87							

Season	Seasonal monthly mean precipitation (inches)				Number of months				Difference in precipitation between entire period and (%)		
	Entire Period	El Niño	La Niña	Other	Entire Period	El Niño	La Niña	Other	El Niño	La Niña	Other
Spring (March–May)	2.62	3.33	2.34	2.53	180	31	46	103	27%	-11%	-3%
Summer (June–August)	2.59	2.74	2.74	2.47	180	43	41	96	6%	6%	-5%
Fall (September–November)	2.77	3.19	2.52	2.64	179	54	53	72	15%	-9%	-5%
Winter (December–February)	1.55	2.24	1.25	1.34	179	48	55	76	45%	-20%	-14%
Seasonal Mean	2.38	2.87	2.21	2.24							

Table 4. Statistical comparisons of annual peak discharges for Hill Country streams during periods of El Niño, La Niña, and other periods. (Note: Streamflow discharges based on period of available data for the 718 month period Jan. 1, 1950 through Sept. 30, 2009.)

Station name	Station number	Entire record		El Niño periods		La Niña periods		Other periods	
		Total number of annual peaks	Mean peak discharge (ft^3/s)	Number of annual peaks	Ratio of mean peak to mean peak for all record	Number of annual peaks	Ratio of mean peak to mean peak for all record	Number of annual peaks	Ratio of mean peak to mean peak for all record
San Saba River at San Saba, TX	08146000	57	13,891	16	1.00	16	1.21	25	0.87
Llano River near Junction, TX	08150000	55	29,837	12	0.87	17	1.14	26	0.97
Llano River at Llano, TX	08151500	59	54,335	16	1.05	17	0.88	26	1.05
Pedernales River near Johnson City, TX	08153500	59	43,019	15	1.11	16	0.56	28	1.19
Johnson Creek near Ingram, TX	08166000	53	9,603	16	0.65	12	0.74	25	1.35
Guadalupe River near Spring Branch, TX	08167500	60	26,094	16	1.37	17	0.87	27	0.86
Blanco River at Wimberley, TX	08171000	60	18,309	20	1.11	15	0.88	25	0.99
San Marcos River at Luling, TX	08172000	60	19,793	18	1.11	11	1.46	31	0.77
Plum Creek near Luling, TX	08173000	53	11,006	14	1.58	12	0.78	27	0.80
Medina River at San Antonio, TX	08181500	59	8,447	23	1.18	12	1.44	24	0.61
Cibolo Creek at Selma, TX	08185000	59	13,121	22	1.37	14	1.56	23	0.31
Nueces River at Laguna, TX	08190000	60	28,826	15	0.55	18	1.70	27	0.79
Nueces River below Uvalde, TX	08192000	60	32,062	15	0.93	16	1.58	29	0.72
Nueces River near Asherton, TX	08193000	59	6,486	17	1.05	17	1.17	25	0.85
Frio River at Concan, TX	08195000	60	17,205	16	1.11	17	1.02	27	0.92
Sabinal River near Sabinal, TX	08198000	60	11,545	16	1.80	16	0.70	28	0.71
Frio River near Derby, TX	08205500	59	10,739	15	1.41	16	1.15	28	0.70

periods is comparable for the stations in the northern and southern part of the area (Fig. 3). However, for the stations in the mid part of the area (the Blanco, San Marcos, and Medina rivers and Cibolo Creek), the number of El Niño annual peaks exceeds the number of La Niña peaks. The reason for such is unknown.

Table 4 presents, for each gaging station, the ratios of the mean discharge for El Niño peaks and the mean discharge for La Niña peaks to the mean discharge for all peaks. The data show that the number of stations for which the mean El Niño peaks exceeds the mean La Niña peaks is about equal to the number of stations for which the mean La Niña peaks exceed the mean El Niño peaks. However, for some of the northern stations (Llano River at Llano, the Pedernales River and Johnson Creek stations) the ratio of the mean "other period" peaks equals or exceeds that for the mean El Niño and mean La Niña peaks. This might be a coincidence. If not, the reason that "other period" peaks are greater than El Niño and La Niña peaks is unknown.

The date and relative peak stage for the nine largest flood peaks during the past 141 years is documented on an old brewery's door on the bank of the Guadalupe River in New Braunfels (Fig. 4). The ENSO index was determined for each of these peaks. The data reveal that five of the nine peaks occurred during El Niño conditions and that only two of the peaks (December 1913 and May 1972) occurred outside hurricane season for the Atlantic Ocean.

An analysis was made for the largest ten annual peaks for the entire period of record for each of three selected stations with the longest period of record. For the stations Llano River at Junction, Guadalupe River near Spring Branch, and Nueces River near Laguna, the number of years of available annual peaks are 90, 89, and 88 years respectively. For each of the stations, about one-half of the largest ten peaks occurred during El Niño conditions and about one-half occurred during La Niña conditions. However, for each of the Llano and Guadalupe River stations, all but one of the peaks occurred during hurricane season; for the Nueces River station, all the peaks occurred during hurricane season. The above analyses indicated that the majority of the largest peaks occurred during hurricane season.

Statistical tests were performed on the annual peak discharge data. These data are not normally distributed, thus the data values were converted to values representing their natural logarithms—such a transformation deemed the data values to be normally distributed. A one-way ANOVA test then was performed on the transformed data. The results revealed no significant differences of annual peaks among ENSO periods

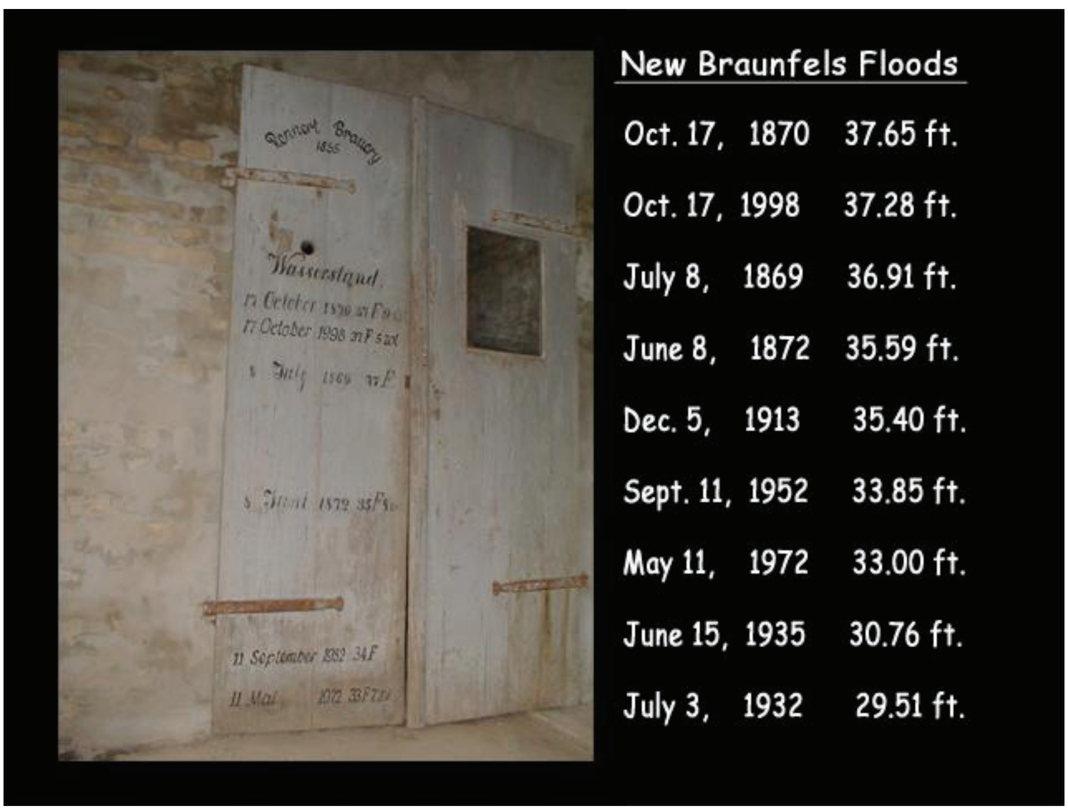


Fig. 4. Documented flood peak marks on the door of old brewery located on the bank of the Guadalupe River in New Braunfels, Texas.

Table 5. Statistical comparisons of mean streamflow discharges for Hill Country streams during periods of El Niño, La Niña, and other periods (Note: Streamflow discharges based on period of available data for the 718 month period Jan. 1, 1950 through Sept. 30, 2009. For data period, El Niño and La Niña each occur about 25% of the time while other periods occur about 50% of the time.)

Station name	Station number	Entire record		El Niño periods	La Niña periods	Other periods
		Number of months	Mean flow (ft^3/s)	Mean flow as ratio of mean flow for entire record	Mean flow as ratio of mean flow for entire record	Mean flow as ratio of mean flow for entire record
San Saba River at San Saba, TX	08146000	670	180	1.17	1.15	0.83
Llano River near Junction, TX	08150000	666	190	1.10	1.09	0.90
Llano River at Llano, TX	08151500	718	392	1.18	1.00	0.91
Pedernales River near Johnson City, TX	08153500	718	210	1.43	0.66	0.97
Johnson Creek near Ingram, TX	08166000	630	28	1.08	0.94	1.00
Guadalupe River near Spring Branch, TX	08167500	718	419	1.58	0.74	0.85
Blanco River at Wimberley, TX	08171000	718	156	1.62	0.74	0.83
San Marcos River at Luling, TX [1]	08172000	718	423	1.51	0.82	0.84
Plum Creek near Luling, TX	08173000	625	119	1.71	0.81	0.75
Medina River at San Antonio, TX	08181500	718	261	1.67	0.83	0.75
Cibolo Creek at Selma, TX	08185000	718	28	2.36	0.86	0.39
Nueces River at Laguna, TX	08190000	718	173	1.16	1.08	0.87
Nueces River below Uvalde, TX	08192000	718	158	1.27	1.12	0.79
Nueces River near Asherton, TX	08193000	718	187	1.26	1.11	0.81
Frio River at Concan, TX	08195000	718	131	1.34	0.88	0.89
Sabinal River near Sabinal, TX	08198000	718	70	1.69	0.90	0.71
Frio River near Derby, TX	08205500	718	149	1.69	0.90	0.71

[1] The mean flow for this station is at least minimally affected by discharges from San Marcos Springs.

for any stations with the exception for the stations Pedernales River near Johnson City ($F = 5.51$, $p < 0.01$, $df = 2$) and Plum Creek near Luling ($F = 4.67$, $p < 0.05$, $df = 2$). In addition to the one-way ANOVA that examined the overall differences, post hoc tests of Tukey Honestly Significant Difference (HSD) or Tamhane were also conducted to compare the ENSO periods piecewise depending on their compliance to the assumption of equal variance. For the Pedernales station, La Niña peaks were significantly different from those during El Niño periods ($p < 0.05$) and for the "other periods" ($p < 0.05$). For the Plum Creek station, El Niño peaks were significantly different that those of the La Niña period ($p < 0.05$) and for the "other periods" ($p < 0.01$).

It is noted that an annual peak can occur in any season of a given year, and Table 4 does not assume the three categories of ENSO period are equally populated by season. As indicated by the uneven number of annual peaks for each period in Table 4, the number of annual peaks for each season was unequal as well. Preliminary analysis revealed no significant differences of annual peak among seasons due to the extreme nature of annual peaks. Nevertheless, the majority of the largest peaks occurred during hurricane season.

Streamflow Runoff Analyses

ENSO Periods

A summary of the findings for the streamflow runoff analyses for ENSO periods is presented in Table 5. The table presents, for each station, the mean discharge for the entire period and the ratio of the mean discharge for El Niño periods to the mean discharge for the entire period. Also presented is the ratio of the mean discharge for La Niña periods to the mean

Table 6. The probability of the resulting Kruskal-Wallis and Mann-Whitney tests on the significant differences of mean monthly flow among the ENSO periods.

Station Name	Station Number	Period	N	Kruskal-Wallis	Mann-Whitney		
					El Niño	La Niña	Other
San Saba River at San Saba, TX	08146000	El Niño	160	0.01**	-		
		La Niña	188		0.02*	-	
		Other	322		0.00*	0.96	-
Llano River near Junction, TX	08150000	El Niño	160	0.04*	-		
		La Niña	188		0.04*	-	
		Other	318		0.01*	0.90	-
Llano River at Llano, TX	08151500	El Niño	176	0.01**	-		
		La Niña	195		0.01**	-	
		Other	347		0.00**	0.83	-
Pedernales River near Johnson City, TX	08153500	El Niño	176	0.00**	-		
		La Niña	193		0.00**	-	
		Other	343		0.00**	0.00**	-
Johnson Creek near Ingram, TX	08166000	El Niño	152	0.12	-		
		La Niña	179		0.05	-	
		Other	299		0.09	0.57	-
Guadalupe River near Spring Branch, TX	08167500	El Niño	176	0.00**	-		
		La Niña	195		0.00**	-	
		Other	347		0.00**	0.03*	-
Blanco River at Wimberley, TX	08171000	El Niño	176	0.00**	-		
		La Niña	195		0.00**	-	
		Other	347		0.00**	0.00**	-
San Marcos River at Luling, TX	08172000	El Niño	176	0.00**	-		
		La Niña	195		0.00**	-	
		Other	347		0.00**	0.00**	-
Plum Creek near Luling, TX	08173000	El Niño	152	0.00**	-		
		La Niña	159		0.00**	-	
		Other	314		0.00**	0.12	-
Medina River at San Antonio, TX	08181500	El Niño	176	0.00**	-		
		La Niña	195		0.00**	-	
		Other	347		0.00**	0.19	-
Cibolo Creek at Selma, TX	08185000	El Niño	176	0.00**	-		
		La Niña	195		0.08	-	
		Other	347		0.00**	0.13	-
Nueces River at Laguna, TX	08190000	El Niño	176	0.01*	-		
		La Niña	195		0.08	-	
		Other	347		0.00**	0.37	-
Nueces River below Uvalde, TX	08192000	El Niño	176	0.45	-		
		La Niña	195		0.70	-	
		Other	347		0.27	0.36	-

Table 6. Continued

Station Name	Station Number	Period	N	Kruskal-Wallis	Mann-Whitney		
					El Niño	La Niña	Other
Nueces River near Asherton, TX	08193000	El Niño	176	0.08	-		
		La Niña	195		0.20	-	
		Other	347		0.02*	0.39	-
Frio River at Concan, TX	08195000	El Niño	176	0.00**	-		
		La Niña	191		0.00**	-	
		Other	347		0.00**	0.63	-
Sabinal River near Sabinal, TX	08198000	El Niño	176	0.00**	-		
		La Niña	195		0.00**	-	
		Other	346		0.00**	0.67	-
Frio River near Derby, TX	08205500	El Niño	176	0.00**	-		
		La Niña	195		0.01*	-	
		Other	347		0.00**	0.00**	-

* Differences significant with $p < 0.05$ is marked with *, whereas $p < 0.01$ is marked with **.

discharge for the entire period. El Niño and La Niña periods each occur about one-quarter of the time while the "other period" occurs about one-half of the time. Table 5 shows that the value for the El Niño ratio exceeds that for the La Niña ratio for all stations. Therefore, for each station, the mean discharge for the El Niño period exceeds that for the La Niña period. These data also document that the El Niño mean discharge only slightly exceeds the La Niña mean discharge for stations in the north part of the area (San Saba and Llano Rivers and Johnson Creek) and for the Nueces River. For all other stations, El Niño means discharges substantially exceed La Niña mean discharges.

The data for Johnson Creek indicate that the mean discharges for El Niño, La Niña, and other periods are comparable. On the other hand, the data for the Cibolo Creek at Selma station show that the El Niño mean discharge exceeds the La Niña mean discharge by 174%. These two stations represent the smallest basins included in this study. It is unknown why such differing results exist for the ENSO flows for these stations and unknown if this trend will continue in the future for these stations.

It should be noted that these reported findings are based on mean discharge for specific periods; they do not represent flow volumes, which are based on streamflow discharges and time duration. However, El Niño and La Niña periods each represent about one-quarter of the period analyzed and the other period represents about one-half of the period; therefore, flow volumes can easily be estimated. For selected streamflow stations, the distribution of flow volumes for the period is presented in Fig. 5. The illustration presents the distribution of flow for ENSO periods and seasons.

As expected, the monthly runoff data are not normally distributed. Thus, as was done for the annual peak data, the monthly flow values were converted to values representing their natural logarithms; however, the transformed data are not normally distributed either. Nonparametric statistical tests, including the Kruskal-Wallis and Mann-Whitney tests, were performed on the transformed data (Table 6). Regarding the overall significant differences among the ENSO periods, the Kruskal-Wallis test revealed that there were significant differences among ENSO periods for most stations with the exception for the stations Johnson Creek near Ingram, Nueces River below Uvalde, and Nueces River near Asherton. The Mann-Whitney tests also revealed that the El Niño period was significantly different from both La Niña and the other periods in most stations. On the other hand, there were only five stations where La Niña was significantly different from the "other period." Additionally, the tests revealed that the stations with the greatest significant differences among stations are those in the northern part of the study area. These differences might be because the impact of El Niño on runoff could be subdued further south from runoff caused by hurricanes and tropical storms.

The interpretation of ONI and how it is used to classify ENSO period is a key element in this research. The 3-month running average is a temporal averaging, and hence this research assumes that it is appropriate to use the middle month as an indicator to label the 3-month period (as opposed to using the middle or last month). A preliminary analysis that moved the labeling scheme of 3-month running average period up a month at the Guadalupe River near Spring Branch and Blanco Creek at Wimberley stations revealed a consistent finding similar to the 17 stations reported in this study. While this study found no significant difference by varying definitions of ENSO period in streamflow, future investigation can explore application- and region-specific schema of ENSO classification indices to model other geographic phenomenon (Royce et al. 2011).

ENSO and Seasonal Periods

A summary of the findings for the streamflow runoff analyses for ENSO periods and seasons is presented in Tables 7 through 10. Table 7 presents streamflow characteristics during the winter season for the ENSO periods. The table shows that, for each station, the winter mean discharge is less than that for the entire period. The table also shows that, for winter flow, the mean discharge for each station during El Niño periods exceeds that for the entire winter season. Also, for each station, winter El Niño mean flow exceeds that during winter La Niña periods. It is interesting that winter flow as a percent of entire flow decreases downstream for the Nueces River stations and represents only 34% of all flow at the most downstream station near Asherton. Also notable is the flow during "other period" winter flow for the station Cibolo Creek at Selma; the ratio of "other period" winter flow to entire winter season flow is only 0.004.

Table 8 presents streamflow characteristics during the spring season for the ENSO periods. The table shows that, in general, spring flow exceeds entire period flow for the stations in the northern part of the study area but is less than entire period

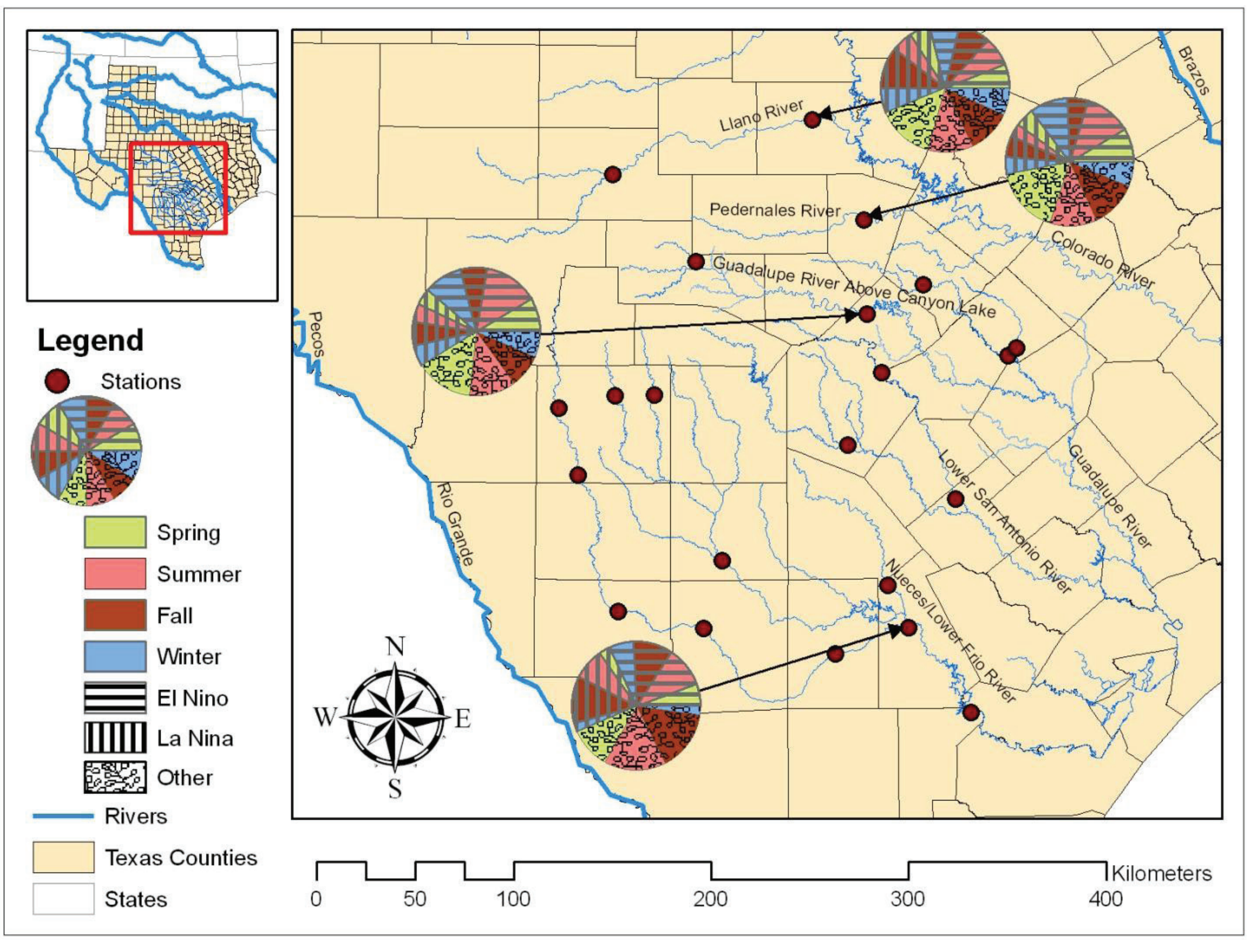


Fig. 5. Distribution of flow volumes by ENSO period and season for four streamflow-gaging stations used in the study.

Table 7. Statistical comparisons of winter streamflow discharges for Hill Country streams during periods of El Niño, La Niña, and other periods. (Note: Streamflow discharges based on period of available data for the 718 month period Jan. 1, 1950 through Sept. 30, 2009. Data based on streamflow during winter conditions--December through February months. For stations, El Niño occurs 27% to 30% of winter period; La Niña occurs 31% to 35% of winter period; and "other periods" occur 42% to 49% of winter period.)

Station name	Station number	Winter season		Winter El Niño		Winter La Niña		Winter other periods	
		Mean flow as		Mean flow as ratio of		Mean flow as ratio of		Mean flow as ratio of	
		ft^3/s	ratio of all mean flow	winter flow	all mean flow	winter flow	all mean flow	winter flow	all mean flow
San Saba River at San Saba, TX	08146000	135	0.75	1.34	1.01	1.03	0.77	0.76	0.57
Llano River near Junction, TX	08150000	136	0.71	1.19	0.85	1.12	0.80	0.79	0.56
Llano River at Llano, TX	08151500	320	0.82	1.37	1.12	0.98	0.80	0.78	0.64
Pedernales River near Johnson City, TX	08153500	170	0.81	1.76	1.43	0.73	0.59	0.71	0.58
Johnson Creek near Ingram, TX	08166000	20	0.72	1.20	0.86	1.14	0.82	0.77	0.56
Guadalupe River near Spring Branch, TX	08167500	361	0.86	1.68	1.45	0.81	0.70	0.71	0.61
Blanco River at Wimberley, TX	08171000	149	0.95	1.67	1.59	0.77	0.73	0.74	0.71
San Marcos River at Luling, TX [1]	08172000	417	0.99	1.66	1.64	0.75	0.74	0.76	0.75
Plum Creek near Luling, TX	08173000	117	0.99	2.14	2.11	0.48	0.47	0.66	0.65
Medina River at San Antonio, TX	08181500	205	0.79	1.67	1.32	0.86	0.68	0.67	0.53
Cibolo Creek at Selma, TX	08185000	15	0.52	3.03	1.57	0.60	0.31	0.004	0.002
Nueces River at Laguna, TX	08190000	127	0.74	1.30	0.95	1.03	0.76	0.79	0.58
Nueces River below Uvalde, TX	08192000	81	0.52	1.53	0.79	1.08	0.56	0.60	0.31
Nueces River near Asherton, TX	08193000	64	0.34	1.78	0.61	0.98	0.34	0.52	0.18
Frio River at Concan, TX	08195000	103	0.79	1.37	1.08	1.00	0.79	0.77	0.60
Sabinal River near Sabinal, TX	08198000	52	0.74	1.72	1.27	0.87	0.65	0.64	0.48
Frio River near Derby, TX	08205500	64	0.43	2.01	0.87	0.93	0.40	0.42	0.18

1 The mean flow for this station is at least minimally affected by discharges from San Marcos Springs.

flow for the stations in the southern part. The table also shows that for spring flow, the mean discharge for each station during El Niño periods exceeds that for the entire spring season and substantially exceeds that during La Niña spring seasons. Notable is the flow during the spring season for the station Cibolo Creek at Selma. For this station, only minimal spring season flow occurs during La Niña periods while El Niño season dominates the spring flow for this station.

Table 9 presents streamflow characteristics during the summer season for the ENSO periods. The table shows that, in general, summer flow is comparable to the entire period flow for the stations in the northern part of the study area but is greater than entire period flow for the stations in the southern part. For most of the stations, El Niño summer flow exceeds that for the entire period summer flow and, except for the first two stations in the table, exceeds that during the La Niña summer season.

Table 10 presents fall characteristics during the summer season for the ENSO periods. The table shows that, in general, fall season flow is comparable to that for the entire period. Also, fall El Niño flow generally is comparable to flow for the entire fall season and comparable to that during La Niña and "other period" in the fall seasons.

CONCLUSION

Table 8. Statistical comparisons of spring streamflow discharges for Hill Country streams during periods of El Niño, La Niña, and other periods. (Note: Streamflow discharges based on period of available data for the 718 month period Jan. 1, 1950 through Sept. 30, 2009. Data based on streamflow during spring conditions—March through May months. For stations, El Niño occurs 17% to 20% of spring period; La Niña occurs 26% to 30% of spring period; and "other periods" occur 57% to 66% of spring period.)

Station name	Station number	Spring season		Spring El Niño		Spring La Niña		Spring other periods	
		Mean flow as		Mean flow as ratio of		Mean flow as ratio of		Mean flow as ratio of	
		ft^3/s	ratio of all mean flow	spring flow	all mean flow	spring flow	all mean flow	spring flow	all mean flow
San Saba River at San Saba, TX	08146000	191	1.06	1.70	1.81	1.08	1.15	0.75	0.80
Llano River near Junction, TX	08150000	162	0.85	1.36	1.16	0.72	0.62	1.01	0.86
Llano River at Llano, TX	08151500	404	1.03	1.39	1.43	0.80	0.82	0.98	1.00
Pedernales River near Johnson City, TX	08153500	252	1.20	1.64	1.97	0.62	0.75	0.98	1.18
Johnson Creek near Ingram, TX	08166000	24	0.85	1.07	0.91	0.88	0.75	1.03	0.87
Guadalupe River near Spring Branch, TX	08167500	454	1.08	1.82	1.97	0.59	0.64	0.94	1.01
Blanco River at Wimberley, TX	08171000	179	1.15	1.84	2.11	0.57	0.66	0.94	1.08
San Marcos River at Luling, TX [1]	08172000	463	1.09	1.75	1.91	0.70	0.76	0.91	1.00
Plum Creek near Luling, TX	08173000	130	1.09	1.66	1.81	1.02	1.12	0.79	0.86
Medina River at San Antonio, TX	08181500	239	0.92	2.04	1.87	0.64	0.59	0.85	0.78
Cibolo Creek at Selma, TX	08185000	22	0.78	4.06	3.16	0.11	0.08	0.48	0.37
Nueces River at Laguna, TX	08190000	143	0.82	1.30	1.07	0.71	0.58	1.04	0.86
Nueces River below Uvalde, TX	08192000	97	0.61	1.53	0.94	0.57	0.35	1.03	0.63
Nueces River near Asherton, TX	08193000	129	0.69	1.63	1.12	0.41	0.28	1.08	0.74
Frio River at Concan, TX	08195000	117	0.90	1.51	1.36	0.71	0.63	0.98	0.88
Sabinal River near Sabinal, TX	08198000	64	0.91	1.80	1.65	0.62	0.57	0.93	0.85
Frio River near Derby, TX	08205500	115	0.77	2.11	1.63	0.60	0.47	0.84	0.65

[1] The mean flow for this station is at least minimally affected by discharges from San Marcos Springs.

Table 9. Statistical comparisons of summer streamflow discharges for Hill Country streams during periods of El Niño, La Niña, and other periods. (Note: Streamflow discharges based on period of available data for the 718 month period Jan. 1, 1950 through Sept. 30, 2009. Data based on streamflow during summer conditions—June through August months. For stations, El Niño occurs 24% to 28% of summer period; La Niña occurs 23% to 26% of summer period; and "other periods" occur 54% to 58% of summer period.)

Station name	Station number	Summer season		Summer El Niño		Summer La Niña		Summer other periods	
		Mean flow as		Mean flow as ratio of		Mean flow as ratio of		Mean flow as ratio of	
		ft^3/s	ratio of all mean flow	summer flow	all mean flow	summer flow	all mean flow	summer flow	all mean flow
San Saba River at San Saba, TX	08146000	145	0.81	0.95	0.77	1.21	0.98	0.93	0.75
Llano River near Junction, TX	08150000	174	0.92	0.84	0.77	1.33	1.22	0.93	0.85
Llano River at Llano, TX	08151500	373	0.95	1.24	1.18	0.97	0.92	0.91	0.86
Pedernales River near Johnson City, TX	08153500	225	1.07	1.83	1.96	0.55	0.59	0.82	0.88
Johnson Creek near Ingram, TX	08166000	27	0.98	1.24	1.21	0.89	0.87	0.94	0.92
Guadalupe River near Spring Branch, TX	08167500	501	1.20	1.91	2.29	0.67	0.80	0.73	0.88
Blanco River at Wimberley, TX	08171000	163	1.05	2.00	2.10	0.74	0.77	0.66	0.70
San Marcos River at Luling, TX [1]	08172000	421	1.00	1.64	1.63	0.77	0.76	0.81	0.81
Plum Creek near Luling, TX	08173000	80	0.67	1.60	1.07	0.85	0.57	0.79	0.53
Medina River at San Antonio, TX	08181500	357	1.37	1.97	2.70	0.64	0.88	0.72	0.98
Cibolo Creek at Selma, TX	08185000	50	1.77	2.55	4.52	0.82	1.46	0.38	0.67
Nueces River at Laguna, TX	08190000	191	1.10	1.40	1.55	1.08	1.20	0.78	0.87
Nueces River below Uvalde, TX	08192000	224	1.42	1.62	2.30	1.21	1.73	0.63	0.90
Nueces River near Asherton, TX	08193000	302	1.61	1.47	2.37	1.37	2.22	0.63	1.02
Frio River at Concan, TX	08195000	166	1.27	1.57	1.99	0.88	1.12	0.79	1.01
Sabinal River near Sabinal, TX	08198000	101	1.45	1.78	2.58	0.78	1.12	0.75	1.08
Frio River near Derby, TX	08205500	278	1.86	1.90	3.54	0.96	1.79	0.61	1.14

[1] The mean flow for this station is at least minimally affected by discharges from San Marcos Springs.

Table 10. Statistical comparisons of fall streamflow discharges for Hill Country streams during periods of El Niño, La Niña, and other periods. (Note: Streamflow discharges based on period of available data for the 718 month period Jan. 1, 1950 through Sept. 30, 2009. Data based on streamflow during fall conditions—September through November months. For stations, El Niño occurs 30% to 34% of fall period; La Niña occurs 30% to 34% of fall period; and "other periods" occur 40% to 46% of fall period.)

Station name	Station number	Fall season		Fall El Niño		Fall La Niña		Fall other periods	
		Mean flow as		Mean flow as ratio of		Mean flow as ratio of		Mean flow as ratio of	
		ft³/s	ratio of all mean flow	fall flow	all mean flow	fall flow	all mean flow	fall flow	all mean flow
San Saba River at San Saba, TX	08146000	200	1.11	0.82	0.91	1.38	1.54	0.86	0.95
Llano River near Junction, TX	08150000	234	1.23	1.00	1.23	1.27	1.56	0.80	0.99
Llano River at Llano, TX	08151500	471	1.20	0.91	1.09	1.20	1.44	0.93	1.11
Pedernales River near Johnson City, TX	08153500	191	0.91	0.77	0.71	0.80	0.73	1.32	1.20
Johnson Creek near Ingram, TX	08166000	27	0.97	0.80	0.78	1.04	1.01	1.12	1.08
Guadalupe River near Spring Branch, TX	08167500	358	0.85	1.06	0.91	0.95	0.81	0.99	0.85
Blanco River at Wimberley, TX	08171000	132	0.85	1.17	0.99	0.92	0.78	0.94	0.79
San Marcos River at Luling, TX [1]	08172000	391	0.92	1.16	1.07	1.06	0.98	0.83	0.77
Plum Creek near Luling, TX	08173000	87	0.73	1.44	1.05	0.71	0.52	0.88	0.65
Medina River at San Antonio, TX	08181500	242	0.93	1.15	1.07	1.25	1.15	0.71	0.65
Cibolo Creek at Selma, TX	08185000	26	0.93	0.95	0.89	1.78	1.66	0.46	0.43
Nueces River at Laguna, TX	08190000	232	1.34	0.81	1.08	1.32	1.76	0.91	1.21
Nueces River below Uvalde, TX	08192000	228	1.45	0.73	1.05	1.33	1.92	0.96	1.39
Nueces River near Asherton, TX	08193000	253	1.35	0.75	1.01	1.30	1.76	0.96	1.30
Frio River at Concan, TX	08195000	136	1.04	1.00	1.04	0.98	1.02	1.02	1.06
Sabinal River near Sabinal, TX	08198000	63	0.90	1.05	0.94	0.94	0.85	1.00	0.90
Frio River near Derby, TX	08205500	139	0.93	1.04	0.97	1.18	1.10	0.84	0.78

[1] The mean flow for this station is at least minimally affected by discharges from San Marcos Springs.

The major findings in this research are highlighted below:

1. Analysis of available literature suggest that, for the Texas Hill Country, greater rainfall generally occurs during El Niño periods for cooler months (December through May) but typically occurs during La Niña periods for warmer months (June through November).
2. Analysis of precipitation data for the Hill Country concludes that:
   a. El Niño and La Niña periods each occur about 25% of the time for the period analyzed (1950 through 2009) and the "other period" occurs about 50% of the total period.
   b. August precipitation for La Niña months exceeds that during El Niño periods.
   c. precipitation depths for the ENSO periods are comparable for other summer months (i.e. June and July).
   d. for all other months, El Niño precipitation exceeds or greatly exceeds La Niña precipitation.
3. Analysis of flood peaks in the Hill Country concludes that:
   a. neither ENSO period could be associated with annual flood peaks or the largest known flood peaks.
   b. almost all of the largest flood peaks analyzed for four streamflow sites occurred during the hurricane season (June through November).
4. Analysis of runoff volumes for the Hill Country concludes that:
   a. for each streamflow station, the mean discharge during the El Niño period exceeds that during the La Niña period.
   b. for the Nueces River and streams in the northern part of the Hill Country (San Saba and Llano Rivers and Johnson Creek), the El Niño period mean discharge only slightly exceeds that during La Niña period.
   c. for all other streamflow stations, El Niño period mean discharges substantially exceeds La Niña period mean discharges.

ACKNOWLEDGEMENT

The authors would like to thank Dr. Charles Jackson and Mr. Larry Land for their constructive comments.

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Texas Water Resources Institute
Texas Water Journal
Volume 2, Number 1, 2011, Pages 23–38

Commentary: 82nd State Legislature Regular Session: Summaries of water-related legislative action

Editor's Note: September 1 of every odd-numbered year is the date that new legislation from the Texas Legislature session that ended the previous spring typically goes into effect. With this in mind, the Texas Water Journal invited five organizations that work closely with the Texas Legislature to provide their take on the changes to Texas water policy and law that were made during the 2011 session. The opinions expressed in these summaries are the opinions of the individual organizations and not the opinion of the Texas Water Journal or the Texas Water Resources Institute.

Organizations:

- Sierra Club, Lone Star Chapter
- Texas Alliance of Groundwater Districts
- Texas and Southwestern Cattle Raisers Association
- Texas Farm Bureau
- Texas Water Conservation Association

Citation: K Kramer, SA Steinbach, J Skaggs, B Howe, D Robbins. 2011.Commentary: 82nd State Legislature Regular Session: Summaries of water-related legislative action. Texas Water Journal. 2(1):23-38. Available from: https://doi.org/10.21423/twj.v2i1.5886.

SIERRA CLUB: OVERVIEW OF WATER IN THE 82ND TEXAS LEGISLATURE

By Ken Kramer, Director, Lone Star Chapter, Sierra Club

As the state-level arm of the national Sierra Club, the Lone Star Chapter has been following water issues in the Texas Legislature for over 45 years with the assistance of volunteer and professional lobbyists. Each session has its own particular set of circumstances, and attention to water policy by legislators has varied considerably from one session to another. In some sessions water has been a high priority issue, even the dominant one. In other sessions water has been barely a blip on the legislative radar screen. In the 2011 regular session the topic of water was at best a mid-level concern.

There were a relatively large number of bills dealing with water and sewer rates for areas served by private water utilities, and there was also the usual torrent of bills creating yet another utility district to facilitate the provision of water and sewer and sometimes other municipal services to newly developing areas. These are always noted with interest, but in the absence of some major environmental controversy about a private water utility or a real estate development to be served by a special district, these pieces of legislation rarely become the focus of the Sierra Club's attention.

In the 2011 session the water topics of major interest to the Sierra Club were groundwater rights and management, funding for water programs and projects, sunset review of the Texas Water Development Board (TWDB) and the Texas Commission on Environmental Quality (TCEQ), water conservation metrics, and a tax break for water stewardship. Following is a brief overview of the legislative outcome on those topics.

Groundwater Rights and Management

Although a number of bills dealing with groundwater management were introduced, undoubtedly the most controversial groundwater issue of the session was the debate over what constitutes groundwater ownership. For months prior to the opening gavel, a number of groups—including prominently the Texas Farm Bureau and Texas and Southwestern Cattle Raisers Association—were beating the drum for the "vested" right of a landowner to the groundwater under his or her land. Their assertion was that regulatory actions by some groundwater districts and potential outcomes in court cases dealing with groundwater were undermining or threatening to undermine what these groups felt to be a landowner's right to groundwater in place.

Other groups, such as the Sierra Club, countered that the concept of "vested" rights conveyed an absolute right of ownership that did not accurately describe Texas groundwater law. The Club and others believe that the landowner's right is a right to capture groundwater under the land, subject to regulations and limitations that may be imposed by groundwater districts or the state on that capture, in order to serve important public purposes, such as the conservation of resources (an authority conveyed in part under Article 16, Section 59 of the Texas Constitution).

The focus of this controversy in the Legislature became Senate Bill (SB) 332 by Senator Fraser. That bill initially stated that surface landowners had a vested right to groundwater under their property. The bill was compromised somewhat in the Senate, thanks in large measure to the efforts of Senator Duncan and others, who were able to add language to the bill in an attempt to assure the authority of groundwater districts to regulate groundwater.

The bill passed the Senate and was modified further by Representative Ritter, the House sponsor and chairman of the House Natural Resources Committee. The term "vested" right was dropped and additional language was added to shore up the authority of groundwater districts. Provisions were added to the bill to "exempt" certain groundwater districts—the Edwards Aquifer Authority and coastal subsidence districts—from any limitations on groundwater districts that might be inferred from the assertion of ownership rights. The House version of the bill passed easily and the Senate concurred with the House changes.

What the passage of SB 332 really means, however, is an open question. Some observers believe that it really makes no changes in existing Texas law and will have no effect on groundwater district actions. That begs the question, of course, of what the proponents of the law actually achieved by its passage. Other observers fear the new statutory language will be used by landowners to assert "takings" claims whenever a groundwater district attempts to put restrictions on groundwater use that might reduce its economic value. The Sierra Club shares that concern. Probably the only certain thing that can be said about the impact of SB 332, however, is that its ultimate meaning will be debated in the courts.

Funding for Water Programs and Projects

This topic generated a good bit of attention in the session for a variety of reasons, the most obvious being the initial estimate of a $27 billion revenue shortfall for the state budget overall for the next two years. As a result of the shortfall and the aversion to new taxes or fees to address that shortfall, the Legislature did not fully fund the baseline budget requests submitted by TWDB and TCEQ. TWDB, for example, was appropriated about $15 million (net) less than requested (the agency actually got $16.7 million less than its baseline request but received an additional $1.6 million as a result of legislative approval of one of its "exceptional item" requests). The Legislature did authorize TWDB to issue $100 million in Economically Distressed Areas Program (EDAP) bonds and $200 million in Water Infrastructure Fund bonds, but only appropriated enough general revenue money to allow the agency to issue approximately half of those bonds.

On the larger issue of funding water infrastructure projects and perhaps other water management strategies in the state water plan, House NR Chairman Ritter took a bold step by introducing legislation to set up new funding mechanisms, including a requirement that at least 20% of a new fund be used for conservation and water reuse projects. The time was not ripe for suggesting new fees to provide that funding, despite the Chairman's valiant efforts. In the end, opposition by certain groups to specific fee proposals and the overall anti-tax and anti-fee attitude of the majority of legislators in the 82nd Legislature torpedoed those efforts.

Much verbiage has been written bemoaning the lack of legislative willingness to fund the state water plan. From an environmental perspective, however, the situation is somewhat more complicated. The Sierra Club and other environmental groups, plus many landowners and others, question the true need for many of the water infrastructure projects proposed in the state water plan. Even the ones that are needed are likely to be funded for the most part by local or regional entities rather than the state government. Thus, the failure to establish a broad new state funding source for infrastructure is not necessarily a bad outcome, but the fact that the House NR Chairman recognized the need for a major new state funding initiative for conservation and reuse was significant. Hopefully that will continue to be a part of the dialogue on funding the state water plan.

The major development in the 82nd Legislature on funding water projects was the passage by 2/3 of both houses of a proposed constitutional amendment that would authorize the TWDB to issue an additional $6 billion in bonds that could be used to pay for both water and wastewater projects in the coming years, and to make that authorization "evergreen" (in other words the agency may continue to issue bonds as bond-funded loans are repaid as long as the $6 billion cap is not exceeded at any one time). The proposed amendment will be on the November 2011 ballot as Proposition 2 and must be approved by the voters in order to take effect. The Sierra Club has not adopted a position on that amendment; the need for more infrastructure money is there, but whether $6 billion is the right amount and whether TWDB should be given "evergreen" authority are open questions.

Sunset Review of Water Agencies

Both TWDB and TCEQ were up for sunset review in this past cycle (so was the Texas State Soil and Water Conservation Board, but it was not a focus for the Sierra Club). In the final analysis the TWDB continuation legislation (SB 660) turned out to be somewhat of a "yawner," with no dramatic changes in the agency (probably much to the relief of the TWDB staff and leadership). Despite a lot of angst and prolonged discussion about the appeals process for "desired future conditions" for groundwater resources that resulted from a joint planning process created by the Legislature several sessions ago, the Legislature basically made no major changes in that process, which was a topic in SB 660. Some language related to water conservation metrics was included in SB 660, similar in many respects to language adopted in separate legislation, SB 181, discussed below.

Most of the issues revolving around TCEQ sunset review were not water-related, at least not directly. A couple of exceptions were provisions in House Bill (HB) 2694, the agency continuation bill that passed, to clarify the authority of TCEQ to address surface water shortages in dry times in river basins that do not have "watermasters" (most of the river basins in the state) and provisions added to HB 2694 in the House, and later modified, that made changes in TCEQ's authority to regulate dam safety. The latter is an issue that will no doubt be back before the Legislature in the next or subsequent sessions as more and more real estate development occurs in here-to-fore rural areas, where homes and businesses could be impacted by the failure of dams on rural properties.

Water Conservation Metrics

One of the ongoing debates in the water realm in Texas in recent years has been over what constitutes appropriate ways of measuring urban water use, which affects how one then measures progress in reducing water use through conservation and efficiency. The biggest controversy is over the metric "per capita water use," termed "gallons per capita per day" or GPCD. The metric has been criticized as too crude a measure to be used to compare different areas in terms of whether those areas are conservative or profligate in their use of water. Without going into the details of the controversy here, suffice it to say that pretty much everyone agrees we need more and better measures of water use, especially to be able to evaluate industrial, commercial, and institutional water use.

This topic was addressed by the recent legislative session in SB 660, the TWDB continuation bill, and SB 181, a separate bill focused only on this topic. Both passed, with slightly different language, but the thrust is the same. The legislation requires the TWDB and TCEQ, in consultation with the state

Water Conservation Advisory Council (on which Sierra Club is represented), to "develop a uniform, consistent methodology and guidance for calculating water use and conservation to be used by a municipality or water utility in developing water conservation plans and preparing reports required under [the Water Code]." Since this process is already underway, that was a no-brainer.

A concern has been raised by some environmentalists and landowners that the some of the language in the legislation may have been put there to undermine the "water conservation" achievements that must be demonstrated by entities seeking an interbasin transfer (IBT) of surface water. Regardless of whether that intent was there or not, the Sierra Club does not believe the new legislation undermines the water conservation test for IBTs and believes instead that better measurement of water use benefits everyone.

Tax Break for Water Stewardship

Rural landowners engaged in agriculture have long enjoyed a property tax break; their land is valued based on its productivity and not its market value. In the 1990s those landowners who qualified for the agricultural tax break were allowed to switch to a wildlife management status and maintain the tax break by demonstrating efforts to maintain wildlife habitat. In the 82nd Legislature a proposed constitutional amendment (and accompanying bill) championed by The Nature Conservancy and supported by Sierra Club and others was introduced to extend the tax break to landowners practicing water stewardship (these landowners must qualify for the agricultural tax break first). The proposed amendment passed both houses easily and will be on the November ballot for voter approval as Proposition 8. Rulemaking would have to follow voter approval in order to establish the process for qualifying for a water stewardship tax break.

In summary there were important pieces of water legislation enacted in 2011 but not the dramatic omnibus bills of some past sessions. But water remains a critical issue in Texas, as the current drought demonstrates, and someday water again is likely to be a dominant legislative issue, perhaps even in the next session.

TEXAS ALLIANCE OF GROUNDWATER DISTRICTS: LEGISLATIVE WRAP-UP OF GROUNDWATER-RELATED BILLS

By Stacey A. Steinbach, Executive Director, Texas Alliance of Groundwater Districts

Despite initial beliefs that the 82nd Legislative Session would not be a water session due to large, looming issues, such as the budget and redistricting, the Legislature tackled a handful of wide-ranging and controversial water issues in 2011. This document provides a summary of groundwater-related bills that passed the Legislature during the 82nd Legislative Session. Although it also includes other bills of possible interest to groundwater conservation districts (GCDs or districts), it does not represent an exhaustive list, nor does it include all administrative bills that may affect GCD governance, such as bills amending election, open meetings/public information, and other administrative laws.

Groundwater Ownership

By far, bills related to groundwater ownership received the most media and overall attention of any groundwater bills filed this session. The bill ultimately passed by the Legislature, SB 332, was effective September 1, 2011, and "recognizes that a landowner owns the groundwater below the surface of the landowner's land as real property." The right entitles the landowner to drill for and produce groundwater, but not the right to capture a specific amount.

The bill provides that the right reaffirmed in SB 332 is subject to the rule of capture for liability purposes. It is also subject to a new section confirming a district's ability to limit or prohibit drilling based on spacing or tract size and regulate the production of groundwater as provided in Chapter 36, specifically incorporating sections 36.113 (relating to the ability to grant or deny permits and protect existing users), 36.116 (relating to spacing requirements and historic use protection), and 36.122 (relating to exports) of the Water Code. The new section also expressly notes that districts are not required to allocate groundwater based on a correlative rights approach.

The bill incorporates three additional considerations for districts in adopting rules: groundwater ownership rights, the public interest in conserving and protecting groundwater and controlling subsidence, and goals found in a district's management plan. It also includes a provision stating that SB 332 does not affect the ability of the Edwards Aquifer Authority, the Harris-Galveston Subsidence District, and the Fort Bend Subsidence District to regulate groundwater pursuant to the enabling legislation of those entities.

Desired Future Conditions, Petitions for Inquiry, and the Texas Water Development Board Sunset Bill

The Texas Water Development Board (TWDB) was subject to sunset review this year, and the Legislature reviewed and reauthorized the agency until 2023 in SB 660.[1] The bill makes a handful of significant changes to Texas groundwater law, including the addition of a groundwater management area (GMA) representative to each applicable regional water planning group (RWPG).[2]

SB 660 also requires regional water plans (RWPs) to be consistent with applicable desired future conditions (DFCs) and adds additional informational requirements for the state water plan. Notably, the bill requires the TWDB and the Texas Commission on Environmental Quality (TCEQ), in consultation with the Water Conservation Advisory Council (WCAC), to develop a uniform water-use calculation system. These changes are consistent with the changes made by SB 181, discussed below.

Consistent with SB 737 (also discussed below), SB 660 changes the term "managed available groundwater" to "modeled available groundwater" in order to better reflect the meaning of the term. SB 660 also makes comprehensive changes to the process for establishing and adopting DFCs in the various GMAs and filing petitions for inquiry at the TCEQ. Due to the importance of these changes for GCDs, they are discussed in greater detail here. Though two separate proposals for amending the DFC appeals process were introduced during the Legislative Session, neither version passed. As a result, the DFC appeals process at the TWDB remains substantively unchanged.

Establishing DFCs

SB 660 adds a definition for DFCs to Chapter 36 and requires districts to ensure that management plan goals and objectives are consistent with achieving applicable DFCs. The bill adds nine new factors that districts must consider when renewing or establishing DFCs:

1. aquifer uses or conditions within the management area, including conditions that differ substantially from one geographic area to another;

[1]Other sunset bills of interest may be HB 1808 (relating to the Texas State Soil and Water Conservation Board) and HB 2694 (relating to the Texas Commission on Environmental Quality).[2]GMA members are required to appoint a representative as soon as possible after the act's effective date of September 1, 2011.

2. the water supply needs and water management strategies included in the state water plan;
3. hydrological conditions, including, for each aquifer in the management area, the total estimated recoverable storage as provided by the executive administrator and the average annual recharge, inflows, and discharge;
4. other environmental impacts, including impacts on spring flow and other interactions between groundwater and surface water;
5. the impact on subsidence;
6. socioeconomic impacts reasonably expected to occur;
7. the impact on the interests and rights in private property, including ownership and the rights of management area landowners and their lessees and assigns in groundwater;
8. the feasibility of achieving the DFC; and
9. any other information relevant to the specific DFCs.

Pursuant to the act, DFCs must also "provide a balance between the highest practicable level of groundwater production and the conservation, preservation, protection, recharging, and prevention of waste of groundwater and control of subsidence in the management area."

The bill also incorporates two changes aimed to improve the information exchange at the GMA level and aid in the development of DFCs. GMA members now have the opportunity to request the TCEQ and the TWDB provide nonvoting technical staff for GMA meetings and may appoint nonvoting advisory committees to represent various interests, such as social, environmental, and economic interests.

Providing Notice of DFCs

It should be noted that SB 660 implements additional notice provisions for considering and adopting DFCs at the GMA and district level. In both instances, notice must be provided pursuant to the Open Meetings Act, plus at least 10 days in advance of the applicable meeting. For GMA meetings, one district may be responsible for fulfilling all notice requirements and providing notice to the Secretary of State, the various county clerks in the GMA, and each district office in the GMA. However, failure or refusal of one or more districts to post notice of a GMA meeting does not invalidate actions at the meeting.

Adopting DFCs

SB 660 requires that two-thirds of all districts in the GMA vote to approve distribution of DFCs to districts in GMA. At that point, a 90-day (minimum) public comment period begins. Each district must hold a public hearing (after giving notice as described above) on the proposed DFCs relevant to the district, making copies of DFC reports available to the public. After the hearing, the district must summarize relevant comments received and any suggested revisions to the proposed DFC for the next GMA meeting. The district GMA representatives must then meet to consider all information and finally adopt the DFCs for the GMA. Again, two-thirds of all districts in the GMA must vote to adopt the proposed DFCs.

Once the DFCs are adopted, the districts, as part of the GMA, must prepare a detailed "DFC explanatory report" that includes the DFCs adopted, the policy and technical justifications for each adopted DFC, documentation showing how the nine new DFC factors were considered, a list of DFCs considered but not adopted and the reasons why, and an analysis of public comments received. This report must be submitted to the TWDB and all GMA districts with documentation of notice of GMA meetings and the resolution adopting the DFCs. As soon as possible after receiving the report, the individual districts must adopt the applicable DFCs, providing the explanatory report, the DFCs adopted, and proof of notice to the TWDB within 60 days of adoption.

Petitions for Inquiry

The provisions of Chapter 36 related to petitions for inquiry at the TCEQ were also substantively amended by SB 660. For the purposes of a petition, the bill defines "affected person" as: (1) a landowner in the GMA; (2) a district in or adjacent to the GMA; (3) a RWPG with a water management strategy in the GMA; (4) a person who holds or is applying for a permit from a district in the GMA; (5) a person who has groundwater rights in the GMA; or (6) any other person as affected by the TCEQ rule. Affected persons are authorized to file a petition with the TCEQ any time a district fails to comply with the following nine requirements (four original requirements are in italics; the others were added by SB 660):

1. submit a management plan to the TWDB;
2. *participate in joint planning;*
3. adopt rules;
4. adopt applicable DFCs adopted by the GMA;
5. update the management plan within 2 years of adoption of new DFCs;
6. update rules to implement applicable DFCs within a year after updating the management plan;
7. *adopt rules designed to achieve DFCs;*
8. *adopt rules that adequately protect groundwater; and*
9. *enforce rules for the adequate protection of groundwater.*

The process for reviewing petitions remains unchanged. As before, penalties are issued in accordance with Texas Water Code § 36.3011, which has been amended to incorporate the nine provisions listed above.

General Groundwater

In addition to the bills concerning groundwater ownership and desired future conditions, there were a number of bills that made general clarifications and relatively minor changes to Chapter 36. One such example, SB 727, simply cleans up all references to GCD management plans in Chapter 36 to achieve consistency among the statutes. Other legislative changes this session relate to permit requirements and exemptions.

Permit Requirements

One legislative and stakeholder objective this session was to change the term "managed available groundwater" to "modeled available groundwater" (MAG) in order to better reflect the intent of the phrase. SB 737 does just that, defining the MAG as the amount of water that the TWDB determines may be produced on an average annual basis to achieve a DFC. The bill also amends Texas Water Code § 36.1132 to clarify that districts should, to the extent possible, issue permits so that exempt and permitted production achieves applicable DFCs. The amended section also requires districts to consider the following five factors when issuing permits: (1) the MAG; (2) exempt groundwater use; (3) previously authorized withdrawals; (4) actual production; and (5) yearly precipitation and production patterns.

HB 3109 makes a small change to Texas Water Code § 36.121, increasing the maximum population size in the statute from 100,000 to 115,000 for applicable municipalities producing groundwater in counties with a population of less than 14,000. In such instances, GCDs located within the county cannot require these municipalities to obtain a permit to produce water from wells purchased or owned, or to which the municipality held rights to, before the date on which the district was created.[3]

Finally, SB 693 provides that hearings on the issuance of a groundwater permit application must be conducted by the State Office of Administrative Hearings (SOAH) if requested by a party to the contested case hearing. The requesting party must bear the costs of the SOAH hearing.

Permit Exemptions

The Legislature passed two bills aimed at clarifying permit exemptions in Chapter 36. SB 691 makes clear that groundwater users must meet all factors to satisfy the domestic and livestock exemption found in Texas Water Code § 36. 117(b)(1) (domestic, poultry, or livestock; 10 acres or more; capable of producing no more than 25,000 gallons per day), rather than just one. Similarly, SB 692 (adopted later in time than SB 691) makes generally the same changes to the domestic and livestock exemption but also clarifies § 36.117 overall to specify that the exemptions provided in that section apply to the use of the water rather than the well itself—if the use of the water from the well changes, a permit may be required.

Priority Groundwater Management Areas

Pursuant to Texas Water Code § 35.007(a), the TCEQ and the TWDB are charged with identifying areas of the state expected to experience critical groundwater problems for the next 25 years. As a result of SB 313, the Legislature has expanded this time period to 50 years in order to allow for more comprehensive data and correspond with statewide water planning efforts.

SB 313 also authorizes the TCEQ to adopt certain rules related to priority groundwater management areas (PGMAs) and amends provisions related to the creation of a GCD in a PGMA, allowing for consolidation of adjacent PGMAs in certain instances. Late amendments to the bill address situations in which land within a PGMA is proposed for inclusion in a GCD that has already approved an ad valorem tax.

Oil and Gas

The Legislature adopted three oil and gas-related bills that contemplate notice for GCDs. HB 444 requires the TCEQ to notify applicable GCDs of permit applications and contested case hearings for an injection well to dispose of industrial and municipal waste. Similarly, SB 430 adds applicable GCDs to the list of entities the TCEQ must notify when the agency receives information of a potential public health hazard due to groundwater contamination.

Another bill, HB 3328, received a great deal of attention late in the session. This bill outlines provisions for disclosing chemicals and processes used in hydraulic fracturing operations. Fracturing is the process by which a well operator pumps a liquid at sufficient power into a rock formation in order to break apart the rock and reach oil and gas reservoirs. Pursuant to the new bill, well operators must complete a form on each well and submit it to the Texas Railroad Commission for public availability. The form must include the total volume of water used in the hydraulic fracturing treatment and the information from the material safety data sheet for each hazardous chemical used in the treatment. The operator must also provide the Railroad Commission with a list of all other intentionally used chemical ingredients not listed on the form. Disclosure of incidental, accidental, or unknown ingredients is

[3] *See also section 181 of HB 2702 (omnibus bracket adjustment bill), which passed this session and incorporates the new ceiling of 115,000, but also includes a municipal population size floor of 100,000 in Texas Water Code § 36.121. It is unclear at this time how this bill and HB 3109 will be read.*

not required. Entities may withhold certain trade secret information, subject to procedures found in the Texas Government Code and rules to be adopted by the Railroad Commission. The bill applies only to hydraulic fracturing treatment performed on a well for which an initial drilling permit is issued on or after the date that the Railroad Commission's rules first take effect.

Water Conservation

This section addresses a sample of bills dealing with water conservation. As it relates to rainwater harvesting, the Legislature passed a few bills related to various aspects, including HB 3391, HB 3372, and SB 1073, the most comprehensive of these being HB 3391. This bill allows for loans for developments using harvested rainwater, provides for rainwater harvesting technology to be used in certain new state buildings, and encourages cities and counties to provide rainwater harvesting incentives. The TCEQ is required to adopt rules for the installation and maintenance of rainwater harvesting systems used for indoor potable purposes and connected to a public water supply system, and the TWDB must now provide training on the subject (mandatory for staff in certain municipalities and counties).

SB 181 amends RWPG requirements such that each RWP must now include information on projected water use and conservation and the implementation of projects necessary to meet the state's projected water demands. As mentioned previously, the bill also requires the TCEQ and the TWDB, in consultation with the WCAC, to develop a uniform methodology for calculating water use and conservation that will be used in developing water conservation plans and preparing reports.

Another water conservation bill that passed the Legislature this session is SB 449, the water stewardship tax exemption bill. This bill authorizes a tax exemption for property used for water stewardship purposes, outlining nine methods of water stewardship, including implementation of practices that reduce the amount of water used from exempt wells and allowing for groundwater monitoring for data collection purposes in accordance with GMA planning. The Texas Parks and Wildlife Department, in conjunction with the State Comptroller and, if requested, the Texas AgriLife Extension Service, will develop standards for approving such exemptions. As with the wildlife tax exemption, the property must first be qualified under an open space or timber exemption before qualifying for the water stewardship exemption. SJR 16 is the proposed constitutional amendment that implements SB 449.

Local District Bills

The Legislature also passed a number of bills related to individual GCDs. SB 1147 makes nonsubstantive changes to the enabling legislation of various districts (specifically, Guadalupe County GCD, Brazos Valley GCD, Cow Creek GCD, Gateway GCD, Goliad County GCD, Hays Trinity GCD, Irion County WCD, Middle Pecos GCD, Refugio GCD, and Texana GCD), codifying such language in the Special District Local Laws Code. Other legislation, described below, created new districts, modified district boundaries and fees, and amended provisions regarding directors and elections.

Created Districts

The Legislature authorized the creation of two new single-county GCDs this session: Terrell County Groundwater Conservation District (HB 2859) and Calhoun County Groundwater Conservation District (SB 1290). If confirmed by voters in an election, Terrell County GCD will be a tax- and fee-based district with five directors appointed by the Terrell County Commissioners Court and the authority to issue bonds. The district will be excluded from Texas Water Code § 36.121 (excluding certain municipal wells from GCD regulation) and will have the authority to impose production and export fees.

If confirmed by voters in an election, Calhoun County GCD will be a fee-based district with five elected directors. The district will not be empowered to impose a tax, but it may impose production and import fees. Interestingly, Calhoun County GCD appears to be the first district to have a mitigation provision in its enabling legislation. The bill authorizes the district to "assist in the mediation between landowners regarding the loss of existing groundwater supply of exempt domestic and livestock users due to the groundwater pumping of others."

Boundaries

Two districts will have changed boundaries after the session. Barton Springs-Edwards Aquifer CD will exclude certain territory in Bastrop County from its boundaries that was included in the Lost Pines GCD when that district was created in 1999. This bill (HB 1060) is a result of Texas Attorney General Opinion GA-0792 (August 2010), which held that "two different political subdivisions may not exercise jurisdiction over the same territory at the same time and for the same purpose."

Similarly, pursuant to SB 1225, landowners of certain Caldwell County property that is currently included in both the Gonzales County UWCD and Plum Creek CD will have the option of selecting the district they want to have jurisdiction over their property. If the landowner does not choose a district, it will automatically fall within Plum Creek CD's boundaries.

Finally, HB 801 repeals a provision of Southern Trinity GCD's enabling legislation that requires the district to include at least one county adjacent to McLennan County in its boundaries by September 1, 2011 or be dissolved by the TCEQ.

Fees

The fee provisions in Northern Trinity GCD's enabling legislation were amended in HB 3818, which sets limits of $1/acre-foot for agricultural use and $0.20/1,000 gallons for use other than agricultural use on the district's production fees for authorized withdrawals or the amount of groundwater actually withdrawn.

Directors and Elections

In HB 3866, SB 564, and SB 1895, the Legislature set the uniform election date as the date for electing directors of the Hill Country UWCD, Middle Pecos GCD, and Texana GCD, respectively. SB 1895 also removes Texana GCD's power of eminent domain and a provision authorizing the district to contract with a river authority for performing district functions.

SB 987 amends the precinct method of electing directors for Colorado County GCD. Because the district had trouble finding candidates for office who live within the three small towns included in the district, the bill changes these city-limit positions to at-large positions. The bill also specifies that term limits apply to two "full" terms, specific to a director's position.

Finally, SB 1492 amends the director positions of the Real-Edwards Conservation and Reclamation District, providing for four seats from Edwards County, four seats from Real County, and one at-large seat but allowing for all voters to vote on all positions.

Looking Ahead

Although it is much too early to identify subjects that may be considered during the 83rd Legislative Session, GCDs can bet that DFCs will be on the table again in 2013. The Legislature stopped short of adopting provisions that would amend the DFC appeals process, despite requests from some Legislators and stakeholders to do just that. It is also probable that water conservation will once again be at the forefront of legislative issues, particularly if the drought continues.

TEXAS AND SOUTHWESTERN CATTLE RAISERS ASSOCIATION: 82ND STATE LEGISLATURE REGULAR SESSION SUMMARY

By Jason Skaggs, Executive Director, Government and Public Affairs, Texas and Southwestern Cattle Raisers Association

During the 82nd State Legislature Regular Session, the Texas and Southwestern Cattle Raisers Association (TSCRA) was directly involved in approximately 6.5 percent of the 6,009 bills filed during the session. Approximately 23 percent of the bills filed were sent to the Governor.

A summary of important legislation TSCRA supported and helped pass during the 82nd State Legislature Regular Session is below.

Priority legislation

SB 18 by Sen. Craig Estes/Rep. Charlie Geren: Reforms state eminent domain laws.

SB 18 requires:

- A public and record vote to initiate eminent domain proceedings.
- Condemning entities to specifically state the public use for which the land is needed.
- Private property only be condemned for public use.
- Entities with eminent domain authority to register with the Comptroller by December 2012.
- Condemning entities to make a bona fide offer in writing based on an appraisal and, if not, pay the landowner's expenses and attorney fees.
- Landowners to be compensated for damages from a loss of direct access to their property.
- Landowners to receive relocation assistance when forced to move off of their property.
- Condemning entities to provide appraisals of the property to landowners during negotiations.
- Landowners, under certain conditions, the right to repurchase their condemned land at the original price if it is not used for the public use it was condemned for within 10 years.

SB 332 by Sen. Troy Fraser/Rep. Allan Ritter: Strengthens landowners' ownership of groundwater below their land.

SB 332 does the following:

- Reaffirms that landowners own the groundwater below their land as real property.
- Entitles landowners to drill for and produce the groundwater below their land.
- Preserves the rule of capture.
- Recognizes that groundwater may continue to be produced and conserved while ensuring fair and impartial regulation of landowners' groundwater ownership rights.

Other important legislation

HB 1808 by Rep. Byron Cook/Sen. Kirk Watson: Continues the Texas State Soil and Water Conservation Board for twelve years.

HB 2694 by Rep. Wayne Smith/Sen. Joan Huffman: Provides more flexibility in the enforcement of state dam safety standards for dams on rural, private property and classified as low or significant hazard.

SB 573 by Sen. Robert Nichols/Rep. Brandon Creighton: Provides more rights for landowners in highly populated counties to have their land released from certificates of convenience and necessity from water and wastewater.

SB 646 by Sen. Robert Nichols/Rep. Byron Cook: Continues the Texas Forest Service for twelve years.

SB 660 by Sen. Juan "Chuy" Hinojosa/Rep. Allan Ritter: Changes the process to determine the desired future conditions (DFCs) of aquifers. SB 660 requires groundwater conservation districts to:

- Consider the groundwater ownership rights of landowners.
- Balance the highest practicable level of groundwater production with conservation.
- Provide more public notice of meetings regarding DFCs.

SB 691 by Sen. Craig Estes/Rep. Tracy King, SB 692 by Sen. Craig Estes/Rep. Doug Miller: Clarifies the criteria for domestic and livestock groundwater well permit exemptions.

TEXAS FARM BUREAU: 82ND STATE LEGISLATURE SUMMARY

By Billy Howe, State Legislative Director, Texas Farm Bureau

For the past two years, it was evident that groundwater management would be a major issue this session. Several factors were converging prior to this legislative session to make it a big one for groundwater management: desired future conditions, the Texas Water Development Board and the Texas Commission on Environmental Quality sunset issue, and the ownership of groundwater.

The first-ever desired future conditions (DFCs) were established by local groundwater conservation districts for each groundwater management area in the state. Once DFCs were established to limit the production of groundwater for the next 50 years, it was inevitable some controversy would ensue. Fortunately, most of the controversy was limited to just two of the 16 management areas. Nevertheless, a group of stakeholders, including the Texas Farm Bureau, worked for the past year to identify and offer recommendations to the legislature on changes to the DFC process. All the recommendations made to the legislature to improve the process were enacted. The most significant change was to establish in law what a DFC was to accomplish—the balancing of the need to produce groundwater for our livelihood with the conservation of the resource for the future. The current law provided no such guidance to the groundwater conservation districts. This language is critical to recognizing that groundwater management is not just about conservation but ensuring that those who depend on groundwater will have access to it.

But, the most controversial DFC issue has not been resolved—the issue of how a DFC can be challenged or appealed. This is a crucial issue that must be addressed before the next DFCs are adopted in 2015. As stated above, DFCs establish the amount of groundwater that can be produced over a 50-year period. It is critical that landowners and other stakeholders have a right to challenge DFCs to protect their rights and provide a balance to the decisions made by the groundwater conservation districts.

When state agencies undergo the sunset review process, everything associated with that agency is subject to change. Therefore, with the two leading water agencies under sunset review, the Texas Water Development Board and the Texas Commission on Environmental Quality, it was imperative to stay alert to changes to water policy that would be detrimental to landowners. To complicate matters, the DFC issue was included in the sunset review of the TWDB. However, this proved to be beneficial because the TWDB sunset bill, supported by the Texas Farm Bureau, passed when the individual DFC bills failed.

Undoubtedly, the groundwater ownership issue became the biggest water issue of the session. The issue became elevated when the Edwards Aquifer Authority argued to the court that landowners did not have any ownership of groundwater prior to its capture. Once that argument was made, Texas Farm Bureau and other landowner organizations became very engaged. Senator Troy Fraser and Representative Allen Ritter committed themselves to recognize that landowners own the groundwater below the surface of the land as real property by passing SB 332—no small accomplishment considering the opposition.

Ownership of groundwater as real property, rather than just as personal property after it is captured, does not and should not prevent its regulation, but it does give every landowner a vested property right to drill for and produce groundwater. This vested property right will prevent unfair regulation biased towards historic use, water utilities, and water projects that would leave landowners without a right to the water under their land. Ownership also gives irrigated farmers a vested property right that will maintain their rights to groundwater regardless of what may happen in the future with groundwater regulation. The passage of SB 332 may be marked as one of the major public policy accomplishments of our organization's history.

TEXAS WATER CONSERVATION ASSOCIATION: RECAP OF 2011 REGULAR LEGISLATIVE SESSION

By Dean Robbins, Assistant General Manager, Texas Water Conservation Association

Who said it wasn't going to be a water session? Even though the State budget and redistricting dominated the news, the legislature still found time to file and pass numerous bills related to issues such as the ownership of groundwater, groundwater management, water and wastewater utility regulation, and the sunset of our two favorite state agencies, the Texas Water Development Board (TWDB) and the Texas Commission on Environmental Quality (TCEQ). Groundwater legislation passed includes virtually all of the recommendations of TWCA's Groundwater Committee. Major eminent domain legislation was also passed as expected as well as legislation related to a number of administrative issues for governmental entities. Included in this article is a chart summarizing bills passed considered to be of general interest to TWCA members.

Statistically, this session was not as active as the 2009 regular session when over 8,000 bills were filed and over 1,700 were passed. By comparison about 6,300 bills were filed this session with about 1,500 passed. TWCA tracked about 340 bills this session, down from about 400 in 2009. Included in this article is a summary of bills considered to be of high priority that passed.

There were also some significant casualties during the session:

- Chairman Ritter's proposal to establish a dedicated source of revenue to fund the State Water Plan failed to pass. However, he was successful in passing a proposed constitutional amendment authorizing the TWDB to issue development fund bonds on a continuing basis such that the aggregate principal amount outstanding does not exceed $6 billion at any one time. This is a critical component for financing the State Water Plan;
- The sunset bill for the Public Utility Commission (PUC) failed to pass, and with it the proposed transfer of the water and wastewater rate program from the TCEQ to the PUC;
- Representative Callegari's major water district clean-up bill died the last weekend of the session; and
- A proposal to increase fees assessed by water districts and water supply corporations to retail customers was stripped from the TCEQ sunset bill in conference committee.

See TWCA's priority legislation summary on the following pages.

Table 1. Priority Legislation, by TWCA

Bill No.	Author/ Sponsor	Summary
HB 628	Callegari Jackson, Mike	**Relating to contracts by governmental entities and related professional services and to public works performance and payment bonds.** Various codes are amended to consolidate and standardize procurement procedures for governmental entities.
HB 1732	Ritter Hinojosa	**Relating to the applicability of the constitutional limit on state debt payable from the general revenues of the state to bonds issued by the Texas Water Development Board.** Chapter 17, Water Code, is amended to ensure that certain bonds authorized by the TWDB are not considered to be state debt payable from general revenue under the Texas Constitution until the legislature makes an appropriation of general revenue to the board to pay the debt service on the bonds. Chapters 15 and 16, Water Code, are amended to prohibit the financing of certain projects until the applicant has completed a water infrastructure financing survey. Also see SJR4.
HB 2226	Truitt Carona	**Relating to authorized investments for governmental entities.** The Public Funds Investment Act (Chapter 2256, Government Code) is amended to require monitoring of rating changes in investments, to define the 2-year training cycle, and to further address authorized investments.
HB 2694	Smith, Wayne Huffman	**Relating to the continuation and functions of the Texas Commission on Environmental Quality (TCEQ) and abolishing the On-site Wastewater Treatment Research Council.** This is the comprehensive sunset bill for the TCEQ. Issues of particular interest include an exemption from dam safety regulation until 2015 for certain dams in rural areas impounding less than 500 acre-feet; transfer of surface casing determinations for oil and gas wells from the TCEQ to the RRC; utilization of compliance history in enforcement and permitting decisions; clarification of the agency's authority to administer surface water rights during droughts and other emergencies; and a requirement to periodically assess the need for additional watermaster programs.
HB 3090	Creighton Nichols	**Relating to the frequency of water audits by certain retail public utilities.** Chapter 16, Water Code, currently requires a retail public utility providing potable water to perform and file with the TWDB every 5 years a water audit computing the utility's water loss. HB3090 requires those retail public utilities receiving financial assistance from the TWDB to perform the audit annually.
HB 3372	King, Tracy Jackson, Mike	**Relating to standards for a structure that is connected to a public water supply system and has a rainwater harvesting system.** Chapter 341, Health and Safety Code, is amended to require the TCEQ and the Texas Department of Health to develop rules for a rainwater harvesting system used for indoor potable purposes and connected to a public water supply system. A person who installs or maintains such a system must be a licensed plumber and certified as a water supply protection specialist. The owner of the public water supply system must be notified before connecting the rainwater harvesting system to the public water supply system. The public water supply system may not be held liable for any adverse health effects of the connection. Also see SB1073.

Table 1. Continued

HB 3391	Miller, Doug Seliger	**Relating to rainwater harvesting and other water conservation initiatives.** Various codes are amended to allow financial institutions to consider making loans for developments that will use harvested rainwater as the sole source of water supply; to require that rainwater harvesting technology be incorporated into the design and construction of certain new state buildings; to address criteria for the installation and maintenance of rainwater harvesting systems that are used for indoor potable purposes and connected to a public water supply system; to require cities and counties to encourage rainwater harvesting; to address prohibitions on rainwater harvesting by property owners associations; and to incorporate the promotion of rainwater harvesting into the water policies of the state.
SB 18	Estes Geren	**Relating to the use of eminent domain authority.** Various codes relating to eminent domain are amended to ensure that a governmental entity may only exercise the authority of eminent domain for a public use; to require a governmental entity to authorize initiation of an eminent domain proceeding through a public meeting; to require all entities with eminent domain authority to document that authority with the Comptroller by 12/31/2012 (or lose it); to require disclosure of certain appraisal information to a landowner; to require a bona fide offer to a landowner that is equal to or greater than the appraised value; to establish procedures for repurchase of property by a landowner when the condemned land is not used for its intended purpose in 10 years; etc.
SB 181	Shapiro Laubenberg	**Relating to the reporting of water conservation measures by municipalities and water utilities.** Chapter 16, Water Code, is amended to require each regional water planning group to report on projected water use and conservation and the implementation of planned projects. The legislature finds that gallons per capita per day is not an accurate measure of water use or conservation without adjustment for certain variables and requires the TWDB and the TCEQ, in consultation with the Water Conservation Advisory Council, to develop a uniform, consistent methodology and guidance for calculating and reporting water use and conservation by a municipality or water utility. Rule-making is authorized as necessary. Timelines are established.
SB 313	Seliger Price	**Relating to priority groundwater management areas.** Chapter 35, Water Code, is amended to change the planning horizon for the priority groundwater management area (PGMA) process to 50 years (current law is 25 years). Language is added to clarify that the TCEQ's rule-making authority for PGMAs also applies to the critical area process that existed before September 1, 1997. Procedures are added to clarify how financing occurs when a PGMA area is added to an existing district. Conforming changes are made to Chapter 36, Water Code.
SB 332	Fraser Ritter	**Relating to the vested ownership interest in groundwater beneath the surface and the right to produce that groundwater.** Chapter 36, Water Code, is amended to recognize that a landowner owns the groundwater below the surface as real property. The landowner is entitled to drill for and produce groundwater subject to the spacing requirements and production limits of a groundwater district. The existence of common law or other defenses to liability under the rule of capture are unaffected. This section does not affect the ability of the EAA or the subsidence districts to regulate in any manner authorized by enabling legislation.
SB 333	Fraser King, Tracy	**Relating to election procedures and qualifications of members of boards of directors for water supply or sewer service corporations.** Chapter 67, Water Code, is amended to establish qualifications and election procedures for board members of water supply corporations.

Table 1. Continued

SB 449	Watson Ritter	**Relating to the appraisal for ad valorem tax purposes of open-space land devoted to water stewardship purposes on the basis of its productive capacity.** The Tax Code is amended to authorize the appraisal of open-space land on the basis of its productive capacity for water stewardship. Practices that may be implemented to promote and sustain water quality and conservation of water resources are designated. The TPWD, with the assistance of the Comptroller, is required to develop qualifying standards. See SJR 16 for the corresponding constitutional amendment.
SB 512	Hegar Creighton	**Relating to the qualification of supervisors of a fresh water supply district.** Chapter 53, Water Code, is amended. Under prior law only the owner of taxable property in a fresh water supply district is eligible for election as a supervisor. Under this amendment a registered voter of the district would also be eligible.
SB 573	Nichols Creighton	**Relating to certificates of public convenience and necessity for water or sewer services.** Chapter 13, Water Code, is amended to establish procedures for the TCEQ to issue a CCN to a retail public utility within the ETJ of a municipality without the municipality's consent; to prohibit the TCEQ from issuing a CCN to a municipality beyond the municipality's ETJ over the objections of a landowner; and to require the TCEQ to grant a petition by the owner of a tract of 25 acres or more to release the tract from a CCN area when the tract is not receiving water or sewer service. The TCEQ may require compensation to the decertified retail public utility. Each of the provisions are bracketed to include or exclude certain counties.
SB 660	Hinojosa Ritter	**Relating to the review and functions of the Texas Water Development Board, including the functions of the board in connection with the process for establishing and appealing desired future conditions in a groundwater area.** This is the comprehensive TWDB sunset bill. The provisions of HB1732, relating to the agency's bonding authority, and SB181, relating to a uniform, consistent method for calculating and reporting water use and water conservation, are incorporated. The bill also amends Chapter 36, Water Code, to define "desired future condition," to codify criteria thatdistricts must consider in establishing DFCs, and to establish procedural requirements for the DFC process. DFC appeals to the TWDB and the TCEQ are further clarified. Changes to the DFC process generally include recommendations of the TWCA Groundwater Committee.
SB 691	Estes King, Tracy	**Relating to the exemption from permitting by groundwater conservation districts for certain water wells used for domestic, livestock, and poultry watering purposes.** Chapter 36, Water Code, is amended to make grammatical changes to the language prohibiting a groundwater district from requiring a permit for a well used for domestic or livestock purposes if the well is located on a tract larger than 10 acres and incapable of producing more than 25,000 gallons per day. This legislation was recommended by TWCA's Groundwater Committee.
SB 692	Estes Miller, Doug	**Relating to exemptions from groundwater conservation district permit requirements.** Chapter 36, Water Code, is amended to clarify that exemptions from permitting apply to the purpose for which groundwater is used, and not to the well itself. This legislation was recommended by TWCA's Groundwater Committee.

Table 1. Continued

SB 693	Estes Price	**Relating to permit application and amendment hearings conducted by groundwater conservation districts and the State Office of Administrative Hearings.** Chapter 36, Water Code, is amended to require a groundwater district to contract with the State Office of Administrative Hearings (SOAH) to conduct a contested case hearing if requested by the permit applicant or other party to the case provided that the party requesting that SOAH conduct the hearing pay all costs of the SOAH contract. The district may still make a final decision on the matter after considering the SOAH recommendations. This legislation was recommended by TWCA's Groundwater Committee.
SB 727	Seliger Beck	**Relating to groundwater conservation district management plans.** Chapter 36, Water Code, is amended to make all references to groundwater conservation district management plans consistent. This legislation was recommended by TWCA's Groundwater Committee.
SB 737	Hegar Price	**Relating to the management of groundwater production by groundwater conservation districts.** Chapter 36, Water Code, is amended to change the term "managed available groundwater" to "modeled available groundwater" and to address how a district may consider actual groundwater production, including exempt use, in making permitting decisions. This legislation was recommended by TWCA's Groundwater Committee.
SB 1480	Hegar Darby	**Relating to the regulation of exotic aquatic species by the Parks and Wildlife Department.** Chapter 66, Parks and Wildlife Code, is amended to restructure and strengthen TPWD's authority to regulate harmful or potentially harmful exotic aquatic plants not normally found in the public waters of the State. The TPWD is required to develop rules to implement this law.
SJR 4	Hinojosa Ritter	**Proposing a constitutional amendment providing for the issuance of additional general obligation bonds by the Texas Water Development Board.** An amendment to the Texas Constitution is proposed to authorize the TWDB to issue certain development fund bonds on a continuing basis such that the aggregate principal amount outstanding does not exceed $6 billion at any one time. Also see HB1732.
SJR 16	Estes Ritter	**Proposing a constitutional amendment providing for the appraisal for ad valorem tax purposes of open-space land devoted to water stewardship purposes on the basis of its productive capacity.** A constitutional amendment is proposed to support the appraisal of open-space land on the basis of its productive capacity for water stewardship. See SB449.

Texas Water Resources Institute
Texas Water Journal
Volume 2, Number 1, Pages 39–53, 2011

Hydrologic Connectivity in the Edwards Aquifer between San Marcos Springs and Barton Springs during 2009 Drought Conditions

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Paula Jo Lemonds, P.G., P.E.[1]

Abstract: A study of water level data collected during the 2009 drought was conducted to determine if there is a hydrologic connection between the San Antonio segment and Barton Springs segment of the Edwards Aquifer. These results showed con-tinuity in the direction of groundwater flow along a preferential groundwater flow zone from San Marcos Springs to Barton Springs during the drought. Using a USGS MODFLOW model, the flow passing San Marcos Springs and flowing toward Bar-ton Springs was estimated at about five cfs.

Near the city of Kyle, major discontinuities in hydraulic gradient and water levels were evident, which indicate a zone of rela-tively low transmissivity. Southwest of Kyle, an area of nearly flat water levels exists and is believed to be a zone of high transmis-sivity. Faults do not appear to be a controlling factor between the zones of relatively high and low transmissivity nor blockage or conduits of groundwater flow. Rapid population growth and increased water demands suggests a continual groundwater level monitoring program between San Marcos Springs and Buda to provide data for future local and regional hydrogeologic analyses.

Keywords: Edwards Aquifer, Barton Springs, San Marcos Springs, MODFLOW, groundwater flow, drought

Errata: A sentence in the Discussion section, first paragraph (page 50) was corrected from:"Numerical models (Scanlon et al. 2001) and water budget studies (Slade et al. 1986) of the Barton Springs segment all consider the boundary between the San Antonio and Barton Springs segments to be a no-flow boundary." to "Numerical models (Scanlon et al. 2001 and Slade et al. 1985) of the Barton Springs segment considers the bound-ary between the San Antonio and Barton Springs segments to be a no-flow boundary. Slade et al. (1986) describes intra-aquifer flow between the two segments during the drought of 1955–56 and during a 1978 dry period." he "Slade et al. 1985" reference was added to the reference list.(2.11.13)

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Citation: LE Land, BB Hunt, BA Smith, PJ Lemonds. 2011. Hydrologic connectivity in the Edwards Aquifer between San Marcos Springs and Barton Springs during 2009 drought conditions. Texas Water Journal. 2(1):39-53. Available from: https://doi.org/10.21423/twj.v2i1.1951.

INTRODUCTION

The Edwards Aquifer is composed predominantly of limestone of early Cretaceous age, belonging to formations in the Edwards Group. It exists under water table conditions in the outcrop and under artesian conditions where it is confined by the Del Rio Clay. In the San Antonio and Barton Springs segments, the Edwards Aquifer is karst and serves as the primary source of water for municipal, industrial, domestic, irrigation, livestock, and wildlife. It is also the source of water for several minor springs and the largest two springs in Texas, Comal Springs in New Braunfels and San Marcos Springs in San Marcos. These two springs are the primary sources of water for the Guadalupe and San Marcos Rivers during drought conditions.

An Edwards Aquifer Recovery Implementation Program (EARIP) is being devised by a voluntary stakeholder group in response to the Texas State Legislature to develop a management plan to protect the federally listed species at Comal Springs and San Marcos Springs. While developing a water management plan to maintain sufficient flow from San Marcos Springs during drought conditions, a question was raised on the long-standing concept of a hydrologic divide separating the San Antonio and Barton Springs segments of the Edwards Aquifer in the vicinity of Onion Creek. For hydrologic separation of the Edwards Aquifer to occur, a groundwater divide (a ridge in the water table and potentiometric surface) must exist to divert recharge south of the divide toward San Marcos Springs and recharge north of the divide toward Barton Springs. The Edwards Aquifer Authority (EAA) is responsible for management of the San Antonio segment, and the Barton Springs/Edwards Aquifer Conservation District (BSEACD) is responsible for management of the Barton Springs segment. The political boundary between the two regulatory entities is generally along Highway 150 west of Kyle and generally follows the watershed divide between Onion Creek and the Blanco River. This is also the watershed divide between the Colorado River and the Guadalupe-San Antonio River basins. It has been assumed that pumping in one segment does not significantly affect groundwater levels or springflow in the other segment. This assumption also applies in the calculation of recharge for the two segments.

A map showing the area between San Marcos Springs and Barton Springs, the Edwards Aquifer, and the regulatory divide between the two segments is shown in Fig. 1.

To address the existence of the hydrologic divide, a study was designed and data were collected during the 2009 drought to document groundwater levels in a study area between San Marcos Springs and Buda. If the 2009 data show that the groundwater divide dissipates, then pumpage in either segment can affect water levels and springflows in both segments during drought. If the groundwater divide persists during a major drought, then recharge and groundwater pumping in one segment does not significantly affect aquifer conditions in the other segment.

The primary purpose of this article is to provide an assessment of the potential for groundwater in the San Antonio segment of the Edwards Aquifer to bypass San Marcos Springs and flow toward Barton Springs under 2009 and other recent drought and pumping conditions. The article also places the 2009 drought in perspective with recent hydrologic conditions, estimates the magnitude of the groundwater flow passing San Marcos Springs toward Barton Springs, if any, and discusses major findings.

PREFERENTIAL GROUNDWATER FLOW ZONE BETWEEN SAN MARCOS SPRINGS AND BARTON SPRINGS

The groundwater flow pattern in the study area is characterized during normal and wet conditions by movement from the outcrop (unconfined) area to the downdip (confined) area. When the flow approaches the poorly permeable zone of the Edwards Aquifer in the saline zone, the groundwater flow south of the divide turns toward San Marcos Springs and groundwater flow north of the divide turns toward Barton Springs. Because of the topography of the groundwater levels, the only significant opportunity for groundwater to flow between the two segments during drought conditions is along the downdip limit of the freshwater zone of the Edwards Aquifer. Because of the complex faulting, some faults may become pathways for preferential groundwater flow and others may form barriers that largely block groundwater flow.

Recent dye trace studies have revealed a hydrologic connection from recharge features in the Blanco River to both San Marcos Springs and Barton Springs under 2009 drought conditions (Johnson SB, written communications, 2010). Similarly, a study by Hunt et al. (2006) demonstrated a hydrologic connection from recharge features to both San Marcos Springs and Barton Springs from Onion Creek under wet conditions. Clearly, the nature of the hydrologic divide between the two segments is very complex and dynamic in the unconfined zone, as demonstrated by these studies. However, this study focuses on the potential for groundwater flow in the deep confined zone of the San Antonio segment of the aquifer to bypass San Marcos Springs (elevation 574 ft-msl) and flow toward Barton Springs, the lowest elevation spring in the Edwards Aquifer (432 ft-msl).

The hydrologic connection between San Marcos Springs and Barton Springs under drought conditions was first discussed by Guyton (1958) and later by Senger and Kreitler (1984). A preferential groundwater flow zone near the fresh-saline water interface was proposed by Hauwert et al. (2004a).

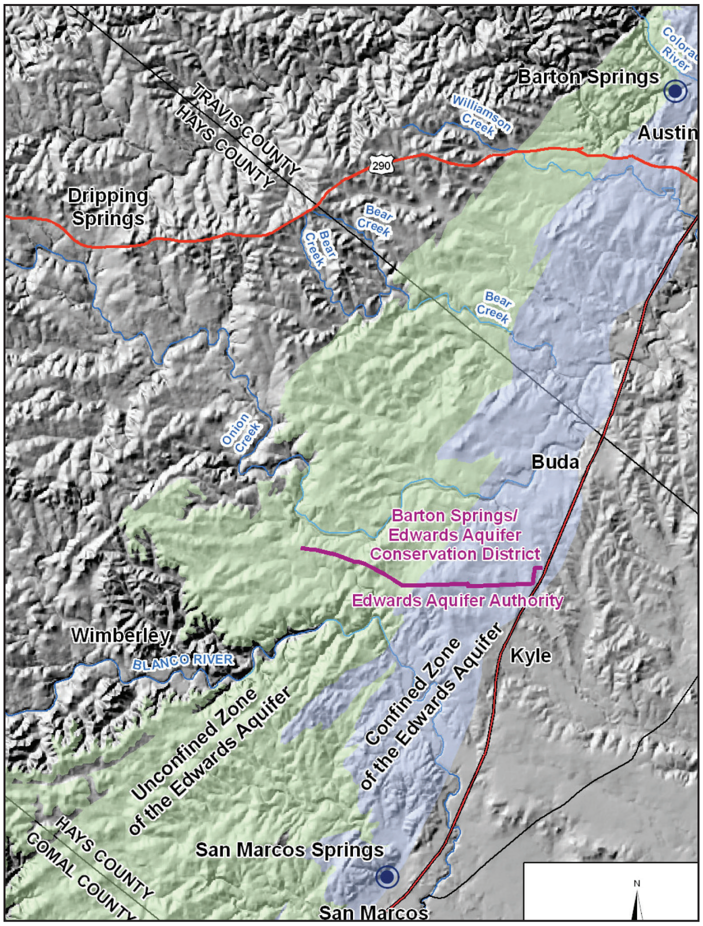

Fig. 1. Location of Study Area, Edwards Aquifer and Jurisdiction of Edwards Aquifer Authority and Barton Springs/Edwards Aquifer Conservation District.

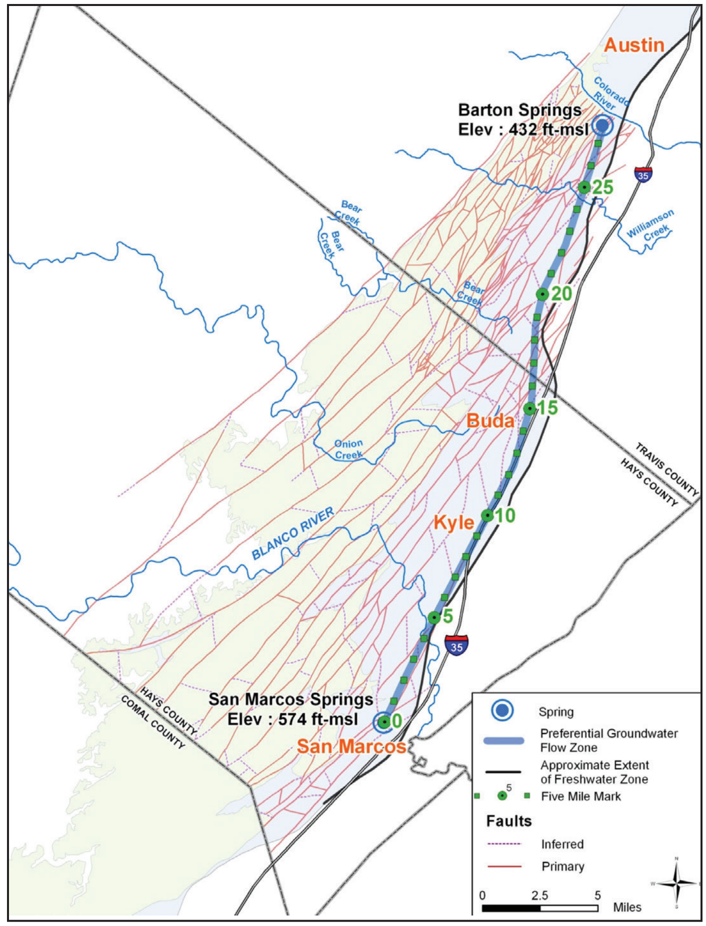

Fig. 2. Location of Preferential Groundwater Flow Zone.

It was delineated in this study on the basis of geologic framework (Hanson and Small 1995; Small et al. 1996), hydrogeologic analyses (Hovorka et al. 1998; Baker et al. 1986; Garza 1962), dye tracing studies (Hauwert et al. 2004b; Hunt et al. 2006), groundwater modeling studies (Lindgren et al. 2004; Scanlon et al. 2001), and water level data. For purposes of this study, the primary hydrologic connection between San Marcos Springs and Barton Springs is believed to occur along this preferential groundwater flow zone between the two springs as shown in Fig. 2. It is believed to have a relatively high transmissivity (Hovorka et al. 1998). It is located within approximately a mile of the fresh-saline water interface or boundary, which is locally defined as groundwater with a total dissolved solids concentration of about 1,000 milligrams per liter (mg/L). A similar zone of high transmissivity has been presented by (Lindgren et al. 2004) in the U. S. Geological Survey (USGS) MODFLOW model of the Edwards Aquifer. All major springs discharging from the Edwards Aquifer and many large pumping centers are in the vicinity of the fresh-saline water boundary and within the preferential flow zone as conceptually defined here.

OVERVIEW OF HYDROLOGIC CONDITIONS

1989-2009 Conditions

Springflow data for San Marcos Springs and Barton Springs were compiled from the USGS database. Hydrographs of these data since 1989 are presented in Fig. 3. From the perspective of springflow, these data show that the 2009 drought had similar severity to the ones in 1989, 1996, 2000, and 2006, although the 2000 drought affected Barton Springs more severely than San Marcos Springs. In addition to dry weather conditions, the springflow also reflects the magnitude of groundwater pumping in the contributing area, which has increased substantially in the Barton Springs Segment of the aquifer in recent years.

2009 Conditions

The drought of 2009 was one of the most severe in Texas since the 1950s drought of record (DOR), which lasted much longer (1951–1957). Annual rainfall totals were similar to the

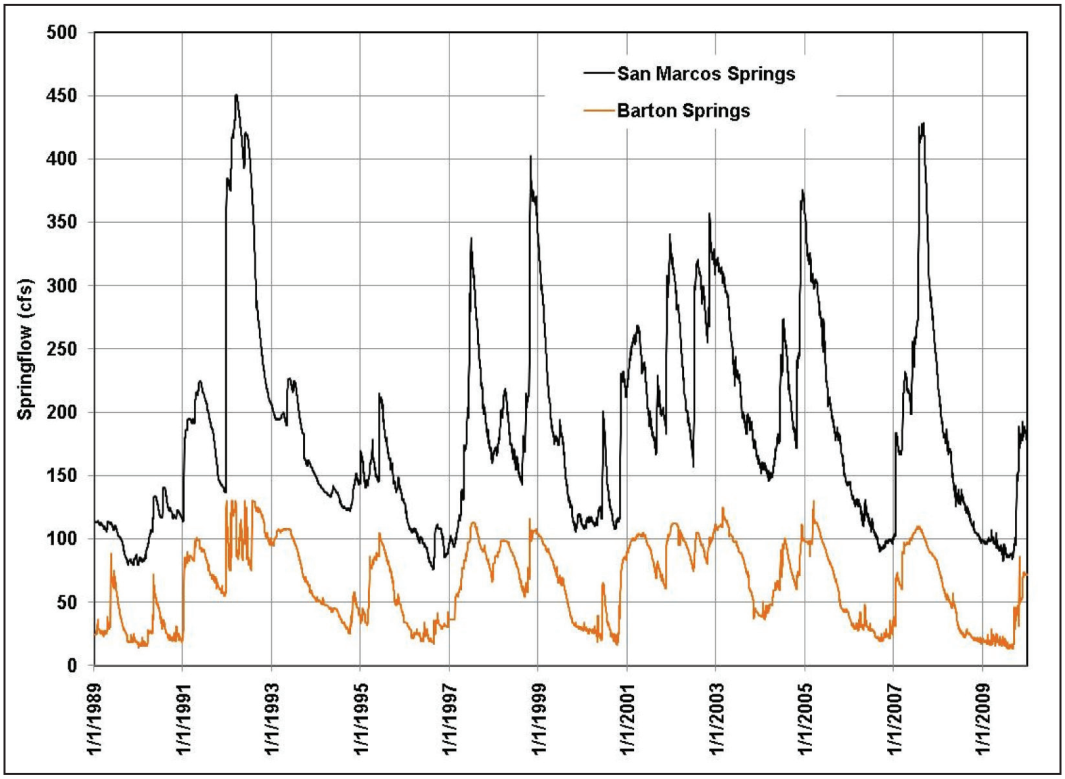

Fig. 3. Discharge hydrographs of San Marcos and Barton Springs (1989–2009).

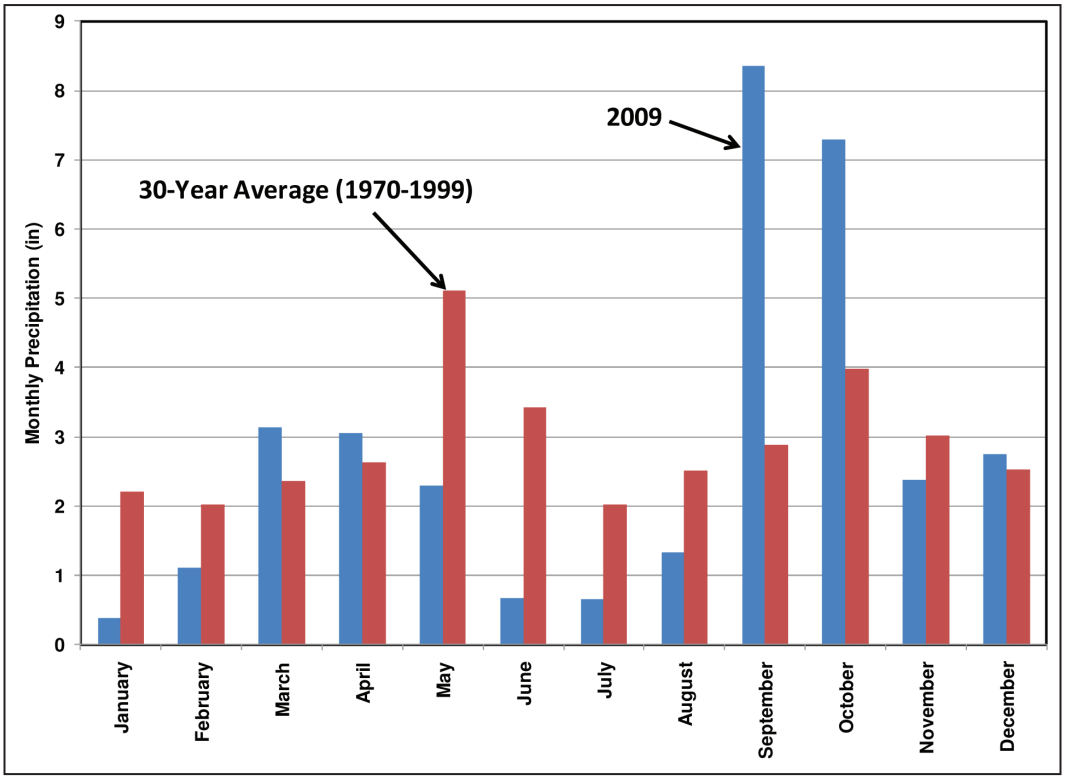

Fig. 4. Monthly precipitation, 2009 and 30-year average.

last year of the DOR, and groundwater elevations approached or were lower in parts of the Edwards Aquifer than during the DOR. However, the total water budget (springflow and pumping) was nearly twice the amount near the end of the 2009 drought (August 2009) than during the DOR, indicating the impacts were not as severe as the DOR (Smith and Hunt 2010). The extended duration (about 7 years) of the DOR in comparison to the 2009 drought, which lasted less than a year, is a critical factor in considering the DOR to be much more severe than the 2009 drought.

For this study the hydrologic conditions during 2009 are characterized with records from USGS streamflow gaging stations: 08159000 Onion Creek at US Hwy 183, 08171000 Blanco River at Wimberley, and 08171300 Blanco River near Kyle. During summer 2009, these data show that the streamflow at Onion Creek and Blanco River near Kyle was zero, except for occasional runoff events immediately following storms. The Blanco River at Wimberley record shows a stable flow of about 12 to 15 cubic feet per second (cfs) through April, decreasing discharge until July, and about 5 to 6 cfs in July and August. With the Blanco River near Kyle having no flow most of the time, it is generally understood that essentially all of the Blanco River at Wimberley streamflow became recharge to the Edwards Aquifer.

The Lower Colorado River Authority's (LCRA) Hydromet precipitation station Onion Creek at Buda was selected to provide information on rainfall during 2009 for the study area. These data are collected electronically at approximately 15-minute intervals and appear to be complete for 2009. From May 25 to about September 12, the total rainfall was about 2.5 inches. From September 12 to the end of the year, about 20 inches was recorded. Graphs of the monthly rainfall data are shown in Fig. 4. Also shown in Fig. 4 is the 30-year average for the National Weather Service's Austin precipitation station.

APPROACH

A 2009 drought data collection program was designed and implemented in the area between San Marcos Springs and Buda. The program was planned by the Guadalupe-Blanco River Authority (GBRA), BSEACD, USGS, and HDR Engineering, Inc. (HDR). Data collection was performed by the USGS and BSEACD at the monitoring wells shown in Fig. 5, which consisted of 10 existing water wells. From late June to December 2009, water levels were measured at approximately 2-week intervals. Four of the 10 wells were instrumented with pressure transducers and electronic data loggers, which were programmed to provide measurements at 1-hour intervals. For purposes of this study, these data are considered to be a continuous recording of water levels. Supplemental data were available from the San Antonio Water System (SAWS) and the

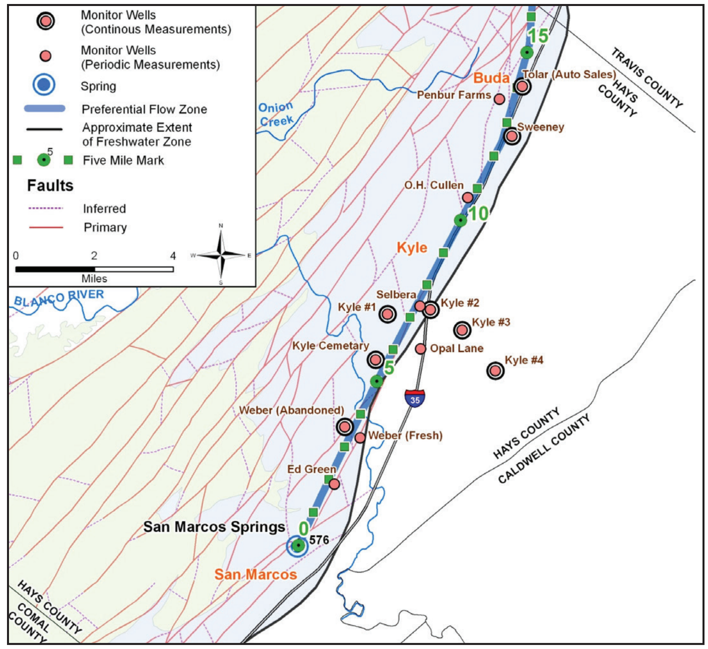

Fig. 5. Location of monitoring wells.

USGS for 4 SAWS monitoring wells along a northwest-southeast transect through Kyle. Data analyses were performed by HDR and included significant consultation with GBRA, BSEACD, and USGS water resource specialists.

Other aquifer data were compiled from Texas Water Development Board (TWDB), BSEACD, EAA, and USGS databases for a hydrologic perspective on the 2009 drought. These data included groundwater levels from wells in the study area and springflow from San Marcos Springs and Barton Springs. In addition, hydrologic conditions for 2009 were characterized with streamflow data from the Blanco River and Onion Creek and precipitation data from the LCRA gage near Onion Creek.

Analyses of the direction of groundwater flow potentials were based primarily on water-level profiles that were drawn along the preferential groundwater flow zone using data collected during this study. Regional synoptic potentiometric maps helped provide supporting information and a broader context for the profiles. Although in the study area the Edwards Aquifer is a heterogeneous, anisotropic karst system, the hydraulic gradient does provide critical information on the potential for groundwater flow, which is based on the slope of the head profile (hydraulic gradient) along the preferential groundwater flow zone. As Kresic (2007) reports, "contour maps showing regional flow patterns in karst aquifers may be justified since groundwater flow generally is from recharge areas toward discharge areas and the regional hydraulic gradients will reflect this simple fact." Indeed, Quinlan (1989) states that, "it is logical, correct, and conventional to interpret the flow direction of ground water perpendicular to the potentiometric contours and downgradient."

To provide some first-order estimates of groundwater flow bypassing San Marcos Springs, the Edwards Aquifer-San Antonio Region Groundwater Availability Model (EA-SAR GAM) (Lindgren et al. 2004) was used. This is a MODFLOW model with a single layer, uniform grid of cells with a 0.25 miles each side, a stress period length of 1 month, and a calibration period from 1947–2000. Attempts to represent karst features include applying barriers for faults that are known to restrict groundwater flow and threads of high hydraulic conductivity to represent expected conduits. Springs are represented with MODFLOW's Drain Package to allow water to leave the model but not flow into it. The model's aquifer parameters were initially estimated from well and geologic data, which were refined by calibration to measured groundwater levels and springflow. In the Barton Springs segment, the hydrogeology was represented with information from the Edwards Aquifer-Barton Springs Segment Groundwater Availability Model (EA-BS GAM) (Scanlon et al. 2001). The rate of groundwater flow near San Marcos Springs was calculated from a simulation using the 1947-2000 calibration dataset and exported from the model for the month with the lowest flow during two major droughts.

RESULTS: 2009 DATA

Periodic Measurements

Periodic water level measurements were made in the network of 10 existing monitoring wells at approximately 2-week intervals from late June through December 2009. The preliminary data provided by the USGS were reviewed and some measurements were revised based on: (1) data measurements by the pressure transducers, (2) consistency with nearby wells, and (3) hydrograph patterns. These data are summarized in Fig. 6 for the monitoring wells between San Marcos Springs and Kyle and in Fig. 7 for wells between Kyle and Buda.

For the monitoring wells between San Marcos Springs and Kyle, the maximum water level fluctuation was about 5 ft and generally had a very consistent pattern among the wells. The Opal Lane well is in the saline zone of the Edwards Aquifer and shows water levels to be about 4 ft higher than nearby freshwater wells. Wells closer to San Marcos Springs (Ed Green, Weber Fresh, and Weber Abandoned) show less fluctuation than wells near Kyle (Kyle Cemetery and Opal Lane).

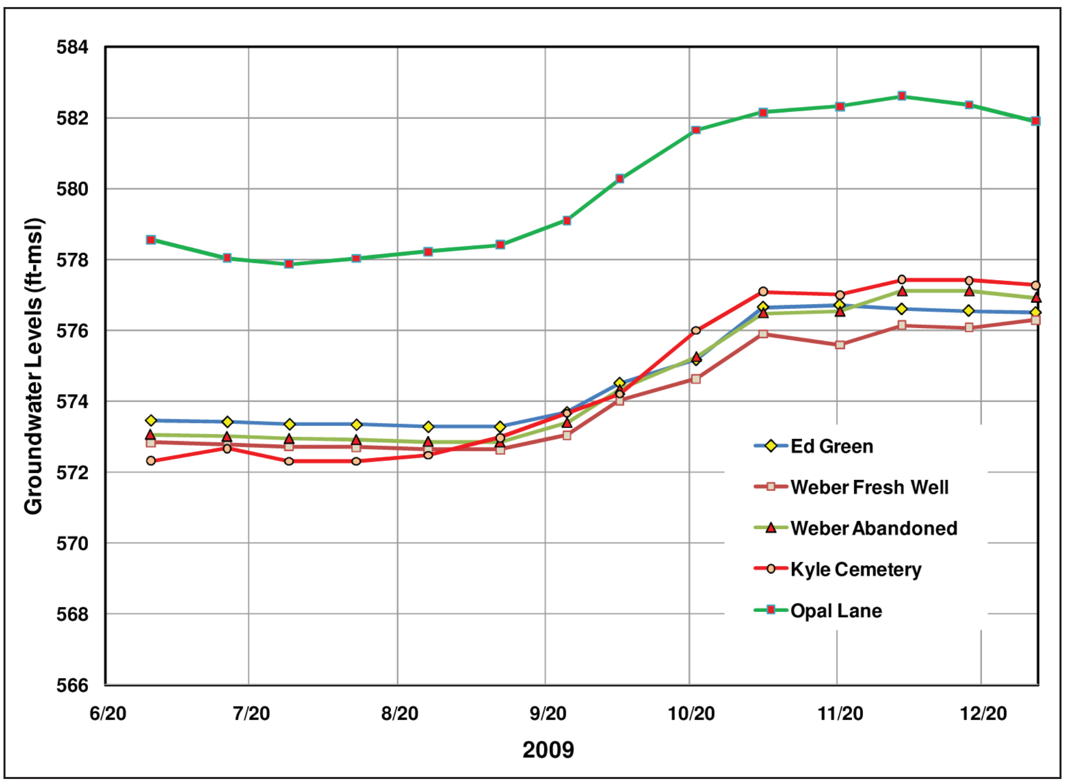

Fig. 6. Groundwater level hydrographs for monitoring wells: San Marcos Springs to Kyle.

Continuous Measurements

Water level measurements were recorded at hourly intervals at the Weber Abandoned, Kyle Cemetery, Sweeney, and Tolar monitoring wells using pressure transducers and digital data loggers. These results are summarized in Fig. 8 and show groundwater level recoveries following a major rainfall event on September 13 and other rainfall events during the remainder of the year. The recovery continued until the end of the year for the wells near Buda but ended in early December for the monitoring wells between San Marcos Springs and Kyle. As shown in Fig. 8, the water level recoveries were only a few feet for Weber Abandoned and several tens of feet for Sweeney and Tolar.

SAWS has conducted a test drilling program and installed 4 monitoring wells in a northwest-southeast transect through Kyle. These monitoring wells are equipped with pressure transducers and digital data loggers. Kyle #1 monitoring well is in the freshwater zone; Kyle #2 is in the transition zone between the freshwater and saline zones; and Kyle #3 and #4 are in the saline zone. Summaries of the 2009 water levels from these wells are presented in Fig. 9. Monitoring wells Kyle #1 and #2 have a hydrograph pattern similar to the Selbera well, where recovery occurs from late July to early November 2009 and rather rapid declines occur during the end of the year. Water levels for monitoring wells in the saline zone were very flat and did not track with the dominant pattern in the freshwater zone.

Pumping by City of Kyle

Groundwater is the most prevalent source of water in the study area, although surface water is being increasingly used to augment groundwater supplies. Most of the pumping in the study area occurs from public water supply systems, such as the Cities of Kyle and Buda. Numerous small domestic wells also occur in the study area, although they pump a relatively minor amount of water. Pumping records for 2009 show the City of Kyle's 5 public supply wells had widely varying monthly pumping rates, as shown in Fig. 10. The City of Kyle has 4 wells permitted in the EAA and one well permitted in the BSEACD. These data show that the well in the BSEACD has a typical demand pattern that trends from about 6.8 million gallons in January to 13.2 million gallons in July to 6.4 million gallons in December. The EAA-permitted wells range from 11.1 million gallons in January to 20.3 million gallons in July, abruptly decrease to 9.4 million and 5 million gallons in August and September, respectively, and abruptly increase

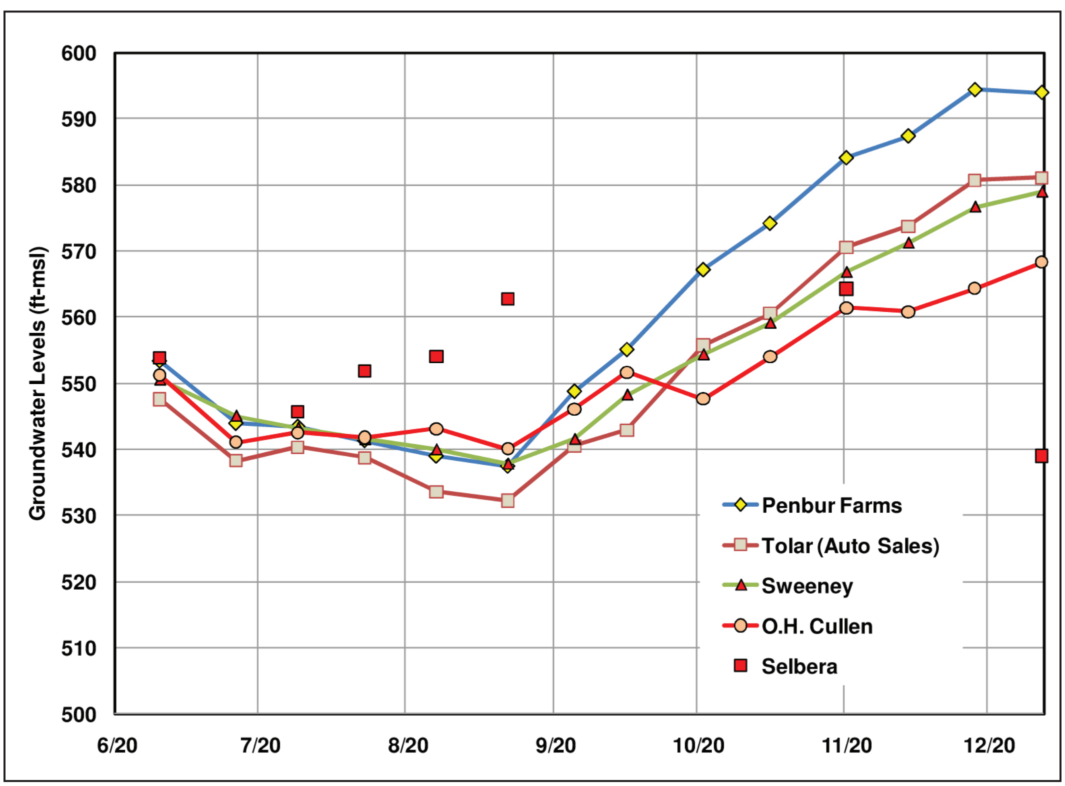

Fig. 7. Groundwater level hydrographs for 2009 study monitoring wells: Kyle to Buda.

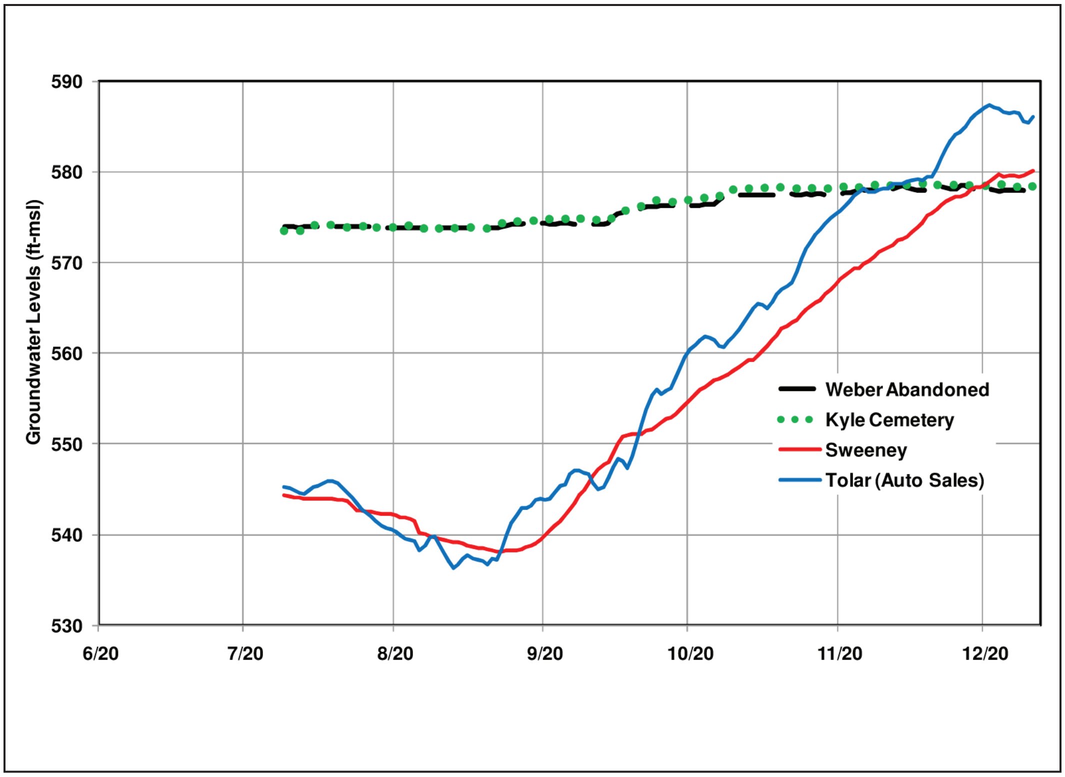

Fig. 8. Groundwater level hydrographs for monitoring wells with data loggers, 2009.

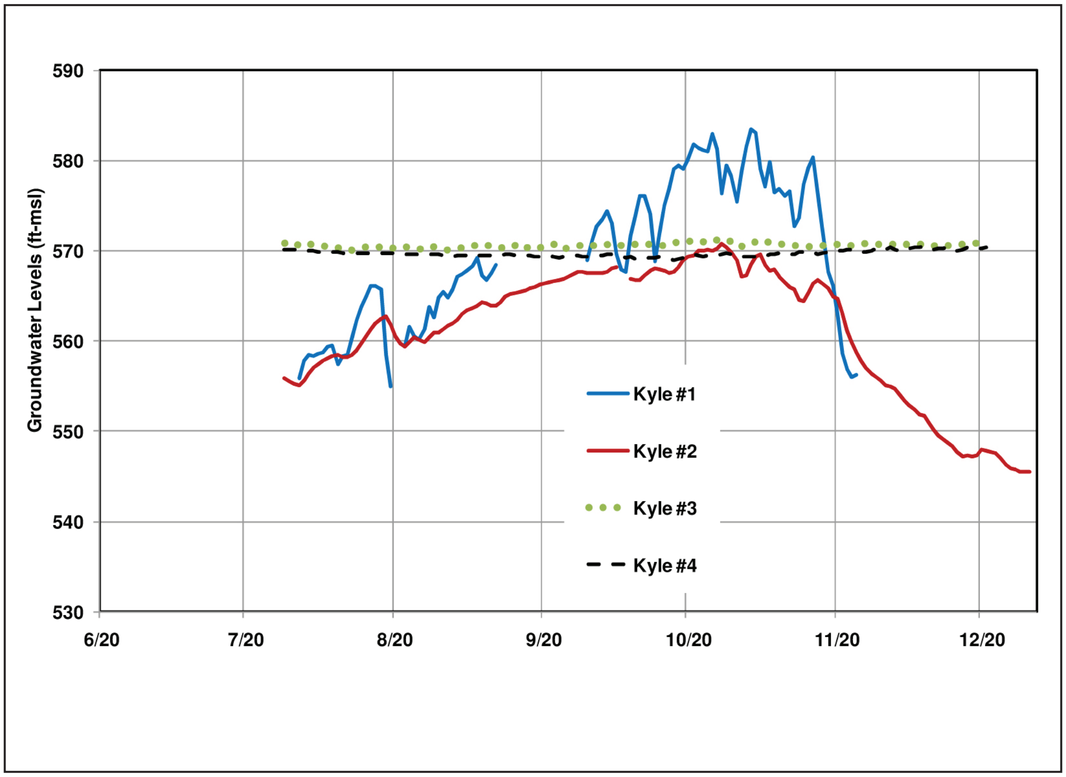

Fig. 9. Groundwater level hydrographs for SAWS monitoring wells along Kyle Transect, 2009.

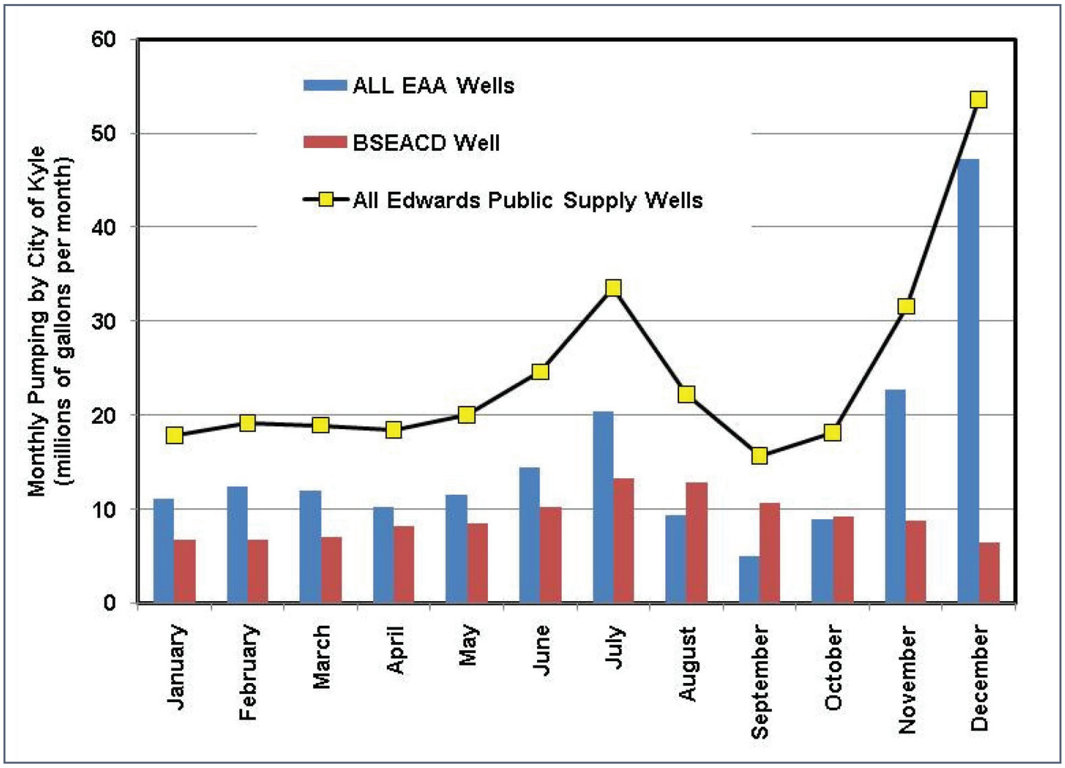

Fig. 10. Monthly pumping by the city of Kyle, 2009.

to 22.8 million and 47.2 million gallons in November and December, respectively.

Data from monitoring wells between Kyle and Buda (Fig. 7) show a maximum fluctuation of about 60 ft, with the lowest levels occurring in early September and the highest levels at the end of the year. The patterns are slightly erratic, which is attributed to nearby pumping wells and occasional recharge events. The Selbera well and SAWS Kyle Wells #1 and #2 have an unusual pattern with slightly rising groundwater levels through October and a noticeable decline by late December. This unusual pumping pattern of the EAA-permitted wells, especially in November and December, is believed to be the cause of the water level fluctuations in the Selbera well and SAWS Kyle Wells #1 and #2 monitoring wells, which are out of phase with regional hydrologic conditions and other water levels. Large-scale depressions in the potentiometric surface attributed to pumping (i.e. cone of depression) in the vicinity of Kyle have been noted in other studies (Hunt et al. 2007 and LBG-Guyton Associates 1994).

GROUNDWATER FLOW

A study of the groundwater divide in Hays County was conducted by LBG-Guyton Associates using potentiometric maps of the area (LBG-Guyton Associates 1994). This report concluded that the groundwater divide between Kyle and Buda was temporally viable and groundwater would move toward both Barton Springs and San Marcos Springs. The report also concluded that different hydrologic conditions could cause the flowpaths to change. As noted above, LBG-Guyton Associates (1994) documented a cone of depression that developed at Kyle every summer and disrupted the normal aquifer water level pattern.

February 2009 Conditions

A synoptic survey of groundwater levels from a large network of monitoring wells was conducted in late February 2009 by the EAA, city of Austin (COA), and BSEACD to evaluate groundwater conditions near the boundary between the two districts. These data were collected during a relatively short time to provide a snapshot of hydrologic conditions. The survey was conducted in the winter to minimize the interference of pumping wells. These data were mapped in the study area and groundwater-level contours are shown in Fig. 11. In the area of key interest, these data indicate that there is a continuously declining hydraulic gradient from San Marcos Springs to Barton Springs along the preferential groundwater-flow zone.

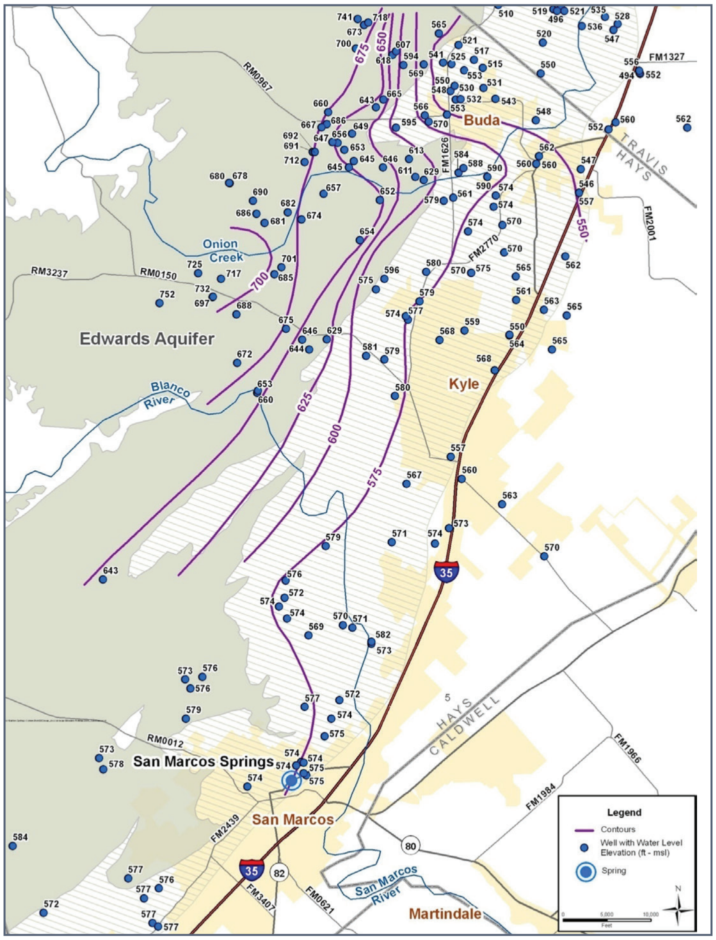

Fig. 11. Groundwater level map for mid-February to mid-March 2009 from synoptic survey by EAA and BSEACD in southern part of study area.

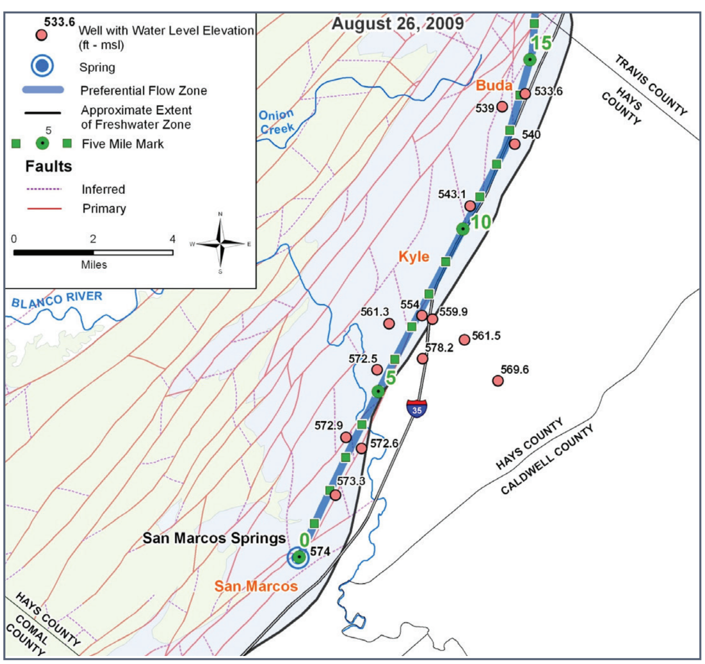

Fig. 12. Groundwater levels for 2009 drought conditions, August 26, 2009.

2009 Drought

The most extreme drought condition during 2009 is considered to be best represented by water level measurements made on August 26. The location of the monitoring wells and the groundwater levels for this condition are shown in Fig. 12. Fig. 13 shows a profile of the groundwater levels along the preferential flow zone that was interpreted from the August 26 measurements. At this time, there was: (1) a very mild slope of the hydraulic gradient from San Marcos Springs to a few miles south of Kyle, (2) a rather steep hydraulic gradient in the vicinity of Kyle toward Barton Springs, and (3) a moderate hydraulic gradient from north of Kyle to Buda and Barton Springs. A cone of depression in the vicinity of Kyle causes a rather steep hydraulic gradient from Buda to Kyle. As discussed earlier, at least part of the cause for the cone of depression near Kyle is related to local pumping. A study of geologic framework maps prepared by Hanson and Small (1995), Small et al. (1996), and Blome et al. (2005) and a compilation of top of Edwards Aquifer data values by Hunt BB (written communications, 2009) do not indicate the occurrences of any major blockage to groundwater flow by major faults (Fig. 14).

Geologic Structures

The structural style of the faults in the study area are *en echelon*, down-to-the-east, normal faults. Geologic structures are well documented to influence groundwater flow in the Edwards Aquifer (Hovorka et al. 1998) as both barriers and conduits. The hydrologic functioning of the structures is therefore highly complex and variable and depending on many factors. Inspection of the geologic maps prepared by Hanson and Small (1995), Small et al. (1996), and Blome et al. (2005), and a compilation of top of Edwards Aquifer data values (Hunt BB, written communications, 2010) do not indicate an obvious occurrence of any major structural discontinuity in the vicinity of Kyle that could be a barrier to groundwater flowing northeast along the flow zone. In fact, the study area occupies a transfer (step-over) zone between 2 large-displacement, northeast-striking fault zones, approximately in the area mapped as the Kyle and Mountain City/Mustang Branch faults. This type of transfer zone has created a northeast-dipping ramp structure between the 2 faults and is common in the Edwards Aquifer (Hovorka et al. 1998) (Fig. 14). Minor cross faults are common with relay-ramp structures but likely would not be a barrier to flow. The influence of the transfer or relay-ramp structure on groundwater flow needs to be examined in future studies.

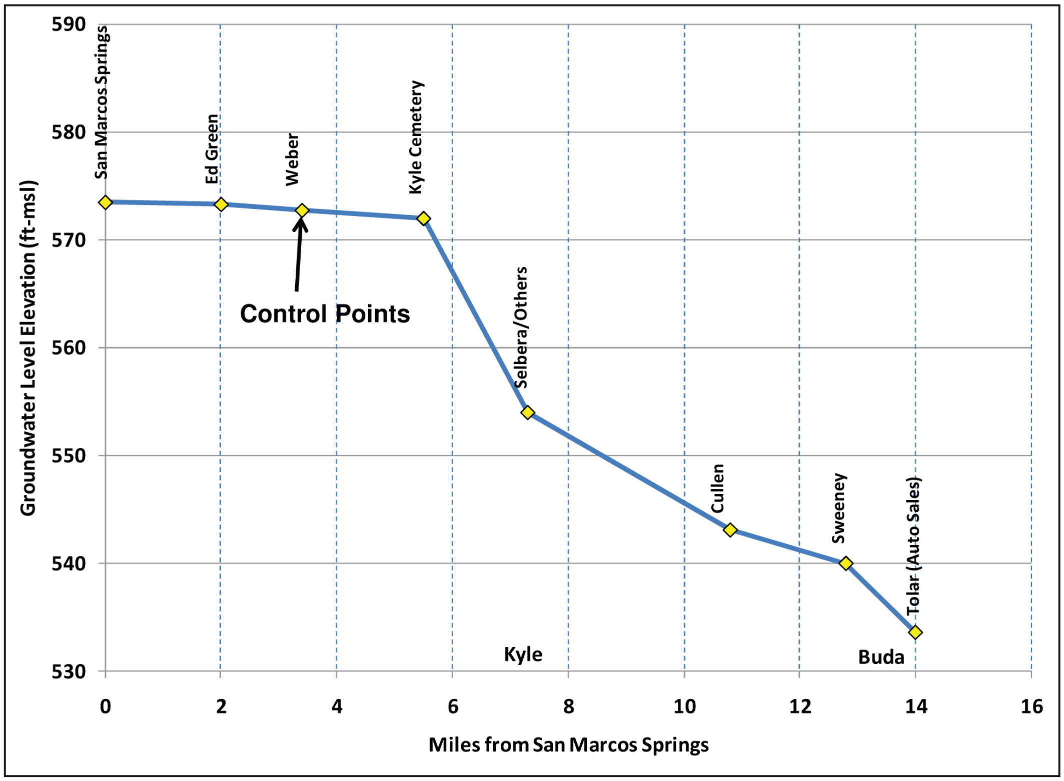

Fig. 13. Groundwater level profile along preferential groundwater flow zone during 2009 drought conditions, August 26, 2009.

Assessment with Groundwater Model

There is not sufficient hydraulic property data along the preferential groundwater flow zone to accurately calculate groundwater flow in the vicinity of San Marcos Springs. As an alternative, calculations of groundwater flow past San Marcos Springs were made with the EA-SAR GAM.

For the 1947 to 2000 model calibration period, the 1996 drought was selected to be most similar to summer 2009 conditions based on flow from San Marcos Springs and Barton Springs. A water level map from the simulation for August 1996 is shown in Fig. 15. This map shows: (1) groundwater levels in the vicinity of San Marcos Springs to be about 587 ft-msl instead of 573 ft-msl for the reported stage of Spring Lake; (2) very flat water level conditions between San Marcos Springs and Kyle; and (3) a relatively wide and steep pattern of water levels from Kyle to Barton Springs. These EA-SAR GAM model simulation results were used to draw profiles between San Marcos Springs and Barton Springs along the preferential groundwater flow zone (Fig. 16). This August 1996 profile shows a nearly flat hydraulic gradient between San Marcos Springs and mile marker 10 (distance from San Marcos Springs along preferential flow zone) in Fig. 17, which is between Kyle and Buda.

A detailed indication of groundwater flow patterns in the form of directional flow vectors was exported from the groundwater model for August 1996 (Fig. 17). This map presents the direction of groundwater flow for each of the model cells but does not provide information on the relative magnitude of groundwater velocity. This vector map indicates that groundwater is flowing past San Marcos Springs and toward Barton Springs. The vector pattern shows the influence of geologic faults and zones of different aquifer transmissivity.

The calculated underflow by the EA-SAR GAM was exported for a column of model cells, called a transect, immediately northeast of the San Marcos Springs model cell and extending completely across the Edwards Aquifer. The location of this transect is shown in Fig. 17. The underflow (flux) across this transect was calculated for the month when the springflow was lowest for each of the two major droughts. The underflow past San Marcos Springs is estimated by the groundwater flow across a 1-mile segment of the transect that is opposite San Marcos Springs. Additional underflow is shown to be occurring in the remaining segment of the transect. For the most recent drought (August 1996) which, as stated earlier, is considered to be more representative of 2009 drought conditions, the model calculates groundwater flow passing San Marcos Springs and toward Barton Springs at a rate of 6.1 cfs. The

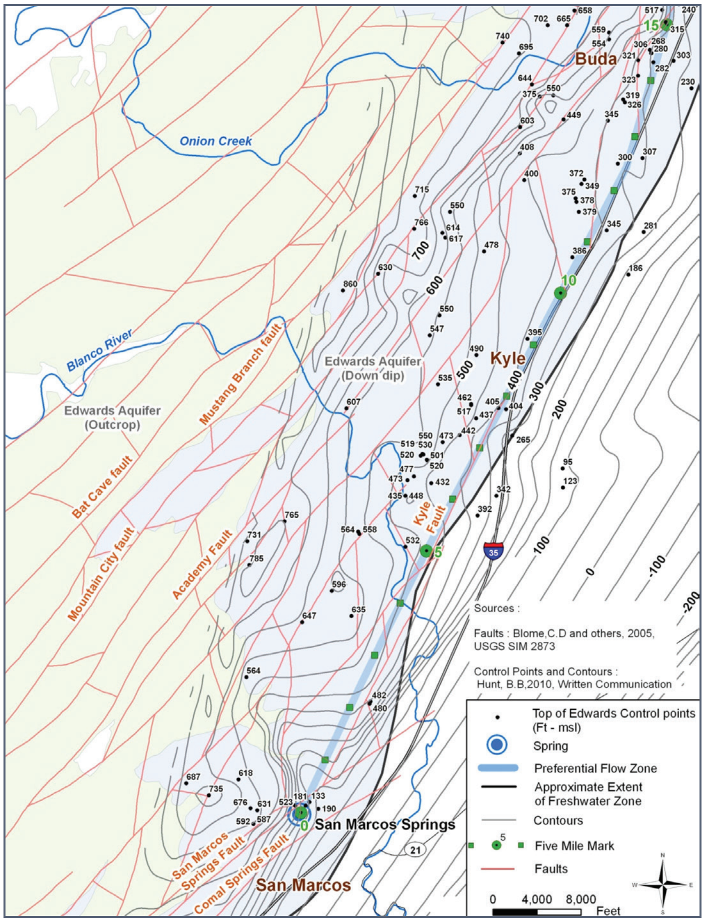

Fig. 14. Geologic structure of the top of the Edwards Aquifer in southern part of study area.

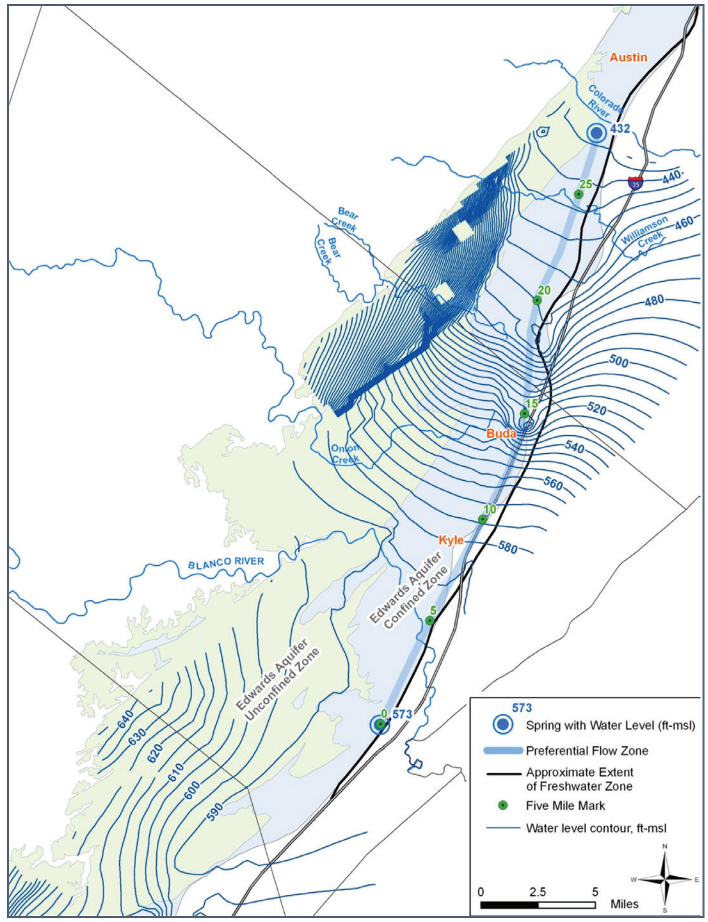

Fig. 15. Modeled groundwater level map from the Edwards Aquifer-San Antonio Segment Groundwater Availability Model for August 1996.

total underflow across the entire length of the transect was 12.0 cfs.

Using the EA-SAR GAM results as a guide, the 2009 drought underflow past San Marcos Springs is estimated at about 5 cfs during the most intense part of the drought. At that time, Barton Springs was flowing about 15 cfs. This analysis does not necessarily mean that groundwater flowing past San Marcos Springs actually discharges from Barton Springs. However, much of the groundwater passing San Marcos Springs probably becomes inflow to the water budget of the Barton Springs segment of the Edwards Aquifer and supports both pumpage and discharge from Barton Springs. The response time between groundwater passing San Marcos Springs and entering the Barton Springs segment from the San Antonio segment is unknown, as is the effect of groundwater flow passing San Marcos Springs on discharge from Barton Spring.

DISCUSSION

In summary, these analyses suggest that during the 2009 drought, groundwater flowing from the San Antonio segment had the potential to bypass San Marcos Springs and flow toward Barton Springs. During the 2009 wet conditions, a hydrologic divide was reestablished in the vicinity of Onion Creek and just south of Kyle. This hydrologic divide reverses the direction of groundwater flow that occurred during drought conditions from the Kyle area toward San Marcos Springs. The implications for this hydrologic connection have bearings on the management and availability of groundwater in the Edwards Aquifer. In particular, the implications are greatest for the Barton Springs segment of the Edwards Aquifer in terms of the conceptual model of source water, overall water budget, and contributing area to Barton Springs. Numerical models (Scanlon et al. 2001 and Slade et al. 1985) of the Barton Springs segment considers the boundary between the San Antonio and Barton Springs segments to be a no-flow boundary. Slade et al. (1986) describes intra-aquifer flow between the two segments during the drought of 1955–56 and during a 1978 dry period.

The findings in this report have been postulated for many decades by other investigators. In addition, the concept of flow bypassing a karst spring is a very common occurrence. In

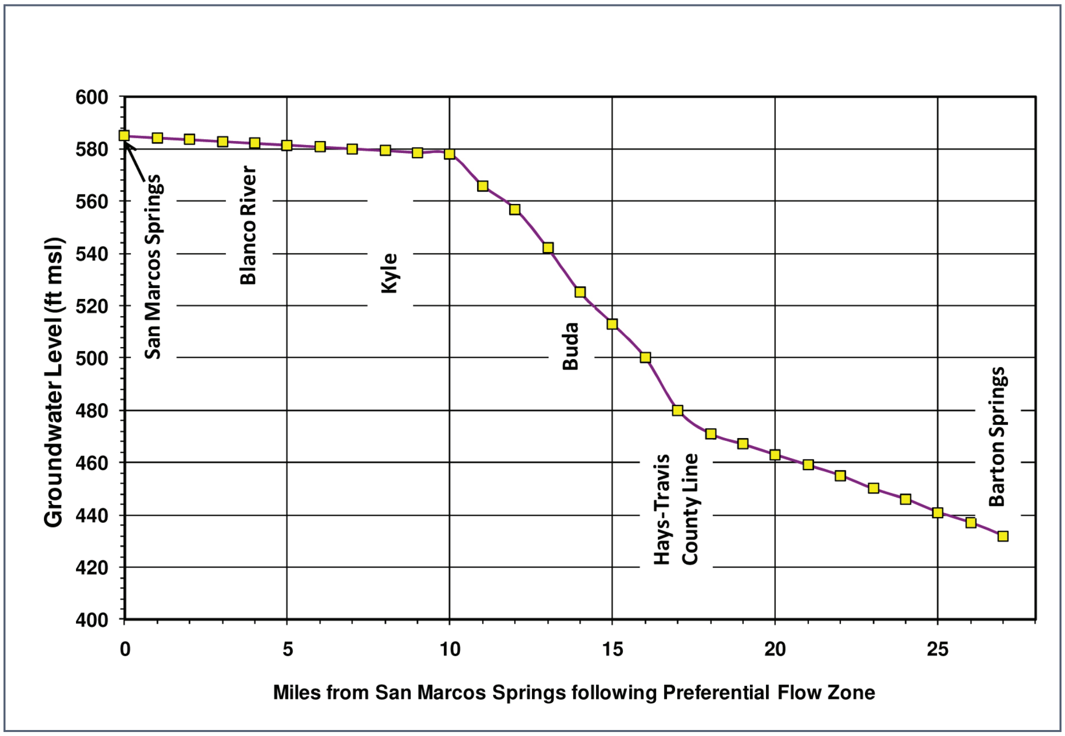

Fig. 16. Modeled groundwater level profile along preferential flow zone from the Edwards Aquifer-San Antonio Segment Groundwater Availability Model for August 1996.

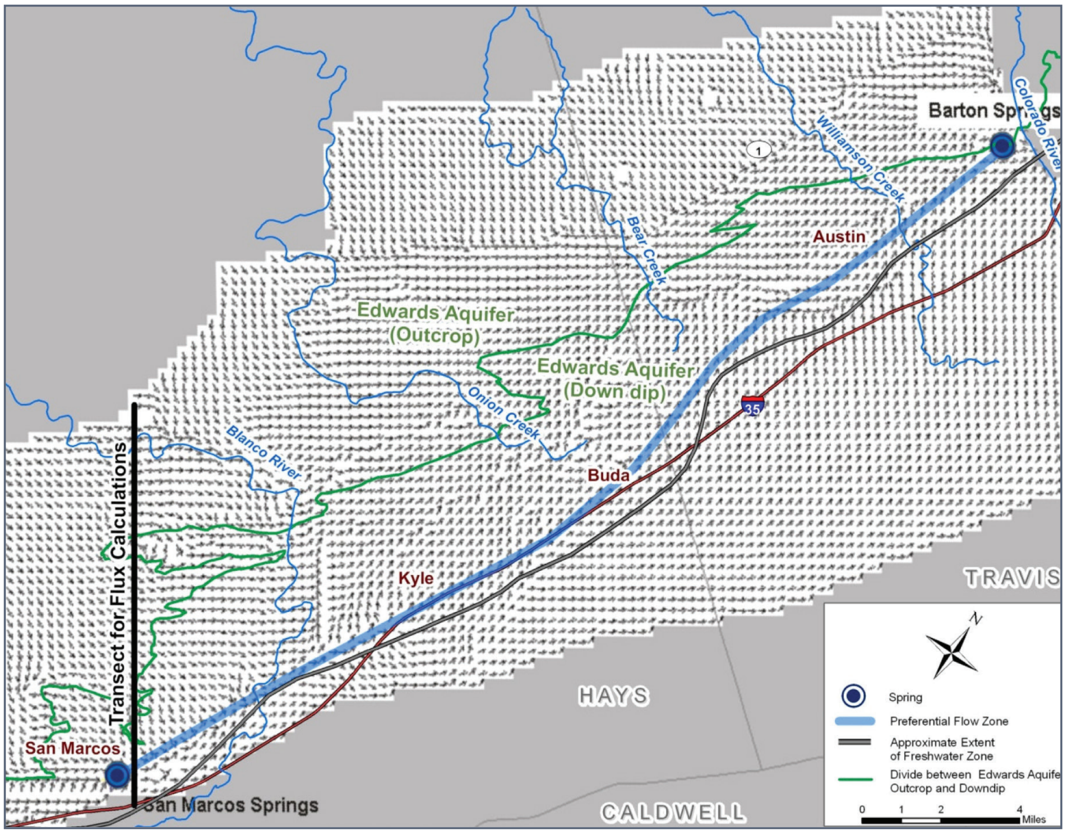

Fig. 17. Modeled groundwater flow direction vectors from the Edwards Aquifer-San Antonio Segment Groundwater Availability Model for August 1996.

fact, flow is thought to bypass Comal Springs to San Marcos Springs (Johnson and Schindel 2008).

The data presented here represent an evaluation of the hydrologic connection between the San Marcos Springs and Barton Springs using primarily hydraulic head information. A better understanding of flow between the San Antonio and Barton Springs segments of the Edwards Aquifer can be obtained by observing head values east and west of the transect of wells included in this study. However, the authors recognize that in a karst aquifer other types of data, such as tracer testing and geochemical analyses, are needed for conclusive results. In addition, the number of wells available for monitoring was fairly limited and the completion of the wells in some cases was unknown (casing depth, partial-penetration, etc.); this interjects uncertainty in some of the interpretation of head data. However, this study has advanced the understanding of a complex karst system and has posed some key findings that can be tested and augmented in the future.

CONCLUSIONS

Analyses of the water level data collected during the 2009 drought were undertaken to determine the potential for a hydrologic connection between the San Antonio and Barton Springs segments of the Edwards Aquifer. The analyses of these water level data and other available data show:

- There appears to be continuity in the direction of groundwater flow along the preferential groundwater flow zone from San Marcos Springs to Barton Springs during the 2009 drought. Thus, there is a potential for groundwater to flow past San Marcos Springs and toward Barton Springs during drought conditions.
- There is a major discontinuity in hydraulic gradient and water levels in the vicinity of Kyle.
- There is an area of nearly flat water levels from San Marcos Springs to near Kyle, which is believed to be a zone of high transmissivity.
- In the vicinity of Kyle, substantial changes in groundwater levels during the 2009 data collection period indicate a zone of relatively low transmissivity.
- Faults do not appear to be a strong controlling factor between the zones of relatively high and low transmissivity in the vicinity of Kyle. However, the structural influence of relay ramps on groundwater flow and aquifer properties in the study area is unknown but could be significant.
- The 2009 drought underflow past San Marcos Springs was about 5 cfs during the most intense part of the drought, which was estimated using the EA-SAR GAM MODFLOW model. This does not necessarily mean that groundwater flowing past San Marcos Springs actually discharges from Barton Springs. However, much of the groundwater flow bypassing San Marcos Springs most likely becomes inflow to the water budget of the Barton Springs segment of the Edwards Aquifer and supports both pumpage and discharge from Barton Springs.
- Due to the rapid growth in water demands in the Kyle and Buda areas, a continual, long-term groundwater level monitoring program, including the installation and operation of dedicated monitoring wells and automated water level recording instruments, is needed between San Marcos Springs and Buda to provide data for a future trend analysis.
- Further study is needed to identify the response time between groundwater passing San Marcos Springs and entering the Barton Springs segment from the San Antonio segment and the effect of groundwater flow passing San Marcos Springs on discharge from Barton Springs.

FUTURE STUDIES

This study has identified some interesting hydrogeologic features not previously documented and in need of further investigation. They include the cause and nature of the flat potentiometric surface between San Marcos and Kyle and the abrupt hydraulic discontinuity at Kyle. A deeper understanding of these two features will help future evaluations of potential groundwater flow from San Marcos Springs to Barton Springs.

Additional field studies examining the hydrologic connection in this area could include additional synoptic measurements, tracer testing, geochemistry of groundwater, surface and borehole geophysical surveys, borehole data collection, and the drilling of monitoring wells in the study area. Future modeling of the Barton Springs segment should consider using southern boundary conditions that allow for flow across the boundary.

ACKNOWLEDGMENTS

This study was planned by Todd Votteler and Tommy Hill of the GBRA, Brian Hunt and Brian Smith of the BSEACD, Mike Dorsey and MaryLynn Musgrove of the USGS, and Larry Land of HDR Engineering, Inc. Data collection was performed primarily by Venezia Chavez of the USGS and Brian Hunt of the BSEACD. The study was greatly supported by existing data made available from the USGS, TWDB, EAA, and the SAWS databases. Larry Land prepared the initial data summaries, analyses, and interpretations. The technical analysis benefitted from contributions, suggestions, and review comments by all of the team members. Paula Jo Lemonds, P.E., P.G. of HDR is credited with the preparation of this article.

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Texas Water Resources Institute
Texas Water Journal
Volume 2, Number 1, Pages 54–96, December 2011

Extended Chronology of Drought in South Central, Southeastern, and West Texas

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Abstract: Short instrumental climatic records prevent appropriate statistical and historical characterization of extreme events such as the extent, duration, and severity of multiyear droughts. The best solution is to extend climatic records through well-understood proxies of climate. One of the best such proxies is climate-sensitive annual tree rings, which can be dated precisely to the year, are easily sampled, and are widely distributed. We created 3 new baldcypress chronologies in South Central Texas and used them, along with existing Douglas-fir chronologies from West Texas and a composite post oak chronology in Central Texas, to calibrate 1931–2008 and reconstruct June Palmer Drought Severity Index (PDSI) in Texas climate divisions 5 (Trans Pecos), 6 (Edwards Plateau), 7 (S. Central), and 8 (Upper Coast) 1500–2008. We validated the reconstructions against observed data not used in calibration.

Most water planners in Texas at present use the drought of the 1950s, 1950–1956, as a worst-case scenario. Our reconstructions show, however, that a number of extended droughts of the past were longer and/or more intense than the 1950s drought. Furthermore, extended droughts have been a consistent feature of southwestern climate since the 800s, including at least 4 megadroughts 15- to 30-years long centered in central or northern Mexico (Stahle et al. 2009; 2011b). This and previous studies indicate that severe decadal-scale droughts have occurred in Texas at least once a century since the 1500s. Current use by water planners of the 1950s drought as a worst-case scenario, therefore, is questionable. When water managers consider past droughts, population growth, and climate change, it becomes highly probable that the future poses unprecedented challenges.

Keywords: Texas, drought of record, Palmer Drought Severity Index (PDSI), paleoclimatology, dendrochronology, tree rings, baldcypress

Note: The University of Texas Austin Environmental Science Institute has a website about this project: http://www.esi.utexas.edu/faculty/featured-research-projects/141-the-tree-project. Texas Parks and Wildlife also produced a short video called "Studying Cypress Trees, the Climate Detective – Texas Parks and Wildlife [Official]" about this project. It can be viewed at: http://www.youtube.com/watch?v=zwPdfWahk4s.

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Citation: Cleaveland MK, Votteler TH, Stahle DK, Casteel RC, Banner JL. 2011. Extended chronology of drought in South Central, Southeastern, and West Texas. Texas Water Journal. 2(1):54-96. Available from: https://doi.org/10.21423/twj.v2i1.2049.

INTRODUCTION

Limited water resources are a serious problem in Texas due to its partially semiarid drought-prone climate, particularly in West and Central Texas (Griffiths and Ainsworth 1981; Votteler 2000). The 1980 heat wave, the worst since 1895 by some measures in some climatic divisions (NCDC Climate Diagnostic Center 2011), caused some $1.5 billion in losses (Karl and Quayle 1981). The drought of the 1950s caused more than $3 billion (about $27 billion in 2010 dollars) in losses to the agriculture sector alone, excluding ranching (Lowry 1959). The more recent droughts of 2006, 2008–2009, and 2011 have also had devastating consequences for Texas agriculture (e.g., Jervis 2009; Parker 2011). The start of meteorological observations in Texas dates from the mid- to late-19th century, but this short record inadequately characterizes those events that occur irregularly, such as prolonged multiyear droughts (Namias 1981). Rodríguez-Iturbe (1969) has also demonstrated that very large numbers of observations may be needed to derive accurate statistical parameters for hydrometeorological phenomena. For these reasons it is highly probable that worse droughts than any seen in the instrumental record have occurred in the past (e.g., Stahle et al. 2000, 2007, 2011b) and such severe drought may have unforeseen consequences (e.g., that affect human health; cf. Acuna Soto et al. 2002).

Prompted by the 1950s drought, Lowry (1959) was commissioned to investigate drought in Texas through rainfall records of deficits. His investigation shows that drought can be highly localized or more widespread. Most of the droughts he reports on occurred in the areas we reconstruct and appear in our reconstructions, but some droughts occurred completely outside of the areas we have reconstructed. Lowry's (1959) report demonstrates that Texas is so large and has such a large precipitation gradient (Banner et al. 2010), that it is rare for the entire state to experience drought at the same time (Votteler 2000). Nevertheless, the whole state and much of the surrounding states can experience severe drought simultaneously, such as in 2011.

One means of overcoming the lack of historically observed climate data investigates long-term drought history through substitutes, or "proxies," for instrumental data. One of the best such proxies is tree rings because annually produced rings are often sensitive to climate, and such trees are widely distributed and readily available. Each ring can be dated precisely to the year in many long-lived trees due to the influence of climate on growth, and the climate information contained in the annual rings is relatively easy to extract from properly dated samples (Stahle 1996; Fritts 2001; Speer 2010).

The paleoclimate of Texas since the last glacial maximum has been investigated with several proxies (e.g., COHMAP Members 1988). Previous efforts to analyze the climate of Texas with proxy series include pollen studies (Bryant 1977; Bryant and Holloway 1985), floral and faunal fossils (e.g., Lundelius 1967; Graham 1976), strontium isotopes (Cooke et al. 2003), carbon isotopes (e.g., Nordt et al. 1994), magnetic susceptibility (Ellwood and Gose 2006), speleothems (e.g., Musgrove et al. 2001), and some of the tree-ring studies by Stahle and Cleaveland (1988, 1992, 1995), Stahle et al. (1985, 1988, 1998a, 1998b, 2007), Cleaveland (2000, 2004, 2006), Dunne et al. (2000), Dunne (2002), Mauldin (2003), and Fye and Cleaveland (2001). Except for the tree-ring studies, all of these methods of reconstructing climate provide lower resolution millennial to centennial scale paleoclimatic data, which give little indication about the extent of multiyear droughts.

The above tree-ring studies that were specifically concerned with Texas paleoclimate used central Texas chronologies but were limited to beginning in the mid- to late-1600s because they were based on post oak (*Quercus stellata* Wangenh.), which usually reaches a maximum age of less than 350 years. Even with the addition of post oak samples from historic buildings, the central Texas post oak record could only be extended to 1648 (Therrell 2000). Very long climate reconstructions of averaged June, July and August (JJA) Palmer Drought Severity Index (PDSI; Palmer 1965) on a 0.5° X 0.5° grid have been produced by Dr. Edward Cook of Lamont-Doherty Earth Observatory (Cook et al. 1999, 2007). Although Cook's gridded central Texas JJA reconstructions are up to 1,000 years long, they extrapolate central Texas climate from distant chronologies in far West Texas, New Mexico, and Louisiana (Cook et al. 1996, 1999, 2004; Cleaveland 2006). In addition, the best monthly PDSI variable to reconstruct in Texas is June, not a JJA average (Stahle and Cleaveland 1988; Cleaveland 2004). To improve central Texas reconstructions, we have produced 3 new local climate sensitive chronologies in South Central Texas that enable us to reconstruct climate 1500–2008.

Warm season drought in Texas is strongly linked to the strength of upper level high pressure that develops and persists in the southern United States and to atmospheric inversion caused by warm air transport from the Rocky Mountains and Mexican Plateau (Myoung and Nielsen-Gammon 2010b). These warm season droughts tend to persist because low soil moisture creates a feedback loop that inhibits convection, reducing warm season precipitation (Myoung and Nielsen-Gammon 2010a).

Evidence indicates that central and northern Mexico, the Southwest, and other regions of North America have experienced severe droughts ("megadroughts") since the 800s (Stahle et al. 2011b), particularly in the mid- to late 1500s and early 1600s (Stahle et al. 1998a, 2000, 2007; Cleaveland et al. 2003; Cook et al. 2007). Paleoclimatic investigations have helped find links in U.S. southwestern climate to global circulation features such as the El Niño/Southern Oscillation (ENSO) (Cleaveland et al. 1992; Stahle and Cleaveland 1993; Stahle et al. 1998b; Fye and Cleaveland 2001; Cook et al.

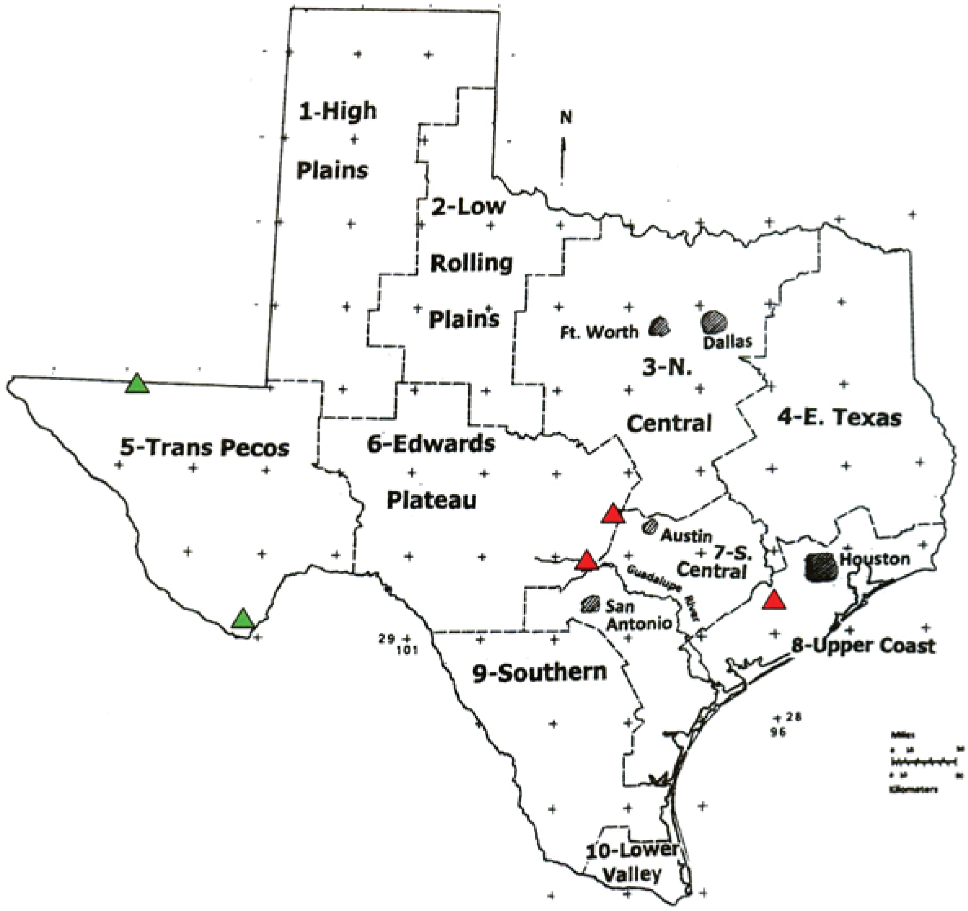

Fig. 1. Map of Texas, showing the climate divisions and chronology locations. June PDSI was reconstructed in climate divisions 5 (Trans Pecos), 6 (Edwards Plateau), 7 (S. Central), and 8 (Upper Coast). The red triangles are locations of baldcypress chronologies and the green triangles are locations of Douglas-fir chronologies. See Table A1 for the locations of the 7 individual chronologies averaged into the Central Texas post oak chronology.

2007; Stahle et al. 2011a). La Niña conditions, the cold phase of ENSO, cause drought across northern Mexico and the southern United States (Trenberth et al. 1998; Aguado and Burt 2007; Cook et al. 2007; Stahle et al. 2011a) and may play a role in extended droughts. La Niña conditions are characterized by below normal sea surface temperature (SST) in the eastern equatorial Pacific (Aguado and Burt 2007). Slade and Chow (2011) investigated the effects of La Niña and El Niño on central Texas precipitation and runoff. La Niña and El Niño each occurred about 25% of the time 1950–2009. Comparing La Niña and El Niño, La Niña August averaged more precipitation, June and July were about equal, and the other 9 months had less precipitation than El Niño. Mean streamflow was less year round under La Niña conditions at all gauges and the differences became greater farther south in central Texas (Slade and Chow 2011). Other patterns of SST, such as the Pacific Decadal Oscillation and the North Pacific mode, may play a role in modulating Texas climate on a multidecadal scale (Mantua et al. 1997; Nigam et al. 1999). Such links to recognized recurring circulation and SST features not only offer clues to the causes of multiyear drought; they also are one path to a reliable, long lead-time climate prediction capability (Barnston et al. 1994).

The negative impact of drought on past societies is undisputed, such as the depopulation of the Mesa Verde region because of drought in the late 1200s (e.g., Burns 1983; Stahle and Dean 2011; Stahle et al. 2011b). The case of climatic effects on modern civilization is more complicated because of the widespread detrimental anthropogenic effects facilitated by technology, e.g., "sod-busting" that led to the epic dust storms of the Dust Bowl era (Stahle and Dean 2011). Advanced societies also suffer from climate extremes but can mitigate the effects through advanced technology and organization (IPCC 2007a). This mitigation may become even more critical in the future because there is strong evidence that weather variability is being made more extreme by anthropogenic climate change

(Min et al. 2011; Pall et al. 2011; Schiermeier 2011).

Another factor is the increasing population of Texas. Since 1950 Texas population has grown from 7,711,194 to 25,145,561 (326% increase) and has experienced a 20.6% increase from 2000 to 2010 (Texas State Library 2011). A population growing at this rate will undoubtedly put stress on water resources regardless of the frequency and duration of future drought.

We have not analyzed the other end of the climate spectrum from drought: extreme wetness. There are several reasons for this. First, many of the most extreme effects of excess rainfall occur over short periods, with voluminous runoff that leads to little increase in soil moisture that trees can respond to. Second, some extreme events will occur when the trees are dormant, not during the growing season. Third, tree growth often responds less to wet conditions; when soil moisture is no longer the factor limiting growth of the tree, growth may become less synchronous among trees (Fritts 2001). Nevertheless, moisture surpluses can be reconstructed and analyzed (Woodhouse et al. 2005), e.g., the 20th century pluvial period, 1905–1917 that led to over-allocation of Colorado River streamflow (Stockton 1990). Even relatively short-duration floods can sometimes be detected and analyzed through anatomical evidence in tree rings (Yanosky 1983, 1984) and flood damage to trees (McCord 1990).

Ideally, water managers in Texas can use augmented knowledge about past climate extremes to outline realistic worst-case scenarios and prepare for them (Rice et al. 2009). Of course, an ill-advised water manager might even choose to use a lesser drought than the 1950s drought as the “drought of record” for planning purposes (Casteel 2005), despite evidence that such droughts or worse recur in the long-term. Improved estimates of climate variability and trends should prepare authorities to cope with ongoing climate change, which is predicted to increase aridity in the Southwest (IPCC 2007b; Seager et al. 2007; Banner et al. 2010) and may help them to prepare mitigation strategies (IPCC 2007a; Furniss et al. 2010). If climate does, in fact, change as has been predicted (IPCC 2007b), then many assumptions of water managers based on stationarity of climate will prove invalid (Milly et al. 2008). In fact, in view of the extreme variability of climate found in this and other paleoclimatic studies, the stationarity of climate has always been an illusion based on a short-term view of climate, prompted by concepts like the National Oceanic and Atmospheric Administration’s (NOAA’s) 30-year “climatic normals.” Paleoclimatic studies enable us to appreciate the magnitude of this variability temporally and geographically.

CLIMATE RECORDS

In the following we refer to material contained in an appendix that is relevant to the research but is too voluminous to reside in the paper itself. Tables and figures contained in the appendix have the prefix “A”, e.g., “Table A1” or “Fig. A3”.

Precipitation, temperature, and PDSI (Palmer 1965) data for the Texas climate divisions begin in 1895 (Fig. 1; See map in Karl et al. 1983, p. 19; NCDC Climate Diagnostic Center 2011). The divisional climatic data often exhibit homogeneity that may be lacking in single stations, because the divisional data average all stations within the division, compensating for any problems that might occur at an individual station (Stahle and Cleaveland 1992). Computation of division averages began in 1931, while NOAA computes division averages from state averages before 1931 (Karl et al. 1983). Because divisional data exhibit better stability and represent larger areas than station data, in this research we investigated past climate in divisions 5 (Trans Pecos), 6 (Edwards Plateau), 7 (South Central), and 8 (Upper Coast) (Fig. 1).

We used the PDSI in our reconstructions of past climate. The PDSI incorporates temperature and precipitation, along with latitude, day length, and soil moisture capacity into a 2 level soil moisture model that is zero centered. Positive indices indicate above normal soil moisture, while negative indices indicate some degree of drought. The degrees of drought and wetness in the PDSI are designated as follows: 0.5 to -0.5 = near normal; 0.5 to 1.0 (-0.5 to -1.0) = incipient wetness (drought); 1.0 to 2.0 (-1.0 to -2.0) = mild wetness (drought); 2.0 to 3.0 (-2.0 to -3.0) = moderate wetness (drought); 3.0 to 4.0 (-3.0 to -4.0) = severe wetness (drought); >4.0 (<-4.0) = extreme wetness (drought) (Karl et al. 1983). The drought indices are standardized by taking into account local averages of temperature and precipitation, so that PDSI values will be comparable across different climate regimes (Palmer 1965; Karl et al. 1983).

The PDSI computation incorporates strong persistence from month to month. Consequently, the single value for June or July PDSI in Texas usually gives a good picture of moisture conditions for the entire growing season as well as precursor conditions during the previous winter that may affect growing season soil moisture. Upon occasion an unusual meteorological event, such as a slow-moving tropical depression, can deliver enough moisture in a short time to reverse a long drought trend (Stahle et al. 1985). Initiation of dry conditions, however, reverses wet conditions more gradually, due to the persistent nature of the soil moisture model (Palmer 1965). Therefore, PDSI seems a robust and appropriate measure of growing season climate and water resources that can be reconstructed from tree rings. Important for water resources, when PDSI values are negative, groundwater recharge will be reduced or eliminated altogether. Combined with increased reliance on groundwater in severe droughts, this means that aquifers will be used unsustainably in these periods (Slade and Chow 2011).

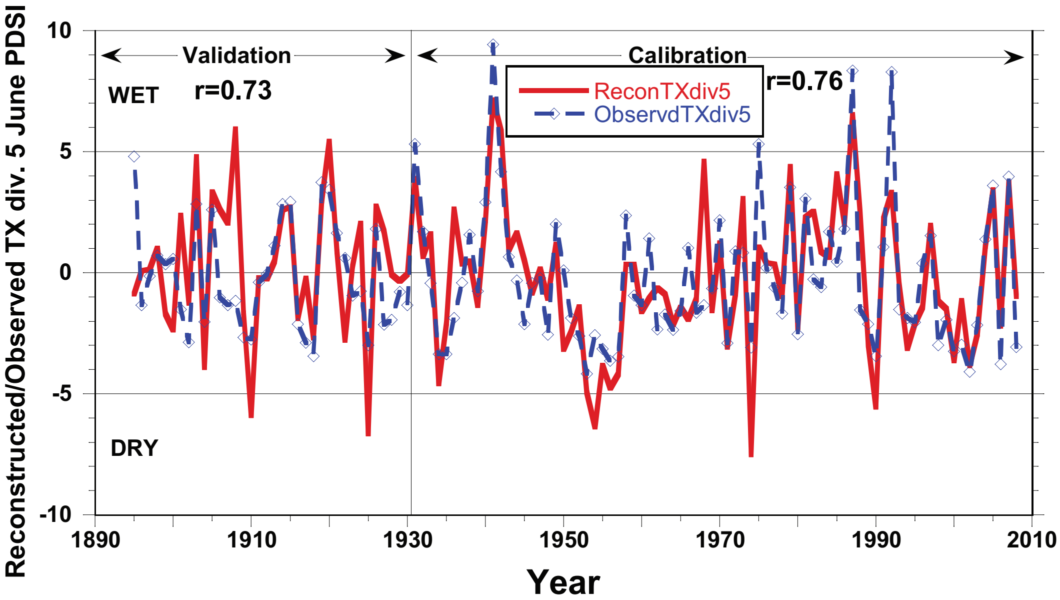

Fig. 2. Climate division 5 (Trans Pecos) June PDSI reconstructed (solid line) and observed (dashed line) series 1895–2008 (Fig. 1, Table A3). $R^2 = 0.580$.

TREE-RING CHRONOLOGIES

Seven post oak (*Q. stellata* Wangenh.) tree-ring chronologies, 3 from living trees and 4 from timbers of old buildings located in divisions 7 and 8 were averaged into a well replicated composite oak chronology for Central Texas (CENOAK) (Therrell 2000; Table A1). The averaged chronology begins in 1648 and ends in 1995. We extended the CENOAK post oak chronology 1996–2008 with regression estimates of the tree-ring indices derived from an average of the June PDSI in divisions 6, 7, and 8. In addition, on the basis of correlations, we chose 2 West Texas Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) chronologies, Guadalupe Peak National Park (GPM; 1362–2008) and Big Bend National Park (BSC; 1473–1992), for possibly reconstructing divisions 5, 6, and 7. We eliminated all the candidates from New Mexico (Table A1) based on their lack of correlation with Texas climate. We extended the indices of the Big Bend tree-ring chronology to 2008 with regression estimates derived from division 5 June PDSI. There is a small degree of circularity in using meteorological records to extend the shorter tree-ring chronologies to match the longest chronologies. We judge it to be minor, however, and preferable to restricting some of the calibrations to end in 1992, the ending date of the unextended BSC chronology.

Because the Central Texas post oak chronology has insufficient length to reconstruct the 1500s megadrought era (Stahle et al. 2000, 2007; Cleaveland et al. 2003; Cook et al. 2010), we collected 7 new sites and derived 3 new long baldcypress (*Taxodium distichum* (L.) Rich.) chronologies (Fig. 1; Table A2) that start in the 1400s. Baldcypress has been used to reconstruct climate in the United States with considerable success (Stahle et al. 1985, 1988, 1998a; Stahle and Cleaveland 1992, 1995; Cleaveland 2000). Because the chronologies began on different dates and had small sample sizes in the 1400s, we started our analyses at 1500.

METHODS

We crossdated tree-ring samples by pattern matching to detect and correct for missing and false rings (Douglass 1941; Swetnam et al. 1985; Stokes and Smiley 1996; Speer 2010). Dated samples were then measured with 0.001mm accuracy, and we checked the crossdating and measurement accuracy with correlation analyses (Holmes 1983; Grissino-Mayer 2001).

Most tree-ring series have growth trends that must be removed in order to create time series with stationary statistical properties that reflect climate influence more accurately than the undetrended ring widths. We transformed individual ring width series (in mm) with different means and nonstationary statistical properties into dimensionless indices with a mean of 1.0 and stationary statistical properties. We used a computer program (ARSTAN) (Cook 1985; LDEO website 2011) that transformed the ring widths then averaged the resulting indices into the ring width chronology and removed variance trend created by changing sample size (Shiyatov et al. 1990). See item 1 in the appendix for more detail.

To find the best variables for reconstruction, we correlated the chronologies with the monthly average temperature, total precipitation, and PDSI in each climate division (not shown).

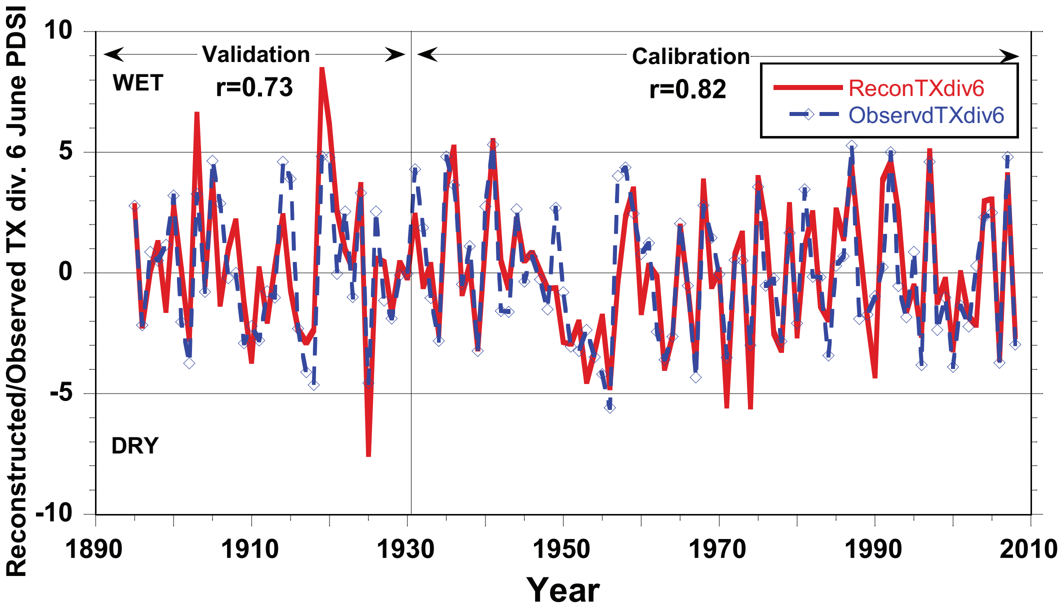

Fig. 3. Climate division 6 (Edwards Plateau) June PDSI reconstructed (solid line) and observed (dashed line) series 1895–2008 (Fig. 1, Table A4). $R^2 = 0.674$.

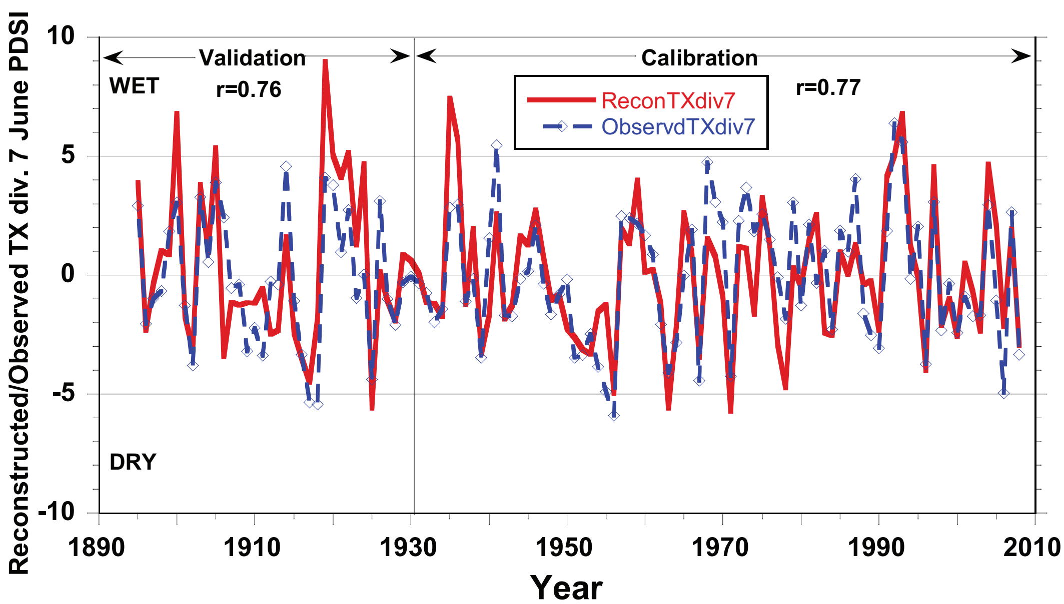

Fig. 4. Climate division 7 (S. Central) June PDSI reconstructed (solid line) and observed (dashed line) series 1895–2008 (Fig. 1, Table A6). $R^2 = 0.595$.

The results show that the February–May or February–June precipitation is best correlated with tree growth in the 4 divisions. Temperatures generally correlate negatively with tree growth but not nearly as strongly as the positive correlation of precipitation. June and July PDSI correlate positively with tree growth even more strongly than precipitation, and June PDSI is usually better correlated. Therefore, we chose to reconstruct June PDSI, which has been used to reconstruct divisional Texas climate previously (Stahle and Cleaveland 1988).

We created climate reconstructions with the program, PCREG (Cook et al. 1996, 1999; LDEO website 2011). PCREG is a complicated program that performs many operations to calibrate a reconstruction and validate that reconstruction against independent climatic data not used in the calibration (Snee 1977). PCREG uses principal components analysis (PCA) (Cooley and Lohnes 1971) to make new tree-

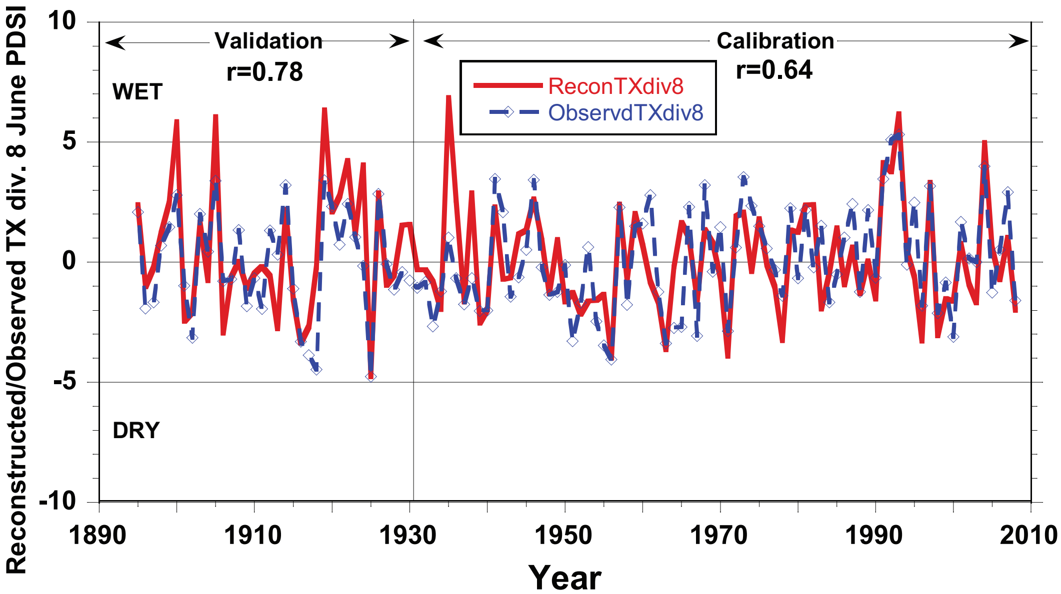

Fig. 5. Climate division 8 (Upper Coast) June PDSI reconstructed (solid line) and observed (dashed line) series 1895–2008 (Fig. 1, Table A8). R^2 = 0.416.

ring variables that maximize the common climate variance and do not correlate with each other. See item 2 in the appendix for further details on PCREG reconstructions.

We did 2 "nested" reconstructions of a single variable (Cook et al. 1999) to make the best use of available tree-ring data (see item 2 in the appendix where we discuss the advantages of this approach and analyze the results). We analyzed the reconstructions for the 20 driest single and multiple consecutive 2-, 3-, 4-, 5-, 6-, 7-, and 10-year droughts, the 10 driest 15- and 20-year droughts, and the 5 driest 30-year droughts, eliminating all periods with overlapping intervals. Although the longest period of consecutive drought years analyzed was 30 years, the reconstructions indicate that there may have been droughts of even longer duration in the past.

RESULTS AND DISCUSSION

The new chronology characteristics are shown in Table A2. In general, high mean sensitivity (MS; a measure of year-to-year variability), high standard deviation (SD; a measure of overall variability), and low serial correlation (r_{-1}; a measure of persistence from year-to-year in the series) are considered favorable characteristics linked to climate sensitivity (Fritts 2001; Speer 2010). Generally, the larger the sample size, the better although sample size does not by any means guarantee sensitivity to climatic influence. The San Bernard River (SBP) chronology seems the best by the first 3 criteria (MS=0.418, SD=0.409, r_{-1}=0.235) and Krause Springs (KSS) the worst (MS=0.225, SD=0.243, r_{-1}=0.422) although KSS is the best

Table 1. Analysis of error in reconstruction of 1974 June PDSI in Texas climate divisions 5 (Trans Pecos), 6 (Edwards Plateau), 7 (S. Central), and 8 (Upper Coast).

	Divisions			
	5	6	7	8
Observed June PDSI	-3.09	-2.98	1.83	2.35
Reconstructed June PDSI	-7.52	-5.54	-1.66	-0.39
Residual	-4.43	-2.56	-3.49	-2.74
Residual % of Observed	143.3%	85.9%	190.7%	116.6%
Observed Rank (1895-2008)	12	18	78	95
Reconstructed Rank (1895-2008)	1	2	37	55

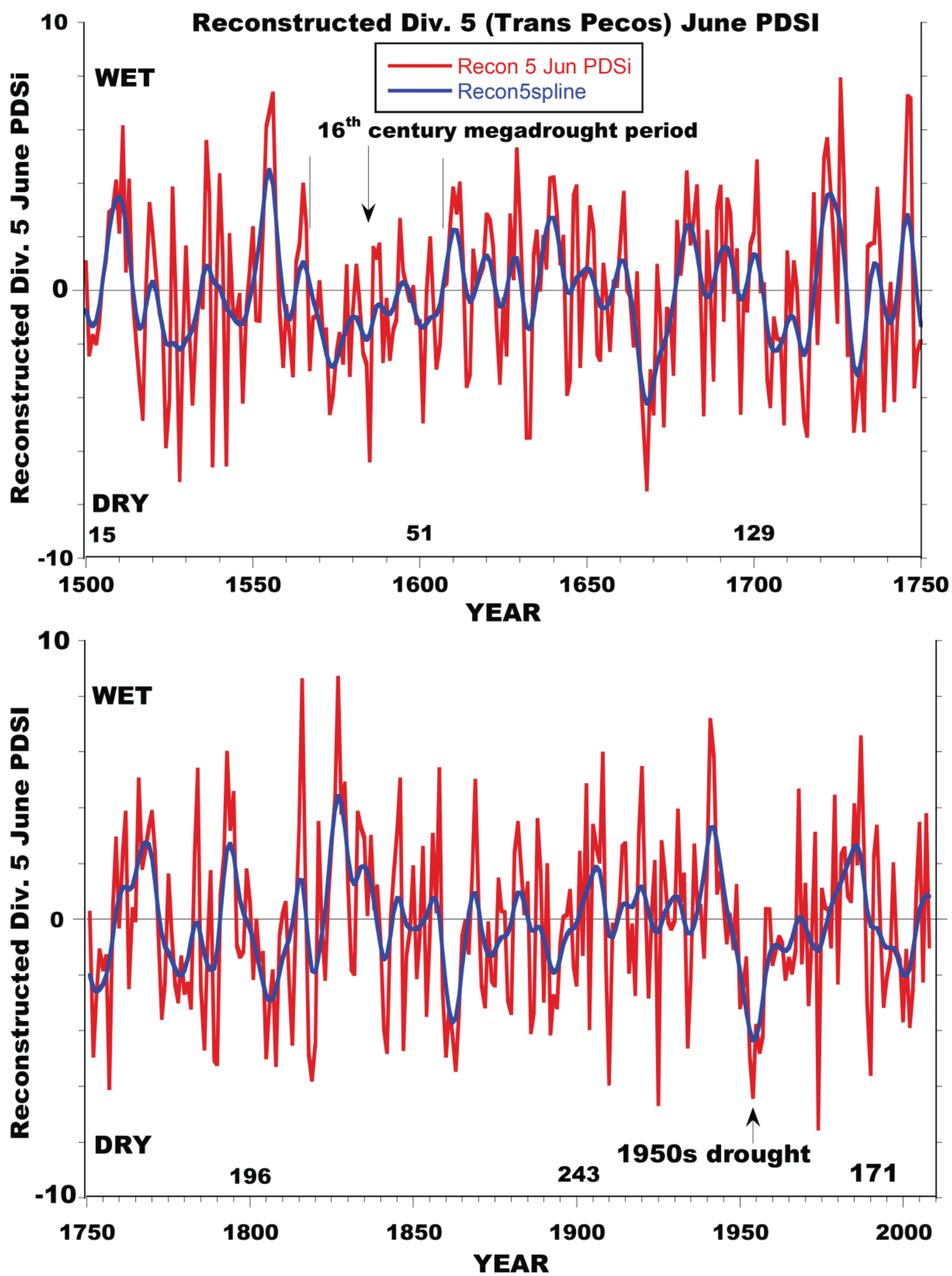

Fig. 6. . Climate division 5 (Trans Pecos) June PDSI reconstruction 1500–2008 based on 2 baldcypress and 2 Douglas-fir chronologies (Fig. 1). The blue line is a cubic spline fitted with parameters that would reduce the amplitude of a 10-year sine wave by 50% (Cook and Peters 1981). Numbers along bottom of plot are the number of radii at that time. The 1500s megadrought and 1950s drought periods are indicated. The megadrought period conditions do not appear as severe as those that are known to have occurred farther west (Stahle et al. 2000, 2007; Cook et al. 2010).

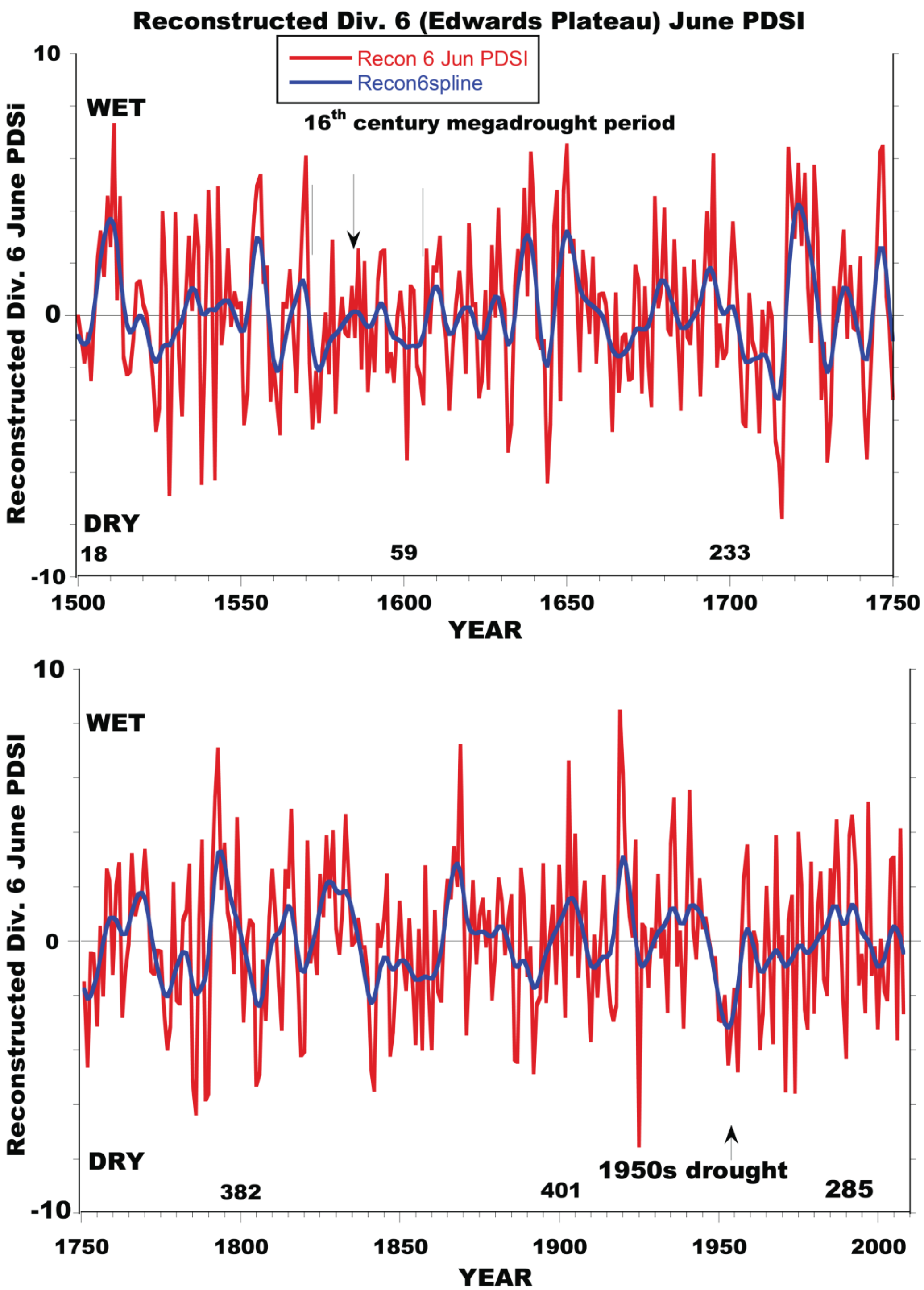

Fig. 7. Climate division 6 (Edwards Plateau) June PDSI reconstruction 1500–2008 (1648–2008 based on 3 baldcypress, 2 Douglas-fir, and a regional composite post oak chronology; 1500–1647 based on the above, without the post oak chronology; Figs. 1 and A1, Tables A4 and A5). The blue line is a cubic spline fitted with parameters that would reduce the amplitude of a 10-year sine wave by 50% (Cook and Peters 1981). Numbers along bottom of plot are number of radii at that time. The 1500s megadrought and 1950s drought periods are indicated. Neither the megadrought nor the 1950s drought conditions appear as severe as those that occurred in division 5 farther west.

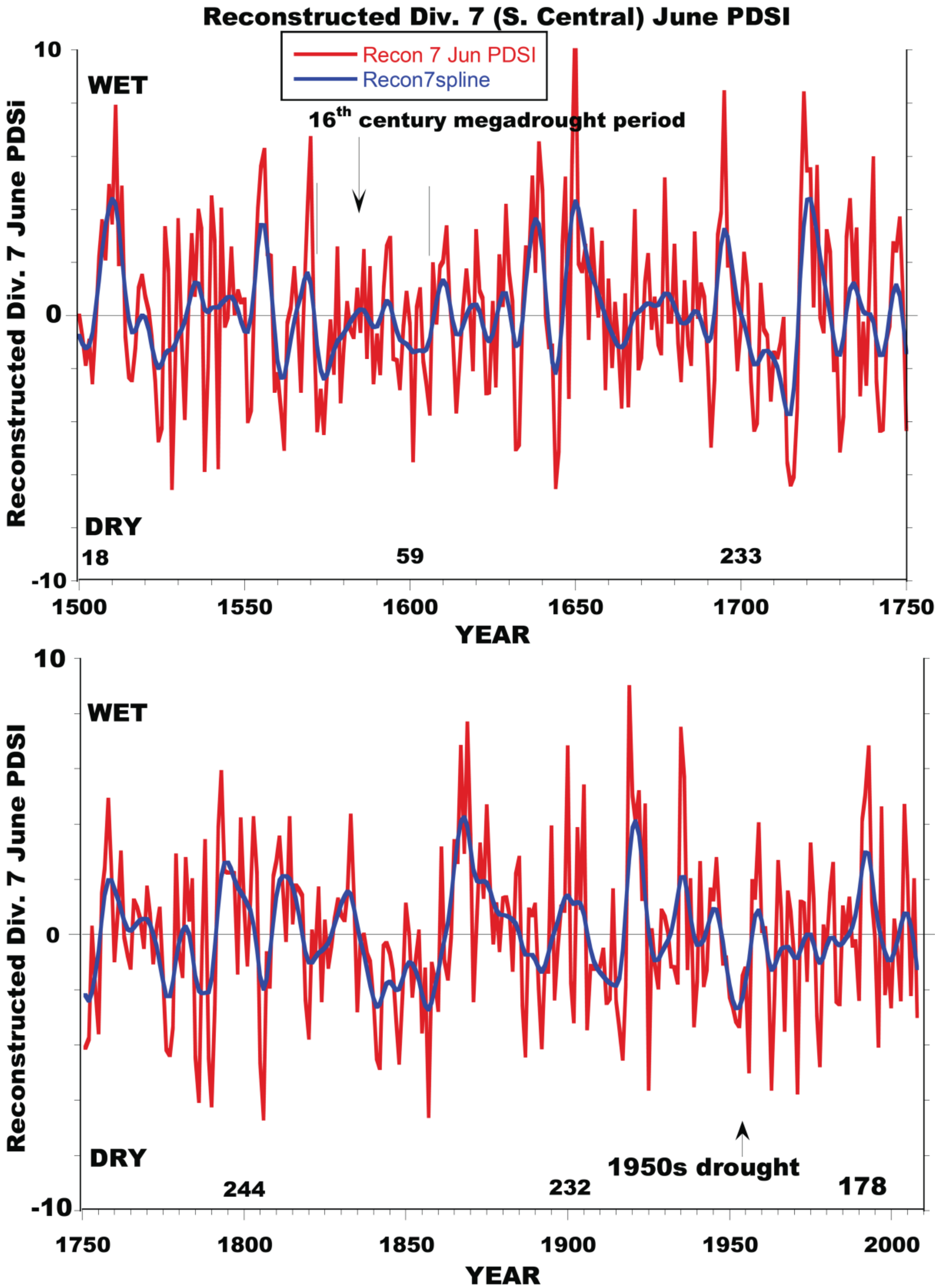

Fig. 8. Climate division 7 (S. Central) June PDSI reconstruction 1500–2008 (1648–2008 based on 3 baldcypress and a regional composite post oak chronology; 1500–1647 based on the 3 baldcypress and 2 Douglas-fir chronologies; Figs. 1 and A2, Tables A6 and A7). The blue line is a cubic spline fitted with parameters that would reduce the amplitude of a 10-year sine wave by 50% (Cook and Peters 1981). Numbers along bottom of plot are number of radii at that time. The 1500s megadrought and 1950s drought periods are indicated. Neither the megadrought nor the 1950s drought conditions appear as severe as those that occurred in divisions 5 or 6 farther west.

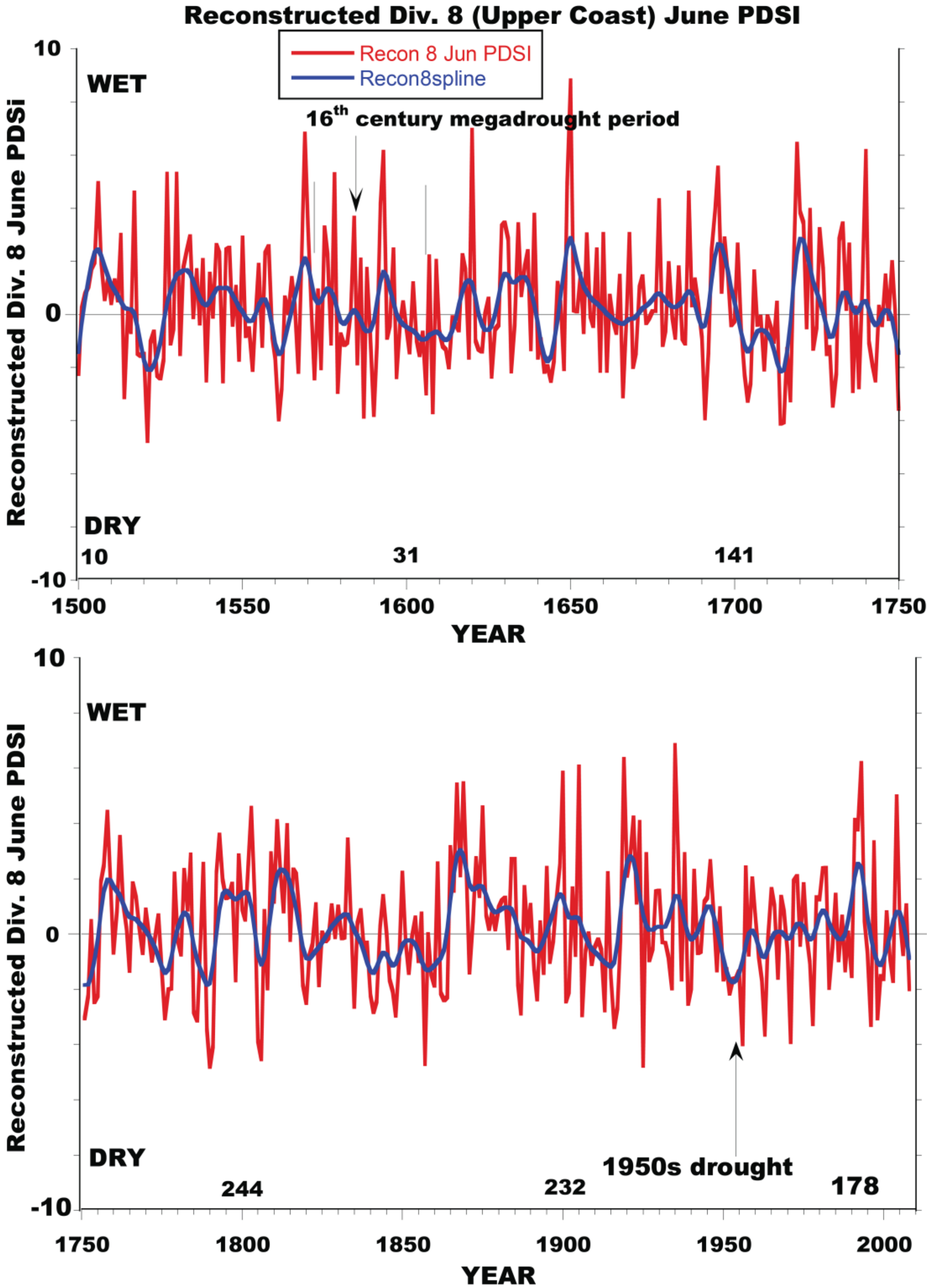

Fig.9. Climate division 8 (Upper Coast) June PDSI reconstruction 1500–2008 (1648–2008 based on 3 baldcypress and a regional composite post oak chronology; 1500–1647 based on the 3 baldcypress chronologies; Figs. 1 and A3, Tables A8 and A9). The blue line is a cubic spline fitted with parameters that would reduce the amplitude of a 10-year sine wave by 50% (Cook and Peters 1981). Numbers along bottom of plot are number of radii at that time. The 1500s megadrought and 1950s drought periods are indicated. The megadrought effects have apparently disappeared and the 1950s drought appears much less severe than is seen in the climate divisions to the west.

Table 2. Climate division 5 (Trans Pecos) June PDSI, 1500–2008 reconstructed droughts of 1-7 and 10-year lengths in order of severity. Overlaps between time periods in a column have been eliminated.

Case	Single Year	2 Year Avg	3 Year Avg	4 Yr/Avg	5 Yr/Avg	6 Yr/Avg	7 Yr/Avg	10 Yr/ Avg
1 Driest	1974* -7.52	1667–68 -6.39	1666–68 -5.26	1667–70 -5.10	1953–57 -4.82	1952–57 -4.25	1951–57 -3.99	1948–57 -3.10
2	1668 -7.44	1953–54 -5.66	1953–55 -5.05	1953–56 -4.98	1666–70 -4.68	1859–64 -3.91	1667–73 -3.64	1667–76 -3.02
3	1528 -7.08	1632–33 -5.50	1818–20 -5.01	1860–63 -4.41	1860–64 -4.20	1665–70 -3.79	1859–65 -3.45	1748–57 -2.54
4	1925 -6.64	1818–19 -5.30	1714–16 -4.30	1730–33 -4.26	1729–33 -3.74	1728–33 -3.51	1728–34 -2.78	1859–68 -2.38
5	1538 -6.54	1789–90 -5.12	1862–64 -4.28	1805–08 -3.76	1804–08 -3.25	1752–57 -2.99	1571–77 -2.63	1804–13 -2.29
6	1542 -6.50	1715–16 -5.10	1730–32 -3.94	1817–20 -3.31	1573–77 -3.03	1803–08 -2.96	1803–09 -2.62	1524–33 -2.18
7	1954 -6.38	1524–25 -4.97	1631–33 -3.88	1714–17 -3.27	1786–90 -2.82	1704–09 -2.88	1751–57 -2.53	1571–80 -2.14
8	1585 -6.36	1862–63 -4.74	1583–85 -3.82	1573–76 -3.11	1524–28 -2.81	1572–77 -2.77	1523–29 -2.51	1707–16 -2.00
9	1757 -6.07	1528–29 -4.62	1523–25 -3.77	1522–25 -3.02	1705–09 -2.79	1785–90 -2.76	1703–09 -2.43	1773–82 -1.94
10	1910 -5.90	1584–85 -4.56	1573–75 -3.61	1582–85 -2.97	1713–17 -2.61	1524–29 -2.70	1785–91 -2.24	1994–2003 -1.85
11	1524 -5.82	1730–31 -4.54	1859–61 -3.55	2000–03 -2.78	1753–57 -2.60	1528–33 -2.47	1776–82 -2.17	1871–80 -1.45
12	1819 -5.76	1956–57 -4.48	1515–17 -3.36	1892–95 -2.72	1999–2003 -2.52	1777–82 -2.46	1579–85 -2.13	1886–95 -1.40
13	1990 -5.55	1841–42 -4.34	1806–08 -3.36	1752–55 -2.63	1778–82 -2.50	1818–23 -2.33	1818–24 -1.88	1583–92 -1.39
14	1632 -5.51	1989–90 -4.27	1527–29 -3.35	1704–07 -2.61	1748–52 -2.48	1998–2003 -2.30	1711–17 -1.86	1728–37 -1.21
15	1633 -5.49	1573–74 -4.25	1892–94 -3.34	1631–34 -2.59	1818–22 -2.36	1711–16 -2.14	1998–2004 -1.82	1891–1900 -1.17
16	1716 -5.42	1516–17 -4.08	1840–42 -3.17	1514–1517 -2.59	1777–81 -2.32	1890–95 -1.98	1890–96 -1.69	1538–47 -1.17
17	1863 -5.41	1860–61 -4.07	1789–91 -3.13	1673–76 -2.45	1785–89 -2.27	1808–13 -1.98	1542–48 -1.60	1597–1606 -1.10
18	1667 -5.33	1732–33 -3.99	1755–57 -3.06	1739–42 -2.39	1890–94 -2.20	1580–85 -1.96	1784–90 -1.60	1958–67 -1.01
19	1730 -5.24	1805–06 -3.97	1817–19 -2.93	1840–43 -2.38	1581–85 -2.19	1956–61 -1.82	1960–66 -1.38	1969–78 -0.78
20	1808 -5.24	1527–28 -3.96	1752–54 -2.91	1779–82 -2.38	1672–76 -2.15	1542–47 -1.75	1600–06 -1.35	1853–62 -0.76

*June PDSI estimates for 1974 had a large amount of error, and were consistently more negative in all 4 divisions reconstructed than the observed values. See discussion of estimation error in general and for 1974 in particular on pages 68–71.

replicated and SBP the least replicated (Table A2c). The performance of these 3 chronologies in the PCA and regression analyses with climate (Tables A3-A9) confirms the apparent ranking in usefulness for climate reconstruction based on chronology statistics.

Site conditions of the new chronologies varied consider-

Table 3. Climate division 6 (Edwards Plateau) June PDSI, 1500–2008 reconstructed droughts of 1-7 and 10-year lengths in order of severity. Overlaps between time periods in a column have been eliminated.

Case	Single Year	2 Year Avg	3 Year Avg	4 Yr/Avg	5 Yr/Avg	6 Yr/Avg	7 Yr/Avg	10 Yr/ Avg
1 Driest	1716 -7.71	1715–16 -6.64	1714–16 -6.02	1714–17 -4.67	1713–17 -3.75	1951–56 -3.21	1950–56 -3.16	1707–16 -2.60
2	1925 -7.51	1785–86 -5.72	1840–42 -3.86	1953–56 -3.57	1952–56 -3.26	1711–16 -3.20	1711–17 -2.83	1948–57 -2.38
3	1528 -6.84	1789–90 -5.70	1643–45 -3.82	1805–08 -3.44	1571–75 -2.73	1785–90 -3.07	1785–91 -2.35	1571–80 -1.75
4	1538 -6.40	1644–45 -5.24	1741–43 -3.70	1728–31 -3.39	1641–45 -2.71	1704–09 -2.40	1571–77 -2.25	1777–86 -1.62
5	1644 -6.35	1805–06 -5.08	1805–07 -3.63	1559–62 -3.23	1786–90 -2.66	1572–77 -2.33	1703–09 -2.24	1840–49 -1.62
6	1786 -6.34	1841–42 -5.08	1785–87 -3.55	1642–45 -3.18	1804–08 -2.63	1750–55 -2.21	1749–55 -1.96	1854–63 -1.49
7	1542 -6.24	1730–31 -4.67	1572–74 -3.51	1571–74 -3.08	1728–32 -2.50	1728–33 -2.12	1523–29 -1.88	1523–32 -1.46
8	1789 -5.82	1632–33 -4.65	1729–31 -3.47	1839–42 -2.95	1559–63 -2.49	1803–08 -2.07	1664–70 -1.84	1748–57 -1.45
9	1790/ -5.57	1886–87 -4.39	1523–25 -3.44	1522–25 -2.81	1838–42 -2.41	1559–64 -2.03	1772–78 -1.80	1800–09 -1.42
10	1715 -5.56	1742–43 -4.18	1954–56 -3.26	1741–44 -2.76	1521–25 -2.25	1523–28 -2.02	1801–07 -1.79	1885–94 -1.38
11	1730/ -5.56	1704–05 -4.13	1560–62 -3.22	1775–78 -2.49	1890–94 -2.15	1776–81 -1.98	1854–60 -1.71	1597–1606 -1.32
12	1974 -5.54	1819–20 -4.12	1776–78 -3.18	1749–52 -2.44	1705–09 -2.08	1838–43 -1.91	1838–44 -1.66	1559–68 -1.27
13	1971 -5.50	1524–25 -3.96	1703–05 -3.18	1891–94 -2.37	1774–78 -2.06	1601–06 -1.85	1600–06 -1.66	1664–73 -1.26
14	1601/ -5.48	1528–29 -3.95	1789–91 -3.16	1854–57 -2.25	1750–54 -2.04	1664–69 -1.75	1886–92 -1.58	1909–18 -1.24
15	1842/ -5.48	1561–62 -3.93	1818–20 -3.16	1703–06 -2.18	1739–43 -1.90	1855–60 -1.72	1728–34 -1.57	1962–71 -1.12
16	1742 -5.44	1953–54 -3.88	1750–52 -3.09	1971–74 -2.16	1528–32 -1.87	1641–46 -1.69	1559–65 -1.49	1696–1705 -0.88
17	1805 -5.28	1847–48 -3.75	1892–94 -3.08	1817–20 -2.12	1666–70 -1.87	1738–43 -1.66	1738–44 -1.41	1850–59 -0.83
18	1632/ -5.18	1538–39 -3.72	1631–33 -3.04	1949–52 -2.12	1963–67 -1.78	1889–94 -1.55	1961–67 -1.25	1925–34 -0.82
19	1785 -5.11	1892–93 -3.59	1847–49 -2.74	1915–18 -2.07	1859–63 -1.73	1847–52 -1.55	1642–48 -1.12	1994–2003 -0.83
20	1806 -4.87	1551–52 -3.55	1950–52 -2.62	1630–33 -2.05	1970–74 -1.70	1962–67 -1.52	1912–18 -1.10	1736–45 -0.70

ably. The Guadalupe River State Park (GRP) and SBP sites are confined to river banks with relatively minor human disturbance. The KSS site contains a long-established commercial park with considerable human disturbance, including bulldozer work, soil compaction by heavy human traffic, extensive modifications to the original hydrology, and anthropogenic damage to the trees. In addition, the KSS trees grow in a wide variety of hydrologic micro-sites, far more variable than the

Table 4. Climate division 7 (South Central) June PDSI, 1500–2008 reconstructed droughts of 1-7 and 10-year lengths in order of severity. Overlaps between time periods in a column have been eliminated.

Case	SingleYear	2 Year Avg	3 YearAvg	4 Yr/Avg	5 Yr/Avg	6 Yr/Avg	7 Yr/Avg	10 Yr/ Avg
1 Driest	1806 -6.67	1715–16 -6.22	1714–16 -5.98	1714–17 -5.36	1713–17 -4.31	1712–17 -3.77	1711–17 -3.45	1708–17 -2.95
2	1857 -6.58	1644–45 -5.78	1789–91 -4.44	1642–45 -3.47	1571–75 -2.85	1785–90 -3.03	1785–91 -2.98	1840–49 -2.43
3	1528 -6.50	1805–06 -5.64	1643–45 -4.23	1805–08 -3.46	1952–56 -2.84	1750–55 -2.88	1950–56 -2.72	1947–56 -2.02
4	1644 -6.46	1789–90 -5.33	1750–52 -4.06	1559–62 -3.43	1855–59 -2.81	1951–56 -2.80	1854–60 -2.38	1851–60 -1.99
5	1715 -6.37	1785–86 -5.22	1805–07 -3.98	1775–78 -3.42	1559–63 -2.80	1855–60 -2.79	1571–77 -2.38	1571–80 -1.87
6	1790 -6.19	1632–33 -4.95	1776–78 -3.97	1572–75 -3.40	1641–45 -2.78	1572–77 -2.66	1749–55 -2.35	1909–18 -1.83
7	1716 -6.06	1841–42 -4.65	1840–42 -3.92	1839–42 -3.19	1786–90 -2.75	1838–43 -2.31	1912–18 -2.20	1523–32 -1.62
8	1786 -6.03	1524–25 -4.47	1572–74 -3.86	1855–58 -3.10	1750–54 -2.74	1559–64 -2.28	1842–48 -2.18	1782–91 -1.56
9	1538 -5.82	1730–31 -4.44	1523–25 -3.81	1728–31 -3.09	1838–42 -2.69	1912–17 -2.26	1523–29 -2.14	1597–1606 -1.48
10	1542 -5.73	1561–62 -4.33	1855–57 -3.78	1522–25 -3.06	1774–78 -2.54	1523–28 -2.16	1703–09 -2.02	1559–1568 -1.41
11	1971 -5.73	1742–43 -4.32	1741–43 -3.69	1915–18 -3.06	1741–45 -2.47	1773–78 -2.07	1772–78 -1.92	1962–71 -1.32
12	1925 -5.58	1776–77 -4.27	1785–87 -3.63	1840–43 -3.04	1521–25 -2.42	1601–06 -2.03	1600–06 -1.78	1772–81 -1.28
13	1963 -5.58	1528–29 -4.27	1560–62 -3.62	1741–44 -2.99	1845–49 -2.36	1704–09 -1.94	1559–65 -1.70	1925–34 -1.09
14	1714 -5.52	1750–51 -4.20	1703–05 -3.60	1750–53 -2.98	1805–09 -2.35	1641–46 -1.88	1835–41 -1.65	1736–45 -1.06
15	1601 -5.46	1704–05 -4.17	1915–17 -3.46	1950–53 -2.83	1913–17 -2.21	1845–50 -1.78	1886–92 -1.47	1885–94 -1.00
16	1645 -5.10	1916–17 -3.98	1729–31 -3.42	1846–49 -2.78	1749–53 -2.21	1741–46 -1.60	1748–54 -1.31	1748–57 -0.89
17	1730 -5.10	1856–57 -3.92	1847–49 -3.27	1788–91 -2.49	1703–07 -2.03	1804–09 -1.59	1642–48 -1.31	1819–28 -0.80
18	1632 -5.04	1538–39 -3.87	1841–43 -3.24	1702–05 -2.43	1727–31 -2.00	1962–67 -1.47	1961–67 -1.23	1977–86 -0.77
19	1562 -5.03	1847–48 -3.86	1632–34 -3.18	1631–34 -2.26	1528–32 -1.94	1705–10 -1.45	1661–67 -1.14	1661–70 -0.76
20	1956 -4.97	1963–64 -3.86	1690–92 -3.10	1784–87 -2.23	1960–64 -1.72	1906–11 -1.45	1725–31 -1.06	1994–2003 -0.65

other sites. Some of the KSS trees grow on the stream banks with their roots in the water, while others grow on the valley slopes at considerably higher elevations, far away from the stream, where they must depend on soil moisture to sustain growth. These heterogeneous site conditions may account for the relatively weak climate signal at the KSS site compared to the less disturbed and hydrologically more homogeneous GRP and SBP sites.

Table 5. Climate division 8 (Upper Coast) June PDSI, 1500–2008 reconstructed droughts of 1-7 and 10-year lengths in order of severity. Overlaps between time periods in a column have been eliminated.

Case	Single Year	2 Year Avg	3 YearAvg	4 Yr/Avg	5 Yr/Avg	6 Yr/Avg	7 Yr/Avg	10 Yr/Avg
1 Worst	1790 -4.81	1790–91 -4.43	1789–91 -4.11	1714–17 -3.18	1713–17 -2.46	1786–91 -2.23	1785–91 -2.31	1708–17 -1.60
2	1925 -4.77	1805–06 -4.19	1714–16 -3.16	1789–92 -2.52	1521–25 -2.23	1712–17 -2.22	1520–26 -2.05	1840–49 -1.34
3	1521 -4.76	1714–15 -4.09	1750–52 -2.95	1805–08 -2.38	1750–54 -2.17	1750–55 -2.18	1711–17 -1.97	1947–56 -1.31
4	1857 -4.71	1561–62 -3.37	1560–62 -2.79	1518–21 -2.32	1952–56 -2.14	1521–26 -2.15	1950–56 -1.95	1517–26 -1.28
5	1806 -4.53	1750–51 -3.31	1703–05 -2.70	1559–62 2.30	1787–91 -2.04	1951–56 -2.00	1749–55 -1.85	1855–64 -1.25
6	1714 -4.12	1520–21 -3.12	1519–21 -2.60	1749–52 -2.19	1751–55 -1.90	1640–45 -1.82	1857–63 -1.43	1909–18 -1.07
7	1715 -4.06	1916–17 -3.03	1915–17 -2.52	1702–05 -2.15	1641–45 -1.86	1912–17 -1.45	1640–46 -1.39	1783–92 -1.02
8	1791 -4.05	1785–86 -2.98	1805–07 -2.51	1953–56 -2.14	1559–63 -1.71	1559–64 -1.42	1703–09 -1.29	1604–13 -0.98
9	1956 -4.00	1704–05 -2.91	1840–42 -2.49	1775–78 -2.11	1838–42 -1.66	1855–60 -1.38	1912–18 -1.28	1746–55 -0.97
10	1561 -3.95	1730–31 -2.83	1776–78 -2.34	1728–31 -2.10	1804–08 -1.65	1641–46 -1.35	1772–78 -1.25	1769–78 -0.85
11	1691 -3.93	1691–92 -2.68	1954–56 -2.31	1642–45 -2.09	1913–17 -1.63	1838–43 -1.34	1586–91 -1.10	1994–2003 -0.81
12	1971 -3.91	1955–56 -2.67	1729–31 -2.29	1857–60 -2.01	1587–91 -1.58	1998–2003 -1.34	1840–46 -1.07	1639–48 -0.76
13	1587 -3.86	1962–63 -2.65	1862–64 -2.27	1915–18 -1.95	1774–78 -1.55	1773–78 -1.30	1559–65 -1.02	1559–68 -0.72
14	1805 -3.85	1841–42 -2.63	1846–48 -2.23	1839–42 -1.95	1845–49 -1.52	1603–08 -1.28	1600–06 -1.00	1962–71 -0.68
15	1590 -3.79	1776–77 -2.53	1642–44 -2.21	1846-49 -1.90	1856–60 -1.46	1702–07 -1.23	1608–14 -0.99	1818–27 -0.60
16	1608 -3.69	1847–48 -2.51	1559–61 -2.14	1523–26 -1.77	1702–06 -1.39	1585–90 -1.09	1994–2000 -0.90	1581–90 -0.50
17	1963 -3.64	1590–91 -2.47	1524–26 -2.14	1587–90 -1.68	1604–08 -1.34	1560–65 -1.05	1819–25 -0.89	1661–70 -0.46
18	1750 -3.55	1524–25 -2.36	1785–87 -2.13	1522–25 -1.60	1727–31 -1.33	1819–24 -1.05	1621–27 -0.86	1886–95 -0.40
19	1789 -3.46	1857–58 -2.36	1690–92 -2.08	1961–64 -1.57	1998–2002 -1.26	1844–49 -1.03	1847–53 -0.80	1698–07 -0.40
20	1730 -3.44	1754–55 -2.35	1998–2000 -2.07	1603–06 -1.54	1579–83 -1.16	1610–15 -0.94	1886–92 -0.78	1925–34 -0.36

The nature and amount of error in the reconstructions deserve consideration. Figs. 2-5 show that very few of the reconstructed PDSI values match the observations exactly. The basic regression equation contains an error term (Draper and Smith 1981) to account for the imperfect relationship between the climate and tree growth variables. Because the new variables created by PCA of the tree-ring chronologies calibrate less than 100% of the climate variance, some amount

Table 6. Average June PDSI reconstructed drought for non-overlapping periods of 15, 20, and 30 consecutive years from Texas climate divisions 5-8, 1500–2008. The driest10 periods are shown for 15- and 20-year periods, but only five 30-year periods are shown because it is difficult to get 10 non-overlapping 30-year periods of drought.

A. Division 5

Case	15-Year Period	Avg June PDSI		20-Year Period	Avg June PDSI		30-Year Period	Avg June PDSI
1	1951–65	-2.29		1950–69	-1.86		1949–78	-1.63
2	1571–85	-1.98		1572–91	-1.72		1568–97	-1.29
3	1662–76	-1.88		1860–79	-1.71		1728–57	-1.07
4	1703–17	-1.79		1654–73	-1.53		1517–46	-1.03
5	1515–29	-1.73		1801–20	-1.37		1797–1826	-0.96
6	1861–75	-1.68		1517–36	-1.26			
7	1799–1813	-1.59		1697–1716	-1.22			
8	1522–36	-1.49		1772–91	-1.16			
9	1777–91	-1.39		1738–57	-1.01			
10	1730–44	-1.34		1668–87	-0.90			

B. Division 6

Case	15-Year Period	Avg June PDSI		20-Year Period	Avg June PDSI		30-Year Period	Avg June PDSI
1	1703–17	-2.20		1697–1716	-1.74		1949–78	-1.24
2	1776–90	-1.59		1841–60	-1.49		1837–66	-0.89
3	1841–55	-1.51		1950–69	-1.40		1573–1602	-0.81
4	1950–64	-1.48		1560–79	-1.16		1688–1717	-0.79
5	1515–29	-1.29		1772–91	-1.14		1728–57	-0.68
6	1729–43	-1.10		1801–20	-0.86			
7	1806–20	-1.06		1738–57	-0.72			
8	1572–86	-1.04		1513–32	-0.67			
9	1884–98	-0.95		1870–89	-0.66			
10	1662–76	-0.90		1657–76	-0.60			

C. Division 7

Case	15-Year Period	Avg June PDSI		20-Year Period	Avg June PDSI		30-Year Period	Avg June PDSI
1	1703–17	-2.54		1841–60	-2.21		1835–64	-1.53
2	1846–60	-2.11		1698–1717	-1.80		1949–78	-1.02
3	1777–91	-1.68		1773–92	-1.36		1573–1602	-0.89
4	1742–56	-1.41		1561–80	-1.30		1688–1717	-0.88

Table 6 (continued)

5	1515–29	-1.37		1948–67	-1.17		1763–92	-0.72
6	1950–64	-1.31		1737–56	-0.98			
7	1561–75	-1.11		1703–22	-0.72			
8	1903–17	-0.94		1590–1609	-0.72			
9	1590–1604	-0.91		1514–33	-0.65			
10	1971–85	-0.83		1971–90	-0.52			

Division 8

Case	15-Year Period	Avg June PDSI		20-Year Period	Avg June PDSI		30-Year Period	Avg June PDSI
1	1703–17	-1.53		1841–60	-1.15		1835–64	-0.90
2	1846–60	-1.14		1699–1718	-0.92		1949–78	-0.58
3	1777–91	-1.00		1773–92	-0.88		1598–1627	-0.47
4	1742–56	-0.99		1948–67	-0.82		1702–31	-0.36
5	1949–63	-0.94		1598–1617	-0.75		1763–92	-0.35
6	1598–1612	-0.87		1737–56	-0.64			
7	1513–27	-0.82		1548–67	-0.36			
8	1903–17	-0.57		1508–27	-0.33			
9	1553–67	-0.55		1605–24	-0.26			
10	1829–43	-0.47		1821–40	-0.22			

of reconstruction error is inevitable. At present, unfortunately, there is no universally accepted way to put confidence limits on the reconstructions.

One factor that influences reconstruction error is replication, that is the variable number of radii in the chronologies through time. Replication diminishes as the number of relatively young samples decreases. This is a reason for beginning the analyses of reconstructions at 1500 although all the baldcypress and Douglas-fir chronologies begin earlier (Tables A1, A2a). This diminished replication tends to inflate variance, which is the reason we detrended the variance when creating chronologies. The number of radii at 1500, 1600, 1700, 1800, 1900, and 1990 are shown along the bottom of the X-axis of Figs. 6–9. In the division 5 reconstruction, for example, replication ranges from a minimum of 15 at 1500, to a maximum of 243 at 1900 (Fig. 6). The degree of replication in the earliest part of these reconstructions is judged to be acceptable, but the amount of error in the estimates necessarily increases as sample size diminishes. In the division 6 reconstruction (Fig. 7) the largest sample size was 401 at 1900, which far exceeds the replication in many tree-ring studies. The number of trees in each chronology is shown in Tables A1 and A2.

An example of a large amount of error in a single year is the reconstruction of 1974. For some reason, the degree of drought was overestimated in all divisional reconstructions, that is, soil moisture conditions must have consistently decreased tree growth more than the observed PDSI would indicate (Table 1). Since the positive and negative deviations from the regression estimates were tested and found to be consistently random (Tables A3–A9), and are constrained to sum to 0.0 in the calibration (Draper and Smith 1981), there should be no systematic errors over the period of calibration, 1931–2008. Errors of the type encountered in 1974, where the PDSI is overestimated, must be balanced by underestimation of other years. The instrumental PDSI rankings of 1974 (12, 18, 78, and 95) in the 1895–2008 period become wetter from west to east, as do the rankings (1, 2, 37, and 55) of 1974 reconstructed PDSI in the 1895–2008 period (Table 1). This shows that the estimates follow the observed climate trend, albeit with considerable error. We cannot explain an error reconstructing a year that seems to be consistent in direction over all the reconstructions, but the error may be created by some inadequacy in the PDSI soil moisture model, which was created for measurement of the effects of drought on row crops, not trees (Palmer 1965).

The worst extended drought in the instrumental climatic data appears to be what is referred to as the 1950s drought. These data show that the 1950s drought actually may have begun in 1948 or even 1947, because 1947, 1948, and 1949 are below average in some of the divisional data (Table A11). We analyzed and compared the reconstructed drought series through time (below) to gauge the relative severity of the 1950s drought. Although the Dust Bowl drought of the 1930s was the overall worst experienced nationally during the 20th century (Cook et al. 1996, 1999), the worst effects in Texas occurred north of our area of reconstruction.

Tables 2 to 5 summarize the 20 worst droughts in the 4 climate divisions over different intervals ranging from a single year to 7 consecutive years, and finally, 10 consecutive years, 1500–2008. We systematically excluded intervals that overlapped, i.e., had 1 or more years in common with other intervals from these tables, and this led to rejecting many possible droughts, especially in the decadal category. For example, in division 5, 145 ranked combinations had to be considered before the 20 in Table 2 could be tallied, so that 125 combinations of 10 consecutive years with overlapping intervals had to be rejected. This shows that drought occurs randomly and sporadically but is concentrated in certain periods and may be a decade or more in length.

The 1950s drought is among the worst, but droughts as bad or worse have occurred in other periods. Table 4 (S. Central, div. 7) shows that the early 1700s dominate the top rankings in that division, with 3 years (1714, 1715, 1716) in the single year category ranking among the most severe and all other time periods of the early 1700s worst in all other categories. Certain periods have experienced long and severe periods of drought, while other periods have been spared. Among these periods of anomalous drought, in rough order of severity from all climate divisions (because the order differs from division to division) are the early 1700s, the mid-1800s (1840–1863), the 1950s (1947–1957), and the 1500s (1571–1580, 1523–1532, 1559–1568, 1581–1590, 1597–1606), the early 1900s (1909–1918, 1925–1934), the late 1700s (1777–1792), the late 20th century (1962–1971, 1977–1986, 1994–2003). Bad droughts clearly recur time after time in these 4 Texas climate divisions.

There are clear differences among the climate divisions. For example, while division 7 has the early 1700s as driest in all categories, the other divisions show more variability. These reconstructions also appear to confirm other reconstructions created using different chronologies (Cook et al. 1996, 1999; Stahle et al. 2000, 2007), e.g., division 5 (Table 2) has five 10-year periods in the 16th and early 17th century (in order of decreasing severity, 1524–1533, 1571–1580, 1583–1592, 1538–1547, 1597–1606). Some of those droughts occur in the period identified as the 1500s megadrought (Stahle et al. 2000, 2007; Cook et al. 2004). The 16th century megadrought appears most clearly in division 5 (Fig. 6), although megadrought conditions were much worse in the region west of Texas (Stahle et al. 2000, 2007). It becomes less pronounced farther east in divisions 6 and 7 (Figs. 7, 8), disappearing almost completely in division 8, the wettest division (Table A2a; Table 5; Fig. 9). The same diminution in severity from west to east also holds true for the 1950s drought (Figs. 2–9, Tables 2–5).

Decadal-length droughts seem to be distributed fairly equally, with one exception. The 1600s appears to have notably fewer droughts of that duration than the other 4 centuries. This appears to be a real phenomenon, another instance of long-term climate variability.

Many of the 10-year droughts reconstructed actually were part of longer drought regimes, e.g., 1772–1781 and 1782–1791, and 1559–1568 and 1571–1580 in division 7 and 1840–1849 and 1854–1863 in division 6. We investigated droughts 15-, 20-, and 30-years long (Table 6). The 1950s drought appears in each division for all 3 drought durations. In division 5 the 1950s drought is the worst at the 15-, 20-, and 30-year durations, culminating in the 1949–1978 period with a 30-year average June PDSI of -1.63. Additional 30-year periods that occurred in 2 or more of the 4 divisions were the mid- to late-1500s, early-, mid-, and late-1700s, and the early- and mid-1800s. The long duration and severity that characterizes megadroughts does not seem to be solely a 16th century phenomenon. Most of the megadroughts identified in the past (Stahle et al. 2000, 2007; Cook et al. 2009), however, appear to have been most extreme in areas west of Texas.

The reconstruction of the 20th century seems to have as many long drought episodes as other centuries (Tables 2–6). While division 5 has only four 10-year periods in the 20th century (Table 2), divisions 6 and 8 have 5 (Tables 3 and 5) and division 7 has 6 (Table 4). This, and the results with the 15-, 20-, and 30-year drought intervals, clearly indicates that, overall, the 20th century in these 4 Texas climate divisions was not anomalously wet or dry and appears typical of the 1500–2008 time period. Therefore, it can be expected that droughts as bad as or worse than the 1950s will occur in the future. A future that may very well see accelerating climate change and continuing rapid population growth does not bode well for Texas water resources (Cook et al. 2007; IPCC 2007a, b; Seager et al. 2007; Banner et al. 2010; Min et al. 2011; Pall et al. 2011).

In the future these reconstructions could be improved by collecting more baldcypress chronologies and collecting samples from historical structures, such as the San Antonio missions, to improve the early replication of existing chronologies and to extend them into the past. In addition, each annual ring is divided into 2 parts, earlywood and latewood (Panshin and de Zeeuw 1970). By measuring these separately and making separate chronologies, the growing season can be divided temporally (Therrell et al. 2002; Cleaveland et al. 2003; Stahle et al. 2009). This temporal division may allow separate intra-annual reconstructions, e.g., of spring and summer climate.

SUMMARY AND CONCLUSIONS

The June Palmer Drought Severity Index (PDSI) for climate divisions 5–8 (Trans Pecos, Edwards Plateau, South Central, and Upper Coast, respectively) was successfully reconstructed for 1500–2008. Decadal or longer droughts appear to be randomly distributed and occur frequently in the reconstructions, although the 1600s may have had fewer protracted droughts than the other 4 centuries. The reconstructions confirm that the 1950s drought was severe but also show that there have been periods when drought was more severe and/or more protracted than the 1950s and that the impact might have been considerably worse. The recurrence of severe prolonged drought in South Central Texas appears to be the norm, not the exception. It would be a questionable strategy for civil authorities to assume that the 1950s drought represents the worst-case scenario to be used for planning purposes in water resources management, at least for western and central Texas. This especially holds true when water managers consider the possible impacts of climate change, combined with a rapidly growing population and new demands on water resources. Water managers must consider intensive water conservation programs and development of new water resources (e.g., desalination of seawater) to meet these challenges (Banner et al. 2010).

ACKNOWLEDGEMENTS

We thank the Guadalupe-Blanco River Authority for its financial and other support, the National Science Foundation grant ATM-0823665 to Banner, and the Geology Foundation and Environmental Science Institute. We are indebted to Dr. David Stahle of the University of Arkansas Tree-Ring Lab, who helped develop the chronologies and Dr. Connie Woodhouse and doctoral student Dan Griffin of the University of Arizona, who updated and improved the Guadalupe Peak chronology and made it available for our use. Numerous private landowners, the Texas Parks & Wildlife Department (especially Guadalupe R. State Park), and Ft. Bend County generously gave us permission to sample. Dr. Dorian Burnette assisted in creating some of the figures. We also thank three anonymous reviewers and the editors, whose suggestions helped improve the paper.

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APPENDIX

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1. THE TRANSFORMATION OF RING WIDTHS INTO CHRONOLOGIES

We generated chronologies with program ARSTAN (Cook 1985) (LDEO website 2011). Most trees have growth trends that must be removed in order to create time series with stationary statistical properties that reflect climate influence more accurately than undetrended ring widths. This program transforms individual ring width series (in mm) with different means and nonstationary statistical properties into dimensionless indices with a mean of 1.0 and stationary statistical properties. These index series are then averaged into the ring width chronology.

For example, many trees have a trend from relatively wide rings when young to much narrower rings as they mature. In addition, competition with adjacent trees may create growth suppression and release that leads to reduction and acceleration in growth rates, respectively, during a tree's lifespan (Cook 1985; Fritts 2001; Speer 2010). If these nonclimatic influences are not minimized, it is difficult to make reliable paleoclimatic inferences from tree rings. Among the curves used, depending on the series, are a negative exponential declining to a fixed value, a flexible cubic spline (Cook and Peters 1981; Cook 1985; Cook et al. 1990), or a regression line (Draper and Smith 1981). After the curve is fitted to a series, the program divides each annual measurement by the corresponding curve value. This process transforms the measurements into new dimensionless time series, with a mean of 1.0 that remains approximately statistically stationary through time. We used an option in the program that performs a second detrending with a stiff cubic spline (Cook and Peters 1981) to improve trend removal.

The program averages the transformed individual radii into a single time series, the standard chronology. One additional step in processing the chronology removes variance trend caused by reduction of sample size in the earliest part of the chronology (Shiyatov et al. 1990). Although the program generates several other types of chronologies, we used the standard chronologies in this research. Statistical properties of the 3 new baldcypress chronologies are shown in Table A2. The chronologies were further transformed by program PCREG (below) in the process of making reconstructions.

2. RECONSTRUCTIONS, THE "NESTING" CONCEPT AND CLIMATE RECONSTRUCTION PROGRAM PCREG

The climate division 5 reconstruction (Table A3), the only one not nested, uses 2 series of principal component factor scores that together incorporate 76.4% of the tree-ring variability in the 4 chronologies and account for 58% of the climate variance in calibration (Table A3a). The BSC and GPM Douglas-fir chronologies on the western edge of climate division 5 correlate better with June PDSI than the 2 baldcypress chronologies, GRP and KSS, on the eastern edge. KSS has the lowest correlation of the 4 chronologies. The superior climate sensitivity of the Douglas-fir chronologies is attributable in part to the more arid climate of their location in West Texas (Banner et al. 2010).

Except for division 5, the divisional reconstructions combine 2 different reconstructions, the first 1648–2008 that uses the Central Texas post oak chronology in combination with longer chronologies, but is limited to begin in 1648 by PCA (Tables A4, A6, A8). The second reconstructions for divisions 6, 7, and 8 only use long chronologies that span at least 1500–2008. The nonoverlapping portion of the longer reconstruction was appended to the shorter series after adjusting its mean and variance to match the shorter series in the overlap period. The reason this technique is preferred over averaging all the chronologies together into a single series or using multiple regression with the tree-ring chronologies, is that it permits the optimal use of all the available tree-ring data and the PCA methodology, which requires all the series input to be the same length. The reconstruction characteristics in Tables A4 through A10 demonstrate the utility of the nested reconstruction concept and chronology response to climate.

How well do the longer reconstructions match the short reconstructions in the 1648–2008 overlap period? The 1500–2008 reconstruction's 1648–2008 overlap period is not used, except for this comparison. The 2 division 6 reconstructions correlate very well in the overlap period ($N=361$, $r=0.954$, $P<0.0001$), indicating that they share about 91% of the variance and that the composite post oak chronology makes only a small improvement in the shorter reconstruction. The agreement is evident when the 2 reconstructions are overlaid (Fig. A1). The division 7 reconstructions do not correlate nearly as well ($N=361$, $r=0.679$, $P<0.0001$), sharing only 46% of the variance 1648–2008 (Fig. A2). The post oak chronology apparently does make a substantial improvement in that case.

The real surprise is that the 2 division 8 reconstructions share 64% of their variance and agree well (Fig. A3), considering that the longer reconstruction R^2 was only 0.18.

The nested reconstructions of divisions 6, 7, and 8 show that the advantages of using the shorter Central Texas post oak chronology (CENOAK; Table A1) vary from division to division. In each case, however, the 1648–2008 PCA factor scores account for more climate variance in regression than the 1500–2008 factor scores that do not include CENOAK, and CENOAK is consistently better correlated with climate than the other chronologies (Tables A4 to A9). Based on climate variance accounted for in regression alone, the reconstructions of division 6 (Tables A4 and A5) are the best, closely followed by division 5 (Table A3), and division 7 (Tables A6 and A7).

The case of reconstructing PDSI in division 8 deserves special consideration. The 1648–2008 reconstruction only accounts for 41.6% of the climate variance in regression (Table A8a). Of the 4 chronologies used (GRP, KSS, SBP and CENOAK), CENOAK is best correlated ($r=0.67$, $P<0.001$) and SBP is next ($r=0.43$, $P<0.001$), but the GRP correlation is barely significant ($r=0.22$, $P=0.048$), and KSS is barely positively and not significantly correlated ($r=0.06$, $P=0.590$) (Table A8a). The 1500–2008 division 8 calibration is the poorest, with only 18% of climate variance calibrated (Table A9a). Nevertheless, the long reconstruction passes all validation tests (Table A9b), indicating that the calibration percentage may be misleading. A trial 1500–2008 reconstruction that included the Big Cypress baldcypress chronology from North Central Louisiana (Table A1) fared worse (not shown). One of the 3 living tree oak chronologies averaged into the central Texas composite oak chronology and one baldcypress chronology, SBP, are actually located in division 8 (Fig. 1; Table A1). The other 2 new baldcypress chronologies are relatively far away, which decreases their correlation with division 8 PDSI. This result also confirms the importance of having long, climate-sensitive chronologies available locally for the best local reconstructions.

Some further analysis also indicates that the division 8 1500–1647 reconstruction may be better than the R^2 statistic indicates. Comparison of the 2 division 8 nested reconstructions, 1648–2008 and 1500–2008 in the period of overlap, shows stronger correlation ($r=0.80$, $P<0.0001$, 64% of the variance shared) than one would expect, given the disparity in the 2 percentages calibrated, $R^2=0.42$ and $R^2=0.18$, respectively. For this reason, the 1500–1647 segment of the division 8 nested reconstruction may actually be quite accurate.

The residuals, differences between the observations and the regression line (i.e., the predicted observation), should be randomly distributed if the model is valid, and are forced to sum to 0.0 (Draper and Smith 1981). The Durbin-Watson statistic (Draper and Smith 1981) tests for the serially random distribution of differences between the regression predictions and the actual observations (residuals), and all the regression models pass this test (Tables A3-A9). Another way to evaluate the relationships between climate and tree growth and the amount of error that might be expected in estimates is by the variance accounted for in regression, the R^2 (Draper and Smith 1981). By this criterion, the 1648–2008 portions of the nested reconstructions ought to contain less error than the 1500–1647 parts and the divisions 5, 6, and 7 reconstructions must contain less error than the division 8 reconstruction, although we have seen that some aspects of the latter assumption are open to question.

Program PCREG

We created climate reconstructions with program PCREG (Cook et al. 1994, 1999; LDEO website 2011). PCREG is a complicated program that performs many operations to calibrate a reconstruction with linear regression and validate that reconstruction against independent climatic data not used in the calibration. The sequence of PCREG operations is as follows:

1. Reads in multiple tree-ring chronologies and the single climate series to be reconstructed.
2. Autoregressively models ("whitens"; Meko 1981; Box et al. 1994) both the tree-ring chronologies and the climate series to remove persistence. This makes linear regression more efficient because the observations in the series become independent of each other (Draper and Smith 1981).
3. Performs a principal components analysis (PCA) (Cooley and Lohnes 1971) on the whitened tree-ring chronologies to generate new variables (factor scores) that maximize the common variance in the tree-ring chronologies. The factor score series are orthogonal (uncorrelated), so use of more than one in multiple regression does not run the risk of multicollinearity (Draper and Smith 1981).
4. Calibrates the reconstruction model by regressing (Draper and Smith 1981) the PCA factor score(s) (independent variable(s)) derived from the whitened tree-ring chronologies against the whitened climate variable (dependent variable).
5. Multiplies the PCA factor score(s) by the regression coefficients from operation 4 above to derive an intermediate reconstruction.
6. Adds the climatic AR model (Box et al. 1994; Meko 1981) removed in operation 2 above to the intermediate reconstruction in order to generate the final "reddened" reconstruction.
7. Compares the standard deviations of the observed and reconstructed climate variable in their overlap period.

The program makes the reconstructed variance match the observed variance by subtracting the reconstruction mean from that series, then multiplying the resulting anomaly series by the ratio of the observed and reconstructed standard deviation, and finally, adding the mean of the observed data back into the reconstructed series.

8. Compares the reconstruction to independent observed data not used in the calibration to measure the validity of the paleoclimatic estimates (Snee 1977; Fritts 2001).

3.

Table A1. Chronologies available for reconstruction of South Central Texas climate. Species codes: QUST=post oak, PSME=Douglas-fir, TADI=baldcypress, PIPO= ponderosa pine, PIED=pinyon pine.

Site Name/State/Code	Species	No. Trees	Latitude	Longitude	Dates/Comments
**Central Texas Post Oak Chronology/TX/CENOAK	QUST	187	Approx. center 29°45′N	Approx. center 97°10′W	1648–1995/Composite of the 7 sites immediately following
*Yegua Creek/ TX/ YEG	QUST	37	30°19′N	96°38′W	1658–1995
*Lavaca River/ TX/ HAL	QUST	42	29°18′N	96°58′W	1668–1995
*Coleto Creek/ TX/ COL	QUST	34	28°46′N	96°43′W	1682–1995
*Gonzales County Pioneer Village/TX/GPV	QUST	28	29°30′N	97°27′W	1649–1995
*Eggleston House/TX/EGG	QUST	18	29°31′N	97°25′W	1669–1845
*McBryde Log House/ TX/ YOK	QUST	21	29°15′N	97°05′W	1668–1847
*West-Adkisson Cabin/ TX/ WAD	QUST	7	30°30′N	97°46′W	1648–1853
**Big Bend National Park/ TX/ BSC	PSME	54	29°15′N	103°18′W	1473–1992
**Guadalupe Peak National Park/ TX/ GPM	PSME	55	30°26′N	104°51′W	1362–2008
Big Cypress State Park/ LA/ BIG	TADI		32°15′N	92°58′W	997–1988
El Malpais National Monument/ NM/ MLC	PSME		34°58′N	108°06′W	-136–1992
Echo Amphitheater/ NM /171	PSME		36°21′N	106°31′W	1362–1989
Satan Pass/ NM	PSME		35°36′N	108°08′W	1312–1990
Fort Burgwin/ NM	PIPO		36°15′N	105°31′W	1482–1989
Elephant Rock/ NM/ ERE	PIPO		36°42′N	105°29′W	1391–1987
Agua Fria/ NM/ AFN	PIED		34°14′N	108°37′W	1403–1987
Ft. Wingate/ NM/ 283	PIED		35°26′	108°32′W	1478–1972
Turkey Springs/ NM/ 273	PIED		35°24′	108°31′W	1411–1972

* Part of the composite Central Texas post oak chronology used in reconstructions
** Used in reconstructions

4. **Table A2a.** Characteristics of chronologies collected in South Central Texas used in reconstructions. All are baldcypress (*Taxodium distichum*).

Site Name/Code	Lat./Long.	Elev. (m)	No. Radii	No.Trees	Dates	County	Site Type
Guadalupe R St Pk/GRP	29°52′N/ 98°30′W	300	37	13	1486–2009	Kendall	Hill country, riverine
Krause Springs/KSS	30°29′N/ 98°09′W	230	55	28	1423–2009	Burnet	Hill country, stream
San Bernard R Pk/SBP	29°26′N/ 96°01′W	27	27	13	1447–2009	Ft. Bend, Wharton	Coastal plain, riverine

Table A2a. (Contd.)

Site Code	Annual Precip.	Substrate	Hydrology	Additional information
GRP	29-33″ (74-84cm)	Limestone	River bank	Some human impact
KSS	29-33″ (74-84cm)	Limestone	Mixed: stream bank, valley slopes	Very large human impact
SBP	49-53″ (124-135cm)	Alluvium	River bank	Minimal human impact

Table A2b. Chronology statistics.

Site name/Code	Mean Sens.[a]	Std. Dev.	Serial[b] Corr.	AR Model	Division June PDSI Correlation/ Probability (1931–2008)			
					5	6	7	8
Guadalupe R. State Park/GRP	0.275	0.291	0.398	2	0.22/ <0.05	0.65/ <0.001	0.32/ <0.01	0.25/ <0.03
Krause Springs/KSS	0.225	0.243	0.422	3	0.06/ =0.14	0.29/ <0.01	0.19/ <0.09	0.02/ =0.88
San Bernard R. Pk/SBP	0.418	0.409	0.235	3	0.18/ =0.12	0.51/ <0.001	0.53/ <0.001	0.45/ <0.001

Table A2c. Common period statistics.

Site name/Code	Common Period	Signal/ Noise	Pearson[c] Corr.	Mean[a] Sens.	Std. Dev.	Serial[c] Corr.
Guadalupe R. State Park/GRP	1890–2008	6.692	0.255	0.388	0.461	0.392
Krause Springs/KSS	1905–2008	10.947	0.225	0.388	0.497	0.467
San Bernard R. Bates Allen Park/SBP	1905–2008	10.418	0.451	0.522	0.529	0.297

[a]Mean sensitivity: "… the average relative difference from one ring width to the next, calculated by dividing the absolute value of the differences between each pair of measurements by the average of the paired measurements, then averaging the quotients for all pairs in the tree ring series …" (Kaennel and Schweingruber 1995) (Fritts 2001).
[b]The Pearson product moment correlation coefficient (Steel and Torrie 1980) between $Year_t$ and $Year_{t-1}$, a measure of persistence in the time series. The relatively high persistence at the KSS site may indicate a lesser sensitivity to climate in that chronology relative to the others.
[c]Pearson product moment correlation coefficient between radii (Steel and Torrie 1980). The low KSS correlation may indicate a lesser sensitivity to climate in that chronology relative to the others.

5. **Table A3a.** Texas climate division 5 (Trans Pecos) reconstruction 1500–2008 of June PDSI, calibration 1931–2008.

	PCA % Variance		Regression		Serial Corr. Residuals	Durbin-Watson Statistic[b]
Chronologies Used	1st PC	2nd PC	#PCs Used	R^2 adj.[a]		
GRP,KSS,BSC,GPM	50.2	26.2	2	0.580	-0.135	2.24NS

NS Not significant, i.e., there is greater than a 5% probability that the result occurred by chance.
[a]R^2 adjusted downward for loss of degrees of freedom (Draper and Smith 1981).
[b]Autocorrelation of the residuals from regression, tested with the Durbin-Watson statistic (Draper and Smith 1981). Failure to reject the null hypothesis indicates that the residuals occur randomly, an indication that the regression model is valid.

Table A3a. (Cont'd)

Chronology	Beta[#]	Std. Error	Corr.	Prob.
GRP: Guadalupe R.	0.0990	0.0260	0.29	0.010
KSS: Krause Springs	-0.0134	0.0402	0.20	0.072
BSC: Big Bend NP	0.4145	0.0309	0.69	0.001
GPM: Guadalupe Peak NP	0.3966	0.0272	0.70	0.001

[#]Regression coefficient in terms of original variable.

Table A3b. Validation 1895–1930 for reconstruction 1500–2008 of Texas climate division 5 (Trans Pecos) June PDSI.

Test	Statistic	Difference	t-stat. or z-score	Prob.	Remark
Equality of means[a]	-------	-0.38	-0.734	0.530	No sig. dif. is desired result
Cross-product means[b]	-------	3.81	3.390	<0.001	
Sign test (+/-)[c]	21/15	--------	0.833	0.202	Only validation failure
Correlation Coefficient[d]	0.53	--------	3.620	<0.0000	
Reduction of Error[e]	0.28	--------	No formal test of significance		
Coefficient of Efficiency[e]	0.27	--------	No formal test of significance		

[a]Paired comparison of observed and reconstructed data means (Steel and Torrie 1980). Note that no difference is the desired result.
[b]Tests the relative magnitude of departures from the mean in the same or opposite directions when reconstruction and observed are compared for each year. Means are subtracted from each series and the residuals are multiplied. A positive product is a "hit." If either observed or reconstructed data lie very near the mean, the year is omitted from the test.
[c]Nonparametric test of the ratio of the number of "hits" to "misses" in the cross-product means test above (Conover 1980).
[d]Pearson product moment correlation coefficient (Steel and Torrie 1980).
[e] Varies from 1.0 to negative infinity. Any positive result is considered evidence of useful information in the paleoclimatic reconstruction (Fritts 2001). The coefficient of efficiency is the more stringent test.

6. **Table A4a.** Texas climate division 6 (Edwards Plateau) reconstruction 1648–2008 of June PDSI, calibration 1931–2008.

Chronologies Used	PCA % Variance		Regression		Serial Corr.[b] of Residuals	Durbin-Watson Statistic[b]
	1st PC	2nd PC	#PCs Used	R^2 adj.[a]		
GRP,KSS,SBP,CENOAK,BSC,GPM	67.0	------	1	0.674	-0.075	2.12NS

NS Not significant, i.e., there is greater than a 5% probability that the result occurred by chance.
[a]R^2 adjusted downward for loss of degrees of freedom (Draper and Smith 1981).
[b]Autocorrelation of the residuals from regression, tested with the Durbin-Watson statistic (Draper and Smith 1981). Failure to reject the null hypothesis indicates that the residuals occur randomly, an indication that the regression model is valid.

Table A4a. (Cont'd)

Chronology	Beta[#]	Std. Error	Corr.	Prob.
GRP: Guadalupe R.	0.2118	0.0071	0.53	<0.000
KSS: Krause Springs	0.1561	0.0039	0.37	<0.001
SBP: San Bernard R.	0.1793	0.0051	0.51	<0.000
CENOAK: Central TX postoak	0.2411	0.0092	0.67	<0.000
BSC: Big Bend NP	0.2345	0.0087	0.66	<0.000
GPM: Guadalupe Peak NP	0.1984	0.0062	0.49	<0.000

[#]Regression coefficient in terms of original variable.

Table A4b. Validation 1895–1930 for reconstruction 1648–2008 of Texas climate division 6 (Edwards Plateau) June PDSI.

Test	Statistic	Difference	t-stat. or z-score	Prob.	Remark
Equality of means[a]	-------	-0.12	-0.020	0.982	No sig. dif. is desired result
Cross-product means[b]	-------	5.68	3.183	<0.002	
Sign test (+/-)[c]	27/9	--------	2.833	0.002	
Correlation Coefficient[d]	0.73	--------	6.159	<0.0000	
Reduction of Error[e]	0.50	--------	No formal test of significance		
Coefficient of Efficiency[e]	0.50	--------	No formal test of significance		

[a]Paired comparison of observed and reconstructed data means (Steel and Torrie 1980). Note that no difference is the desired result.
[b]Tests the relative magnitude of departures from the mean in the same or opposite directions when reconstruction and observed are compared for each year. Means are subtracted from each series and the residuals are multiplied. A positive product is a "hit." If either observed or reconstructed data lie very near the mean, the year is omitted from the test.
[c]Nonparametric test of the ratio of the number of "hits" to "misses" in the cross-product means test above (Conover 1980).
[d]Pearson product moment correlation coefficient (Steel and Torrie 1980).
[e] Varies from 1.0 to negative infinity. Any positive result is considered evidence of useful information in the paleoclimatic reconstruction (Fritts 2001). The coefficient of efficiency is the more stringent test.

7. **Table A5a.** Texas climate division 6 (Edwards Plateau) reconstruction 1500–2008 of June PDSI, calibration 1931–2008. Used 1500–1647 in combination with 1648-2008 reconstruction (Table A4).

Chronologies Used	PCA % Variance		Regression		Serial Corr.[b] of Residuals	Durbin-Watson Statistic[b]
	1st PC	2nd PC	#PCs Used	R^2 adj.[a]		
GRP,KSS,SBP,BSC,GPM	43.6	23.1	1	0.599	-0.031	2.04NS

NS Not significant, i.e., there is greater than a 5% probability that the result occurred by chance.
[a]R^2 adjusted downward for loss of degrees of freedom (Draper and Smith 1981).
[b]Autocorrelation of the residuals from regression, tested with the Durbin-Watson statistic (Draper and Smith 1981). Failure to reject the null hypothesis indicates that the residuals occur randomly, an indication that the regression model is valid.

Table A5a. (Cont'd)

Chronology	Beta[#]	Std. Error	Corr.	Prob.
GRP: Guadalupe R. SP	0.2512	0.0111	0.53	<0.000
KSS: Krause Springs	0.2068	0.0075	0.37	<0.001
SBP: San Bernard R.	0.1916	0.0065	0.51	<0.000
BSC: Big Bend NP	0.2519	0.0112	0.49	<0.000
GPM: Guadalupe Peak NP	0.2668	0.0125	0.66	<0.000

[#]Regression coefficient in terms of original variable.

Table A5b. Validation 1895–1930 for reconstruction 1500–2008 of Texas climate division 6 (Edwards Plateau) June PDSI.

Test	Statistic	Difference	t-stat. or z-score	Prob.	Remark
Equality of means[a]	-------	0.194	0.327	0.742	No sig. dif. is desired result
Cross-product means[b]	-------	5.25	3.648	<0.0005	
Sign test (+/-)[c]	25/11	--------	2.167	0.015	
Correlation Coefficient[d]	0.73	--------	6.159	<0.0000	
Reduction of Error[e]	0.50	--------	No formal test of significance		
Coefficient of Efficiency[e]	0.50	--------	No formal test of significance		

[a]Paired comparison of observed and reconstructed data means (Steel and Torrie 1980). Note that no difference is the desired result.
[b]Tests the relative magnitude of departures from the mean in the same or opposite directions when reconstruction and observed are compared for each year. Means are subtracted from each series and the residuals are multiplied. A positive product is a "hit." If either observed or reconstructed data lie very near the mean, the year is omitted from the test.
[c]Nonparametric test of the ratio of the number of "hits" to "misses" in the cross-product means test above (Conover 1980).
[d]Pearson product moment correlation coefficient (Steel and Torrie 1980).
[e] Varies from 1.0 to negative infinity. Any positive result is considered evidence of useful information in the paleoclimatic reconstruction (Fritts 2001). The coefficient of efficiency is the more stringent test.

8. **Table A6a.** Texas climate division 7 (South Central) reconstruction 1648–2008 of June PDSI, calibration 1931–2008.

Chronologies Used	PCA % Variance		Regression		Serial Corr.[b] of Residuals	Durbin-Watson Statistic[b]
	1st PC	2nd PC	#PCs Used	R^2 adj.[a]		
GRP,KSS,SBP,CENOAK	51.7	20.8	2	0.595	0.084	1.83NS

NS Not significant, i.e., there is greater than a 5% probability that the result occurred by chance.
[a]R^2 adjusted downward for loss of degrees of freedom (Draper and Smith 1981).
[b]Autocorrelation of the residuals from regression, tested with the Durbin-Watson statistic (Draper and Smith 1981). Failure to reject the null hypothesis indicates that the residuals occur randomly, an indication that the regression model is valid.

Table 6a. (Cont'd)

Chronology	Beta[#]	Std. Error	Corr.	Prob.
GRP: Guadalupe R.	0.2013	0.0178	0.45	<0.000
KSS: Krause Springs	0.0116	0.0557	0.30	<0.008
SBP: San Bernard R.	0.3746	0.0251	0.52	<0.000
CENOAK: Central TX postoak	0.4077	0.0314	0.79	<0.000

[#]Regression coefficient in terms of original variable.

Table 6b. Validation 1895–1930 for reconstruction 1648–2008 of Texas climate division 7 (South Central) June PDSI.

Test	Statistic	Difference	t-stat. or z-score	Prob.	Remark
Equality of means[a]	-------	-0.43	-0.678	0.505	No sig. dif. is desired result
Cross-product means[b]	-------	4.24	2.149	0.0184	
Sign test (+/-)[c]	32/4	--------	4.500	0.000	
Correlation Coefficient[d]	0.76	--------	6.797	<0.0000	
Reduction of Error[e]	0.52	--------	No formal test of significance		
Coefficient of Efficiency[e]	0.52	--------	No formal test of significance		

[a]Paired comparison of observed and reconstructed data means (Steel and Torrie 1980). Note that no difference is the desired result.
[b]Tests the relative magnitude of departures from the mean in the same or opposite directions when reconstruction and observed are compared for each year. Means are subtracted from each series and the residuals are multiplied. A positive product is a "hit." If either observed or reconstructed data lie very near the mean, the year is omitted from the test.
[c]Nonparametric test of the ratio of the number of "hits" to "misses" in the cross-product means test above (Conover 1980).
[d]Pearson product moment correlation coefficient (Steel and Torrie 1980).
[e]Varies from 1.0 to negative infinity. Any positive result is considered evidence of useful information in the paleoclimatic reconstruction (Fritts 2001). The coefficient of efficiency is the more stringent test.

9. **Table A7a.** Texas climate division 7 (South Central) reconstruction 1500–2008 of June PDSI, calibration 1931–2008. Used 1500–1647 in combination with 1648–2008 reconstruction (Table A6).

Chronologies Used	PCA % Variance		Regression		Serial Corr.[b] of Residuals	Durbin-Watson Statistic[b]
	1st PC	2nd PC	#PCs Used	R^2 adj.[a]		
GRP,KSS,SBP,BSC,GPM	43.6	23.1	1	0.433	0.086	1.81NS

NS Not significant, i.e., there is greater than a 5% probability that the result occurred by chance.
[a]R^2 adjusted downward for loss of degrees of freedom (Draper and Smith 1981).
[b]Autocorrelation of the residuals from regression, tested with the Durbin-Watson statistic (Draper and Smith 1981). Failure to reject the null hypothesis indicates that the residuals occur randomly, an indication that the regression model is valid.

Table A7a. (Cont'd)

Chronology	Beta[#]	Std. Error	Corr.	Prob.
GRP: Guadalupe R. SP	0.2143	0.0132	0.45	<0.000
KSS: Krause Springs	0.1764	0.0090	0.30	<0.008
SBP: San Bernard R.	0.1634	0.0077	0.52	<0.000
BSC: Big Bend NP	0.2149	0.0133	0.40	<0.000
GPM: Guadalupe Peak NP	0.2726	0.0149	0.52	<0.000

[#]Regression coefficient in terms of original variable.

Table A7b. Validation 1895–1930 for reconstruction 1500–2008 of Texas climate division 7 (South Central) June PDSI.

Test	Statistic	Difference	t-stat. or z-score	Prob.	Remark
Equality of means[a]	-------	-0.189	-0.345	0.730	No sig. dif. is desired result
Cross-product means[b]	-------	4.32	3.474	<0.0008	
Sign test (+/-)[c]	24/12	--------	1.833	0.0334	
Correlation Coefficient[d]	0.65	--------	4.986	<0.0000	
Reduction of Error[e]	0.42	--------	No formal test of significance		
Coefficient of Efficiency[e]	0.42	--------	No formal test of significance		

[a]Paired comparison of observed and reconstructed data means (Steel and Torrie 1980). Note that no difference is the desired result.
[b]Tests the relative magnitude of departures from the mean in the same or opposite directions when reconstruction and observed are compared for each year. Means are subtracted from each series and the residuals are multiplied. A positive product is a "hit." If either observed or reconstructed data lie very near the mean, the year is omitted from the test.
[c]Nonparametric test of the ratio of the number of "hits" to "misses" in the cross-product means test above (Conover 1980).
[d]Pearson product moment correlation coefficient (Steel and Torrie 1980).
[e] Varies from 1.0 to negative infinity. Any positive result is considered evidence of useful information in the paleoclimatic reconstruction (Fritts 2001). The coefficient of efficiency is the more stringent test.

10. Table A8a. Texas climate division 8 (Upper Coast) reconstruction 1648–2008 of June PDSI, calibration 1931–2008.

Chronologies Used	PCA % Variance		Regression		Serial Corr.[b] of Residuals	Durbin-Watson Statistic[b]
	1st PC	2nd PC	#PCs Used	R^2 adj.[a]		
GRP,KSS,SBP,CENOAK	51.7	20.8	2	0.416	0.093	1.81NS

NS Not significant, i.e., there is greater than a 5% probability that the result occurred by chance.
[a]R^2 adjusted downward for loss of degrees of freedom (Draper and Smith 1981).
[b]Autocorrelation of the residuals from regression, tested with the Durbin-Watson statistic (Draper and Smith 1981). Failure to reject the null hypothesis indicates that the residuals occur randomly, an indication that the regression model is valid.

Table A8a. (Cont'd)

Chronology	Beta[#]	Std. Error	Corr.	Prob.
GRP: Guadalupe R.	0.0830	0.0214	0.22	<0.048
KSS: Krause Springs	-0.2072	0.0668	0.06	<0.590
SBP: San Bernard R.	0.3590	0.0302	0.43	<0.000
CENOAK: Central TX postoak	0.4021	0.0377	0.67	<0.000

[#]Regression coefficient in terms of original variable.

Table A8b. Validation 1895–1930 for reconstruction 1648–2008 of Texas climate division 8 (Upper Coast) June PDSI.

Test	Statistic	Difference	t-stat. or z-score	Prob.	Remark
Equality of means[a]	-------	-0.43	-0.904	0.630	No sig. dif. is desired result
Cross-product means[b]	-------	3.25	3.952	<0.0003	
Sign test (+/-)[c]	30/6	--------	3.833	<0.0001	
Correlation Coefficient[d]	0.78	--------	7.285	<0.0000	
Reduction of Error[e]	0.57	--------	No formal test of significance		
Coefficient of Efficiency[e]	0.57	--------	No formal test of significance		

[a]Paired comparison of observed and reconstructed data means (Steel and Torrie 1980). Note that no difference is the desired result.
[b]Tests the relative magnitude of departures from the mean in the same or opposite directions when reconstruction and observed are compared for each year. Means are subtracted from each series and the residuals are multiplied. A positive product is a "hit." If either observed or reconstructed data lie very near the mean, the year is omitted from the test.
[c]Nonparametric test of the ratio of the number of "hits" to "misses" in the cross-product means test above (Conover 1980).
[d]Pearson product moment correlation coefficient (Steel and Torrie 1980).
[e] Varies from 1.0 to negative infinity. Any positive result is considered evidence of useful information in the paleoclimatic reconstruction (Fritts 2001). The coefficient of efficiency is the more stringent test.

11. **Table A9a.** Texas climate division 8 (Upper Coast) reconstruction 1500–2008 of June PDSI, calibration 1931–2008. Used 1500–1647 in combination with 1648–2008 reconstruction (Table A8).

Chronologies Used	PCA % Variance		Regression		Serial Corr.[b] of Residuals	Durbin-Watson Statistic[b]
	1st PC	2nd PC	#PCs Used	R^2 adj.[a]		
GRP,KSS,SBP	55.9	24.3	2	0.180	0.090	1.82NS

NS Not significant, i.e., there is greater than a 5% probability that the result occurred by chance.
[a]R^2 adjusted downward for loss of degrees of freedom (Draper and Smith 1981).
[b]Autocorrelation of the residuals from regression, tested with the Durbin-Watson statistic (Draper and Smith 1981). Failure to reject the null hypothesis indicates that the residuals occur randomly, an indication that the regression model is valid.

Table A9a. (Cont'd)

Chronology	Beta[#]	Std. Error	Corr.	Prob.
GRP: Guadalupe R. SP	0.0786	0.0338	0.22	<0.046
KSS: Krause Springs	-0.0674	0.0645	0.06	<0.583
SBP: San Bernard R.	0.4338	0.1023	0.43	<0.000

[#]Regression coefficient in terms of original variable.

Table A9b. Validation 1895–1930 for reconstruction 1500–2008 of Texas climate division 8 (Upper Coast) June PDSI.

Test	Statistic	Difference	t-stat. or z-score	Prob.	Remark
Equality of means[a]	-------	-0.075	-0.185	0.848	No sig. dif. is desired result
Cross-product means[b]	-------	1.36	2.841	<0.0037	
Sign test (+/-)[c]	27/9	--------	2.833	0.0023	
Correlation Coefficient[d]	0.60	--------	4.425	<0.0001	
Reduction of Error[e]	0.34	--------	No formal test of significance		
Coefficient of Efficiency[e]	0.34	--------	No formal test of significance		

[a]Paired comparison of observed and reconstructed data means (Steel and Torrie 1980). Note that no difference is the desired result.
[b]Tests the relative magnitude of departures from the mean in the same or opposite directions when reconstruction and observed are compared for each year. Means are subtracted from each series and the residuals are multiplied. A positive product is a "hit." If either observed or reconstructed data lie very near the mean, the year is omitted from the test.
[c]Nonparametric test of the ratio of the number of "hits" to "misses" in the cross-product means test above (Conover 1980).
[d]Pearson product moment correlation coefficient (Steel and Torrie 1980).
[e] Varies from 1.0 to negative infinity. Any positive result is considered evidence of useful information in the paleoclimatic reconstruction (Fritts 2001). The coefficient of efficiency is the more stringent test.

12. **Table A10.** Statistics of the Trans Pecos (division 5) June PDSI reconstruction 1500–2008 and nested June PDSI reconstructions of Edwards Plateau (division 6), South Central (division 7), and Upper Coast (division 8) 1500–2008.

Statistic	Reconstructed Data (Divisions)				Observed Data (Divisions)1895–2008			
	5	6	7	8	5	6	7	8
N	509	509	509	509	114	114	114	114
Mean	-0.11	0.02	0.07	0.24	-0.22	-0.00	-0.11	0.04
Median	-0.07	0.06	-0.01	-0.06	-0.76	-0.23	-0.34	-0.21
Std.Dev.	2.98	2.82	2.94	2.30	2.71	2.78	2.74	2.21
Variance	8.90	7.96	8.62	5.29	7.33	7.72	7.52	4.87
Range	16.18	16.15	17.54	13.62	13.61	10.91	12.28	10.06
Maximum	8.66	8.44	10.87	8.81	9.44	5.33	6.39	5.31
Minimum	-7.52	-7.71	-6.67	-4.81	-4.17	-5.58	-5.89	-4.75
Serial[a] Corr.	0.34	0.20	0.32	0.12	0.14	-0.01	0.16	0.08
Normal[b] Distrib.?	P>0.15 Yes	P>0.15 Yes	P>0.15 Yes	P<0.01 No	P<0.01 No	P=0.11 Yes	P=0.04 No	P=0.12 Yes
Skewness	0.11	0.05	0.26	0.47	1.13	0.23	0.07	0.11
Kurtosis	-0.23	-0.14	0.16	0.22	1.52	-0.94	-0.70	-0.65

[a]The Pearson product moment correlation coefficient (Steel and Torrie 1980) between $Year_t$ and $Year_{t-1}$.
[b]Kolmogorov-Smirnov nonparametric test of distribution normality (Conover 1980; Steel and Torrie 1980).

13. Table A11. Reconstructed, observed June PDSI data for TX divs 5,6,7,8(Trans Pecos, Edwards Plateau, S. Central, Upper Coast, respectively); The observed data 1895–2009 was downloaded from the NOAA National Climatic Data Center website: http://www1.ncdc.noaa.gov/pub/data/cirs.

Chronologies used (#s 1-3 baldcypress [*Taxodium distichum*], #4 post oak [*Quercus stellata*] an average of 3 living tree and 4 historic timber chronologies, #s 5-6 Douglas-fir [*Pseudotsuga menziesii*]):

1. Guadalupe R. St. Park (GRP) 1486–2009, 29°52.294'N, 98°29.958'W; 37 radii
2. Krause Springs Park (KSS) 1423–2009, 30°28.789'N, 98°08.69'W; 55 radii
3. San Bernard R., Bates-Allen Park (SBP)1447–2009, 29°25.901'N, 96°00.552'W; 27 radii
4. Central TX post oak chronology (CENOAK) 1648–1995,composed of 3 live tree and 4 historical chronologies; extended to 2008 by regression with the average of climate divisions 6,7 and 8; Constituent chronologies: YEG (Yegua Ck 30.317°N 96.633°W, 1658–995); HAL (Lavaca R [or Hallettsville] 29.308°N 96.967°W, 1668–1995); COL (Coleto Ck 28.767°N 97.183°W, 1682–1995); GPV (Gonzales Pioneer Village 29.500°N 97.450°W, 649–1995); EGG (Eggleston House 29.517°N 97.417°W, 1669–1845); YOK (McBryde [or Yoakum] Log House 29.250°N 97.083°W, 1668–1847); WAD (West-Adkisson House 30.50°N 97.767°W, 1648–1853)
5. Big Bend Nat. Park (BSC) 1473–1992, 29.245°N 103.294°W; 95 radii; extended to 2008 by regression with climate division 5
6. Guadalupe Peak Nat. Park (GPM) 1362–2008, 31.892°N, 104.851°W; 105 radii

Reconstructions:

RTX5: from GRP,KSS,BSC,GPM
RTX6: 1648–2008 from GRP, KSS, SBP, CENOAK, BSC, GPM
1500–1647 from GRP, KSS, SBP, BSC, GPM
RTX7: 1648–2008 from GRP, KSS, SBP, CENOAK
1500–1647 from GRP, KSS, SBP, BSC, GPM (better than reconstruction from GRP,KSS,SBP only)
RTX8: 1648–2008 from GRP, KSS, SBP, CENOAK
1500–1647 from GRP, KSS, SBP (adding BIG, a long LA baldcypress chronology, did not help)

YEAR	RTX5	RTX6	RTX7	RTX8	OTX5	OTX6	OTX7	OTX8
1500	1.07	-0.05	0.01	-2.25	.	.	.	.
1501	-2.40	-0.81	-0.76	0.22	.	.	.	.
1502	-1.69	-1.77	-1.84	0.77	.	.	.	.
1503	-1.99	-0.71	-0.95	1.07	.	.	.	.
1504	-1.15	-2.44	-2.53	1.72	.	.	.	.
1505	0.36	-0.19	-0.54	1.98	.	.	.	.
1506	1.13	2.19	2.15	4.96	.	.	.	.
1507	2.90	3.19	3.57	1.95	.	.	.	.
1508	3.02	1.53	2.14	0.56	.	.	.	.
1509	4.07	4.51	4.88	1.40	.	.	.	.
1510	2.19	2.68	3.49	0.41	.	.	.	.
1511	6.09	7.29	7.87	1.29	.	.	.	.
1512	0.74	0.64	1.93	0.52	.	.	.	.
1513	4.10	4.48	4.82	3.01	.	.	.	.
1514	-0.27	-1.58	-0.77	-3.13	.	.	.	.
1515	-1.92	-2.24	-2.31	0.12	.	.	.	.
1516	-3.36	-2.13	-2.44	-0.67	.	.	.	.
1517	-4.80	-0.86	-1.19	4.59	.	.	.	.
1518	0.04	1.17	1.02	-1.48	.	.	.	.
1519	3.23	1.31	1.51	-1.57	.	.	.	.
1520	2.15	0.44	0.73	-1.47	.	.	.	.
1521	0.55	-0.00	0.16	-4.76	.	.	.	.
1522	-0.78	-0.91	-0.83	-1.05	.	.	.	.
1523	-1.37	-2.42	-2.49	-0.65	.	.	.	.
1524	-5.82	-4.38	-4.71	-2.30	.	.	.	.
1525	-4.11	-3.53	-4.22	-2.41	.	.	.	.
1526	3.81	3.93	3.29	-1.70	.	.	.	.
1527	-0.83	1.11	1.68	5.31	.	.	.	.
1528	-7.08	-6.84	-6.50	-1.10	.	.	.	.
1529	-2.15	-1.06	-2.03	-0.50	.	.	.	.
1530	1.61	3.88	3.59	5.30	.	.	.	.
1531	-1.55	-1.52	-0.90	-1.50	.	.	.	.
1532	-4.24	-3.79	-3.87	1.74	.	.	.	.
1533	-1.41	0.59	0.02	2.39	.	.	.	.
1534	-0.08	2.99	3.03	2.95	.	.	.	.
1535	-0.65	0.23	0.76	-0.12	.	.	.	.
1536	5.54	3.81	3.96	1.67	.	.	.	.
1537	3.60	2.57	3.24	-0.35	.	.	.	.
1538	-6.54	-6.40	-5.82	2.05	.	.	.	.
1539	-0.27	-1.04	-1.92	-2.50	.	.	.	.
1540	4.31	4.72	4.45	1.55	.	.	.	.
1541	1.28	2.07	2.81	-0.10	.	.	.	.
1542	-6.50	-6.24	-5.73	2.62	.	.	.	.
1543	2.07	4.87	3.99	2.31	.	.	.	.
1544	-0.69	-1.08	-0.40	-2.53	.	.	.	.
1545	-1.04	-0.03	-0.04	2.43	.	.	.	.
1546	-0.16	2.50	2.53	2.52	.	.	.	.
1547	-4.16	-0.38	0.07	-0.39	.	.	.	.
1548	-0.71	0.87	0.93	1.04	.	.	.	.
1549	0.56	0.30	0.49	-1.72	.	.	.	.
1550	2.34	0.49	0.61	2.89	.	.	.	.
1551	-1.10	-4.14	-3.98	-0.82	.	.	.	.
1552	-1.14	-2.96	-3.54	-0.51	.	.	.	.
1553	2.49	1.90	1.38	-2.09	.	.	.	.
1554	6.11	3.77	4.02	0.04	.	.	.	.
1555	6.65	4.93	5.59	1.88	.	.	.	.
1556	7.35	5.34	6.25	-1.19	.	.	.	.
1557	2.66	1.28	2.31	2.30	.	.	.	.
1558	-0.69	1.84	2.24	2.57	.	.	.	.
1559	-2.82	-3.25	-2.84	-0.84	.	.	.	.
1560	-0.58	-1.80	-2.20	-1.64	.	.	.	.
1561	-1.72	-3.34	-3.63	-3.95	.	.	.	.
1562	-3.17	-4.52	-5.03	-2.78	.	.	.	.
1563	1.03	0.45	-0.30	0.64	.	.	.	.
1564	1.72	0.31	0.30	0.04	.	.	.	.
1565	3.96	1.70	1.79	1.38	.	.	.	.
1566	2.44	-0.25	0.08	0.34	.	.	.	.
1567	-2.95	-2.91	-2.84	-2.16	.	.	.	.
1568	-1.04	0.95	0.55	1.77	.	.	.	.
1569	-0.94	3.89	4.01	6.80	.	.	.	.
1570	0.31	6.04	6.70	3.30	.	.	.	.
1571	-1.77	-1.79	-0.68	0.08	.	.	.	.
1572	-1.46	-4.28	-4.33	-2.41	.	.	.	.
1573	-4.58	-2.19	-2.82	0.92	.	.	.	.

Table A11 (Cont'd)

YEAR	RTX5	RTX6	RTX7	RTX8	OTX5	OTX6	OTX7	OTX8
1574	-3.91	-4.05	-4.44	-2.03	.	.	.	.
1575	-2.34	-1.35	-2.00	3.28	.	.	.	.
1576	-1.62	0.06	-0.21	2.22	.	.	.	.
1577	-2.71	-2.18	-2.16	-1.11	.	.	.	.
1578	0.91	2.84	2.54	5.28	.	.	.	.
1579	-3.16	-3.70	-3.24	-2.92	.	.	.	.
1580	-0.77	-0.87	-1.33	-0.75	.	.	.	.
1581	0.93	0.65	0.48	-1.15	.	.	.	.
1582	-0.44	-0.63	-0.51	-1.05	.	.	.	.
1583	-2.34	-0.80	-0.83	0.07	.	.	.	.
1584	-2.75	1.07	0.98	3.64	.	.	.	.
1585	-6.36	-0.80	-0.60	-1.86	.	.	.	.
1586	1.59	2.50	2.44	2.07	.	.	.	.
1587	1.22	-2.00	-1.56	-3.86	.	.	.	.
1588	1.73	2.01	1.80	1.73	.	.	.	.
1589	-2.64	-2.87	-2.53	-0.81	.	.	.	.
1590	-0.34	-0.39	-0.74	-3.79	.	.	.	.
1591	-2.56	-2.11	-2.18	-1.15	.	.	.	.
1592	-1.47	1.35	1.05	4.14	.	.	.	.
1593	-1.09	2.39	2.59	6.13	.	.	.	.
1594	2.63	2.49	2.94	-0.89	.	.	.	.
1595	0.74	-2.15	-1.63	-0.39	.	.	.	.
1596	0.12	-1.47	-1.68	2.45	.	.	.	.
1597	-0.40	-2.52	-2.74	-2.36	.	.	.	.
1598	0.13	-0.03	-0.41	-0.40	.	.	.	.
1599	-1.22	0.89	0.87	0.46	.	.	.	.
1600	-1.14	-0.50	-0.32	-0.58	.	.	.	.
1601	-4.90	-5.48	-5.46	-1.44	.	.	.	.
1602	-0.05	1.11	0.29	1.17	.	.	.	.
1603	1.96	0.91	1.00	-0.97	.	.	.	.
1604	-0.43	-1.91	-1.70	-1.54	.	.	.	.
1605	-2.90	-2.35	-2.57	-0.68	.	.	.	.
1606	-2.00	-3.37	-3.71	-2.97	.	.	.	.
1607	0.13	2.49	1.94	2.19	.	.	.	.
1608	0.28	-0.64	-0.28	-3.69	.	.	.	.
1609	2.43	1.84	1.84	2.02	.	.	.	.
1610	3.81	1.71	2.04	-0.63	.	.	.	.
1611	2.89	2.98	3.34	-1.20	.	.	.	.
1612	3.99	-0.02	0.55	-1.32	.	.	.	.
1613	1.17	-0.85	-0.71	-2.00	.	.	.	.
1614	-3.58	-3.57	-3.63	-0.10	.	.	.	.
1615	-3.13	-1.15	-1.67	-0.37	.	.	.	.
1616	1.49	0.39	0.17	-0.62	.	.	.	.
1617	0.21	1.64	1.71	2.24	.	.	.	.
1618	0.53	0.17	0.48	1.68	.	.	.	.
1619	0.91	-2.16	-2.03	-1.63	.	.	.	.
1620	2.84	3.47	3.18	6.96	.	.	.	.
1621	2.60	0.38	0.93	-0.99	.	.	.	.
1622	1.63	0.43	0.63	-1.33	.	.	.	.
1623	-1.39	-3.11	-2.95	-1.40	.	.	.	.
1624	-3.46	-2.48	-2.90	0.01	.	.	.	.
1625	-0.33	0.90	0.49	0.60	.	.	.	.
1626	-2.40	-2.78	-2.65	-2.35	.	.	.	.
1627	2.81	2.62	2.24	-0.56	.	.	.	.
1628	0.44	-0.01	0.39	-0.40	.	.	.	.
1629	5.27	4.05	4.14	3.33	.	.	.	.
1630	2.84	0.93	1.63	3.47	.	.	.	.
1631	-0.65	0.19	0.50	2.84	.	.	.	.
1632	-5.51	-5.18	-5.04	-2.15	.	.	.	.
1633	-5.49	-4.12	-4.85	-0.37	.	.	.	.
1634	1.28	1.06	0.34	3.40	.	.	.	.
1635	2.20	2.47	2.56	0.71	.	.	.	.
1636	0.03	1.78	2.23	1.79	.	.	.	.
1637	2.00	4.81	5.20	2.38	.	.	.	.
1638	0.84	0.80	1.67	-1.32	.	.	.	.
1639	4.18	6.20	6.49	3.76	.	.	.	.
1640	4.23	3.61	4.67	-1.64	.	.	.	.
1641	2.91	-0.81	-0.02	-0.93	.	.	.	.
1642	0.99	-1.25	-1.20	-2.17	.	.	.	.
1643	2.00	-0.98	-1.12	-1.94	.	.	.	.
1644	-3.87	-6.35	-6.46	-2.52	.	.	.	.
1645	-3.32	-4.14	-5.10	-1.74	.	.	.	.
1646	3.51	3.38	2.61	1.20	.	.	.	.
1647	3.89	4.73	5.17	0.46	.	.	.	.
1648	-2.83	-3.21	-3.08	-2.07	.	.	.	.
1649	0.40	4.72	5.78	4.93	.	.	.	.
1650	0.70	6.51	10.87	8.81	.	.	.	.
1651	3.11	2.43	1.97	0.15	.	.	.	.
1652	2.19	2.86	1.65	0.10	.	.	.	.
1653	-2.35	0.84	2.64	1.54	.	.	.	.
1654	-2.60	-2.12	-0.85	-0.67	.	.	.	.
1655	0.96	2.44	3.24	3.02	.	.	.	.
1656	-0.41	0.94	1.26	-0.07	.	.	.	.
1657	-2.23	-0.64	-0.01	-0.44	.	.	.	.
1658	0.35	2.17	2.75	2.45	.	.	.	.
1659	0.15	-1.76	-2.75	-2.13	.	.	.	.
1660	1.72	0.78	1.33	3.04	.	.	.	.
1661	3.64	0.84	-1.91	-2.13	.	.	.	.
1662	0.05	0.44	0.44	0.72	.	.	.	.
1663	-0.20	-0.87	-1.02	-0.17	.	.	.	.
1664	-2.07	-4.39	-3.44	-0.71	.	.	.	.
1665	0.65	0.82	0.76	1.46	.	.	.	.
1666	-3.01	-2.89	-3.39	-3.10	.	.	.	.
1667	-5.33	-0.87	0.55	-0.24	.	.	.	.
1668	-7.44	-0.72	3.94	3.03	.	.	.	.
1669	-3.01	-2.46	-2.01	-1.99	.	.	.	.
1670	-4.60	-2.39	-1.55	-1.45	.	.	.	.
1671	0.93	1.89	1.23	1.01	.	.	.	.
1672	-0.99	1.31	2.29	1.45	.	.	.	.
1673	-5.04	-2.93	-0.47	-0.32	.	.	.	.
1674	-0.67	1.05	0.64	-0.15	.	.	.	.
1675	-0.94	-1.86	-1.07	0.13	.	.	.	.
1676	-3.13	-3.44	-1.44	0.12	.	.	.	.
1677	2.56	4.49	5.13	4.31	.	.	.	.
1678	0.61	0.33	-0.24	-1.15	.	.	.	.
1679	1.68	1.05	-0.24	-0.59	.	.	.	.
1680	4.41	4.06	2.63	1.95	.	.	.	.
1681	1.75	-0.47	-1.00	-0.11	.	.	.	.
1682	2.60	-0.75	-2.45	-0.89	.	.	.	.
1683	3.89	2.85	1.26	1.77	.	.	.	.
1684	-0.28	-0.85	-1.07	-0.91	.	.	.	.
1685	-4.64	-3.58	-1.84	-1.11	.	.	.	.
1686	2.18	1.80	3.09	4.59	.	.	.	.
1687	0.04	-0.78	-0.07	0.33	.	.	.	.
1688	-3.34	-1.08	1.17	1.32	.	.	.	.
1689	3.05	2.08	0.66	0.36	.	.	.	.
1690	3.88	0.11	-1.98	-0.88	.	.	.	.
1691	-1.11	-3.02	-4.91	-3.93	.	.	.	.
1692	3.39	1.18	-2.42	-1.43	.	.	.	.
1693	2.86	3.93	3.01	2.38	.	.	.	.
1694	-0.07	1.36	3.89	3.88	.	.	.	.
1695	1.51	6.13	8.41	5.53	.	.	.	.
1696	-4.57	-1.94	1.87	0.84	.	.	.	.
1697	-0.27	-0.38	1.97	2.87	.	.	.	.
1698	-0.76	-1.63	0.23	1.41	.	.	.	.
1699	1.71	-1.36	-2.04	-0.41	.	.	.	.
1700	2.15	1.16	-0.41	-0.25	.	.	.	.
1701	4.82	3.54	2.33	2.63	.	.	.	.
1702	-0.04	1.34	1.10	-0.50	.	.	.	.
1703	0.24	-1.27	-2.48	-2.27	.	.	.	.
1704	-3.30	-4.03	-4.32	-3.26	.	.	.	.
1705	-4.33	-4.23	-4.01	-2.56	.	.	.	.
1706	-1.04	0.80	1.16	1.63	.	.	.	.
1707	-1.78	-1.01	-0.52	-0.40	.	.	.	.

Table A11 (Cont'd)

YEAR	RTX5	RTX6	RTX7	RTX8	OTX5	OTX6	OTX7	OTX8
1708	-1.85	-1.52	-0.77	-0.09	.	.	.	.
1709	-4.97	-4.43	-3.18	-2.08	.	.	.	.
1710	1.43	0.16	-1.38	-0.06	.	.	.	.
1711	-1.06	-1.53	-1.58	-0.47	.	.	.	.
1712	1.07	0.48	-1.06	-1.03	.	.	.	.
1713	0.04	-0.10	-0.11	0.44	.	.	.	.
1714	-2.70	-4.78	-5.52	-4.12	.	.	.	.
1715	-4.78	-5.56	-6.37	-4.06	.	.	.	.
1716	-5.42	-7.71	-6.06	-1.29	.	.	.	.
1717	-0.17	-0.61	-3.48	-3.25	.	.	.	.
1718	3.60	6.38	3.49	1.56	.	.	.	.
1719	-1.96	4.39	8.38	6.42	.	.	.	.
1720	0.73	3.00	5.46	3.86	.	.	.	.
1721	4.93	5.77	5.52	3.45	.	.	.	.
1722	5.65	2.72	0.37	-0.49	.	.	.	.
1723	3.67	5.39	5.60	3.94	.	.	.	.
1724	1.80	1.09	-0.05	-1.31	.	.	.	.
1725	-1.18	-0.99	-0.61	-0.47	.	.	.	.
1726	7.88	5.68	3.19	3.21	.	.	.	.
1727	3.99	2.76	2.35	1.71	.	.	.	.
1728	-2.41	-3.16	-2.07	-1.51	.	.	.	.
1729	-1.63	-1.07	-1.39	-1.22	.	.	.	.
1730	-5.24	-5.56	-5.10	-3.44	.	.	.	.
1731	-3.84	-3.78	-3.78	-2.21	.	.	.	.
1732	-2.75	1.05	2.94	2.82	.	.	.	.
1733	-5.22	-0.20	4.35	3.43	.	.	.	.
1734	1.63	1.76	1.22	0.20	.	.	.	.
1735	1.74	3.21	3.25	2.63	.	.	.	.
1736	1.78	-0.82	-2.98	-2.89	.	.	.	.
1737	3.80	1.86	-0.30	0.27	.	.	.	.
1738	1.30	-0.45	-2.58	-2.75	.	.	.	.
1739	-4.49	-0.56	1.64	1.14	.	.	.	.
1740	-1.19	2.18	5.93	6.17	.	.	.	.
1741	0.25	-2.76	-2.44	-1.04	.	.	.	.
1742	-4.11	-5.44	-4.35	-1.90	.	.	.	.
1743	-1.11	-2.91	-4.29	-2.50	.	.	.	.
1744	0.55	0.06	-0.90	0.30	.	.	.	.
1745	3.00	1.81	-0.36	-0.41	.	.	.	.
1746	7.25	6.18	2.73	1.47	.	.	.	.
1747	7.14	6.46	2.43	-0.17	.	.	.	.
1748	-3.59	0.76	3.67	1.97	.	.	.	.
1749	-2.28	-0.47	0.84	0.11	.	.	.	.
1750	-1.88	-3.15	-4.28	-3.55	.	.	.	.
1751	0.24	-1.54	-4.11	-3.06	.	.	.	.
1752	-4.91	-4.58	-3.78	-2.25	.	.	.	.
1753	-2.71	-0.46	0.26	0.48	.	.	.	.
1754	-1.11	-0.48	-1.80	-2.47	.	.	.	.
1755	-1.81	-3.07	-3.55	-2.22	.	.	.	.
1756	-1.31	0.49	1.45	1.88	.	.	.	.
1757	-6.07	-1.98	2.40	2.48	.	.	.	.
1758	0.47	2.62	4.89	4.43	.	.	.	.
1759	2.90	2.18	2.39	1.94	.	.	.	.
1760	-0.27	-1.18	-0.93	-0.68	.	.	.	.
1761	2.33	2.02	0.91	0.86	.	.	.	.
1762	3.83	2.84	2.98	3.53	.	.	.	.
1763	-2.45	-2.75	-0.08	1.14	.	.	.	.
1764	0.36	-0.98	-0.75	0.22	.	.	.	.
1765	-0.05	-0.07	-1.21	-1.33	.	.	.	.
1766	5.01	3.17	1.24	1.85	.	.	.	.
1767	1.83	0.98	0.95	1.31	.	.	.	.
1768	2.47	1.46	0.55	0.28	.	.	.	.
1769	3.29	1.73	-0.46	-0.70	.	.	.	.
1770	3.86	3.33	1.71	0.89	.	.	.	.
1771	2.38	1.73	0.72	0.04	.	.	.	.
1772	-0.45	-1.08	-1.01	-0.97	.	.	.	.
1773	-3.54	-1.20	0.28	-0.05	.	.	.	.
1774	-2.29	-0.35	0.94	0.69	.	.	.	.

YEAR	RTX5	RTX6	RTX7	RTX8	OTX5	OTX6	OTX7	OTX8
1775	1.57	-0.40	-1.76	-1.42	.	.	.	.
1776	-0.38	-2.47	-4.15	-3.05	.	.	.	.
1777	-2.30	-3.97	-4.38	-2.00	.	.	.	.
1778	-2.96	-3.11	-3.37	-1.97	.	.	.	.
1779	-1.37	2.10	2.87	2.20	.	.	.	.
1780	-2.66	-2.15	-0.66	-0.17	.	.	.	.
1781	-2.31	-2.29	-1.51	-0.75	.	.	.	.
1782	-3.18	0.75	2.75	2.33	.	.	.	.
1783	2.33	1.11	0.53	0.87	.	.	.	.
1784	5.37	2.78	1.97	2.89	.	.	.	.
1785	-2.43	-5.11	-4.42	-2.81	.	.	.	.
1786	-4.65	-6.34	-6.03	-3.14	.	.	.	.
1787	-0.91	0.79	-0.45	-0.45	.	.	.	.
1788	1.69	3.66	3.39	2.55	.	.	.	.
1789	-5.04	-5.82	-4.46	-3.46	.	.	.	.
1790	-5.20	-5.57	-6.19	-4.81	.	.	.	.
1791	0.85	1.92	-2.68	-4.05	.	.	.	.
1792	2.28	5.28	3.87	2.23	.	.	.	.
1793	5.97	7.05	5.90	3.60	.	.	.	.
1794	3.23	1.95	2.29	1.98	.	.	.	.
1795	4.55	3.56	2.24	1.30	.	.	.	.
1796	-0.92	1.08	2.25	1.36	.	.	.	.
1797	-1.35	0.48	2.24	1.84	.	.	.	.
1798	-1.14	-1.14	-1.38	-1.68	.	.	.	.
1799	1.76	4.49	4.18	2.85	.	.	.	.
1800	0.51	0.31	0.92	0.92	.	.	.	.
1801	-2.12	-2.93	-1.09	0.51	.	.	.	.
1802	-0.05	-0.08	1.28	2.53	.	.	.	.
1803	-1.49	0.77	4.23	4.58	.	.	.	.
1804	-1.21	0.58	2.21	1.25	.	.	.	.
1805	-4.96	-5.28	-4.60	-3.85	.	.	.	.
1806	-2.98	-4.87	-6.67	-4.53	.	.	.	.
1807	-1.86	-0.74	-0.67	0.84	.	.	.	.
1808	-5.24	-2.86	-1.89	-1.98	.	.	.	.
1809	-0.58	0.87	2.10	2.93	.	.	.	.
1810	0.16	2.60	2.65	1.16	.	.	.	.
1811	0.59	0.99	3.52	4.09	.	.	.	.
1812	-2.31	-1.60	1.59	2.19	.	.	.	.
1813	-4.48	-3.23	-0.20	0.81	.	.	.	.
1814	0.13	2.58	4.22	3.96	.	.	.	.
1815	3.23	2.00	0.43	-0.22	.	.	.	.
1816	8.58	4.79	1.78	2.35	.	.	.	.
1817	1.81	0.98	1.65	2.16	.	.	.	.
1818	-4.84	-1.23	1.40	0.62	.	.	.	.
1819	-5.76	-4.20	-2.34	-1.83	.	.	.	.
1820	-4.44	-4.04	-3.73	-2.50	.	.	.	.
1821	3.46	3.64	0.11	-0.79	.	.	.	.
1822	-0.24	-0.77	-0.79	-0.38	.	.	.	.
1823	-2.14	0.14	1.68	1.09	.	.	.	.
1824	0.80	-1.17	-2.39	-1.86	.	.	.	.
1825	2.60	2.40	0.48	0.06	.	.	.	.
1826	4.31	0.94	-1.17	-0.27	.	.	.	.
1827	8.66	3.83	-0.41	-0.14	.	.	.	.
1828	3.83	1.63	0.54	1.05	.	.	.	.
1829	4.87	4.01	1.28	-0.13	.	.	.	.
1830	1.39	0.48	0.72	1.00	.	.	.	.
1831	-1.79	-0.44	0.52	-0.16	.	.	.	.
1832	-1.98	1.19	1.62	-0.13	.	.	.	.
1833	3.83	4.60	4.31	3.43	.	.	.	.
1834	3.32	2.46	1.55	0.71	.	.	.	.
1835	2.94	-0.14	-2.75	-2.64	.	.	.	.
1836	0.17	0.04	-0.21	0.39	.	.	.	.
1837	2.96	0.80	0.01	0.88	.	.	.	.
1838	0.40	-0.24	-0.70	-0.53	.	.	.	.
1839	1.18	-0.22	-1.00	-0.30	.	.	.	.
1840	-0.83	-1.43	-2.45	-2.21	.	.	.	.
1841	-3.90	-4.67	-4.47	-2.83	.	.	.	.

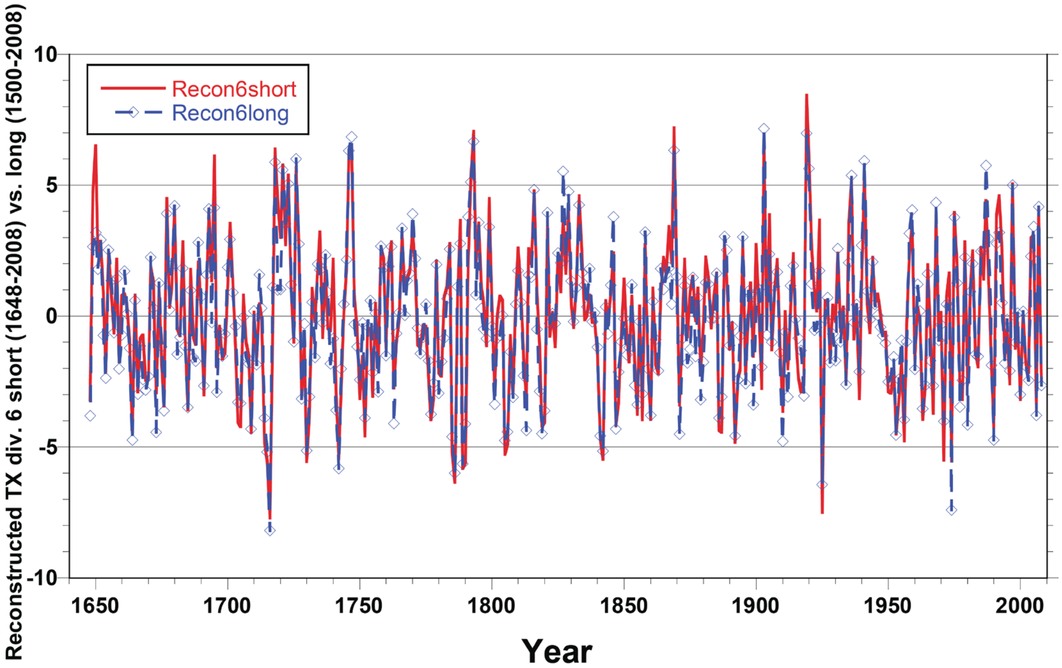
Table A11 (Cont'd)

YEAR	RTX5	RTX6	RTX7	RTX8	OTX5	OTX6	OTX7	OTX8
1842	-4.77	-5.48	-4.83	-2.44	.	.	.	.
1843	-0.03	0.59	-0.42	0.26	.	.	.	.
1844	1.58	-0.19	-0.29	1.39	.	.	.	.
1845	3.19	0.83	-0.68	0.01	.	.	.	.
1846	5.01	2.42	-1.31	-1.66	.	.	.	.
1847	-4.67	-4.19	-3.07	-2.07	.	.	.	.
1848	-1.29	-3.30	-4.65	-2.96	.	.	.	.
1849	-0.40	-0.73	-2.08	-0.90	.	.	.	.
1850	1.86	1.43	1.09	2.24	.	.	.	.
1851	-2.08	-0.73	-0.03	-0.37	.	.	.	.
1852	-0.56	-1.76	-2.23	-1.41	.	.	.	.
1853	2.57	0.78	-0.98	-0.11	.	.	.	.
1854	-3.44	-1.66	0.11	0.61	.	.	.	.
1855	-0.74	-3.76	-3.51	-0.99	.	.	.	.
1856	3.03	0.39	-1.26	0.75	.	.	.	.
1857	0.28	-3.97	-6.58	-4.71	.	.	.	.
1858	5.39	2.73	-1.05	-0.00	.	.	.	.
1859	-2.50	-1.77	-1.63	-1.45	.	.	.	.
1860	-4.91	-3.94	-2.73	-1.88	.	.	.	.
1861	-3.23	1.08	3.13	2.57	.	.	.	.
1862	-4.07	-1.83	-0.97	-2.13	.	.	.	.
1863	-5.41	-2.20	-1.61	-2.40	.	.	.	.
1864	-3.36	0.79	-0.07	-2.28	.	.	.	.
1865	-0.64	2.24	3.39	3.15	.	.	.	.
1866	-0.06	1.60	2.61	1.56	.	.	.	.
1867	-1.21	3.42	6.80	5.41	.	.	.	.
1868	1.63	2.05	2.98	2.13	.	.	.	.
1869	4.97	7.19	7.65	5.46	.	.	.	.
1870	0.62	1.75	3.60	2.14	.	.	.	.
1871	-2.35	-3.40	-2.39	-1.40	.	.	.	.
1872	-3.13	-0.52	0.77	0.48	.	.	.	.
1873	-0.15	2.18	3.27	2.76	.	.	.	.
1874	-2.19	-0.79	1.36	1.37	.	.	.	.
1875	-2.39	0.91	4.66	4.59	.	.	.	.
1876	1.44	1.53	1.69	0.70	.	.	.	.
1877	0.29	-0.17	-0.30	0.17	.	.	.	.
1878	0.26	1.08	1.10	0.83	.	.	.	.
1879	-2.90	-2.12	-0.57	0.16	.	.	.	.
1880	-3.38	-0.37	1.31	0.96	.	.	.	.
1881	2.36	2.27	1.36	1.21	.	.	.	.
1882	3.46	1.45	0.69	1.33	.	.	.	.
1883	1.85	-0.46	-1.29	-0.52	.	.	.	.
1884	0.22	0.75	2.17	2.72	.	.	.	.
1885	1.30	1.66	2.79	2.72	.	.	.	.
1886	-4.05	-4.34	-2.53	-1.81	.	.	.	.
1887	-3.33	-4.44	-4.40	-2.88	.	.	.	.
1888	3.57	2.64	0.92	1.70	.	.	.	.
1889	1.70	1.44	0.68	0.08	.	.	.	.
1890	-2.93	-1.26	1.08	1.07	.	.	.	.
1891	1.95	-0.25	-1.93	-1.24	.	.	.	.
1892	-4.10	-4.82	-4.09	-2.37	.	.	.	.
1893	-2.76	-2.36	-1.20	0.43	.	.	.	.
1894	-3.16	-2.05	-1.36	-1.41	.	.	.	.
1895	-0.88	2.80	3.89	2.40	4.81	2.78	2.91	2.10
1896	0.08	-2.21	-2.32	-1.01	-1.34	-2.16	-2.05	-1.93
1897	0.14	0.08	-0.35	-0.23	-0.13	0.86	-0.98	-1.67
1898	1.03	1.27	1.02	1.22	0.72	0.52	-0.67	0.70
1899	-1.69	-1.55	0.85	2.47	0.36	1.16	1.84	1.47
1900	-2.35	2.75	6.79	5.85	0.57	3.21	3.05	2.81
1901	2.39	0.18	-1.71	-2.45	-1.51	-2.02	-1.28	-0.98
1902	-1.26	-2.76	-3.15	-2.09	-2.88	-3.74	-3.80	-3.14
1903	4.81	6.58	3.82	1.66	2.83	3.26	3.27	2.02
1904	-3.92	-0.49	0.95	-0.76	-2.02	-0.78	0.56	0.44
1905	3.36	3.88	5.37	6.07	2.60	4.65	3.91	3.40
1906	2.62	-1.29	-3.41	-2.94	-1.01	2.88	2.42	-0.78
1907	2.06	0.99	-1.13	-0.62	-1.33	-0.22	-0.54	-0.70
1908	5.95	2.16	-1.26	0.04	-1.16	0.00	-0.40	1.34
1909	-1.66	-1.23	-1.16	-1.10	-2.68	-2.92	-3.21	-1.83
1910	-5.90	-3.65	-1.18	-0.48	-2.76	-2.21	-2.22	-0.66
1911	-0.19	0.18	-0.54	-0.18	-0.39	-2.80	-3.39	-1.95
1912	-0.25	-2.01	-2.48	-0.58	-0.06	-0.76	-0.28	1.33
1913	0.48	0.25	-2.31	-2.77	1.12	-1.03	-0.40	0.31
1914	2.60	2.38	1.61	2.21	2.83	4.60	4.57	3.22
1915	2.73	-0.68	-2.41	-1.52	2.94	3.91	-1.08	-1.11
1916	-1.89	-2.37	-3.45	-3.37	-2.13	-2.30	-3.35	-3.30
1917	-0.22	-2.89	-4.51	-2.68	-2.89	-4.11	-5.34	-3.88
1918	-2.69	-2.35	-1.87	-0.22	-3.44	-4.65	-5.42	-4.47
1919	2.95	8.44	8.97	6.34	3.74	4.83	4.11	3.41
1920	5.44	6.15	5.05	2.10	3.42	4.79	3.79	2.32
1921	0.87	2.55	4.09	2.76	1.63	-0.03	0.97	0.74
1922	-2.78	0.95	5.17	4.23	0.61	2.54	2.74	2.43
1923	0.27	0.20	1.27	1.13	-0.93	-1.00	-0.96	1.04
1924	2.06	3.67	4.68	4.07	-0.77	3.30	0.02	-0.15
1925	-6.64	-7.51	-5.58	-4.77	-2.99	-4.56	-4.39	-4.75
1926	2.77	0.61	0.16	2.90	1.82	2.55	3.11	2.83
1927	1.72	0.45	-1.07	-0.96	-2.14	-1.13	-1.00	-0.07
1928	-0.07	-1.65	-1.93	-0.52	-1.94	-1.88	-2.08	-1.13
1929	-0.35	0.43	0.88	1.55	-0.79	-0.09	-0.32	-0.41
1930	-0.05	-0.21	0.62	1.57	-1.34	-0.03	-0.06	-0.77
1931	3.90	2.41	0.06	-0.30	5.33	4.29	-0.34	-1.05
1932	0.67	-0.57	-1.16	-0.31	1.70	1.87	-0.75	-0.82
1933	1.61	0.36	-1.17	-0.82	-0.42	-1.04	-1.99	-2.67
1934	-4.59	-2.58	-1.75	-1.97	-3.36	-2.81	-1.44	-1.21
1935	-2.08	3.55	7.45	6.85	-3.36	4.83	2.85	1.02
1936	2.65	5.22	5.67	2.58	-1.86	3.64	2.98	-0.67
1937	0.37	-0.87	-1.23	-1.66	-0.41	-0.48	-1.09	-1.75
1938	0.50	0.32	1.98	2.90	1.59	1.10	-0.16	-0.67
1939	-1.36	-3.15	-3.30	-2.53	-0.76	-3.23	-3.45	-2.02
1940	2.16	1.20	-1.69	-1.96	2.92	2.75	1.56	-2.01
1941	7.15	5.50	2.59	2.30	9.44	5.33	5.46	3.46
1942	5.82	0.48	-1.84	-0.70	4.18	-1.57	-1.70	2.09
1943	0.94	-0.62	-1.25	-0.64	0.65	-1.61	-1.73	-1.43
1944	1.66	2.25	1.65	1.16	-0.30	2.64	-0.15	-0.62
1945	0.49	0.49	1.26	1.32	-2.13	-0.35	0.17	0.51
1946	-0.85	0.85	2.74	2.65	-0.42	0.70	2.08	3.44
1947	0.16	0.07	0.76	0.90	-0.21	-0.26	-0.34	-0.21
1948	-1.05	-0.67	-1.06	-1.31	-2.56	-1.51	-1.66	-1.36
1949	1.19	-0.61	-0.83	0.94	2.00	2.70	-0.81	-1.23
1950	-3.16	-2.87	-2.25	-1.66	0.10	-0.81	-0.17	-0.12
1951	-2.44	-2.95	-2.61	-1.25	-1.87	-3.05	-3.45	-3.28
1952	-1.40	-2.03	-3.13	-2.17	-2.62	-3.23	-3.36	-1.70
1953	-4.94	-4.51	-3.33	-1.62	-4.17	-2.36	-2.47	0.63
1954	-6.38	-3.24	-1.53	-1.59	-2.57	-3.48	-3.86	-2.46
1955	-3.82	-1.78	-1.23	-1.34	-3.15	-4.19	-4.89	-3.46
1956	-4.77	-4.76	-4.97	-4.00	-3.64	-5.58	-5.89	-4.04
1957	-4.19	-0.39	1.95	2.43	-3.46	4.01	2.49	2.28
1958	0.37	2.33	1.33	-0.75	2.37	4.37	2.41	-1.76
1959	0.35	3.49	4.00	2.03	-0.94	2.46	2.16	1.51
1960	-1.62	-1.66	0.12	0.69	-1.34	0.79	1.68	1.61
1961	-1.06	0.33	0.24	-0.80	1.43	1.24	0.88	2.80
1962	-0.63	-0.17	-1.22	-1.65	-2.34	-2.43	-2.07	-1.23
1963	-0.88	-3.95	-5.58	-3.64	-1.74	-3.60	-4.11	-3.39
1964	-2.14	-2.62	-2.14	-0.19	-2.36	-2.64	-2.84	-2.73
1965	-1.42	1.96	2.63	1.65	-1.58	2.06	-0.02	-2.70
1966	-1.92	-0.59	0.93	1.02	1.03	-0.52	1.91	2.31
1967	-1.11	-3.72	-3.45	-1.59	-1.64	-4.33	-4.42	-3.07
1968	4.62	3.83	1.53	1.36	-1.33	2.81	4.75	3.22
1969	-1.56	-0.56	0.78	0.80	-0.64	1.46	3.08	-0.39
1970	1.25	0.14	-0.91	-0.65	2.17	-0.06	2.23	1.47
1971	-3.06	-5.50	-5.73	-3.91	-2.90	-3.51	-4.24	-2.86
1972	-0.87	0.75	1.20	1.92	0.89	0.54	2.29	0.61
1973	3.08	1.65	1.12	2.10	0.84	0.52	3.69	3.54
1974*	-7.52	-5.54	-1.66	-0.39	-3.09	-2.98	1.83	2.35
1975	1.07	3.96	3.27	1.82	5.31	3.57	2.56	1.50

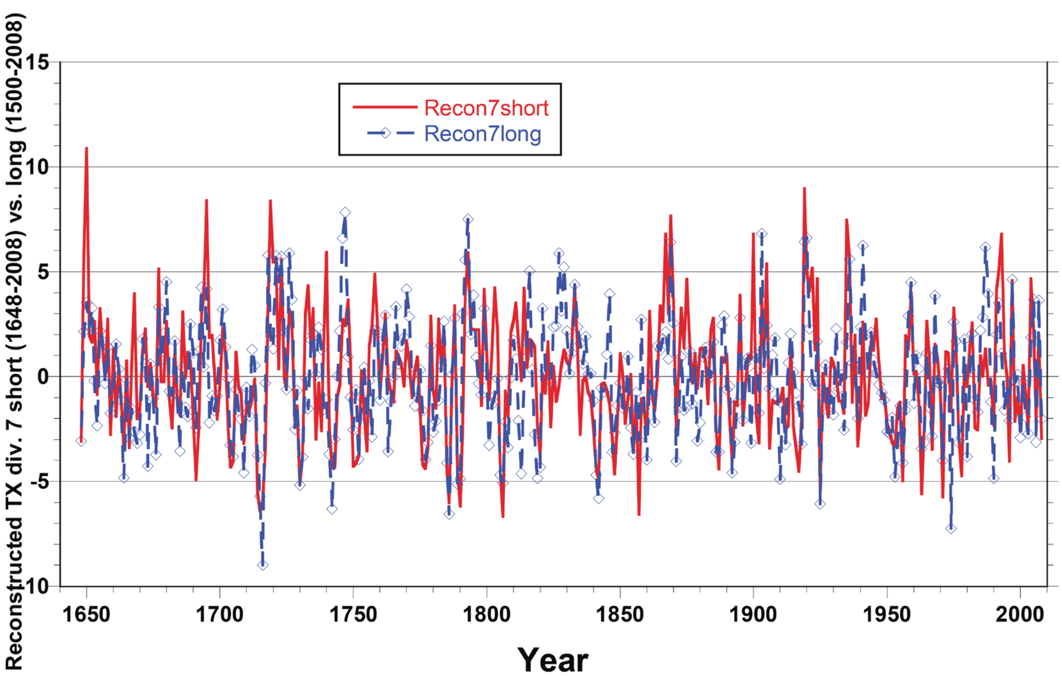
Table A11 (Cont'd)

YEAR	RTX5	RTX6	RTX7	RTX8	OTX5	OTX6	OTX7	OTX8
1976	0.42	2.02	1.25	-0.09	0.19	-0.53	1.50	0.58
1977	0.35	-2.47	-2.91	-1.02	-0.60	-0.24	-0.10	-0.32
1978	-0.98	-3.20	-4.74	-3.26	-1.69	-2.83	-1.83	-1.40
1979	4.40	2.85	0.31	1.34	3.53	1.66	3.06	2.24
1980	-2.28	-2.61	-0.48	1.24	-2.54	-2.08	-1.28	-0.66
1981	2.29	1.06	1.46	2.39	3.06	3.47	2.12	2.18
1982	2.55	2.50	2.57	2.41	-0.26	-0.16	-0.33	-0.21
1983	0.86	-1.35	-2.41	-1.95	-0.59	-0.18	1.03	1.52
1984	0.64	-1.95	-2.53	-0.46	1.70	-3.41	-2.29	-1.67
1985	4.09	2.62	0.99	1.44	0.45	0.30	1.88	-0.51
1986	1.99	1.41	0.02	-0.95	1.81	0.69	0.99	1.02
1987	6.53	4.42	1.31	0.64	8.35	5.28	4.04	2.43
1988	2.51	1.26	-0.41	-1.31	-1.53	-1.90	-1.60	-1.23
1989	-2.99	-1.84	-0.23	0.07	-2.12	-1.72	-2.52	2.17
1990	-5.55	-4.26	-2.34	-1.52	-3.44	-0.96	-3.06	-0.64
1991	2.23	3.85	4.14	4.15	1.07	0.24	1.85	3.46
1992	3.33	4.59	5.04	3.77	8.29	5.01	6.39	5.10
1993	-0.48	2.54	6.79	6.19	-1.51	-0.54	5.59	5.31
1994	-3.12	-1.57	1.23	0.49	-1.86	-1.83	-0.15	-0.09
1995	-2.11	-0.53	-0.05	-0.63	-2.04	0.87	2.05	2.48
1996	-1.41	-2.59	-4.02	-3.29	0.40	-3.82	-3.73	-1.80
1997	1.97	5.06	4.58	3.33	1.55	4.60	3.08	3.18
1998	-1.18	-1.22	-2.13	-3.06	-3.00	-2.35	-2.33	-2.12
1999	-1.49	-0.25	-0.98	-1.51	-1.95	-1.01	-0.36	-0.85
2000	-3.63	-3.18	-2.60	-1.63	-3.25	-3.89	-2.42	-3.11
2001	-1.13	0.03	0.52	0.80	-2.97	-1.35	-0.90	1.67
2002	-3.83	-1.81	-0.69	-0.91	-4.09	-2.22	-1.72	0.15
2003	-2.54	-2.15	-2.35	-1.70	-2.16	0.30	-1.70	0.00
2004	1.09	2.97	4.67	4.99	1.38	2.30	2.96	4.00
2005	3.43	3.08	2.10	0.60	3.60	2.50	-1.05	-1.25
2006	-2.21	-3.59	-2.17	-0.73	-3.77	-3.72	-4.95	0.51
2007	3.75	4.08	1.98	1.05	3.98	4.81	2.65	2.92
2008	-0.98	-2.63	-2.96	-2.00	-3.06	-2.97	-3.34	-1.59
2009	.	.	.	.	-0.88	-3.41	-5.85	-2.87
2010	.	.	.	.	1.35	1.98	2.55	-0.93
2011	.	.	.	.	-5.20	-5.10	-4.04	-3.95

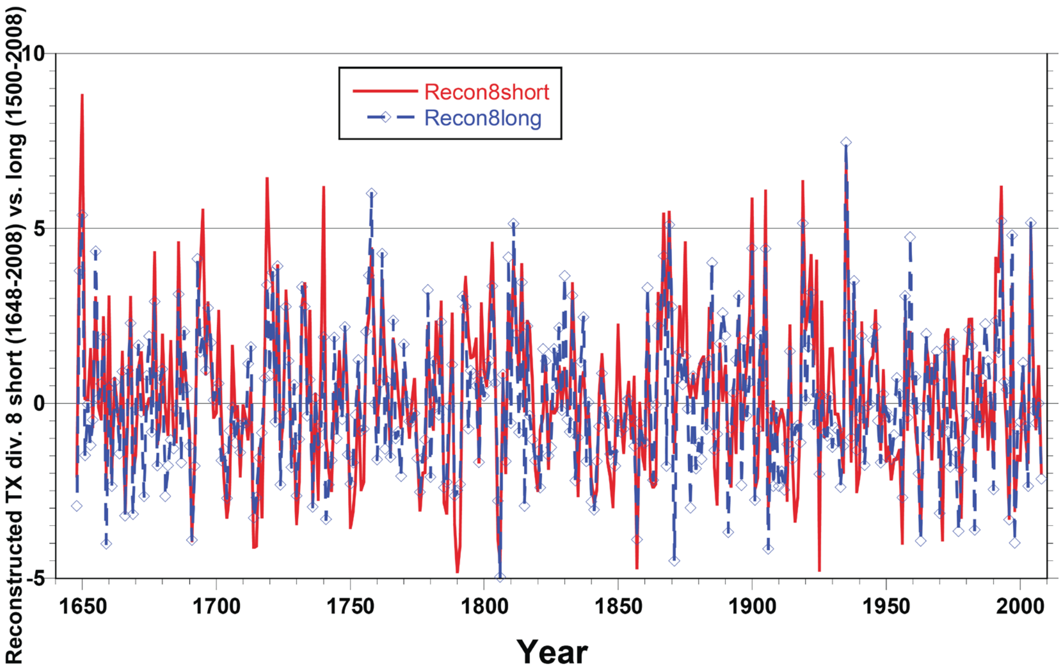
*June PDSI estimates for 1974 had a large amount of error, and were consistently more negative in all 4 divisions reconstructed than the observed values. See discussion of estimation error in general and for 1974 in particular on pages 68–71.



14. **Fig. A1.** Climate division 6 (Edwards Plateau), 2 reconstructions of June PDSI in the 1648–2008 overlap period. Blue is the long reconstruction (1500–2008) and red is the short reconstruction (1648–2008).



15. **Fig. A2.** Climate division 7 (S. Central), 2 reconstructions of June PDSI in the 1648–2008 overlap period. Blue is the long reconstruction (1500–2008) and red is the short reconstruction (1648–2008).



16. **Fig. A3.** Climate division 8 (Upper Coast), 2 reconstructions of June PDSI in the 1648–2008 overlap period. Blue is the long reconstruction (1500–2008) and red is the short reconstruction (1648–2008).

Texas Water Resources Institute
Texas Water Journal
Volume 2, Number 1, Pages 97–111, December 2011

History of Water and Habitat Improvement in the Nueces Estuary, Texas, USA

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Abstract: Reservoir impoundments in the Nueces watershed (Texas, USA) have reduced Nueces River flows to the coast by more than 50% since the 1980s. Reductions in freshwater inflows prompted state and local managers, along with scientists, to embark on a 3-decade process of ecosystem-based restoration and habitat improvement in the Nueces Estuary. Current management efforts in the estuary have increased freshwater flow to the Rincon Bayou and habitat has been protected from land acquisition in the Nueces Delta. Restoring freshwater flow and acquiring land in the Nueces Delta was not easily accomplished but has been successful through the efforts of federal, state, local agencies, and nongovernmental organizations. This paper also describes mitigation activities that have taken place in the Nueces Estuary.

Keywords: Coastal conservation, habitat sustainability, freshwater inflow, ecosystem-based management

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Citation: EM Hill, BA Nicolau, PV Zimba. 2011. History of water and habitat improvement in the Nueces estuary, Texas, USA. Texas Water Journal. 2(1):97-111. Available from: https://doi.org/10.21423/twj.v2i1.2104.

INTRODUCTION

According to archaeological and geological records dating back to 6000 B.C., drought and water shortages in the lower Nueces River affected early inhabitants and explorers of the lower Texas Gulf Coast. Cunningham (1999) states that human appearance and disappearance coincided with drought periods for the Aransas group (2000 B.C.–1300 A.D.) and the Rockport group, also known as the Karankawas (1400 A.D.–1848). Water shortages were likely one of several factors that affected initial population growth of early settlers. Corpus Christi, Texas began as trading post in 1838 and from 1845–1846 the area was occupied by US troops under General Zachary Taylor in preparation for war with Mexico before becoming officially incorporated in 1852 (Table 1). To meet human demands for water, reservoirs were built on

Table 1. Chronology of population of Corpus Christi, Texas, and impoundments constructed on the Nueces River. Data compiled from the US Census and Cunningham (1519–2010).

Year	Population	Water Supply Availability	Remarks
1519	Undocumented census of Native Americans	Undocumented water supply.	Spanish explorer Alonzo Alvarez de Pineda discovered what is now Corpus Christi, Texas.
1845	6000	Artesian well, 116 m deep, determined non-potable because of high sulfide.	Of the population, 4000 were temporary Army soldiers.
1850	689	1852: Water shortage. $1.50/ barrel of river water. 1853: Artesian well drilling begins.	City of Corpus Christi incorporated. Supply of water for emergencies.
1860	175	Artesian	
1870	2140	Artesian	
1880	3257	Artesian	
1890	4387	1893: City builds water system from Nueces River. 1898:Calallen diversion dam constructed.	Saltwater intrusion from Nueces Bay in public water supply. Decided to build Calallen saltwater diversion dam. Height of Calallen dam was 0.46 m above high tide and reservoir was 1.1 x 10^6 m^3.
1900	4703		
1910	8222	1915: Replacement dam built for Calallen diversion dam that increased the size of Calallen Reservoir.	Increased height of Calallen dam to 0.76 m above high tide and reservoir to1.2 x 10^6 m^3.
1920	10,522	1929: La Fruta Dam built.	Created Lovenskiold Reservoir with 74 x 10^6 m^3 storage capacity; Dam was rebuilt in 1935.
1930	27,741	1931: Increased the Calallen Reservoir.	Increased height of Calallen dam to 1.07 m above high tide and reservoir to 1.4 x 10^6 m^3.
1940	57,301		
1950	108,287	1951: Increased the Calallen Reservoir. 1958: Wesley Seale Dam built.	Increased height of Calallen dam to 1.37 m above high tide and reservoir to 1.6 x 10^6 m^3. Lake Corpus Christi with 317 x 10^6 m^3 storage capacity.
1960	167,690		
1970	204,525		
1980	231,999	1982: Choke Canyon Dam built.	Choke Canyon Reservoir with 857 x 10^6 m^3 storage capacity.
1990	257,453	1998: 163 km Mary Rhodes Pipeline built. Transports water from Lake Texana to the City's O.N. Stevens Water Treatment Plant; State approved the Garwood transbasin diversion for another water source.	Mary Rhodes Pipeline delivers 66.4 x 10^6 m^3 of water per year to the city of Corpus Christi but is capable of delivering 138.1 x 10^6 m^3. Six wastewater treatment plants with combined capacity of 135,503 m^3 d^{-1}.
2000	277,454		
2010	305,215		

the Nueces River (Cunningham 1999). These impoundments have resulted in reduced inflows affecting nutrient loads to the coast and biological productivity of the Nueces Delta (BOR 2000). Reduced inflows coupled with drought conditions have resulted in periods of hypersalinity, creating a negative or reverse estuary (Palmer et al. 2002, Ward et al. 2002).

The Nueces River is the main freshwater inflow source for the Nueces Delta and the Nueces Estuary, which is one of 7 major estuarine systems in Texas (Fig. 1) (Matthews and Mueller 1987; Weaver 1985; Longley 1994). The Nueces River provides water for urban, agriculture, and industry use for the City of Corpus Christi (City) and surrounding region (Anderson 1960).

The Calallen Diversion Dam, constructed in 1898, was the first impoundment on the lower Nueces River tidal segment developed for surface water storage (Norwine et al. 2005). Located 24 km west of Corpus Christi, this small rock-filled dam created a barrier restricting Nueces Bay saltwater from entering the Calallen Pool (Henley and Rauschuber 1981; Cunningham 1999). The Calallen Diversion Dam has been raised several times to meet the City's water demands and is currently 1.63 m above mean sea level (msl) with an average storage capacity of 1.45 x 10^6 m^3 (1175 acre-ft) (Cunningham 1999).

As population and economic growth increased in Corpus Christi, water demands were met by construction of the La Fruta Dam in 1929 (rebuilt in 1935), which created the Lovenskiold Reservoir located approximately 56 river km upstream of the Calallen Dam with an approximate storage capacity of 68 x 10^6 m^3 (55,000 acre-ft) (Cunningham 1999). In 1958, the Wesley Seale Dam replaced the La Fruta Dam and created Lake Corpus Christi with a storage capacity of 317 x 10^6 m^3 (257,260 acre-ft). The most recent impoundment, Choke Canyon Reservoir, was constructed in 1982 and is located 80 river km upstream of Lake Corpus Christi on the Frio River with a current storage capacity of 857 x 10^6 m^3 (695,271 acre-ft) (Corpus Christi Water Department, Lake Corpus Christi and Choke Canyon Reservoir 2011). An additional potable water source is also supplied to Corpus Christi from Lake Texana via the Mary Rhodes Pipeline. The 163 km pipeline was built in 1998 and delivers between 36% to 44% of the drinking water to the City (Corpus Christi Water Department, Lake Texana 2011).

Precipitation is a key factor in determining surface flow in

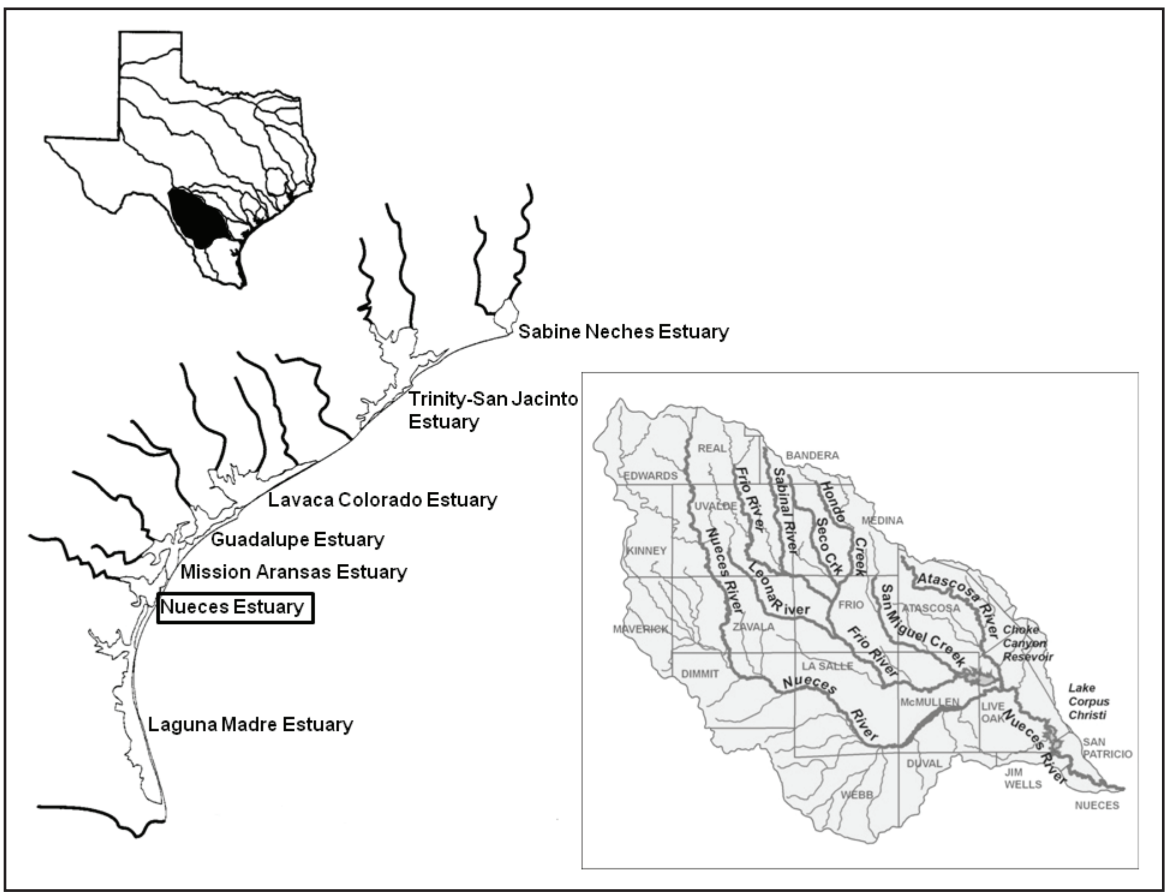

Fig. 1. Map of the 7 estuaries located along the Texas coast. Shaded area identifies the Nueces River Basin.

rivers. In the Nueces Estuary, precipitation is variable and can be influenced by El Niño and La Niña years. From 1948–2010, precipitation has increased slightly, especially during El Niño years (Fig. 2). Along with precipitation, the 2 existing reservoirs on the Nueces River control inflow into the Nueces Estuary. Using Asquith et al.(1997) in determining the mean annual flow into the Nueces Estuary, comparison of pre-construction (1940–1957) to post-construction of dams (1983–2010), shows a 39% decrease of inflow into the estuary (USGS gage 08211000, Nueces River near Mathis, Texas) (Fig. 3).

Estuaries need varying degrees of freshwater inflow to trigger cyclical patterns in salinity and other physicochemical variables essential to flora and fauna (Ritter et al. 2005). Reduced inflows to the Nueces Delta combined with low and variable precipitation and high evaporation rates, results in periods of hypersaline conditions. Negative ecological effects of hypersaline conditions, particularly to the shrimping industry (Matthews and Mueller 1987; Whitledge and Stockwell 1995), prompted the state of Texas to develop inflow criteria for freshwater inflows for the Nueces Estuary in 1990 (reviewed in Montagna et al. 2009). US Geological Survey data from 1941–1974 showed average annual inflow to the Nueces Delta prior to construction of the 2 dams was 774 x 10^6 m^3 yr^{-1} (627,492 acre-ft yr^{-1}) (Henley and Rauschuber 1981). Lack of inflow into the Nueces Estuary prompted several mandates from the Texas Commission on Environmental Quality over the years. The current Agreed Order mandated in 2001 that the Nueces Estuary receive no less than 186 x 10^6 m^3 yr^{-1} (151,000 acre-ft yr^{-1}) of freshwater inflow per year. While restoring some flow, this mandate represented a 76% decrease in historical annual (1941–1974) inflows into the Nueces Estuary.

The intent of this paper is to describe the Nueces Estuary region, document recent activities and research projects designed to improve, restore, and enhance habitat by use of alternative freshwater sources, river diversions, and land acquisition to meet biological and hydrological inflow requirements to the Nueces Delta.

REGIONAL DESCRIPTION

Nueces River Watershed

The Nueces River Basin covers 4.3 million ha and encompasses 5 ecoregions: the Edwards Plateau, Southern Texas

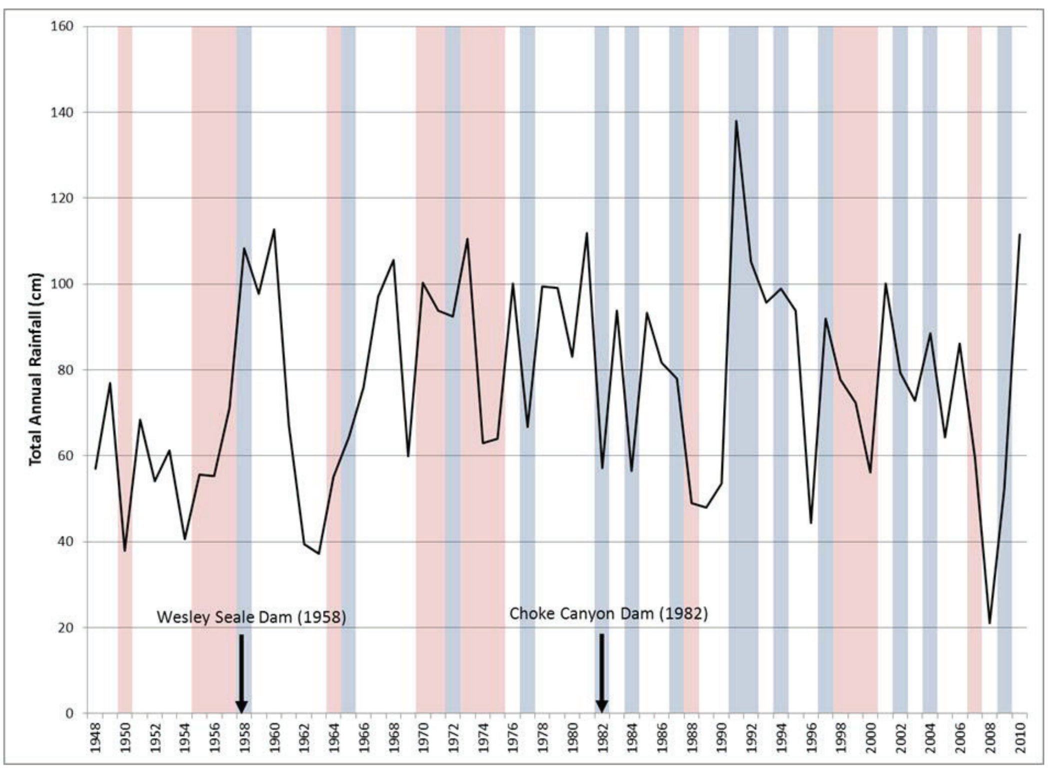

Fig. 2. Total annual precipitation recorded from the Corpus Christi International Airport from 1948–2010 and historical record of El Niño (blue) and La Niña (Red) years. (Precipitation data from National Climatic Data Center station 20024190 and El Niño-Southern Oscillation data from NOAA Climate Prediction Center.)

Plains, East Central Texas Plains, Western Gulf Coastal Plains, and the Texas Blackland Prairies (Griffith and Omernik 2009). Tributaries of the Nueces River include the Frio, Sabinal, Leona, and Atascosa rivers, and the Seco, Hondo, and San Miguel creeks (see Fig. 1). All rivers and creeks originate from seeps and springs in the Edwards Plateau (Henley and Rauschuber 1981). From 1934 through 2009 the streams crossing the Balcones Fault Zone contributed approximately 885 x 10^6 $m^3\ yr^{-1}$ (717,481 acre-ft yr^{-1}) of flow into the Edwards aquifer; recharge varies from year to year based on precipitation (Eckhardt 2011). The Nueces is the only river that regularly maintains some surface flow beyond the recharge zone in the basin. In the lower reaches of the river, rainfall provides much of the stream flow for the Nueces and its tributaries south of the Balcones Fault Zone.

Originating in Real County at an elevation of around 730 m (TPWD 1974; Benke and Cushing 2005) the Nueces River flows for approximately 507 km in a southeasterly direction to its mouth at Nueces Bay (TPWD 1974). After passing the Calallen Diversion Dam, the Nueces River flows along the southern edge of the Nueces Delta and empties into Nueces Bay, bypassing the delta except during periods of flooding. Historical data (1940–2000) show Nueces River reservoir operations have reduced freshwater inundation frequencies to the Nueces Delta from 2.3 flood events to 1.2 events annually (BOR 2000). The Nueces Overflow Channel, a river modification located east of Interstate Highway 37, was built in 1995 as part of a demonstration project to divert freshwater into the delta interior. The overflow channel lowered the minimum flood threshold of the upper delta from 1.64 m above sea level to sea level increasing the probability for freshwater inflows to the upper delta (BOR 2000; Palmer et al. 2002).

Nueces Delta

The Nueces Delta is one component of the Nueces Estuary. The estuary includes 20 km of the Nueces River tidal segment below the Calallen Diversion Dam; one primary bay, Corpus Christi Bay; one secondary bay, Nueces Bay; and 2 tertiary bays, Oso Bay and Redfish Bay (Henley and Rauschuber 1981) (Fig. 4). The Nueces Delta is 75 km^2 and consists of approximately 58.5 km^2 of middle and high marsh and 0.35 km^2 of low marsh. Middle and high marsh vegetation of the Nueces Delta includes species such as *Borrichia frutescens, Limonium nashi, Lycium carolinianum, Rayjacksonia phyllocephala, Opuntia engelmannii* var. *lindheimeri,* and *Spartina spartinae*. The low marsh includes species such as *Batis maritima, Distichlis spicata, Monanthochloe littoralis, Salicornia bigelovii, Salicornia*

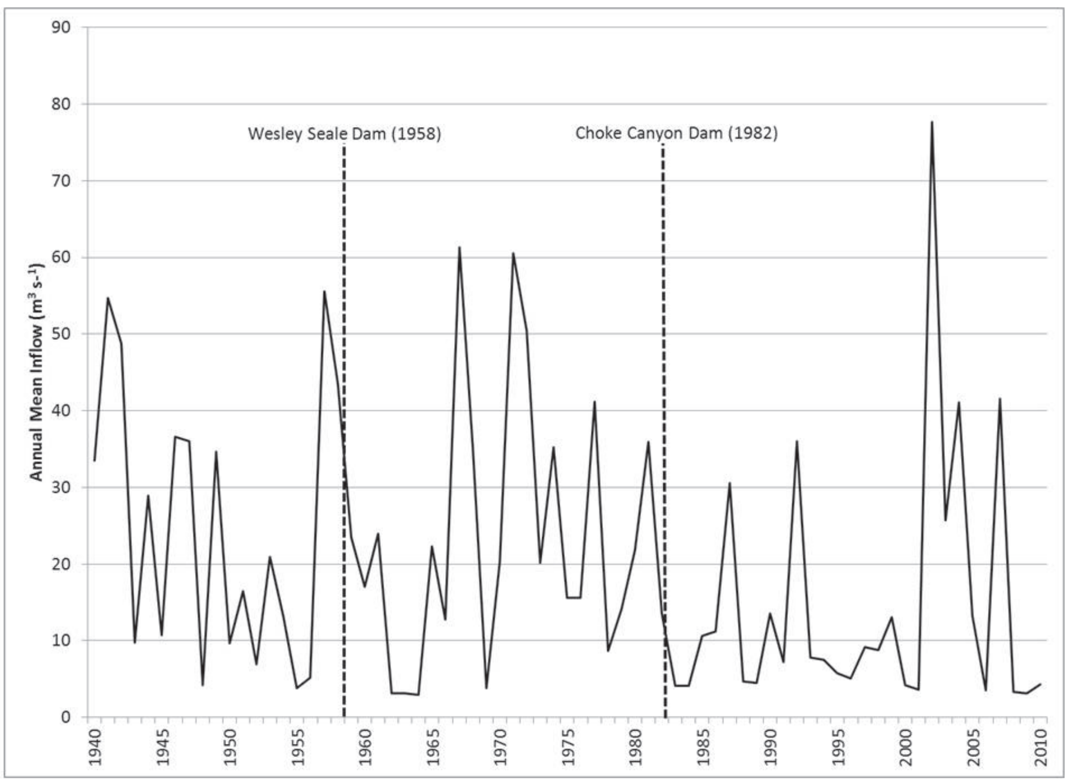

Fig. 3. Average annual Nueces River inflow ($m^3\ s^{-1}$) into Nueces Bay from 1940–2010. (Data from US Geologic Survey gauge 08211000, Nueces River at Mathis, Texas, USA.)

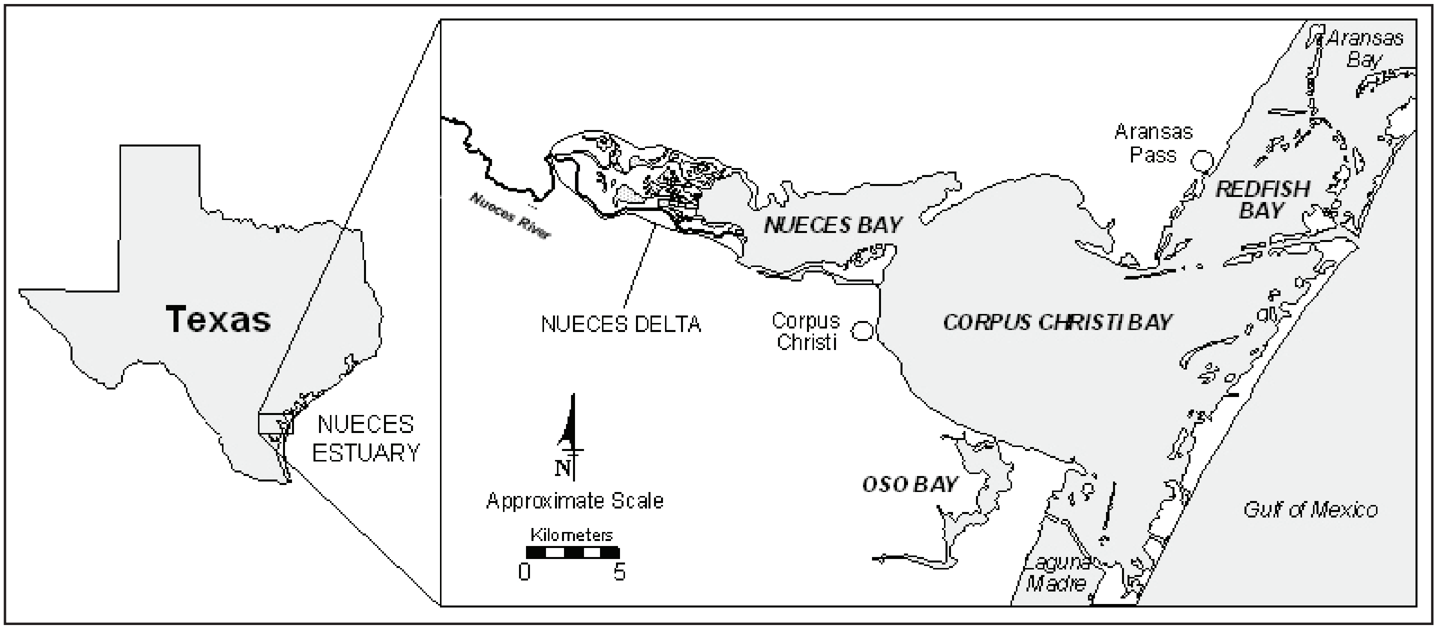

Fig. 4. Map detailing location of the Nueces Estuary (map modified after the BOR 2000).

virginica, Schoenoplectus maritimus with *Spartina alterniflora* scattered along the periphery of tidal channels (Ockerman 2005; Henley and Rauschuber 1981; Espey, Huston & Associates 1981). Seagrasses, *Halodule wrightii* and *Ruppia maritima*, and relic and extant oyster reefs of *Crassostrea virginica* are scattered throughout Nueces Bay and cover approximately 2.94 km^2 (Tunnell et al. 1996; Pulich and White 1997).

Located between a humid subtropical region to the northeast and a semiarid region to the west and southwest, the area has a net annual moisture loss of approximately 31 cm yr^{-1} (TWC 1991). Summers are hot and humid, and moderate winters produce an occasional freeze following strong northerly frontal passages (Jones 1975; Chabreck 1990). Mean annual precipitation is approximately 77.6 cm yr^{-1} (NOAA 2010). However, this is offset by evaporation rates that typically range from 90 to 115 cm yr^{-1} but may reach as high as 150 cm yr^{-1} (TWC 1991). Southeasterly prevailing winds serve as a primary source of atmospheric moisture with tropical storms and hurricanes occasionally yielding substantial amounts of rainfall during late summer and early fall (Armstrong 1987).

NUECES DELTA PROJECTS

While many estuarine organisms tolerate hypersaline conditions, extended periods of hypersalinity resulting from reduced inflow in the Nueces Delta have impacted biological productivity, vegetation cover, species richness, and species diversity over the past 6 decades (Alexander and Dunton 2002; Montagna et al. 2002; Palmer et al. 2002). Hypersaline conditions have reduced populations of commercially and recreationally important faunal species, particularly shrimp and oysters (Murray and Jinnette 1974; Longley 1994; Montagna et al. 2002; Palmer et al. 2002). In response to negative environmental and economic impacts from reduced flows, management projects were initiated to increase biological productivity of the Nueces Delta by restoring freshwater flow. The water rights permit issued in October 1976 stated that following the completion and filling of Choke Canyon Reservoir scheduled water releases from Lake Corpus Christi would be no less than 186 x 10^6 m^3 yr^{-1} (151,000 acre-ft) into the Nueces Estuary via reservoir spills, releases, or return flows. At that time, flow in the Nueces River bypassed the interior delta and flowed directly into Nueces Bay. Mandated water releases from the city's municipal water supply, Lake Corpus Christi, raised concern from residents especially during drought conditions when water restrictions were in place. These concerns of human needs versus environmental needs resulted in management evaluation of alternative water resources to meet estuarine freshwater requirements of the delta.

Nueces Delta Mitigation Project 1989–1997

The first project in the Nueces Delta was a mitigation plan that involved aquatic and marsh habitat creation. In March 1987, the US Army Corps of Engineers and the Port of Corpus Christi Authority excavated an 0.81 km^2 upland borrow area in the Nueces Delta to create salt marsh habitat to offset habitat losses from the Corpus Christi Ship Channel 45-Foot Dredging Project. Nueces Delta Mitigation Project participants included the US Fish and Wildlife Service, National Marine Fisheries Service, US Environmental Protection Agency, Texas Parks and Wildlife, and the Texas General Land Office (FWS 1984).

Marsh habitat was created by constructing a series of channels and ponds that maximized circulation and edge effect by planting smooth cordgrass, *S. alterniflora* (Fig. 5). The US Army Corps of Engineers and US Fish and Wildlife Service implemented a 5-year monitoring program in June 1989 to evaluate success of *S. alterniflora* establishment and the biological response to the created marsh using biometrics based on monitoring of benthic infauna, epifaunal invertebrates, nekton, avian usage, and hydrological data (Nicolau and Tunnell 1999).

The initial planting failed within 6 months because 1) a construction design failure resulted in complete marsh submergence during low tide (when plants should have been emergent) and 2) higher than optimum salinity that was too stressful for the *S. alterniflora* transplants (Nicolau and Tunnell 1999). The salinity in the Nueces Delta during planting exceeded 40 practical salinity units (PSU) for over 6 months, and exceeded the optimum salinity for *S. alterniflora* of 10-20 PSU (Ruth 1990; Linthurst and Seneca 1981; Webb 1983).

A multi-agency planning conference in May 1993 discussed the design failure and reconstruction alternatives to satisfy mitigation requirements. The discussions resulted in a design to build a smaller marsh at 0.04 km^2 within the mitigation area before attempting the full-scale site modification (Fig. 6). Because of time and monetary constraints, construction was postponed to February 1994 and the test area decreased from 0.04 km^2 to 0.024 km^2. Two weeks before completion, with approximately 75% of the area elevated to grade, a wind-driven high tide event breached all levees and completely inundated the area. When the waters receded, a more natural design appeared than originally planned and construction was stopped. The planting area now included several small islands for birds to nest on and a network of channels and ponds for aquatic species to take refuge in during low tides. When the 5-year study concluded in August 1994, birds were utilizing the area for nesting and new plant growth was established within the Nueces Delta Mitigation Project area (Nicolau and Tunnell 1999). The 0.024 km^2 test marsh was considered a success and plans to move forward and build the full-scale mitigation site were initiated. In August 1995, a plan was designed after a successful US Fish and Wildlife Service project in the Sabine National Wildlife Refuge in Louisiana. The Sabine National Wildlife Refuge used *in situ* material to construct low levees or islands in a grid pattern to maximize inter-tidal habitat for *S. alterniflora*. After the US Army Corp of Engineers completed plans and specifications for the Nueces Delta Mitigation Project, construction began in January 1997. Construction ended in late February 1997, followed by planting of *S. alterniflora* in March 1997 (Fig. 7). Wind-driven tidal events soon after planting resulted in high tides, which destroyed some *S. alterniflora*, but by August 1997, new growth was established at many new levee locations and the US Army Corp of Engineers declared the project a success. Through management efforts of multiple agencies, the Nueces Delta Mitigation Project created new aquatic and marsh habitat.

Rincon Bayou Overflow Channel Demonstration Project 1993–1999

The US Bureau of Reclamation initiated and funded the Rincon Bayou Overflow Channel Demonstration Project in 1993 to increase freshwater inflows to the upper Nueces Delta. Two main project objectives were: 1) to increase the probability of freshwater inflow events to reach the upper Nueces Delta and 2) to monitor subsequent changes in biological productivity within the delta. Baseline monitoring took place from October 1994 through October 1995 (BOR 2000). Two channels, the Nueces Overflow Channel and the Rincon Overflow Channel, were excavated to divert river water to the Upper Rincon Bayou and were completed October 1995 (Fig. 8). The Nueces Overflow Channel, excavated to 0.6 m msl, connected the Nueces River to the delta and increased flow exchange during periods of river flood and high tide conditions. The Rincon Overflow Channel, excavated to 1.22 m msl upstream (south) and 0.91 m msl downstream (north), was constructed to increase the exchange of water from the Rincon Bayou to the northernmost reaches of the Nueces Delta (BOR 2000).

Changes in water column productivity, benthic macrofauna (species composition, density and biomass), and vegetation communities were used to evaluate biological productivity in response to the overflow channels from October 1994 to December 1999. During the 50-month demonstration project, the amount of freshwater diverted from the Nueces River to the upper Rincon Bayou increased approximately 732% when comparing inflow data from 1982 to 1995. Five significant freshwater inflow events occurred resulting in flow through the Rincon Overflow Channel and inundation of the marsh and tidal flats in the northern part of the delta (BOR 2000). These events were substantial enough to lower the salinity gradient in the upper delta below hypersaline conditions. Data collected during the study period showed the diversion channels significantly lowered the minimum flooding threshold of the upper Nueces Delta. Positive responses to the increased freshwater were identified in the water column, benthic infauna, and vegetation (BOR 2000). However, in September 2000, in accordance with project guidelines and due to failed attempts to purchase the land on which the channel was constructed, the Bureau of Reclamation filled in the Nueces Overflow Channel. Then, in October 2001, the City reopened the Nueces

Fig. 5. Aerial photograph showing the first stage of the Nueces Delta Mitigation Project site (Lanmon Aerial 991-B5, 9 February 1991).

Fig. 6. Aerial photograph showing the second stage of the Nueces Delta Mitigation Project site (Lanmon Aerial 3295-1, 11 February 1995).

Fig. 7. Aerial photograph showing the completed cells of the Nueces Delta Mitigation Project site (Lanmon Aerial 9497-1, 3 May 1997).

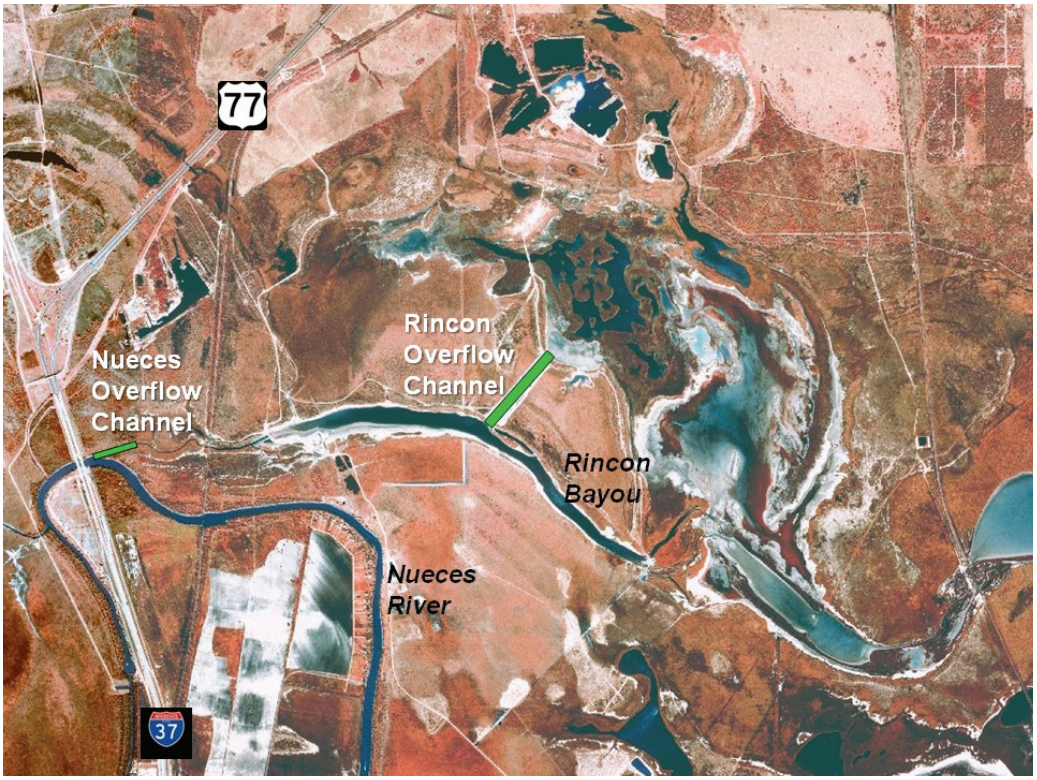

Fig. 8. Map showing placement of the Nueces Overflow Channel and Rincon Overflow Channel on the Nueces River (BOR 2000).

Overflow Channel (excavated to a depth of 0.3 m msl) as part of a permanent diversion to restore flows to the Nueces Delta.

Effluent Diversion Demonstration Project 1998–2003

Based on recommendations in the Regional Wastewater Planning Study-Phase II Nueces Estuary (HDR 1993), the City developed a full-scale demonstration project in the lower Nueces Delta that used treated municipal effluent as an alternative freshwater source (Dunton and Hill 2006). The diversion provided a supply of nutrient-rich freshwater that also facilitated reductions in hypersalinity.

In June 1997 three 0.013 km^2 earthen cells were built at the Effluent Diversion Demonstration Project site to receive treated effluent from the Allison Wastewater Treatment Plant. The project site is located 900 m northeast of the Allison Wastewater Treatment Plant, 300 m north of the Nueces River, and approximately 3.5 km west of Nueces Bay (Fig. 9). Once the pipeline and cells were determined to be fully functional, 7570 m^3 d^{-1} (6.14 acre-ft d^{-1}) of effluent began to be pumped to the diversion site.

One project goal was to assess the feasibility of enhancing productivity in the Nueces Delta using treated effluent discharges. Specific objectives were 1) to determine if "no harm" occurred because of the diversion and 2) to assess changes in the marsh ecosystem due to the diversion. To measure ecological changes occurring in response to the discharge, the City established a comprehensive monitoring program that met the requirements of the Texas Natural Resource Conservation Commission permit (now Texas Commission on Environmental Quality). Monitoring of productivity focused on 1) phytoplankton primary production and biomass, 2) zooplankton and mesozooplankton biomass and species abundance, 3) emergent vegetation biomass, species composition, percent cover, and plant canopy structure, 4) benthic density, biomass, and diversity, 5) nekton catch per unit effort, biomass, and diversity, 6) avifauna species abundance, diversity, and habitat usage and, 7) physiochemical effects including sediment porewater salinity and inorganic nitrogen levels (Dunton and Hill 2006).

The volume of effluent diverted into South Lake decreased salinity at the diversion site and created a 0.07 km^2 emergent vegetation marsh that attracted many species of birds (Dunton and Hill 2006). Birds used the area for feeding, resting, and breeding and as a freshwater source and refuge during times of drought. The high inorganic nitrogen and phosphorus at the diversion site was rapidly assimilated (50%–80% reduction) by the vegetation within 325 m downstream of the site (Alexander and Dunton 2002). In meeting the permit requirements established by the Texas Natural Resource Conservation Commission for this diversion project, the City began initial development of a comprehensive regional water resources management program that integrated local water supply and effluent treatment facilities to manage water resources in the most environmentally productive, dependable, and affordable approach.

Rincon Bayou Nueces Delta Study 2003–2010

The Rincon Bayou Nueces Delta study was funded by the City and followed the 2001 Texas Commission on Environmental Quality Agreed Order requiring the City to construct and operate a 1.5 m diameter water pipeline to deliver up to 3.7×10^6 m^3 d^{-1} (3000 acre-ft) of freshwater to the Rincon Bayou in accordance with the 1995 Texas Commission on Environmental Quality pass-through order. To facilitate the objective, in October 2001 the City reopened the Nueces Overflow Channel (0.3 m msl) making the diversion channel a permanent feature of the Nueces Delta (see Fig. 8). This project, like the Effluent Diversion Demonstration Project, required the City to implement a monitoring program to facilitate a management program for freshwater inflows into the estuary and determine if "no harm" resulted from the diversions.

Field studies began October 2003 at 9 stations recommended in the 2002 Nueces Estuary Advisory Council Monitoring Plan. Monitoring objectives for the Rincon Bayou Diversion Project focused on biological effects related to the Nueces Overflow Channel, Rincon Overflow Channel, and the Rincon Bayou pipeline diversions to the Nueces Delta (see Fig. 8 and Fig. 9). Original project recommendations called for a 5 year monitoring plan; 2 year pre-pipeline, 2 year post-pipeline, with 1 year for data analysis and final report. Delays in pipeline construction (completed in 2008) extended the monitoring timeline to 7 years. Data parameters collected included 1) emergent vegetation biomass, species composition, percent cover and plant canopy structure, 2) benthic invertebrate density, biomass, and diversity, 3) nekton catch per unit effort, biomass and diversity, 4) avifauna species abundance, diversity, and habitat usage. and 5) physiochemical effects resulting from the diversion.

The monitoring program was intended to assess benefits of the diversion on productivity in Rincon Bayou and assist in development of an optimal operation management plan for the pipeline. Once the monitoring requirements were

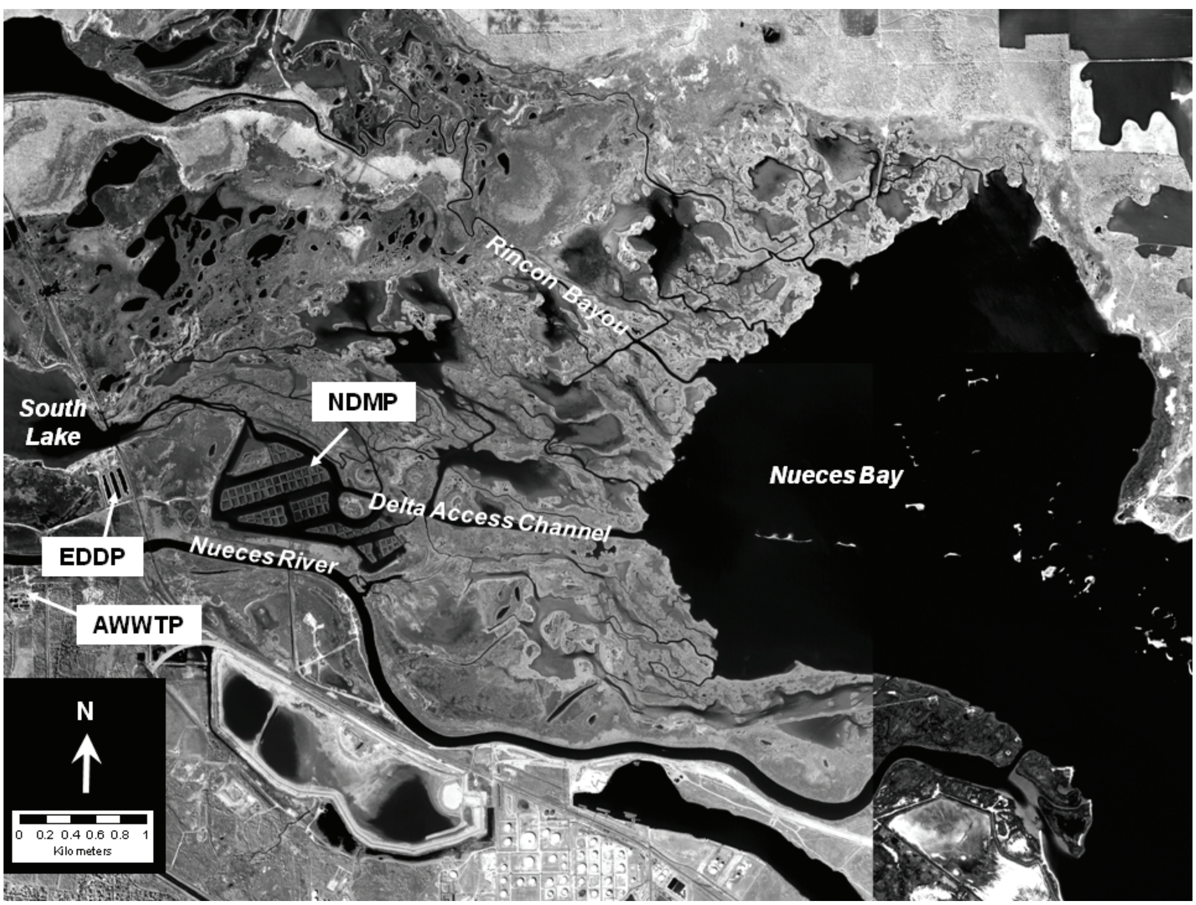

Fig. 9. Lower Nueces Delta showing locations of the Nueces Delta Mitigation Project (NDMP), Effluent Diversion Demonstration Project (EDDP), and Alison Wastewater Treatment Plant (AWWTP).

met, biological monitoring was stopped with only 3 pipeline releases occurring during the study (September 2009, January 2010, and May 2010). Since the completion of the project in September 2010, 3 more releases have occurred: March 2011, May 2011, and June 2011. Salinity monitoring is still active and is the parameter being measured to determine the spatial effects of freshwater into the delta via the pipeline (Adams and Tunnell 2010). Salinity gauges are maintained by the Conrad Blucher Institute at Texas A&M University–Corpus Christi (Conrad Blucher Institute 2011).

Nueces Delta Preserve Land Acquisition (2004–2011)

The Nueces Delta Preserve was established in 2003 when approximately 5.7 km^2 of Nueces River Delta property was acquired by the Coastal Bend Bays & Estuaries Program with funds from US Environmental Protection Agency Supplemental Environmental Project Settlements and the US Department of Interior's Coastal Impact Assistance Program (Fig. 10). Along with the $1.5 million Supplemental Environmental Project funds, the Coastal Bend Bays & Estuaries Program also received an additional $2.5 million in matching funds and completed 3 land acquisitions and habitat protection projects. The Coastal Bend Bays & Estuaries Program worked with The Nature Conservancy of Texas, Texas Commission on Environmental Quality, the City, the US Department of Agriculture Natural Resources Conservation Service, and the US Fish and Wildlife Service to acquire lands and conservation easements on delta property with high ecological value and/or subject to high development pressure.

The Coastal Bend Bays & Estuaries Program has protected 6 rookery islands and approximately 0.024 km^2 of colonial waterbird rookery island habitat in Nueces Bay and planted *S. alterniflora* along eroding shorelines in Nueces Bay to help reduce erosion and create habitat. In total, the Coastal Bend Bays & Estuaries Program has acquired approximately 21.85 km^2 and is currently working to add another 20.64 km^2.

DISCUSSION

Freshwater is a valuable environmental resource and its accessibility is less than 1% (11 million km^3) of the total volume of water on Earth (Batchelor 1999). Many factors affect freshwater availability including population growth, pollution, economics, land usage, and climate change (Davies and Simonovic 2011). Finding the balance between human and environmental freshwater needs within a river basin is complex but has been possible in other management efforts. Using an adaptive approach in management plans to protect this resource is essential. Most policy makers and scientists now accept this new methodology allowing modifications to plans when objectives are not being met (Rammel et al. 2007; Cundill and Fabricius 2009; Wilby et al. 2010).

As done in the Nueces Estuary, the Australian government passed laws to improve water quality resources after river dam construction and drought conditions had detrimental effects on the Murray Darling Basin located in southeastern Australia (Kingsford 2000). The basin drains Australia's 3 longest rivers—the Murray 2530 km, the Darling 2740 km, and the Murrumbidgee 1690 km (Kingsford 2000; McNamara 2007)—and covers 1,061,469 km^2, equal to 14% of Australia's land area (Walker 1985; Kingsford 2000). Since 1920 there has been a 5-fold increase in water diverted from the Murray Darling system (irrigation being the largest at 95% of diversion volume), which has resulted in hypersaline water, increased algal blooms, habitat alteration, and increased water temperature, all which have adversely affected native plants and animals (Walker 1985; Kingsford 2000). Since the 1980s Australia's government has implemented laws to restore inflows and restore water quality of the Murray Darling Basin. These efforts culminated in 2008 when the Murray-Darling Basin Authority assumed sole responsibility for planning integrated management of the basin water resources in an effort to ensure that future sustainable water use provides sufficient water for a healthy environment as well as agriculture, industries, and human use. Success in managing the Murray Darling Basin is a result of strong relationships among state and local organizations, agriculture, industry, and the public. Comparable efforts for the Nueces Delta brought independent stakeholders together in establishing objectives for the Nueces Delta and Nueces Estuary. These efforts were critical in instituting ecosystem management practices for the delta's habitats and restoring freshwater inflows to the Nueces Delta. The partnerships between scientists, resource managers, and stakeholders were necessary in determining environmental and economic needs to maintain this ecosystem, while also fulfilling residential, agricultural, economic, and industrial demands of the coastal bend.

Given as an example, the success of the Murray Darling Basin efforts have shown adaptive management programs work and are increasingly becoming a management tool in much of the United States and other countries (Becu et al. 2003; Schlüter and Rüger 2007; Cundill and Fabricius 2009; Kallis et al. 2009; Allen et al. 2011; Fontaine 2011; Moore et al. 2011). To some extent, an "adaptive" approach is currently being practiced in managing the Rincon Bayou Pipeline in the Nueces Delta, in terms of timing, volume, and duration of flow. This "adaptive" approach in managing diverted freshwater gives flexibility to resource decision makers during drought or flood conditions and the ability to increase or decrease volume depending on water availability. However, as of now, no biological monitoring is required to evaluate the spatial and

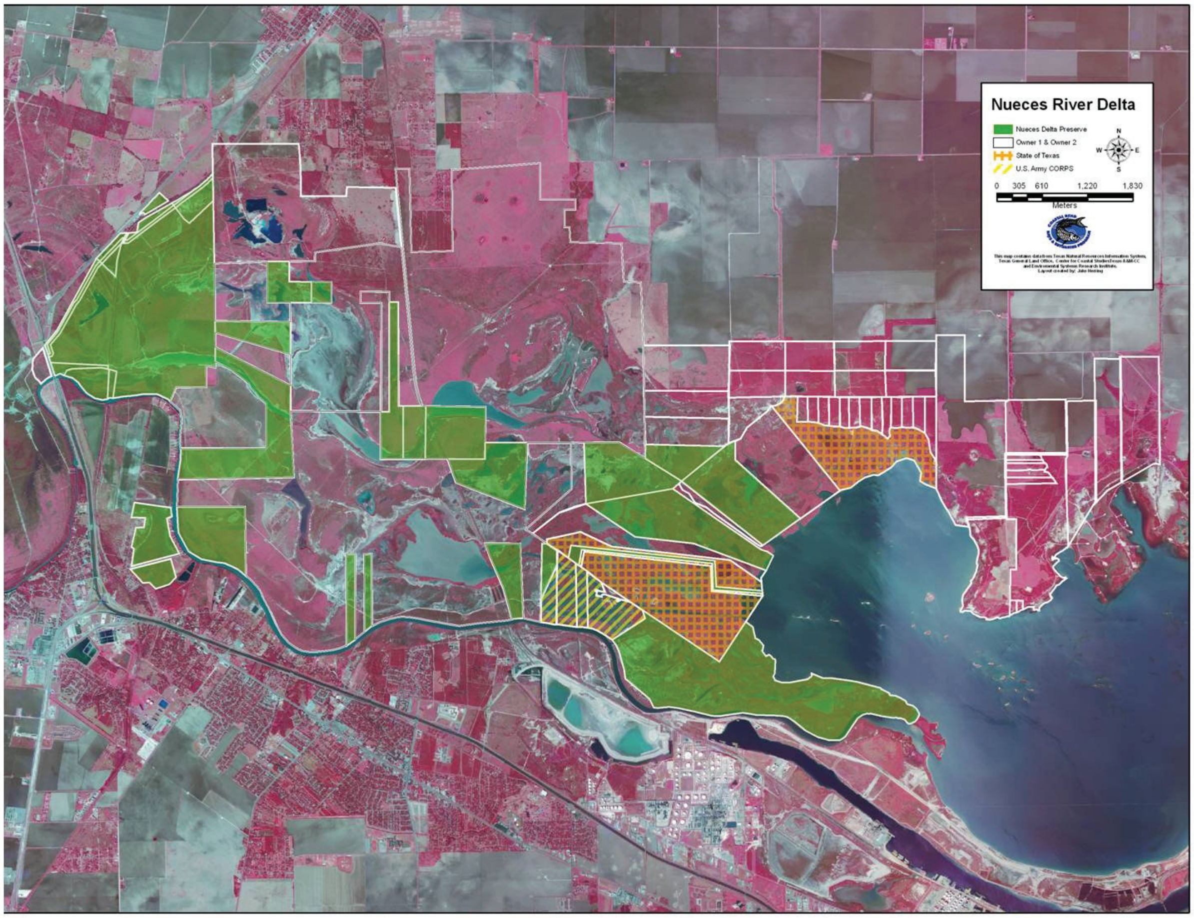

Fig. 10. Nueces Delta land acquisition: Coastal Bend Bays & Estuary Program (green shaded area), State of Texas (orange checked), and US Army Corps of Engineers. (Photo courtesy of Coastal Bend Bays & Estuary Program).

temporal effects of the Rincon Bayou Pipeline and to determine if the current plan optimizes ecosystem benefits. Without those data, this management plan cannot (1) be evaluated for ecological effectiveness, (2) ascertain ecosystem benefits from the plan, and (3) identify if plan objectives have been met other than salinity changes. When only one parameter or scale is used to determine system change, in this case salinity, processes occurring at different scales and rates may be masked (Cundill and Fabricius 2009). This is why it is important to have both biological and physio-chemical data collected at different scales since communities and chemicals react to change at different rates.

Monitoring provides the data tools for effective decision making when using an adaptive approach to manage resources (Steyer and Llewellyn 2000; Fontaine 2011; McFadden et al. 2011; Williams 2011b; Cundill and Fabricius 2009). Both biological and chemical data are needed to justify changes to environmental plans and identify if the objectives have been met (McFadden et al. 2011; Williams 2011a). The current effort in restoring and maintaining existing connectivity between river, delta, and bay in the Nueces Estuary with freshwater flow enhances chemodiversity (i.e. salinity gradient, pH), which in turn supports a variety of habitats essential to fauna and flora. These valuable delta habitats (i.e. uplands, high marsh, low marsh, wetlands, and mudflat) are now being protected from commercial and agricultural development through the efforts of the Coastal Bend Bays & Estuary Program land acquisition program. Protecting the delta's habitats and implementing adaptive management practices in future environmental projects provides natural resource managers with the tools required to make the decisions necessary to maintain a functional estuary.

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Texas Water Resources Institute
Texas Water Journal
Volume 2, Number 1, Pages 112–114, December 2011

Book Review: Water Policy in Texas: Responding to the Rise of Scarcity

Griffin, R. C. (Ed). 2011. Water policy in Texas: Responding to the rise of scarcity. Washington, DC: RFF Press. ISBN: 978-1-93311-589-4, 250 pages, US$94.95.
URL: www.earthscan.co.uk/?TabId=102395&v=512412

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This review has been modified from a previously published version (Sugg 2011).

Citation: Sugg ZP. 2011. Book Review: Water Policy in Texas: Responding to the Rise of Scarcity. Texas Water Journal. 2(1):112-114. Available from: https://doi.org/10.21423/twj.v2i1.6134.

"The free lunches of the original Texas water endowment have been consumed" (p. 238). This statement nicely captures the current crossroads of water policy in the state of Texas. Like many places where water is over-allocated and demands are ever-increasing, in Texas it is no longer possible to allocate water to one use without reducing the allocation to another. Future water management will largely be about managing trade-offs, and a burning question for water policy scholars and practitioners is how best to go about it. *Water Policy in Texas: Responding to the Rise of Scarcity* aims to convey the Texas experience to date in the hope of making lessons learned, good and bad, available to a wide audience of researchers, practitioners, and the public. The two main aims of this particular volume are (1) to see what has been learned in the Texas water policy experience and (2) to evaluate the current status of water management in Texas, in light of recent changes and future possibilities. The social, economic, and environmental impacts associated with the hottest summer and the driest 12-month period in Texas recorded history only serve to highlight the timeliness of this volume and the critical need to take stock of water policies.

The chapters are intentionally relatively short, with the difficult aim of providing enough substance to be useful as summaries without getting into excessive detail. The authors largely succeed at this. For readers who might need only a well-researched summary on one or more topics, the amount of information given in the chapters will probably be enough, but they are also well-referenced so that those who want to dig deeper into a particular topic will be able to do so, a major source of value of this volume. Although the chapters are mostly written to stand alone, chapters 2 (background information) and 3 (water law) are integral to understanding many of the others. Chapters 3 and 4 and 6 and 7 work well as pairs.

Interestingly, the term "sustainability" is intentionally jettisoned throughout the book due to its ambiguity, which has lent itself to cynical manipulation by some interests. Additionally, water "needs" and "demands" are both given specific definitions. I note this because the problematic ambiguity of such commonly used terms in the "water jargon" is not always identified and clarified up front as it is here. I appreciated these choices and I would wager most other readers will as well.

Texas is introduced in the opening chapter as a policy laboratory where unique responses have been applied to globally ubiquitous water problems. A number of conditions contribute to the uniqueness of the Texas situation, such as the relatively minimal presence of federal agencies in both landownership and water rights, even in federally constructed water storage facilities. Additionally, there is broad geographical and climatic diversity, a strong culture of respect for private property rights, a huge and highly irrigated agricultural economy, and 5 of the 20 largest cities in the US, all of which are experiencing rapid growth. Add to this a long coastline and a shared international watercourse border and you have a recipe for a highly complex water puzzle. These characteristics shape many of the issues in the rest of the volume.

Chapter 2 provides a useful backdrop for the rest of the chapters, describing the highly diverse hydro-geography of the state, as well as the current trends of increasing demand, the impact of water use on environmental quality thus far, and the history of state-level water resources planning. The rest of the chapters address various scarcity-related topics such as water law, water marketing and pricing, boundary compacts and treaties, water for the environment, groundwater depletion and management, and technological water alternatives. Most of the policy issues cannot be understood without first grasping the basic legal doctrines, which are described clearly and effectively in chapter 3. These consist primarily of (1) prior appropriation rights (first in time, first in right) to surface water granted by state permits and (2) a separate "rule of capture" law for groundwater, a doctrine where unquantified and unprotected (from interference of others) rights to pump are attached to private property rights in overlying land. Indeed, much of the rest of the book is about various efforts to work around and within this dissonant legal framework.

All of the chapters contain valuable information that seems useful to both researchers and practitioners. I found the strongest and most illuminating of these to be chapter 5 on the regulation of the Edwards aquifer, chapter 8 on transboundary compacts, and chapter 7 on water for the environment. Chapter 6 is particularly engagingly written; while the information it presents on the scientific challenges of quantifying instream flows and estuary health is less explicitly policy-oriented than in other sections, chapter 7 balances it with the necessary legal and policy context. Unfortunately, the same cannot be said for chapter 10, which provides excellent technical information about different desalination and reuse processes but misses an opportunity to engage with any number of important policy-related questions. These questions include topics regarding the environmental impact of brine waste disposal, pricing and access to desalinated water; and public perceptions of reused and reclaimed water and how these alternative strategies are being worked into the existing legal and institutional settings.

Although not intended to be comprehensive, this volume strategically covers a range of very important scarcity-related topics. However, it could have been even more complete with the inclusion of a chapter exclusively devoted to urban water issues, particularly the relationships between water provision, planning, zoning laws, and urban growth. Texas has several major urban areas, and there are likely lessons to learn from the ways they have managed urban water provision and suburban development. Additionally, some treatment of scarcity issues related to water provision in colonias (the poor communities along parts of the Texas-Mexican border) would have been a welcome contribution. A handful of other interesting issues receive mention but could have been developed further, e.g., various conflicts between users in different demand sectors, the accumulation of private land by private interests in order to profit from the sale of the attached groundwater rights, and the water-energy nexus.

In the end, one does get the sense that Texas has pursued a fairly unique path with regard to water resources, which has been dictated largely by its legal doctrines and the apparent unwillingness to change them on the part of either the state courts or the legislature. Much of the legal and policy change that has occurred has been precipitated by severe droughts, which may remain the case in the future. Many of the lessons contained in this volume are of the cautionary variety and not things that others will want to repeat. The state's public Texas Water Trust, for example, has no funding to acquire water rights and, consequently, has just two water rights for environmental use after over a decade of existence. However, the fact that Texas is bumping up against some hard limits has yielded some interesting developments that deserve wider attention. For one, the experience in Texas with water marketing (chapter 4) should be compared to other similar water markets in other states and countries, given the continual debate over their use as an allocation mechanism. Additionally, the jury is still out on the ideal way to manage and regulate groundwater depletion, and consequently the localised Texas Groundwater Conservation District model (chapters 3 and 9) warrants consideration given that more centralised models in other states have not exactly been panaceas either. Similarly, the creation of a regulated cap and trade model of sorts based on adjudicated groundwater rights for the Edwards aquifer constitutes a ground-breaking rejection of the rule of capture law governing the rest of the state's groundwater that appears likely to yield some important lessons. It will also be interesting to see how the various transboundary compacts Texas is party to will adapt to changing climatic conditions that could alter the baseline flows on which current allocations rely upon. Finally, it seems that there is potential to make some major strides towards allocating water for environmental uses through the environmental flows program authorised by the state legislature in 2007.

As noted in chapter 5, the consensus of future climate model projections for the Southwest, including central Texas, is there will be increases in overall aridity and in the intensity of drought events during La Niña conditions (Seager 2007). The current La Niña-induced severe drought appears to be in line with these predictions, which draws attention to two points. The first is that it will be critical to integrate considerations of climate change into water policy, management, and planning in a meaningful way in order to mitigate the kinds of impacts currently being felt around the state. Unfortunately, this book does not directly address the issue of whether and to what extent this integration may be occurring in Texas, though the assessment in chapter 8 of the flexibility of compacts and treaties governing water resources on the Texas-Mexico border is rather negative on this point. Second, by exacerbating and highlighting already-existing water issues, the current drought should be a useful moment in which to identify the ways that Texas water policy can be made more effective at mitigating the more deleterious impacts of drought in the future. In that respect, the lessons in this book could not be more timely.

In sum, like most places struggling with water scarcity problems, the Texas case offers a mixed bag of positive and negative experiences. But there are valid reasons for those outside the state to pay attention to how recent developments play out over the coming years. Overall, *Water Policy in Texas* does a laudable job relating the Texas water story in a digestible but highly substantive way. By showing that the types of problems Texas faces are not unique, but that the responses often are, the book successfully makes the case that it is a story worth reading.

REFERENCES

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Sugg ZP. 2011. Review of *Water Policy in Texas: Responding to the Rise of Scarcity*. Griffin, R.C. (Ed.). Water Alternatives. 4(2):245-247.

Editors Note: Chapter names and authors are as follows:
Chapter 1: Experiments in Water Policy, Ronald C. Griffin
Chapter 2: Texas Water Resources, John B. Ashworth and Ric Jensen
Chapter 3: Texas Water Law and Organizations, Ronald Kaiser
Chapter 4: Texas Water Marketing and Pricing, Ronald C. Griffin
Chapter 5: The Edward Aquifer: Hydrology, Ecology, History, and Law, Todd Haydn Votteler
Chapter 6: The Importance of Freshwater Inflows to Texas Estuaries, Paul Montagna, Ben Vaughan, and George Ward
Chapter 7: Water for the Environment: Updating Texas Water Law, Mary E. Kelly
Chapter 8: Texas Boundary Water Agreements, Kathy Alexander Martin
Chapter 9: Ground Water Depletion in the Texas High Plains, David B. Willis and Jeffrey W. Johnson
Chapter 10: Advanced Technologies for Tapping Unconventional Texas Waters, David Jassby, Andrew J. Leidner, Yao Xiao, Andreas Gondikas, and Mark R. Wiesner
Chapter 11: Water Management Guidance from Texas, Ronald C. Griffin