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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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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.

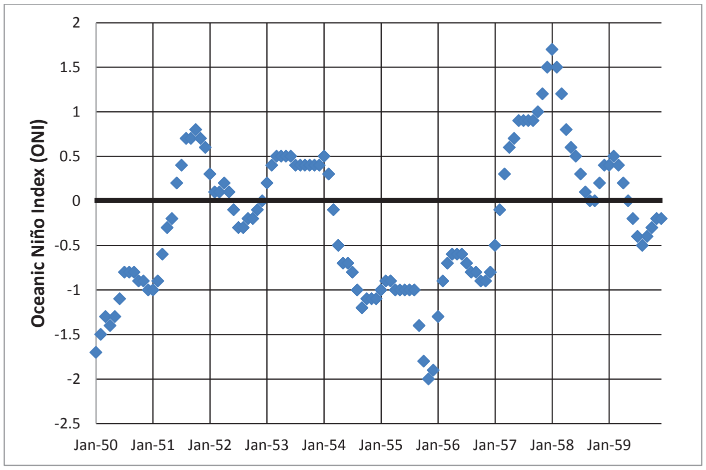
Climate anomalies associated with flood and droughts can be attributed to the regional ocean temperature phenomena commonly known as El Niño and La Niña. In addition to their influence in the short-term or cyclic variation of precipitation and temperature, El Niño and La Niña periods also have direct 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.



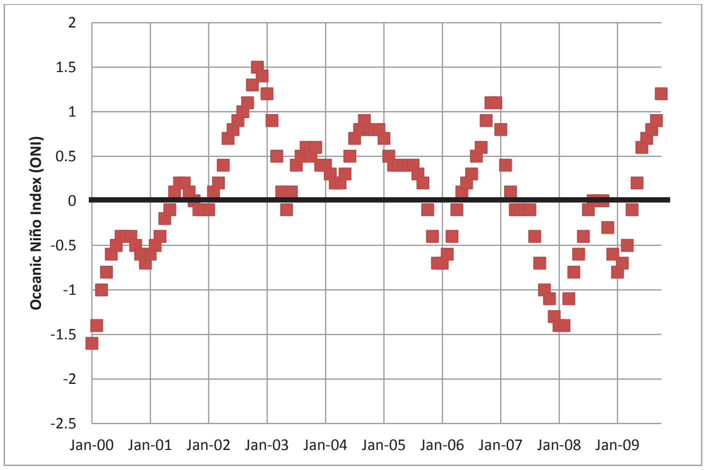


Fig. 1. The monthly Oceanic Niña Indices (ONI) of Niño 3.4 region during 1950s and 2000s.

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 NIŇO AND LA NIŇA 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

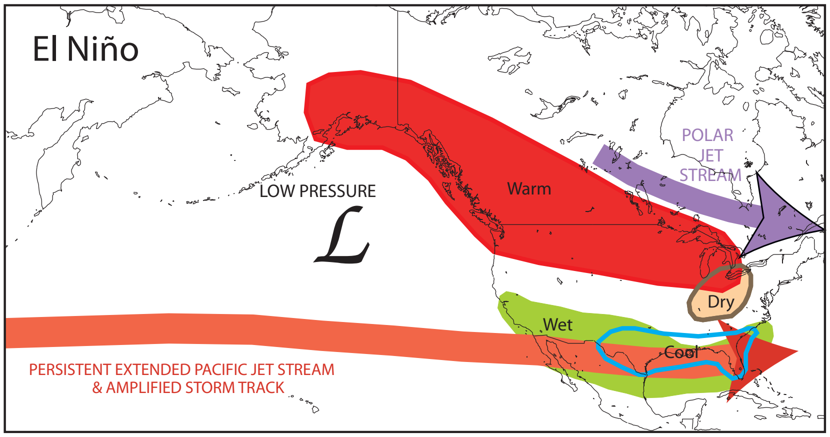
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Year	**DJF**	**JFM**	**FMA**	**MAM**	**AMJ**	**MJJ**	**JJA**	**JAS**	**ASO**	**SON**	**OND**	**NDJ**
1990	0.1	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.3	0.4
1991	0.4	0.3	0.3	0.4	0.6	0.8	1	0.9	0.9	1	1.4	1.6
1992	1.8	1.6	1.5	1.4	1.2	0.8	0.5	0.2	0	-0.1	0	0.2
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)

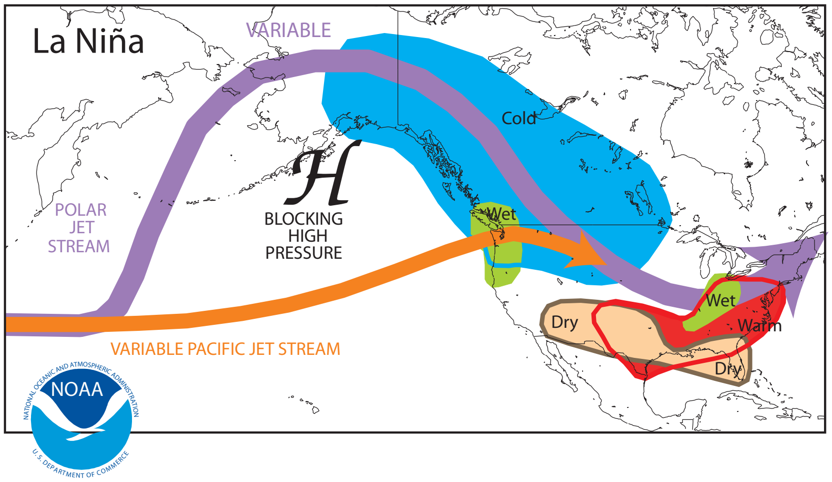
on floods in the southwestern United States. Piechota et al. (1979) analyzed flood data for 79 streamflow gaging stations in the western half of the United States and found eight regions for which flood peaks tend to co-vary with El Niño periods. None of the gaging stations for this study was in Texas, 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

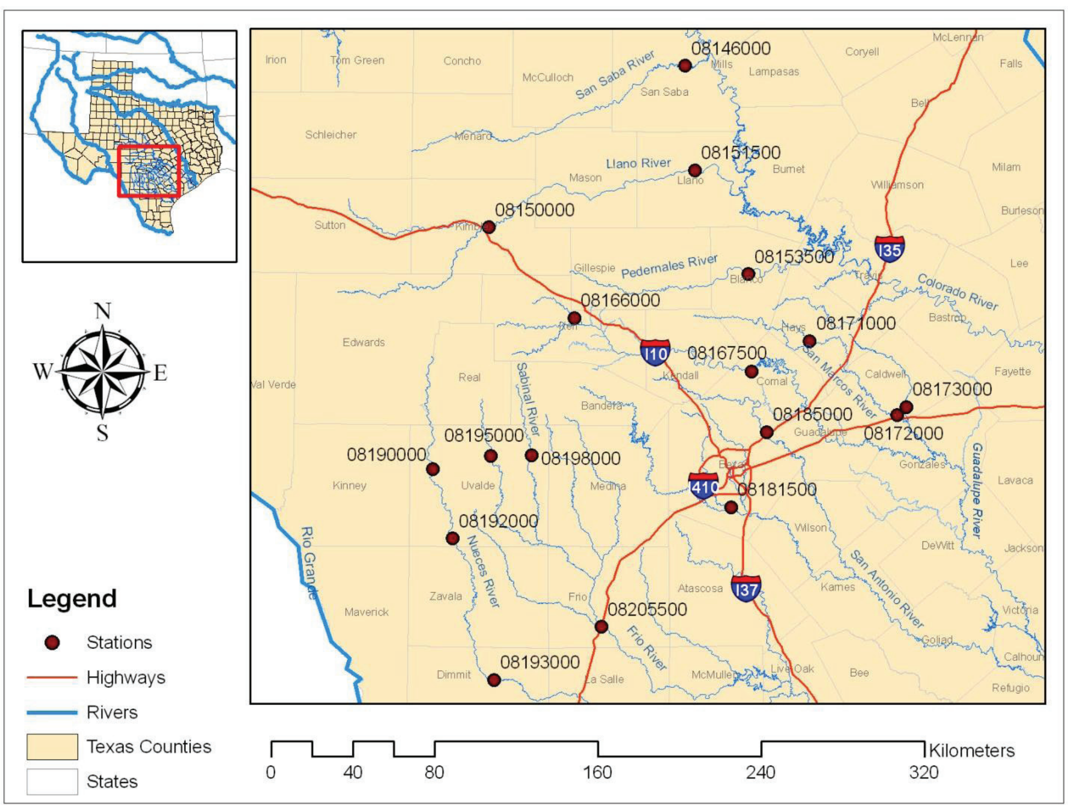


Fig. 3. Locations of streamflow-gaging stations used for analyses.

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

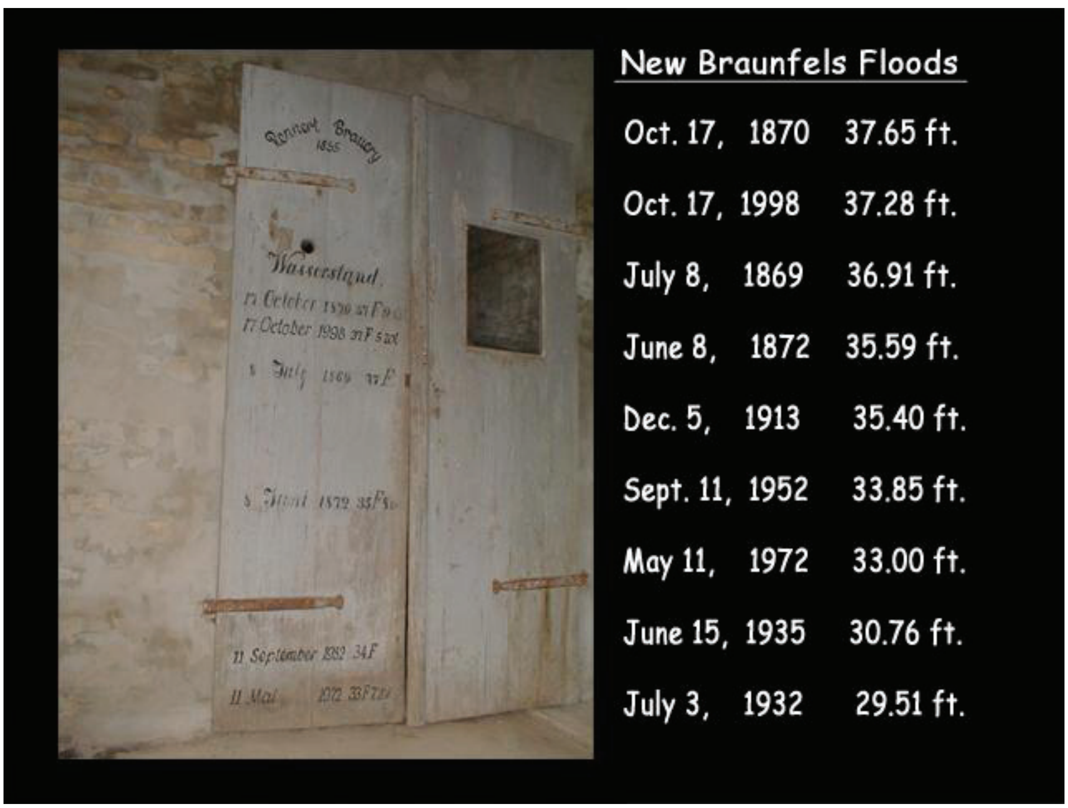


Fig. 4. Documented flood peak marks on the door of old brewery located on the bank of the Guadalupe River in New Braunfels, Texas.

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

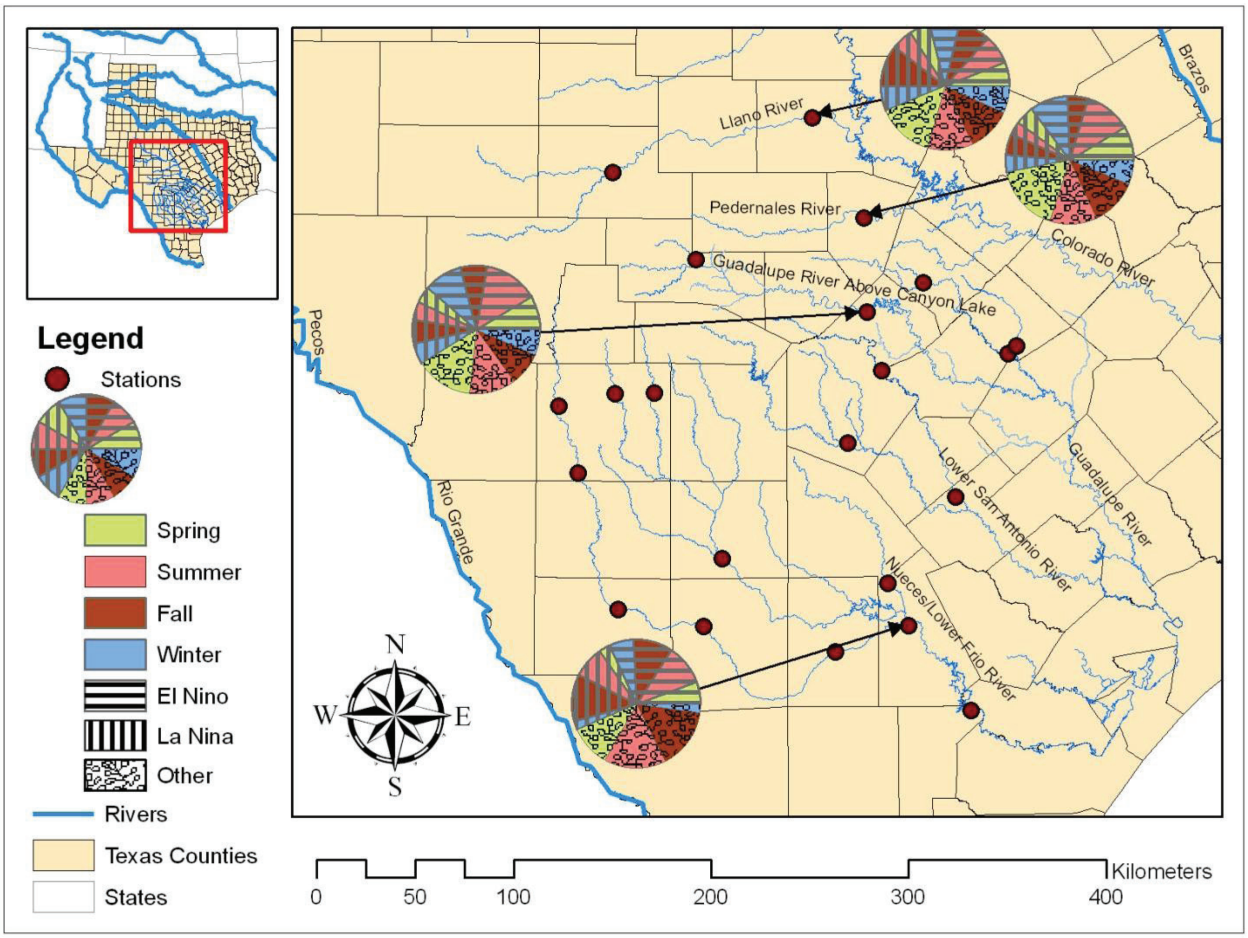


Fig. 5. Distribution of flow volumes by ENSO period and season for four streamflow-gaging stations used in the study.

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.

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