Temporal Trends in Precipitation and Hydrologic Responses Affecting the Barton Springs Segment of the Edwards Aquifer, Central Texas

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ABSTRACT

The Barton Springs segment of the Edwards Aquifer, a karstic aquifer in Central Texas, is the source of drinking water for an estimated 60,000 people, and its springs are habitat for endangered species. A substantial increase in the total discharge from the aquifer has occurred over the past 60 years. This paper reviews historical precipitation and hydrologic data from Central Texas and characterizes temporal trends proximate to the aquifer. The analyses focus on precipitation, streamflow, water-level, and springflow sites with long-term data (since 1930s) and within a 75-mile radius of Barton Springs. Data were analyzed with hydrographs, best-fit linear temporal trend lines, and statistical evaluations. Over the period of record by decade, annual mean temperatures increased up to 3%, annual precipitation increased about 13%, streamflows increased about 112%, and discharges at Barton Springs increased about 86%. Streamflow and springflow data indicate that a change to a wetter climate has occurred since the 1960s. For the period of record, low stream baseflows and springflows have increased only modestly compared to higher flows. However, over the past 30 to 40 years stream baseflows and low springflows have been decreasing despite the wetter climate since the 1960s. Significant increases in pumping during the last 40 years in the area are likely the major cause for this trend of decreasing stream baseflows and springflows. Decreasing stream baseflows and increased pumping will cause decreased water availability during future droughts. Higher flows during wet periods will not significantly decrease the impacts of droughts.

INTRODUCTION

The Barton Springs segment of the Edwards Aquifer (Barton Springs aquifer) is the sole or primary source of drinking water for an estimated 60,000 people. Barton Springs is habitat for the endangered Barton Springs salamander. Understanding the temporal hydrologic trends of the region is important for managing water resources. This paper reviews historical (1850s to present) hydrologic and meteorologic data from Central Texas to characterize the past and present trends in the hydrologic cycle influencing water resources, and in particular the Barton Springs aquifer.

Precipitation, air temperature, springflow, and streamflow data from Central Texas within a 75-mile radius of Barton Springs were aggregated and analyzed for this study (Fig. 1). The focus is on sites with long periods of record (extending through the 1950s drought) and on the upgradient (contributing zone) locations to the Edwards

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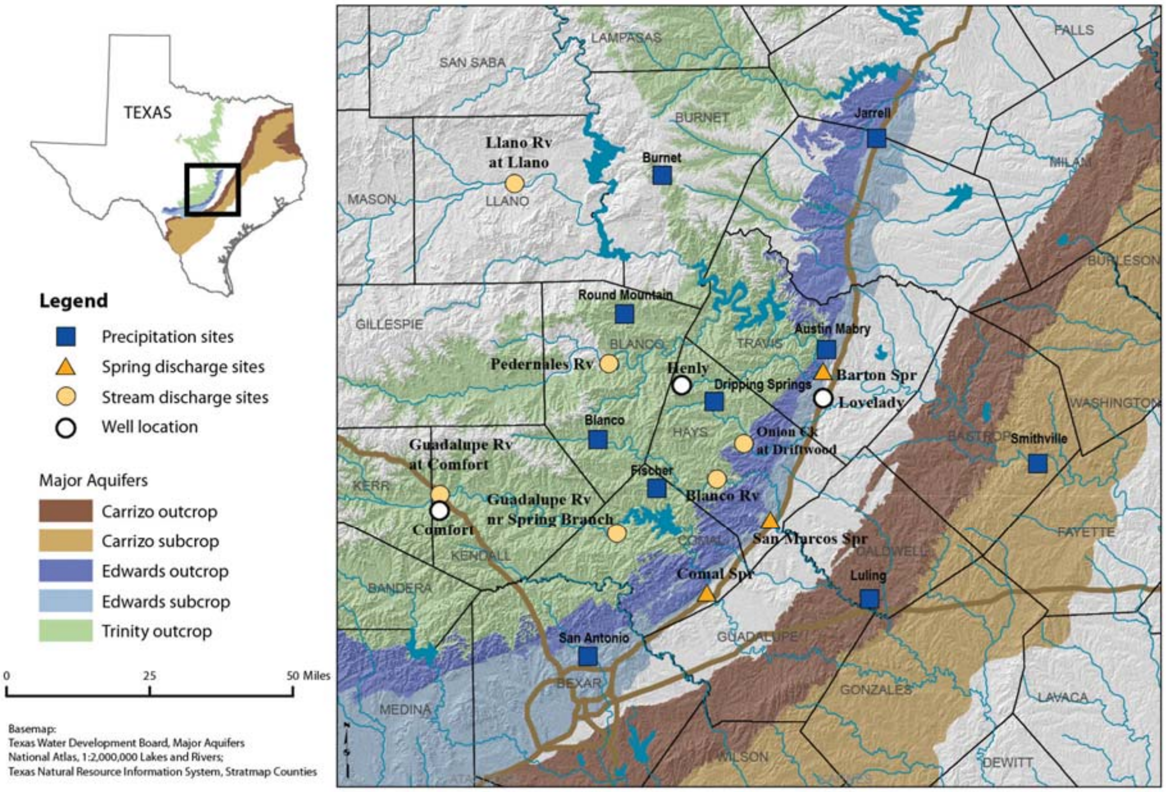


Figure 1. Location map of the study area, showing locations of data sites.

Aquifer. This resulted in data from ten precipitation, five streamflow, and three springflow sites. Additional data include regional pumping data and water levels from the Trinity and Edwards aquifers (Table 1).

Previous Work

Recent studies on climate and hydrology appear to present conflicting results for this region. Global Circulation Models show increasing temperatures and a general drying of Texas are expected presently and in the future (Banner et al., 2010). Although temperatures are increasing, there has been an overall increase in discharge from the Barton Springs aquifer over the period of record since 1917 (Sharp et al., 2009; Smith and Hunt, 2010). Below is a short summary of previous work relevant to this study.

Smith and Hunt (2010) compared the total water budget of the Barton Springs aquifer between recent (2009) and historic (1950s) droughts. They reported that there is nearly twice the amount of water available in the recent 2009 drought compared to the 1950s drought. This appears to be in contrast to a study by Loaiciga (2008) that concludes there has been no change in recharge to the San Antonio segment of the Edwards Aquifer since the 1930s.

Slade (2001) discussed short- and long-term precipitation and streamflow trends of Central Texas using statistics as in this report. Annual precipitation was reported to have a greater range more recently (1948–1999) than historically (1895–1947). The magnitude and variability of streamflow for the more recent period (1970–1999) greatly exceeded historical period (1940–1969). Subsequent studies by Slade (2007) discussed the 2006 drought's disproportionate impacts on decreasing baseflows of contributing streams and water-supply wells, relative to 2006 precipitation, and attributed the disproportionate impacts to increased levels of pumping from the Trinity Aquifer.

Table 1. Station and data inventory.

Site Name	Type	Source	Site ID	County	Start Year	Latitude	Longitude	Elevation (ft-msl)	Drainage Area (sq. mi.)	Comments
Blanco River at Wimberley, TX	Streamflow	USGS	08171000	Hays	1924	29.99417	-98.08861	797	355	
Pedernales River near Johnson City, TX	Streamflow	USGS	08153500	Blanco	1939	30.29167	-98.39917	1097	901	
Guadalupe River near Spring Branch, TX	Streamflow	USGS	08167500	Comal	1922	29.86028	-98.38333	948	1315	
Guadalupe River at Comfort, TX	Streamflow	USGS	08167000	Kendall	1939	29.96524	-98.89717	1371	839	
Llano River at Llano, TX	Streamflow	USGS	08151500	Llano	1939	30.90111	-98.66944	970	4197	
San Marcos Springs	Springflow	USGS	08170000	Hays	1947	29.88889	-97.93389	558	n/a	1947–1955 data from Lindgren et al., 2004
Comal Springs at New Braunfels, TX	Springflow	USGS	08168710	Comal	1940	29.70583	-98.12222	583	n/a	
Barton Springs at Austin, TX	Springflow	USGS	08155500	Travis	1917	30.26333	-97.77111	439	n/a	1917–1977 from Slade et al., 1986
Austin Mabry	PPT & Temp	NCDC	410428	Travis	1856	30.31822	-97.76071	670	n/a	
Blanco	PPT & Temp	NCDC	410832	Blanco	1931	30.10000	-98.43333	1380	n/a	
Burnet	PPT & Temp	NCDC	411250	Burnet	1931	30.76667	-98.23333	1285	n/a	
Luling	PPT & Temp	NCDC	415429	Caldwell	1903	29.68333	-97.65000	400	n/a	
San Antonio	PPT & Temp	NOAA	417945	Bexar	1871	30.31822	-97.76071	847	n/a	
Smithville	PPT & Temp	NCDC	418415	Bastrop	1931	30.01667	-97.15000	340	n/a	
Dripping Springs	PPT	PRISM	n/a	Hays	1930	30.21500	-97.98800	1120	n/a	
Fischer	PPT	Fischer	n/a	Comal	1890	29.97650	-98.26460	1150	n/a	
Jarrell	PPT	NCDC	414556	Williamson	1931	30.85000	-97.60000	850	n/a	
Round Mountain	PPT	NCDC	417787 (414033)	Blanco	1958	30.41667	-98.35000	1350	n/a	
Lovelady Well	Well	BSEACD	5850301	Travis	1950	30.21035	-97.78159	654	n/a	Edwards Aquifer
Comfort TWDB Well	Well	TWDB	6801314	Kendall	1984	29.97222	-98.89472	1405	n/a	Middle Trinity Aquifer
Henly Church Well	Well	HTGCD	5755401	Hays	1999	30.19629	-98.21244	1326	n/a	Middle Trinity Aquifer

BSEACD: Barton Springs/Edwards Aquifer Conservation District
TWDB: Texas Water Development Board
HTGCD: Hays Trinity Groundwater Conservation District
USGS: U.S. Geological Survey
NCDC: National Climate Data Center
NOAA: National Oceanic and Atmospheric Administration
PRISM: Prism Climate Group
Fischer: Fischer Store Records
PPT = precipitation
Temp = temperature

Asquith and Heitmuller (2008) presented streamflow statistics for all streamflow-gaging stations in Texas. Stations in the Texas Hill Country, such as the Blanco River at Wimberley, show an increase in streamflow (in a flow-duration curve) over the most-recent 10 years (1995–2005) compared to the period of record (1924–2005).

Changes in land use influence the hydrologic cycle in Central Texas. Urbanization increases recharge to the Edwards Aquifer (Sharp, 2010; Sharp et al., 2009). Sharp et al. (2009) discussed how the cumulative discharge from Barton Springs has increased since the 1920s, presenting two possible mechanisms for this, including increased rainfall in the contributing zones and increased urban recharge. They dismissed the former and presented compelling information on the influence of increased urbanization and resulting recharge. Management of Ashe juniper has also been documented to influence potential recharge (Banta and Slattery, 2011).

A paper by Mace and Wade (2008) discussed the potential impacts on Texas aquifers from climate change. They state that rapidly responding aquifers (like the Edwards Aquier) are more sensitive to impacts from climate change and would show little lag time.

Trends in water levels throughout Texas have been studied by Boghici (2011). He pointed out that, for the period of comparison (1995–2005), Central Texas experienced wetter-than-normal conditions with the Palmer Drought Severity Index (PDSI) greater than zero 50–75% time. However, he reported the median water level change for the Edwards was -0.5 ft. A map depicting results for the Trinity Aquifer in the Hill Country showed overall declines in water levels for Hays and Travis counties. Decreasing water-level trends of the Hill Country Trinity Aquifer are also described in Hunt and Smith (2010) and Wierman et al. (2010). Those studies indicate groundwater-level data from the Trinity Aquifer show declines of about 1 to 3 feet per year over the past 25 years in some areas.

To extend the instrumental climatic records, Cleaveland et al. (2011) used tree ring analysis. The results provide a record of reconstructed PDSI for south-central Texas from 1500–2008. The study documented frequent droughts, with equivalent and worse droughts than the historic 1950s drought. No trend analyses were done for that study that would relate to the more recent trends analyses of this study.

SETTING

The study area and data stations occur primarily within the Colorado and Guadalupe river basins of Central Texas. These major river systems flow from northwest to southeast to the Gulf of Mexico and are largely rural in nature except around the U.S. Interstate Highway 35 urban corridor between San Antonio and Austin. The Balcones Escarpment is a prominent physiographic feature within the study area and is developed along a zone of faulting characterized by a system of northeast-trending normal faults. The zone of faulting is known as the Balcones Fault Zone (BFZ). Land surface altitudes increase abruptly to the northwest at the Balcones Escarpment, rising hundreds of feet (400 feet to over 1000 feet). The focus of this study is on sites located primarily within the physiographic regions of the Texas Hill Country (eastern Edwards Plateau) and Blackland Prairies of Central Texas. These two physiographic regions are underlain by the Trinity and the Edwards aquifers, respectively (Fig. 1).

The Hill Country Trinity Aquifer is composed of a heterogeneous package of Lower Cretaceous-age limestones and dolostones. The aquifer units are locally faulted and fractured and karstic. Recharge to the aquifer occurs through direct precipitation and infiltration and along losing stream reaches of the various rivers. Recharge is estimated to be about 4 to 6% of total annual rainfall (Jones et al., 2011). Surface discharge from the Trinity occurs from wells, seeps, and springs. Seeps and springs provide baseflow to the creeks and rivers that flow through the Hill Country and recharge the Edwards Aquifer (Fig. 2). The reader is referred to Barker et al. (1994), Ryder (1996), Mace et al. (2000), and Wierman et al. (2010) for a detailed description of the hydrogeology of the Trinity Aquifer.

The Edwards Aquifer is composed of lower Cretaceous-age limestones and dolostones. The aquifer units are highly fractured and faulted and karstic. Recharge to the aquifer occurs through direct precipitation and infiltration, but primarily along losing stream reaches of the various creeks that cross the outcrop of the Edwards (Slade et al., 1986). Groundwater flow is very rapid with well-documented conduit flow (Hauwert et al., 2004). Discharge from the Edwards occurs from wells and from some of the largest springs in Texas such as Comal, San Marcos, and Barton Springs. The reader is referred to Ryder (1996), Scanlon et al. (2001), and Lindgren et al. (2004) for an overall summary of the hydrogeology of the Edwards Aquifer.

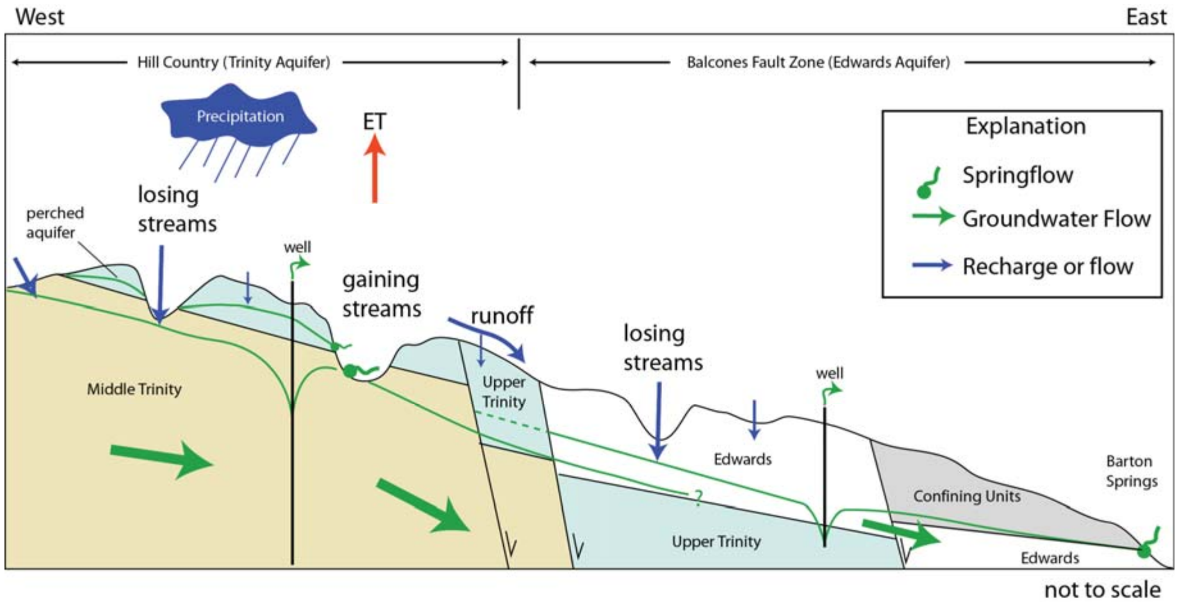


Figure 2. Conceptual hydrologic and hydrogeologic cross section through the study area.

The eastern portion of the study area corresponds to the western edge of the interior Coastal Plains and is underlain by the Cenozoic-age sand and gravel comprising the Carrizo/Wilcox Aquifer. The northwestern part of the study area is within the Llano Uplift, a topographic basin exposing various fractured Precambrian- and Paleozoic-age aquifers (Fig. 1). Hydrologic trends and their influence on groundwater resources in the northwestern and eastern areas are not the focus of this paper.

Climate and Runoff

Most of the study area is humid subtropical, characterized by hot summers and dry mild winters (Larkin and Bomar, 1983), with protracted wet and dry periods (Diaz, 1983). Potential evaporation exceeds precipitation. Annual average rainfall for Austin's Camp Mabry is 33.4 inches (1856–2010) with a range of 64.7 inches (1919) to 11.4 (1954). Rainfall is fairly evenly distributed throughout the year; the maximum monthly average precipitation is bimodal and generally occurs in May with a secondary peak occurring in September.

Large rainstorms (May-July) are caused by warm and cold fronts encountering moisture-laden air from the Gulf. Tropical storms, depressions, and hurricanes originating in the Gulf and oceans typically occur in September and October. The triggering of large storms by meteorological conditions is also aided by the orographic effect of the Balcones Escarpment (Slade, 1986). Consequently, the study area has some of the most intense rainfall per drainage area in the world and flooding is greater in the Balcones Escarpment than in any other region in the U.S. Factors contributing to flooding include: the intense (though non-uniform) storms; rapid runoff due to steep slopes; and limited infiltration due to exposed bedrock, relatively thin soils, and sparse vegetation (Caran and Baker, 1986).The relationship between annual precipitation and annual runoff is relatively poor because the majority of runoff is produced by large individual or clustered storms. About three to four large storms produce about three quarters of the annual runoff volume most years in the Texas Hill Country. For some years, there may be four or five large runoff-producing storms, but little additional precipitation, so annual precipitation totals are normal, but runoff is high. Antecedent moisture is also a major controlling factor to runoff. Minor precipitation events generate wetter soils and therefore more runoff.. Accordingly, changes in climate that affect the intensity and duration of precipitation events may be a significant influence on runoff.

Weather and climate in Texas are strongly influenced by atmospheric jet stream patterns from the South Pacific. Slade and Chow (2011) discussed the influence of El Niño Southern Oscillation (ENSO) on precipitation, and runoff volumes and annual peaks in the streams of Central Texas. They conclude that more precipitation and runoff generally occurs during El Niño, and less precipitation and runoff during La Niña periods.

Conceptualized Hydrologic and Hydrogeologic Model

The focus of this paper is on the trends in the hydrologic cycle influencing the Trinity and Edwards aquifer systems in Central Texas. Figure 2 is a schematic cross section depicting the conceptualized hydrologic system of the study area. The majority (~85%) of annual precipitation falling within the Hill Country is lost to evapotranspiration (Banta and Slattery, 2011). About 4 to 6% of annual rainfall is recharged into the Trinity Aquifer (Jones et al., 2011). The remaining percentage of annual precipitation generates runoff for the creeks that flow through the Hill Country. Those same streams provide recharge to the Trinity Aquifer in losing stretches. Some portions of the streams are gaining and support baseflows (Wierman et al., 2010). Baseflows, combined with runoff, flow downstream, and enter the BFZ, and subsequently provide the primary source of recharge to the Edwards Aquifer along numerous losing stream reaches (Slade, 1986).

METHODS AND DATA

The approach and methods used in this study consist of elementary statistical evaluations of hydrologic data. Hydrographs were constructed of streamflow and springflow data using mean monthly, mean annual, and mean annual by decade data. Precipitation data were plotted using running totals and mean annual totals by decade. Percentiles of streamflow and springflow were computed for the sites for each decade. Best-fit trend lines were plotted to show overall trends. Some data gaps exist in historic precipitation records, which were populated with data as discussed in Gary et al. (2011).

Terms and Expressions

A percentile is the value of a variable (such as springflow) below which a certain percent of observations occur. For this study, low flows are defined as equal to or less than the 25th percentile, also known as the lower quartile (Q1). Low-flow percentiles, low flows, and baseflows are synonymous in this paper. High flows are equal to or greater than the 75th percentile, also known as the third quartile (Q3). The interquartile range (IQR) is a measure of difference between the Q1 and Q3 and is a measure of the variability of data.

Trend Slope

In order to more readily compare and normalize the changes over time for the various data sets, the trend slope was calculated. For the purposes of this study the trend slope represents the mean change as a percent over the period of record. The trend slope is computed using the total change in values spanning the linear best-fit trend line (derived from Microsoft Excel), divided by the value at the beginning of the trend line (Fig. 3).

Data Sources

Data used in this study are readily available to the general public and are listed in Table 1. The authors purchased monthly precipitation totals and monthly mean temperature data from the National Climatic Data Center (NCDC, 2012) for most precipitation sites, with a few exceptions. Annual data for the Fischer precipitation were obtained from records in Fischer, Texas—a long-standing member of the the National Oceanic and Atmospheric Administration's (NOAA's) National Weather Service Cooperator Program (NWS-COOP, 2012). Annual data for Dripping Springs were extracted from the PRISM (Parameter-elevation Regressions on Independent Slopes Model) Climate Group data (PRISM, 2012).

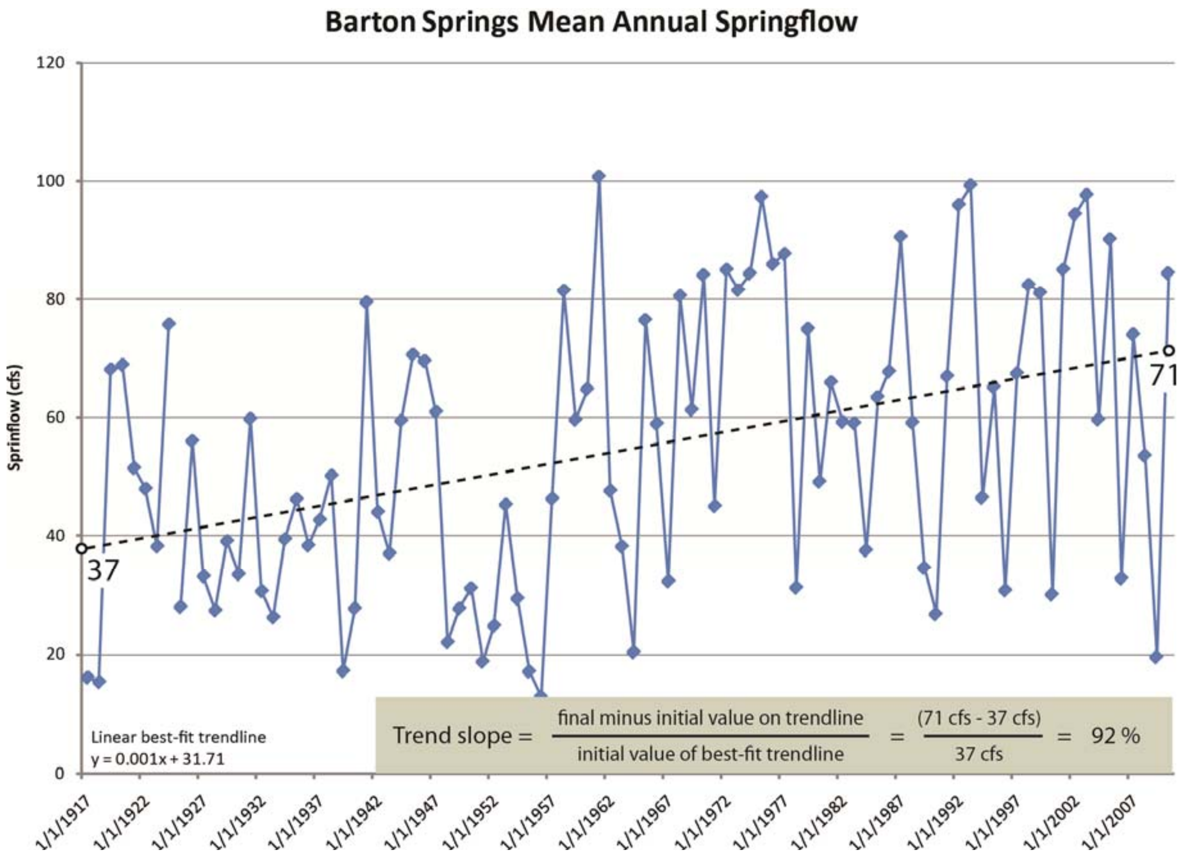


Figure 3. Example of the calculation of the trend slope using the hydrograph of mean annual Barton Springs flow.

The U.S. Geological Survey (USGS) is the source for all mean monthly and mean annual streamflow and springflow data used in this study, with a few exceptions. Mean monthly springflow values for Barton Springs from 1917 to 1978 were obtained from a USGS report by Slade (1986). Digital historic data for Comal and San Marcos Springs were obtained from the USGS, as originally published in Lindgren et al. (2004) (Table 1). The period of record for most precipitation and streamflow sites in this study begins about 1930 and extend to the present. A few sites have data that extend into the late 1800s (Table 1).

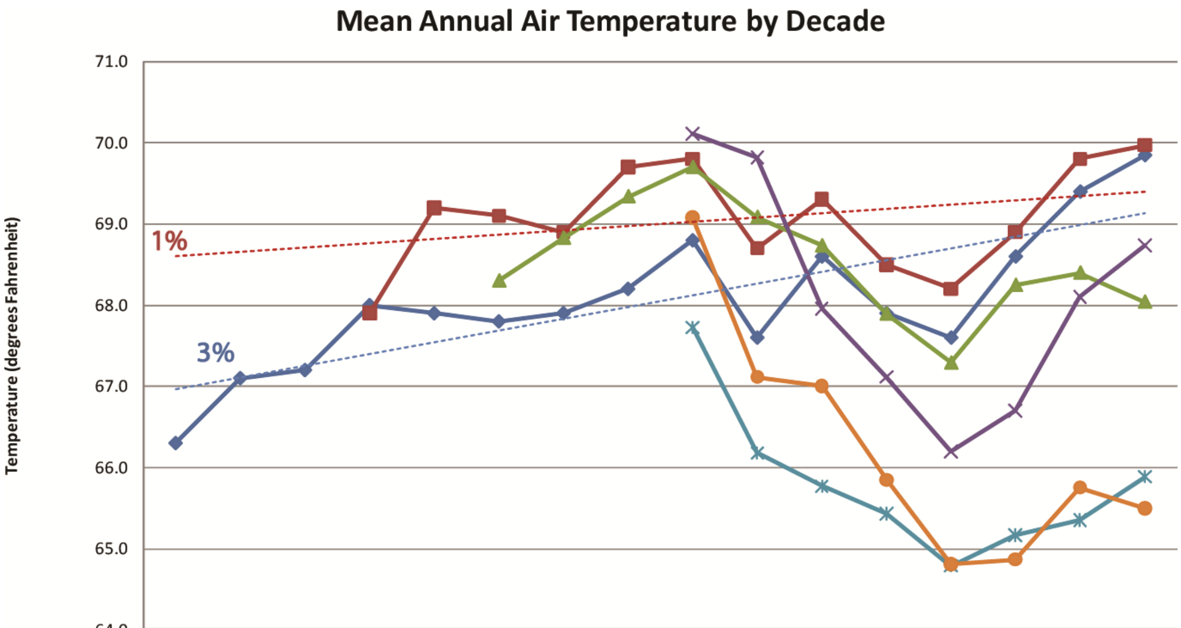
Water-level data for the water wells in this study came from the Barton Springs/Edwards Aquifer Conservation District (BSEACD, unpub. data), Texas Water Development Board (TWDB, 2012a), and the Hays Trinity Groundwater Conservation District (HTGCD, 2012) (Table 1).

Mean monthly pumping data for the Barton Springs aquifer were obtained from the BSEACD (unpublished data) and Hunt et al. (2006). Annual estimates of pumping for the Hill Country Trinity Aquifer were obtained from Jones et al. (2011), and the most-recent estimate from 2008 was derived from Hutchison and Hassan (2011).

RESULTS

Air Temperature

Figure 4 shows the mean annual air temperature by decade for the study area. Mean annual temperatures have increased up to 3% over the period of record (1850–2009). The data from all stations follow a similar pat-



	1850-1859	1860-1869	1870-1879	1880-1889	1890-1899	1900-1909	1910-1919	1920-1929	1930-1939	1940-1949	1950-1959	1960-1969	1970-1979	1980-1989	1990-1999	2000-2009
Austin	66.3	67.1	67.2	68.0	67.9	67.8	67.9	68.2	68.8	67.6	68.6	67.9	67.6	68.6	69.4	69.9
San Antonio				67.9	69.2	69.1	68.9	69.7	69.8	68.7	69.3	68.5	68.2	68.9	69.8	70.0
Luling						68.3	68.8	69.3	69.7	69.1	68.7	67.9	67.3	68.2	68.4	68.0
Smithville									70.1	69.8	68.0	67.1	66.2	66.7	68.1	68.7
Blanco									67.7	66.2	65.8	65.4	64.8	65.2	65.4	65.9
Burnet									69.1	67.1	67.0	65.8	64.8	64.9	65.8	65.5

Figure 4. Mean annual air temperature by decade. Dashed lines indicate best-fit trend lines with Austin Mabry showing a mean increase of about 3%, and San Antonio a mean increase of about 1%. Temperatures over the last 30 years have steadily increased about 1 to 2 degrees Fahrenheit at most stations.

tern over time since the 1930s. Only Austin, San Antonio, and Luling have continuous data prior to 1930. Those stations also show a similar pattern. There has been an overall increase in temperature by about 3 degrees Fahrenheit since the 1850s in Austin. The 1920s and 1930s were relatively warm, indeed the hottest decades for some stations, and were followed by a relatively cool (and wet) period centered around the 1970s. Temperatures over the last 30 years have increased by about 1 to 2 degrees Fahrenheit at most stations, and at a greater rate of increase than historic increases (Fig. 4).

Precipitation

The study area has had an overall increase in precipitation over the period of record—especially since the 1960s. Precipitation data were plotted in Figure 5 as a running 4-year total of precipitation from selected sites. Most stations show an increasing (positive) best-fit trend line when plotted in this manner. Figure 6 is a plot of mean annual precipitation by decade for each of the ten stations. Table 2 presents summary statistics of the precipitation by site. Mean annual change in precipitation as a percent (trend slope) are positive (increasing) for all stations, and the average for all sites is about 13% over the period of record.

The notable exception to the increasing precipitation trend is the Austin site. Austin has a nearly flat best-fit trend line with a trend slope of only 2%, relatively unchanged.

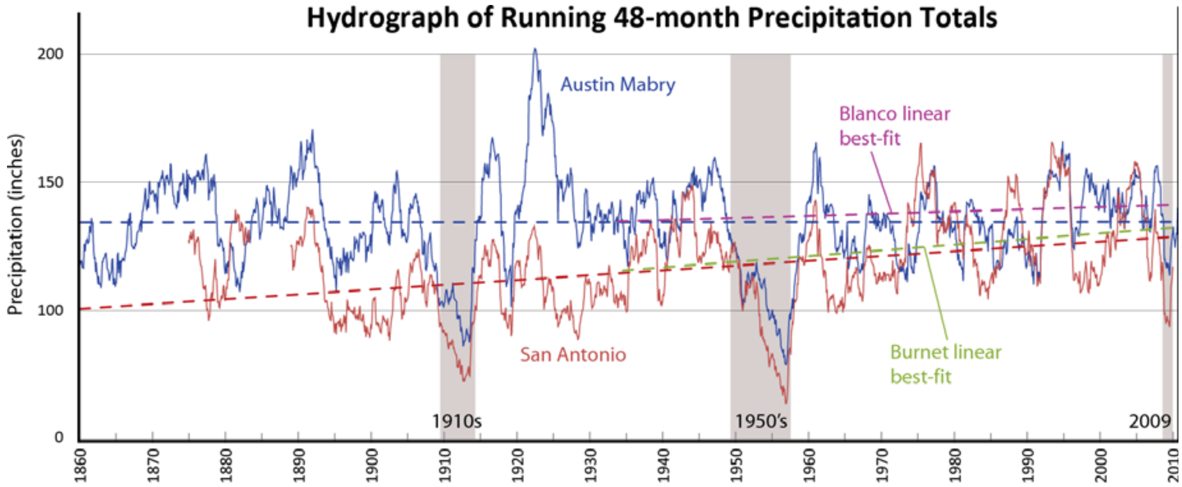


Figure 5. Hydrograph of running 48-month precipitation totals from selected stations. Note the best-fit trend lines are positive for all the stations except Austin Mabry, which is relatively flat.

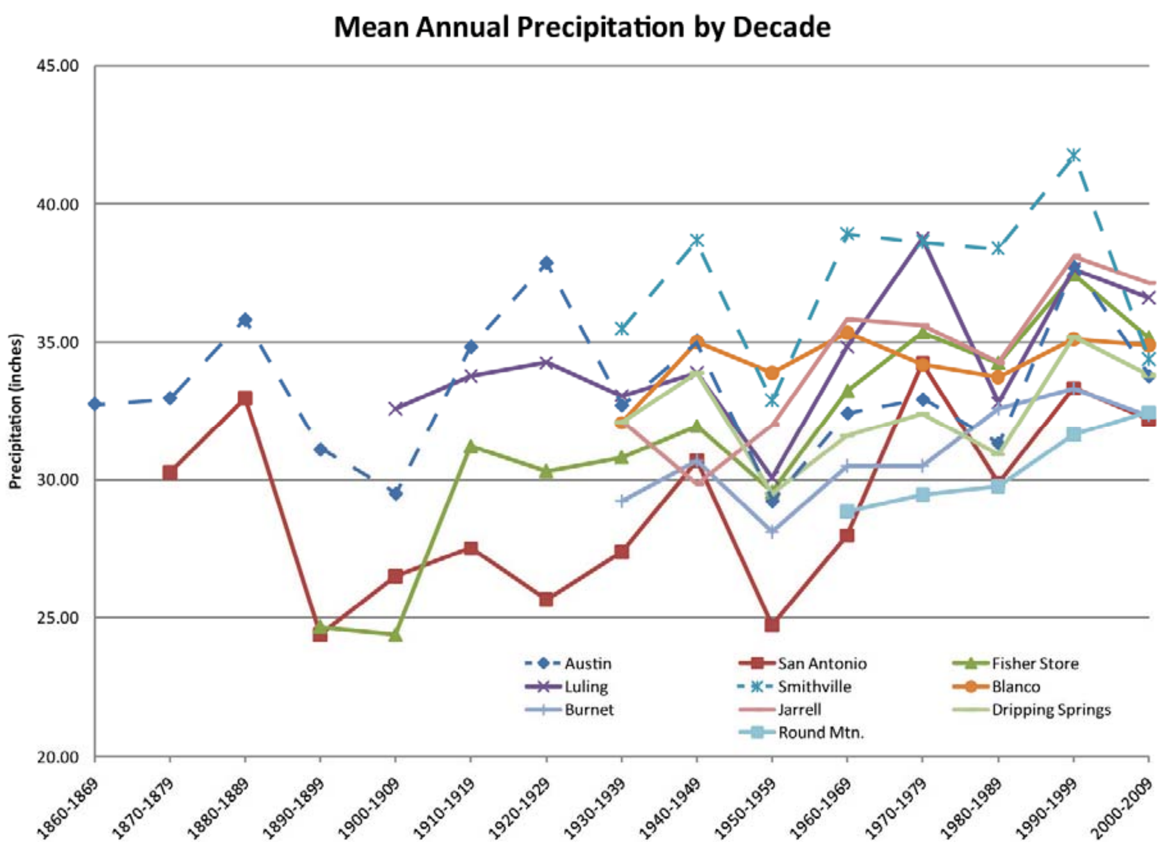


Figure 6. Hydrograph of mean annual precipitation by decade for all sites. All sites have a positive (increasing) trend, except for Austin Mabry and Smithville indicated by dashed lines.

Table 2. Mean annual precipitation (inches) by decade for each station.

Rainfall by decade	Austin	San Antonio	Fisher Store	Luling	Smith-ville	Blanco	Burnet	Jarrell	Dripping Springs	Round Mtn.
1860–1869	32.77									
1870–1879	32.98	30.26								
1880–1889	35.82	32.98								
1890–1899	31.09	24.39	24.69							
1900–1909	29.50	26.51	24.39	32.59						
1910–1919	34.83	27.52	31.20	33.77						
1920–1929	37.88	25.66	30.31	34.26						
1930–1939	32.71	27.39	30.80	33.07	35.51	32.08	29.23	32.11	32.10	
1940–1949	35.06	30.67	31.95	33.88	38.69	35.01	30.67	29.83	33.90	
1950–1959	29.22	24.73	29.55	30.07	32.88	33.90	28.13	31.99	29.50	
1960–1969	32.43	27.98	33.24	34.83	38.92	35.35	30.50	35.83	31.60	28.83
1970–1979	32.93	34.24	35.35	38.75	38.63	34.18	30.49	35.60	32.40	29.45
1980–1989	31.32	29.89	34.25	32.80	38.39	33.73	32.59	34.26	30.90	29.76
1990–1999	37.74	33.34	37.45	37.65	41.77	35.12	33.33	38.12	35.20	31.63
2000–2009	33.78	32.22	35.16	36.62	34.39	34.89	32.34	37.13	33.80	32.46
Mean (inches)	33.34	29.13	31.53	34.39	37.40	34.28	30.91	34.36	32.43	30.43
Mean change as % (Trend Slope)	2%	14%	37%	12%	5%	4%	14%	22%	6%	13%

Streamflow

Streamflows increased about 112% over the period of record (1930–2007) with a significant shift to higher flows since about 1960 (Figure 7 and Table 3). Mean streamflows after 1960 increased 67 cubic feet per second (cfs) for the Blanco River and 24 cfs for Barton Springs. Figure 8 includes the trend line for the Blanco and all other streamflow sites, which show a similar increasing trend. Table 3 summarizes flow by decade and trend slope for the streams. However, linear best-fit trendlines do not adequately characterize the entire flow regime over time.

Figure 9 illustrates that the flows are not uniformly increasing each decade when flow percentiles for the Blanco River are examined. Most annual high-flow percentiles are increasing each decade with more modest increases for low-flow percentiles. Minimum flows appear relatively unchanged, while the variability of flow as represented by the inter-quartile range is increasing (Fig. 9). This is consistent for most stream sites evaluated in this study. Figure 10 shows baseflows, as represented by the 10th flow percentiles, for all stream sites in this study. Figure 11 shows high flows, as represented by the 90th flow percentiles, for all stream sites in this study. The last 30 to 40 years have resulted in increasing high flows for nearly all stream sites (Fig. 11). At the same time, the low-flow percentiles and minimum flows are decreasing (Fig. 10).

The Llano River at Llano is an exception to the observed trends of other river sites. In contrast to other rivers, low-flow data over the last 40 years are relatively unchanged (Fig. 10). High-flow data over the period of record are relatively unchanged, and over the past 30 to 40 years have decreased (Fig. 11).

Groundwater Levels

Few continuous water-level datasets from monitor wells exist compared to the precipitation, streamflow, and springflow data in the study area. However, a few wells with relatively long periods of water-level data exist showing discernable trends (Fig. 1 and Table 1). Figures 12 and 13 are hydrographs from the Middle Trinity and Edwards aquifers, respectively. As these figures and previous investigations demonstrate, water levels in the Trinity Aquifer have been steadily declining throughout the period of record (1980s to present). Water-level data show a decrease of about 2 to 4 feet per year and have a trend slope of -3% over the period of record (Fig. 12). Figure 13 is a hydrograph of the drought-trigger well for the District (BSEACD). The well has periodic data

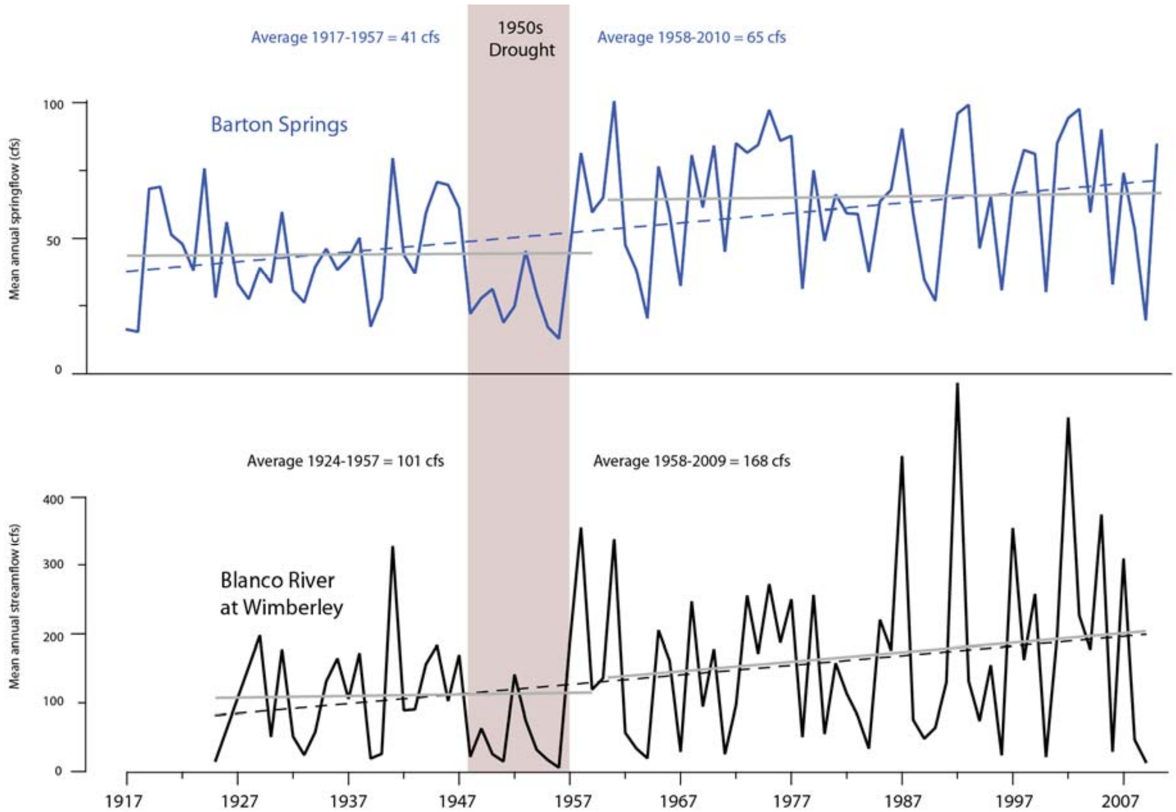


Figure 7. Hydrograph of mean annual flow for Barton Springs and the Blanco River at Wimberley. Dashed lines represent the linear best-fit trendlines. Grey lines indicate trendlines prior to 1960 and after 1960. There is a visible shift in the hydrograph after the 1950s drought of record to wetter and higher flow conditions. Mean streamflows after 1960 increased by 67 cfs for the Blanco River. Mean springflows after 1960 increased by 24 cfs for Barton Springs.

Table 3. Mean annual flow by decade.

Flow by decade	Barton Springs	Barton Springs Total Discharge (Springflow + pumping)	Guad. River near Spring Branch	Comal Springs	Blanco River	Guad. River near Comfort	Peder-nales River	Llano River	San Marcos Springs
1910–1919	33	33							
1920–1929	47	47	185						
1930–1939	38	38	328	330	96				
1940–1949	50	50	307	329	123	173	166	301	
1950–1959	37	37	195	186	98	96	157	305	167
1960–1969	58	60	258	264	132	148	137	329	152
1970–1979	76	79	536	345	175	307	263	498	188
1980–1989	59	63	457	261	142	293	197	371	158
1990–1999	66	71	510	286	192	286	257	459	181
2000–2009	64	71	551	336	191	308	239	387	194
Mean	53	55	370	292	144	230	202	378	173
Mean change as % (Trend Slope)	86%	124%	189%	4%	102%	154%	70%	42%	17%

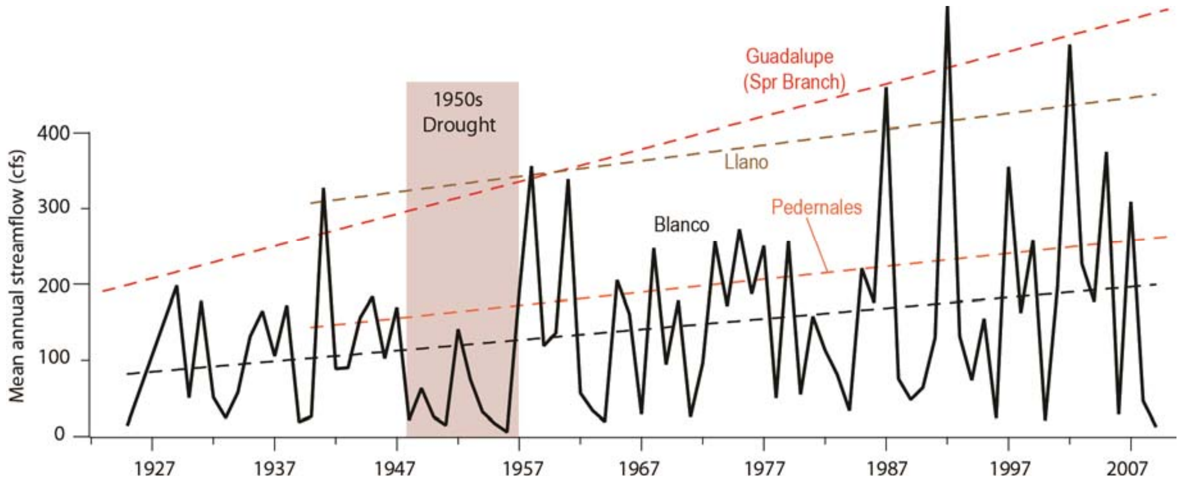
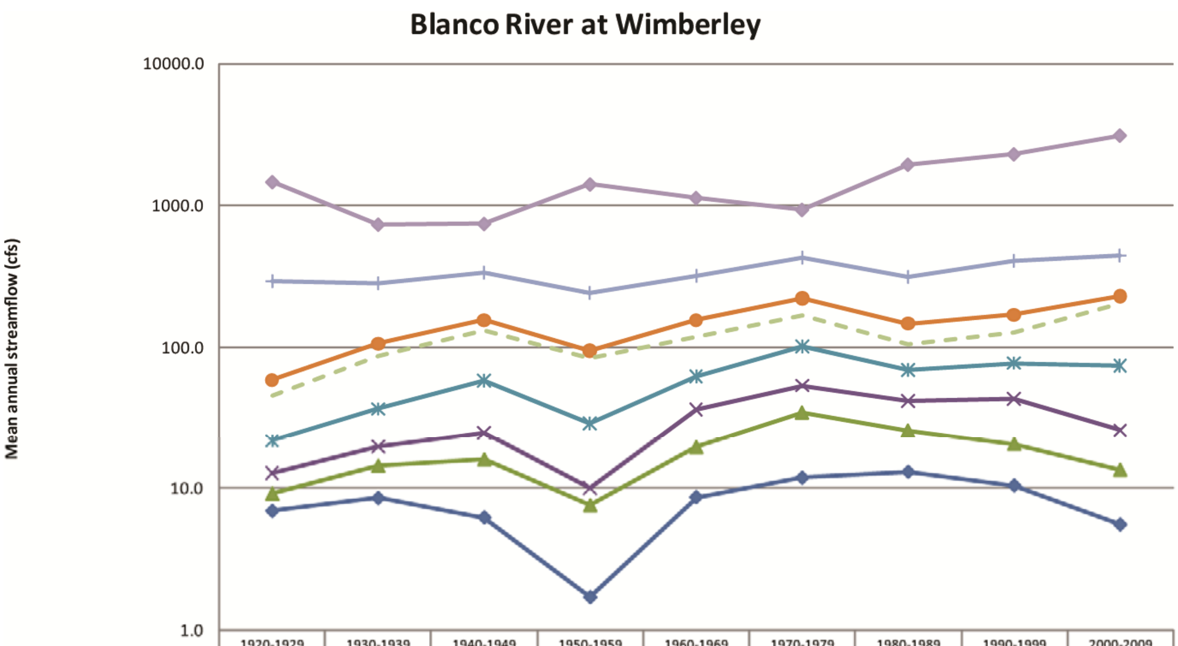
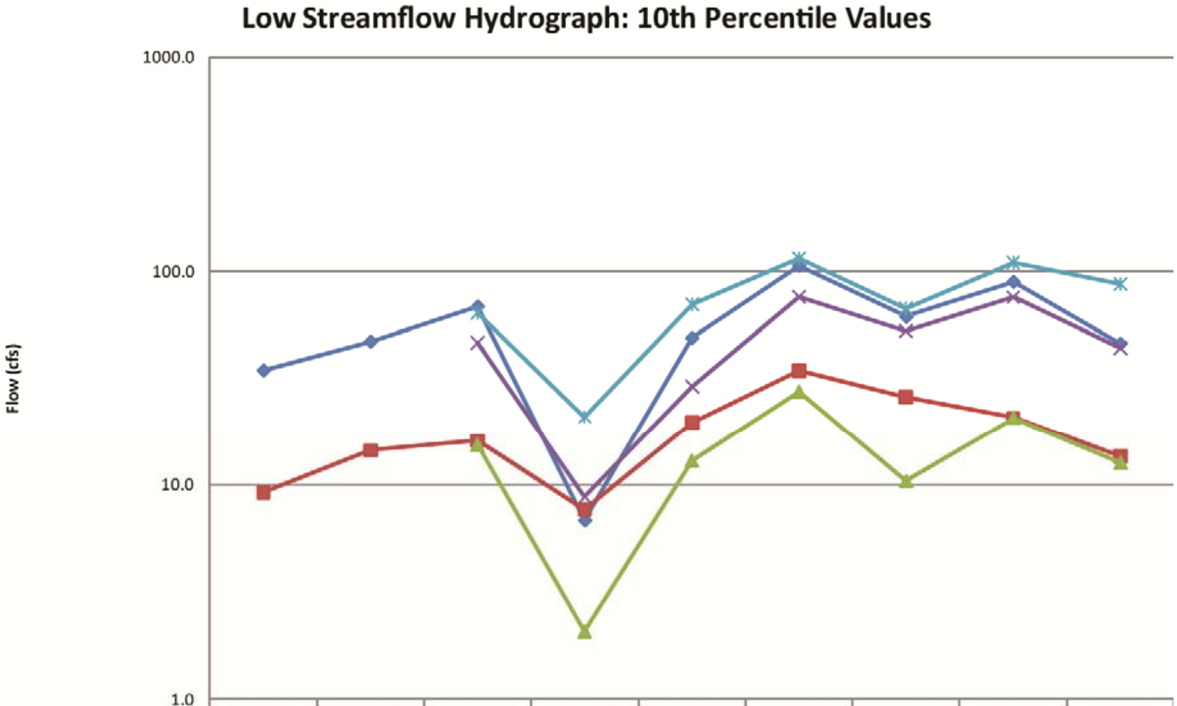


Figure 8. Hydrograph of mean annual flow for the Blanco River with a best-fit line plotted. Linear best-fit lines are also plotted for other streams in this study and all show a positive trend over time.



	1920-1929	1930-1939	1940-1949	1950-1959	1960-1969	1970-1979	1980-1989	1990-1999	2000-2009
Minimum	6.9	8.5	6.2	1.7	8.7	11.9	13.1	10.5	5.6
10th percentile	9.2	14.5	16.1	7.7	19.7	34.5	25.8	20.7	13.6
25th Percentile	12.8	19.9	24.9	10.1	36.3	53.8	41.6	43.3	26.0
50th Percentile	21.8	36.8	58.2	29.1	62.3	101.4	69.0	77.5	73.9
75th Percentile	58.8	106.1	155.4	94.1	155.4	222.5	147.2	169.3	228.8
90th Percentile	292.5	281.2	336.4	241.2	319.8	428.1	311.9	407.4	441.5
Maximum	1470.0	735.5	743.9	1413.0	1134.0	935.4	1950.0	2308.0	3130.0
Inter Quartile Range (IQR)	46.0	86.2	130.5	84.0	119.1	168.7	105.6	126.0	202.8

Figure 9. Hydrograph of Blanco River (at Wimberley) with flow statistics by decade. High-flow percentiles are getting higher, while low-flow percentiles are flat or decreasing in recent decades. Note logarithmic scale.



	1920-1929	1930-1939	1940-1949	1950-1959	1960-1969	1970-1979	1980-1989	1990-1999	2000-2009
Guadalupe Spring Branch	34.6	47.2	68.7	6.8	49.1	106.7	61.6	89.6	46.1
Blanco River at Wimberley	9.2	14.5	16.1	7.7	19.7	34.5	25.8	20.7	13.6
Pedernales			15.4	2.1	13.0	27.4	10.4	20.6	12.7
Guadalupe Nr Comfort			46.6	8.8	29.0	76.0	52.6	75.7	44.0
Llano River			63.9	20.9	70.0	115.3	67.3	110.3	87.0

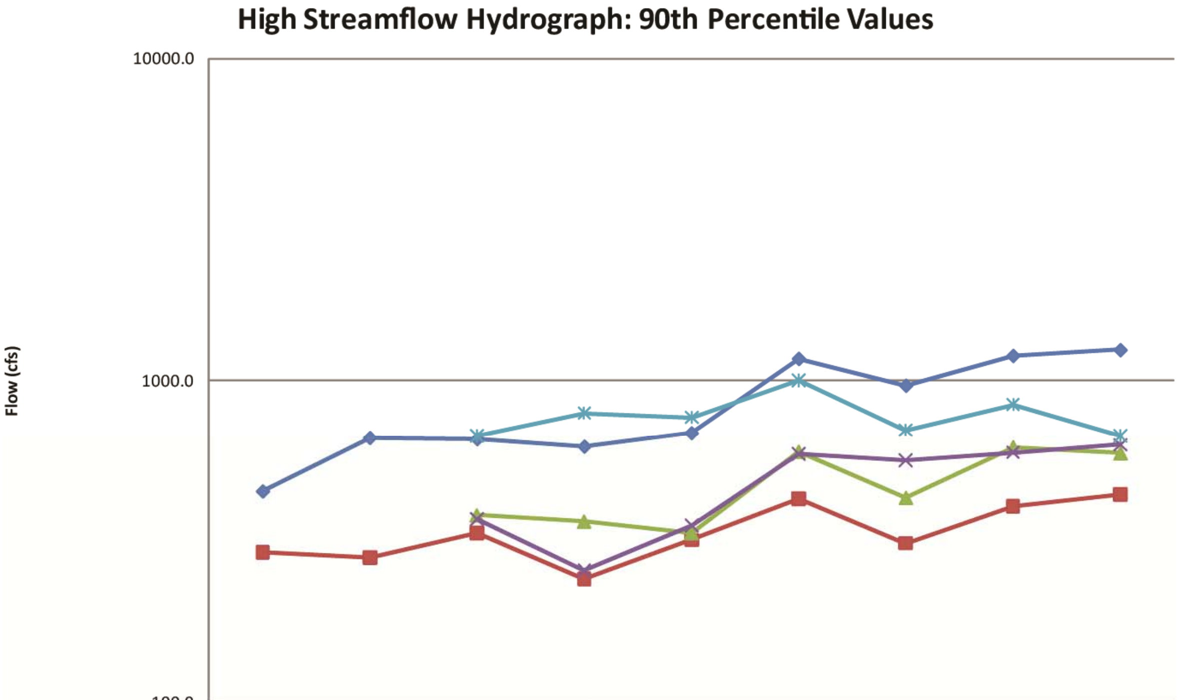
Figure 10. Low-flow hydrograph by decade as represented by the 10th percentile values. Note logarithmic scale.

from the 1950s until the 1990s when daily data were collected. Median values by decade were calculated to normalize the data density each decade. The median values have a positive trendline with a trend slope of about 7% over the period of record. However, after about 1960 the trend is relatively unchanged, suggesting a new equilibrium in storage was reached (Fig. 13).

Pumping

Pumping in the Edwards and Trinity aquifers has increased substantially since the 1950s. Figure 14 is a hydrograph showing the magnitude and trend of pumping in the region. Pumping from the Barton Springs segment of the Edwards Aquifer has been metered since about 1987 (Hunt et al., 2006). An estimate of pumping in the 1950s of about 472 acre-feet per year was reported in Brune and Duffin (1983). Pumping from the 1950s to the 1980s was extrapolated (Kirk Holland, 2010, pers. comm.).

Pumping data for the Trinity Aquifer were obtained from estimates within the modeling report by Jones et al. (2011). A more recent 2008 estimate is derived from Hutchison and Hassan (2011). No estimates of Trinity pumping between 1998 and 2008 were available.



	1920-1929	1930-1939	1940-1949	1950-1959	1960-1969	1970-1979	1980-1989	1990-1999	2000-2009
Guadalupe Spring Branch	453.7	665.6	659.8	625.1	688.7	1173.0	968.4	1198.6	1248.2
Blanco River at Wimberley	292.5	281.2	336.4	241.2	319.8	428.1	311.9	407.4	441.5
Pedernales			381.7	365.1	336.4	601.7	432.6	621.6	594.7
Guadalupe Nr Comfort			370.7	256.7	355.2	592.8	565.9	598.5	632.3
Llano River			672.8	794.5	770.3	1005.8	702.5	844.4	674.0

Figure 11. High-flow hydrograph by decade as represented by the 90th percentile values. Note logarithmic scale.

Springflow

Hydrographs of mean annual flow from Comal, Barton, and San Marcos Springs have a similar pattern, with an overall increasing linear best-fit trendline over the period of record. This increasing trend suggests more water within the Edwards Aquifer over time (Fig. 15). However, similar to the streamflow hydrographs, simple best-fit trendlines do not adequately describe the entire flow regime.

Figures 16–18 are hydrographs of flow percentiles by decade for Barton, San Marcos, and Comal springs, respectively. The total discharge (pumping plus springflow) from the Barton Springs aquifer is also presented in Figure 16 (dashed lines).

Evaluation of flow percentiles reveals a similar trend between San Marcos and Barton springs, but divergent trends when those are compared with Comal Springs. Median and high-flow percentiles for Barton and San Marcos springs are increasing each decade, indicating more high-flow springflow is occurring each decade. Barton Springs may have an upper discharge limit (and recharge limit), as the maximum flow is flat, while San Marcos Springs appears less constrained as the maximum values increase each decade. The variability of Barton and San Marcos Springs is also increasing each decade as shown by the IQR (Figs. 16 and 17). Over the last 30 years, high-flow percentiles and variability have increased significantly at Barton and San Marcos Springs when compared to the low-flow percentiles.

Low-flow percentiles at Barton Springs over the past 30 years have been decreasing (Fig. 16). The trends of total discharge (dashed lines in Fig. 16) are similar to springflow, but shift in magnitude corresponding to in-

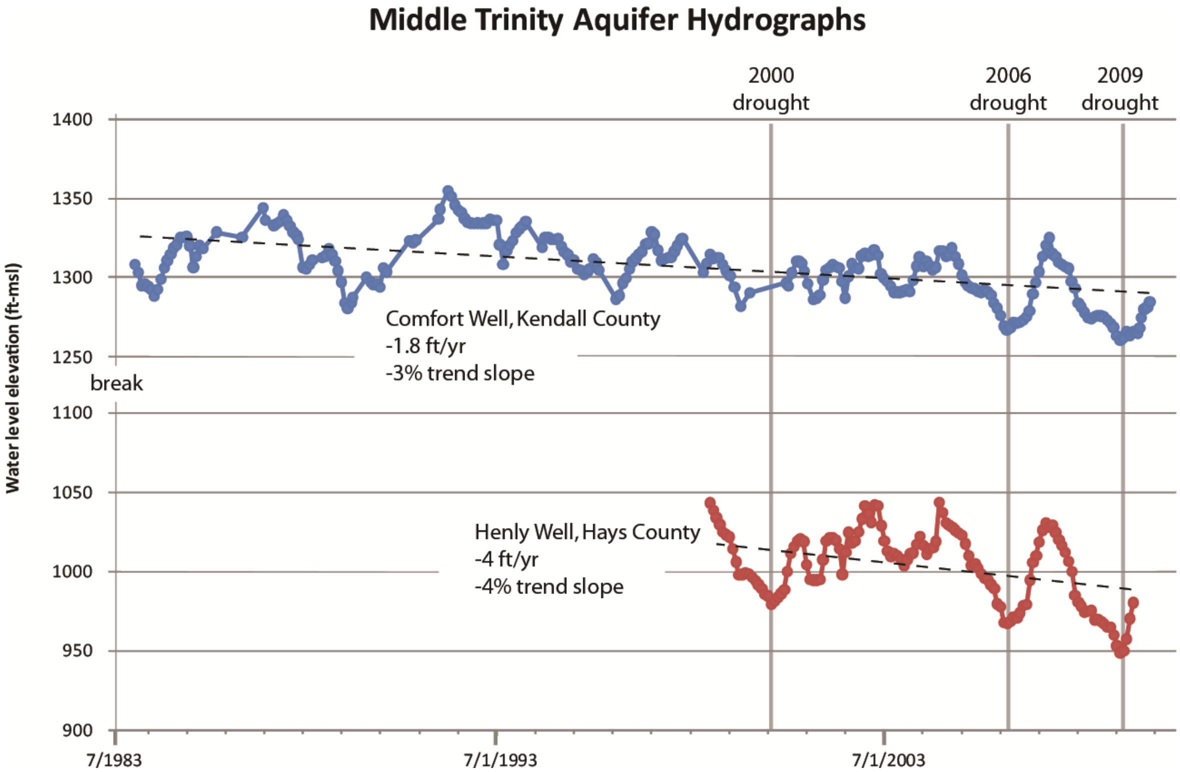


Figure 12. Hydrograph of two Middle Trinity wells. Variations in the hydrograph reflect seasonal and climatic changes over time. The overall decreasing water-level trend is thought to be a result of increases in regional pumping over time.

creased pumping over time (Fig. 14). However, the minimum flows at Barton Springs over the last 30 years have been decreasing, while the total discharge is relatively unchanged (Fig. 16).

The hydrograph of flow statistics for Comal Springs (Fig. 18) stands in stark contrast with Barton Springs and San Marcos Springs (Figs. 16 and 17). Comal Springs shows a slight increasing trend for most flow statistics over the period of record. Low flows are relatively unchanged over the period of record. However, low flows over the last 30 years have increased (Fig. 18). In addition, the trend of flow variability (as represented by the IQR) at Comal Springs has increased modestly over the period, and has been relatively constant over the past 30 years, unlike Barton and San Marcos Springs.

DISCUSSION

This study documents an increase in the overall water budget for the study area for the historical record (1860–present). We assume the apparent shift to wetter conditions after 1960 corresponds to a change in the climate of the study area and is most notable in Figure 7. Increasing streamflow trends (Figs. 7 to 9, and 11) are similar to previous investigations by Slade (2001) and Asquith and Heitmuller (2008). The climatic shift and increasingly wet conditions that occurred after about 1960 may explain much of the apparent two-fold increase in the water budget during drought as discussed by Smith and Hunt (2010) for the Barton Springs aquifer.

This study has demonstrated that an increase in precipitation each decade has influenced the overall water budget of the aquifer. Although these increasing precipitation trends (Figs. 5 and 6) have translated into increases in higher streamflows over time, those precipitation increases have not translated into higher baseflows,

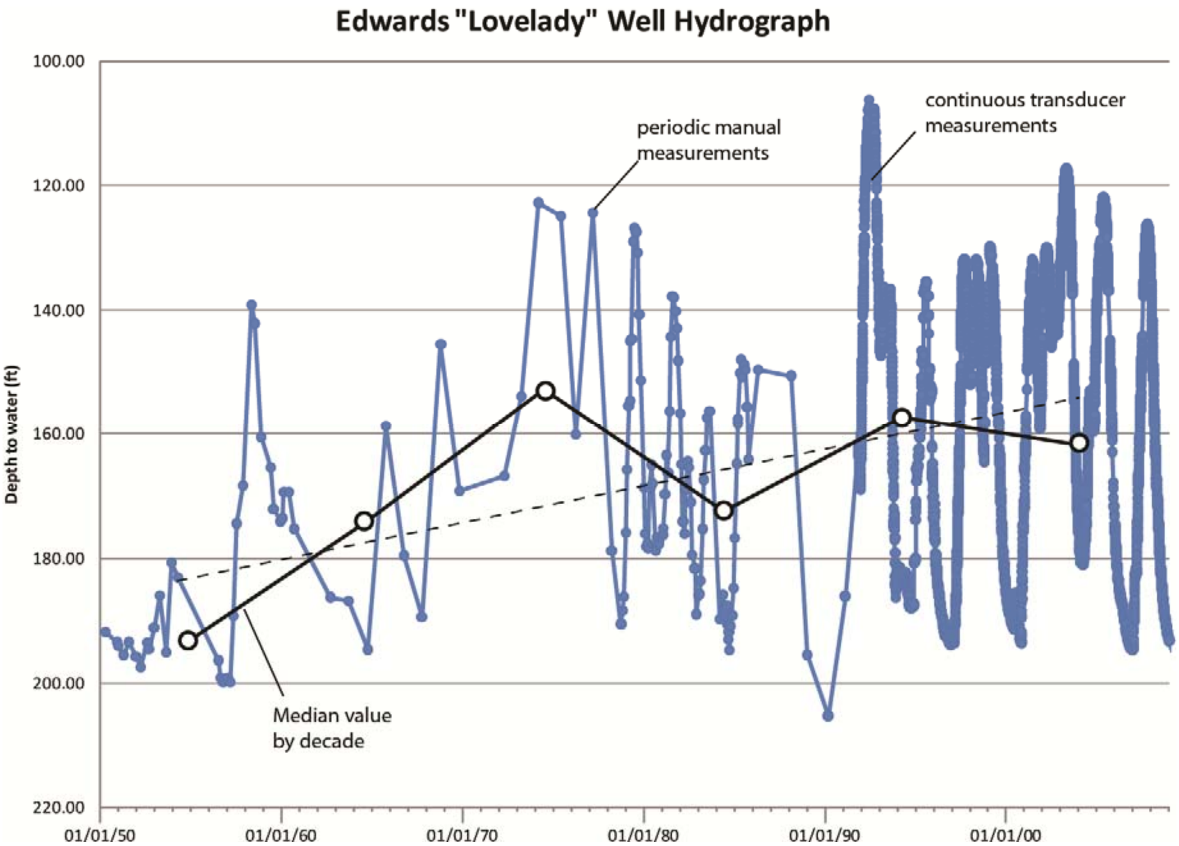


Figure 13. Edwards (Lovelady) well hydrograph. This is the drought trigger well for the BSEACD. Blue lines and points are all of the data available for the site. The black circles and line represents median values by decade and have a positive trendline (indicated by the dashed line) of about 7%. After about 1960 the trend is relatively unchanged, suggesting a new equilibrium.

especially over the last 30 to 40 years. Increasing precipitation and runoff have not increased storage in the Trinity Aquifer. Decreasing storage in the Trinity Aquifer is documented (Fig. 11) and corresponds to a period of increased pumping (Fig. 14) and decreasing baseflows (Fig. 10).

Despite the increase in the overall water budget, baseflows are either unchanged or decreasing. Possible mechanisms to explain this decrease include (ranked in order of significance): 1) Increasing groundwater production capturing groundwater before it discharges to the contributing streams (Fig. 2). The decrease in water levels in the Trinity (Fig. 12) is well documented in Boghici (2008) and Wierman et al. (2011) and corresponds with increasing levels of pumping (Fig. 14). Increased pumping is cited as the primary mechanism for decreasing streamflows in Slade (2007), and from numerical modeling studies (Jones et al., 2011). 2) Increasing temperatures and evapotranspiration may reduce recharge to the Trinity. Additional indirect impacts of increasing temperature are increases in pumping. 3) Land-use practices, such as overgrazing, can impact the water budget by increasing the evapotranspiration. The proliferation of Ashe juniper in the Hill Country could be an example (Banta and Slattery, 2011).

The change to a wetter climate since the 1960s has benefited the Edwards Aquifer, while the benefit to the Trinity Aquifer is less apparent. The Barton Springs aquifer is strongly and quickly influenced by climate changes as evidenced by the similarity of Barton Springs springflow to streamflow hydrographs (Fig. 7) and in the flow statistics (Figs. 9 and 16). This is in agreement with Mace and Wade (2008) and suggests rapidly-responding aquifers (such as the karstic Edwards Aquifer) are particularly susceptible to climate change. In the

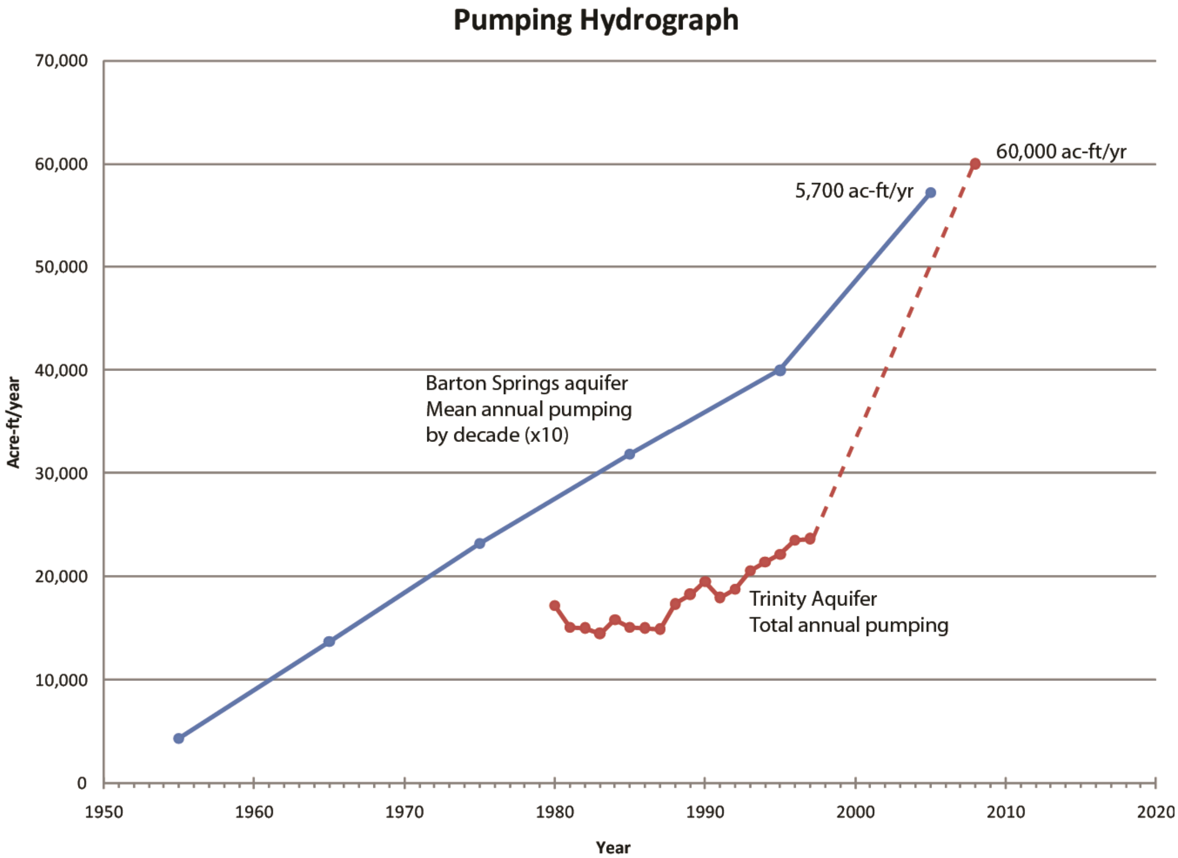


Figure 14. Hydrograph of pumping for the Edwards and Trinity aquifers. Data for the Trinity are from Jones et al. (2011) and the 2008 estimate is from Hutchison and Hassan (2011). Edwards data are multiplied by a factor of 10x and are unpublished data from BSEACD.

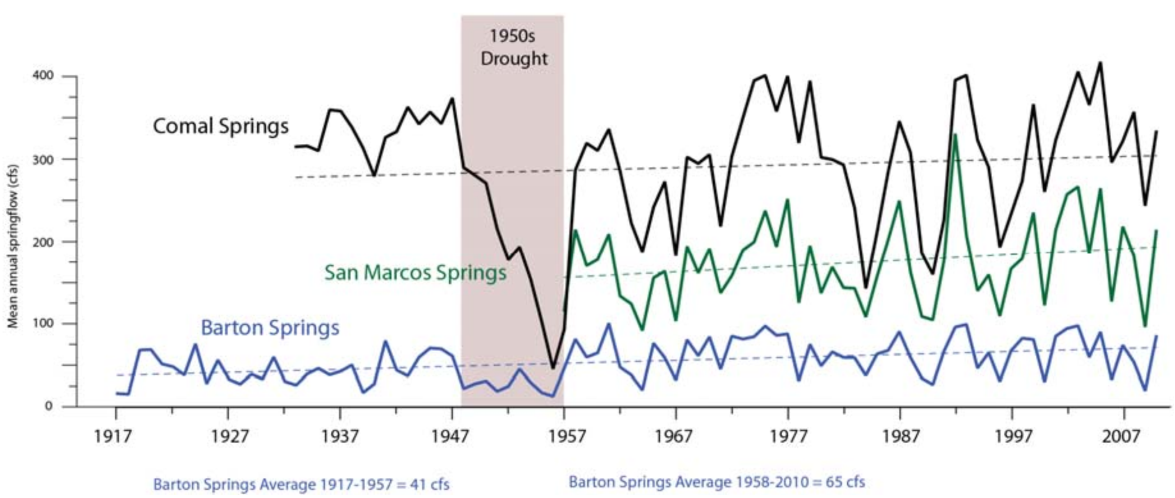
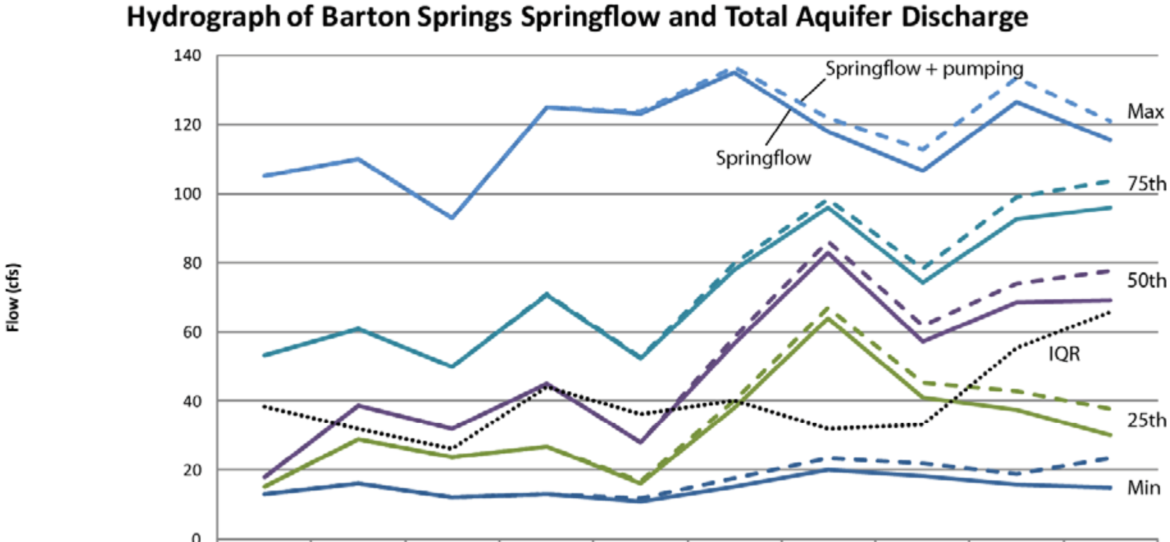


Figure 15. Hydrograph of the three major springs issuing from the Edwards Aquifer. Trendlines of the mean annual springflow values are positive.



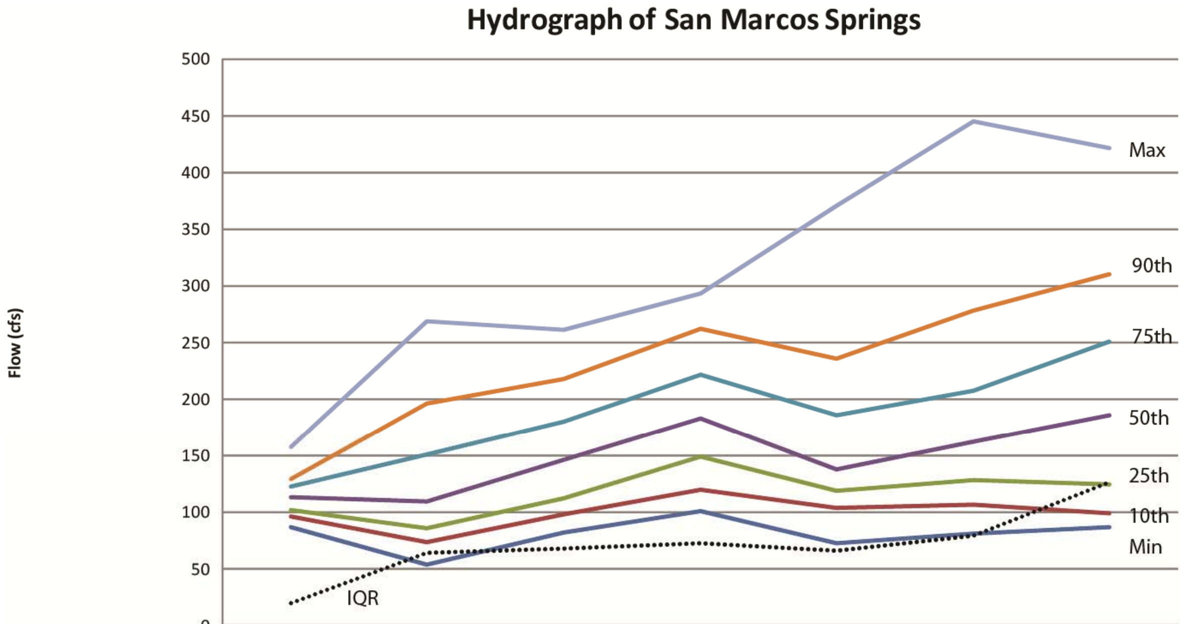
	1910-1919	1920-1929	1930-1939	1940-1949	1950-1959	1960-1969	1970-1979	1980-1989	1990-1999	2000-2009
Minimum	13	16	12	13	11	15	20	18	16	15
Min discharge	13	16	12	13	12	18	23	22	19	23
25th Percentile	15	29	24	27	16	38	64	41	37	30
25th discharge	15	29	24	27	17	40	67	45	43	38
50th Percentile	18	39	32	45	28	57	83	57	69	69
Median discharge	18	39	32	45	28	58	86	62	74	78
75th Percentile	53	61	50	71	52	78	96	74	93	96
75th discharge	53	61	50	71	53	80	98	78	99	104
Maximum	105	110	93	125	123	135	118	107	127	115
Max discharge	105	110	93	125	124	137	122	113	134	121
Interquartile Range (IQR)	38	32	26	44	36	40	32	33	55	66

Figure 16. Hydrograph of Barton Springs springflow and total aquifer discharge (springflow plus pumping); percentiles by decade.

Barton Springs aquifer, storage after 1960 is relatively constant, reflecting a new equilibrium of the wetter climatic period (Fig. 13). The Trinity Aquifer does not appear to have the same response as the Edwards Aquifer, and thus groundwater levels continue to decline due to aquifer mining despite the increasing wet conditions (Fig. 12). While pumping within the Barton Springs aquifer is not mining the aquifer, pumping does influence the magnitude of springflow and the trend of low springflow. The decrease in minimum flows each decade at Barton Springs appears directly related to Edwards pumping (Fig. 16).

This study substantiates the direct and indirect influence of pumping on groundwater resources. Pumping from the Trinity Aquifer directly influences storage and may be the mechanism for decreased baseflows of the streams contributing flow to the Edwards Aquifer. By decreasing baseflows in the contributing streams, pumping from the Trinity Aquifer indirectly reduces recharge to the Edwards Aquifer.

More work needs to be done to understand the influence of increasing temperatures and land-use changes on the overall water budget. Temperatures have been steadily rising and are projected to increase significantly (Banner et al., 2010). The current magnitude of air temperature change may play only a minor role in influencing streamflows and springflows in the aquifers compared to pumping, however, that may change as temperatures continue to increase. Change to a wetter climate after the 1960s may have influenced the intensity and duration of precipitation events and could be a significant influence on runoff. This variable was not evaluated as part of this study, but could be a part of future studies.



	1940-1949	1950-1959	1960-1969	1970-1979	1980-1989	1990-1999	2000-2009
Minimum	86.5	53.5	81.8	100.6	72.2	80.7	86.6
10th percentile	96.3	74.0	97.7	120.1	103.6	106.5	99.2
25th Percentile	102.0	86.1	112.1	149.4	119.2	128.3	124.4
50th Percentile	113.3	109.1	146.4	183.3	137.7	162.0	185.5
75th Percentile	122.1	150.5	179.7	221.9	185.3	207.7	250.6
90th Percentile	129.2	196.4	218.1	262.4	235.6	278.3	310.1
Maximum	157.4	268.5	261.0	293.2	370.6	445.4	421.1
Inter Quartile Range (IQR)	20.1	64.3	67.6	72.6	66.1	79.4	126.2

Figure 17. Hydrograph of San Marcos Springs; flow percentiles by decade.

CONCLUSIONS

This study has demonstrated that increases in precipitation and streamflows have not resulted in increases in baseflow or low springflow values. Higher flows during wet periods will not significantly decrease the impacts due to droughts. Pumping appears to be the primary mechanism for decreasing water levels in the Trinity Aquifer, which result in lower baseflows to the streams contributing flow to the Edwards Aquifer. The Edwards Aquifer is susceptible to changes in baseflows of contributing streams. Lower baseflows combined with pumping within the Edwards have resulted in decreasing low springflows from the Edwards Aquifer. A continuation of decreasing baseflows, as seen over the past 30 to 40 years and increased pumping, will cause decreased water availability during future droughts.

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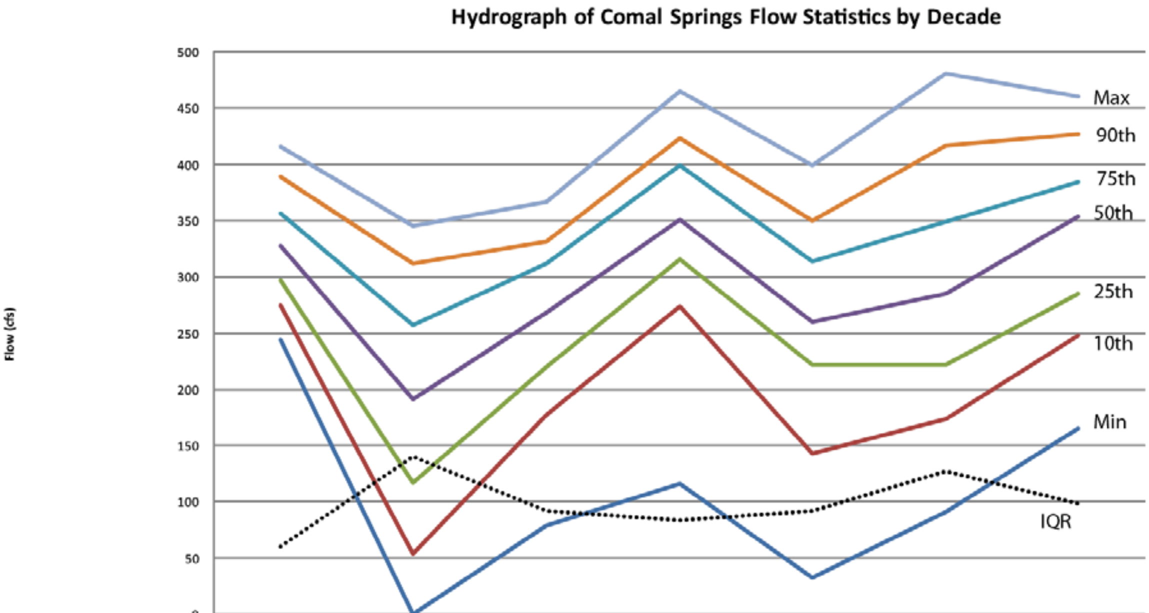

	1940-1949	1950-1959	1960-1969	1970-1979	1980-1989	1990-1999	2000-2009
Minimum	244	0	79	116	33	92	165
10th percentile	275	54	178	273	143	174	248
25th Percentile	297	117	220	316	222	222	285
50th Percentile	328	191	268	351	260	285	353
75th Percentile	357	257	312	399	313	349	384
90th Percentile	389	312	332	423	350	416	427
Maximum	416	345	367	465	399	481	461
Interquartile Range (IQR)	60	140	92	83	92	127	99

Figure 18. Hydrograph of Comal Springs; flow percentiles by decade.

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