A Comparison of the 1950s Drought of Record and the 2009 Drought, Barton Springs Segment of the Edwards Aquifer, Central Texas

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ABSTRACT

The Barton Springs segment of the Balcones Fault Zone Edwards Aquifer is an important resource for water supply and environmental flows; however extreme droughts can limit the amount of available water. The Barton Springs/Edwards Aquifer Conservation District has developed its drought management policies specifically for a recurrence of the 1950s drought of record (DOR). A comparison was made between the DOR and the 2009 drought using springflow, streamflow, rainfall, and water-level data. Generally, the values of these parameters for the DOR are slightly lower than those during the 2009 drought. The 24-month rainfall total for the 2009 drought was almost the same as the value for the last 2 years of the DOR, 35.2 and 34.8 inches, respectively. However, from a water-budget perspective, there was almost twice the amount of water being discharged (by pumping and springflow) at the end of the 2009 drought compared to the DOR. Several possible explanations for the difference in water budgets between the DOR and the 2009 drought are: (1) the DOR was considerably longer so the amount of water in storage was more depleted; (2) there was a long-term shift to wetter conditions after 1957 leading to more water in storage during the 2009 drought; and (3) increased pumping since the 1950s could have been offset by an increase in flow from adjacent and underlying aquifers, or even urban recharge such as leaking water pipes. However, it is likely that during a recurrence of the DOR, springflow will decrease below rates observed during the DOR owing to higher rates of pumping.

INTRODUCTION

The Barton Springs segment of the Balcones Fault Zone (BFZ) Edwards Aquifer (Barton Springs aquifer) is a significant source of water for people in south Austin and northern Hays County (Fig. 1). The outlets at Barton Springs are home to an endangered salamander, and the swimming pool that was constructed around the main spring outlet on Barton Creek depends on a consistent flow of high quality water from the springs. During periods of drought, water levels in the aquifer drop, springflow decreases, and water quality is degraded. Droughts occur frequently in central Texas with moderate to severe droughts having occurred seven times over the past 20 years. The combination of severe droughts and high rates of pumping is likely to cause numerous water-supply wells to go dry and for the endangered salamanders to be in jeopardy. This study compares a recent drought (June 2008 – December 2009) with the drought of record that occurred between 1947 and 1957. An understanding of the similarities and differences between these two droughts will help with planning for future droughts so that negative impacts can be minimized.

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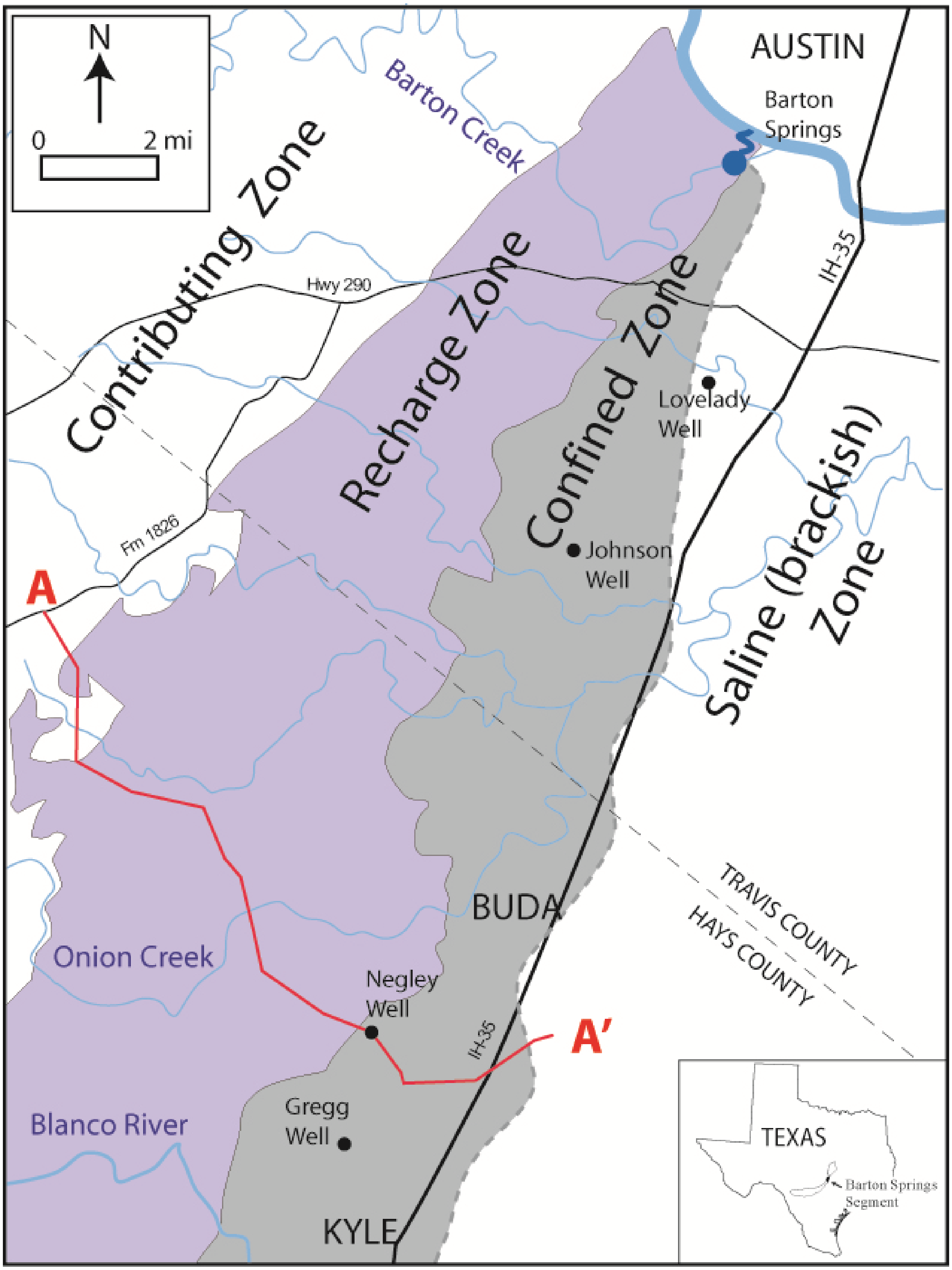

Figure 1. Location map of the Barton Springs segment of the Edwards Aquifer.

BACKGROUND

The focus of this study is on the Barton Springs aquifer, a small segment of the larger BFZ Edwards Aquifer. Studies of the Edwards Aquifer and the rocks that make up the aquifer have been conducted for more than 100 years, but concerns about the sustainable yield of the Edwards Aquifer and the individual segments of the aquifer have been the topic of studies for only the past 25 years. Over that period of time regulations have gradually been put in place to limit pumping from different parts of the aquifer.

Regional Setting

The Edwards Aquifer of Central Texas is a prolific karst aquifer developed in faulted and fractured Cretaceous-age limestones and dolostones. The aquifer system lies within the Miocene-aged BFZ that forms the Balcones Escarpment of Central Texas. Hydrologic divides separate the Edwards Aquifer into three segments: northern, central (Barton Springs), and southern (San Antonio) (Fig. 1). The entire aquifer system is about 270 miles long covering an area of about 4,350 square miles with about 1,700 square miles of recharge zone and 2,650 square miles of confined, or artesian, zone for the freshwater part of the aquifer. The aquifer ranges in width from 2 miles to almost 40 miles and from 400 feet to more than 600 feet in thickness.

The Edwards Aquifer is geologically and hydraulically heterogeneous and anisotropic, both of which strongly influence groundwater flow and storage (Slade et al., 1985; Maclay and Small, 1986; Hovorka et al., 1996; Hovorka et al., 1998; Hunt et al., 2005). Karst aquifers such as the Barton Springs segment are commonly described as triple porosity (and permeability) systems consisting of matrix, fracture, and conduit porosity (Ford and Williams, 1992; Quinlan et al., 1996; Palmer et al., 1999). Hovorka and others (1998) has described the Edwards Aquifer as having permeability ranging over eight orders of magnitude. Most storage of water in the Edwards Aquifer is within the matrix porosity (Hovorka et al., 1998); therefore, volumetrically, flow through the aquifer is predominantly diffuse. However, groundwater dye-tracing studies demonstrate that significant components of groundwater flow occur in a well integrated network of conduits, caves, and smaller dissolution features (Hauwert et al., 2002).

Discharge from the greater Edwards Aquifer occurs at some of the largest springs and water-supply wells in the southwestern United States. The aquifer system is the sole-source of water for 2 million people with pumping totaling about 474,400 acre-feet/year (155 billion gallons, 655 cubic feet per second [cfs]) (Smith et al., 2005). The three largest springs in Texas issue from the Edwards Aquifer and include Comal, San Marcos, and Barton springs. These springs have a mean annual historical flow of 200,900 acre-feet/year (277 cfs), 114,300 acre-feet/year (199 cfs), and 38,400 acre-feet/year (53 cfs), respectively. Each of these springs provide habitat for federally-listed endangered aquatic species.

Barton Springs Aquifer

The Barton Springs aquifer is bounded to the north by the Colorado River, by a groundwater divide to the south, by the interface between the fresh- and saline-water zones to the east, and by the outcrop and saturated thickness of the Edwards Group to the west (Fig. 1). The Barton Springs aquifer is 155 square miles in area (Fig. 1), with about 80% of the area under unconfined conditions, and a maximum thickness of about 450 feet (Fig. 2).

The Barton Springs aquifer provides water for about 60,000 people and currently has about 7,800 acre-feet/year (2.5 billion gallons; 11 cfs) of authorized pumping from 94 permit holders. Groundwater use is characterized as 80% public-supply, 13% industrial (quarry operations), and 7% irrigation (golf courses). There are about 1,230 operational wells within the District, with the majority producing water from the Edwards (Hunt et al., 2006). The Barton Springs/Edwards Aquifer Conservation District (District) is tasked with managing pumping from the Barton Springs aquifer.

The largest natural discharge point of the Barton Springs aquifer is Barton Springs, located in Barton Creek about one quarter mile upstream of its confluence with the Colorado River (Fig. 1). Barton Springs consists of four major outlets, the largest discharging directly into Barton Springs pool, a major recreational attraction of the City of Austin. Each of the spring outlets provides habitat for the federally-listed Barton Springs Salamander.

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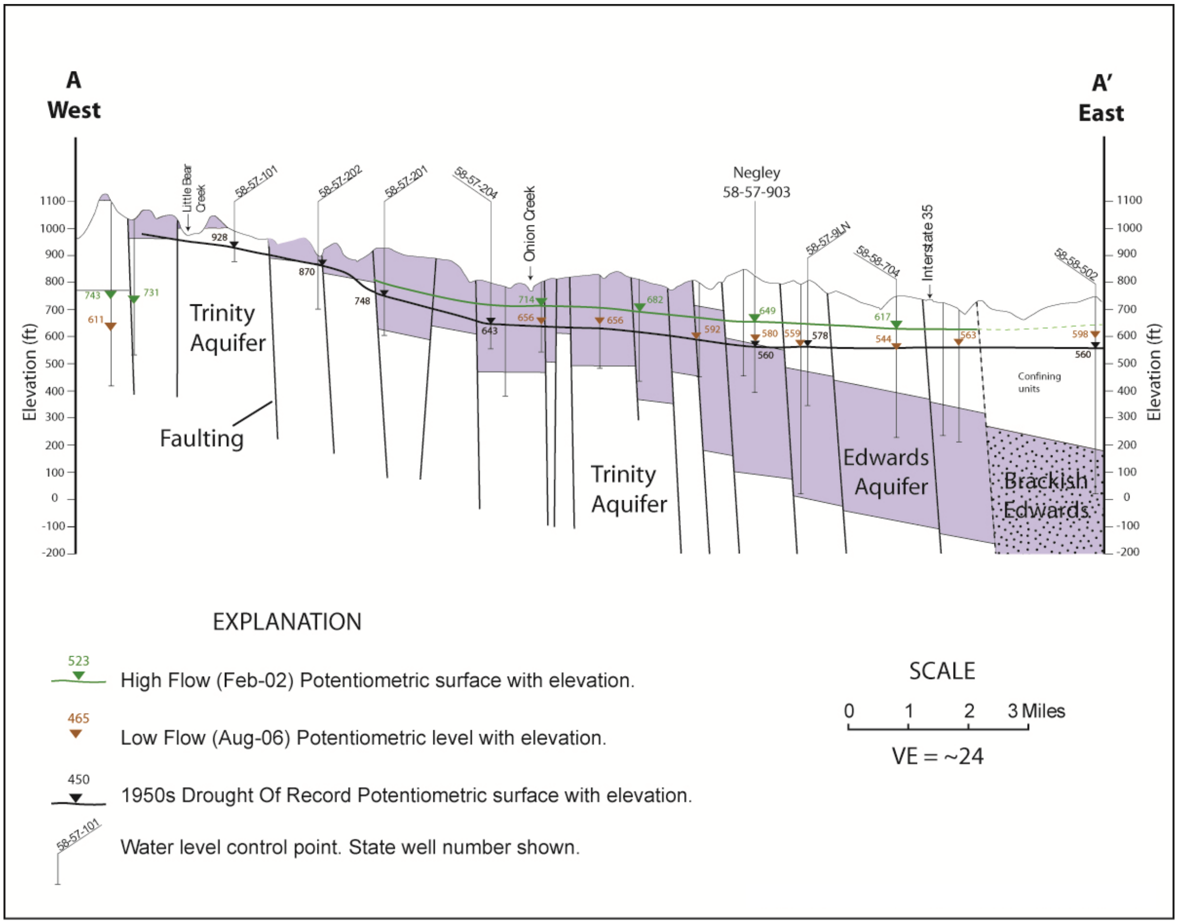

Figure 2. Cross section of study area (modified after Smith and Hunt, 2004). Line of cross section is shown in Figure 1.

The formation of the aquifer was influenced significantly by fracturing and faulting associated with the Miocene-age BFZ and dissolution of limestone and dolostone units by infiltrating meteoric water (Sharp, 1990; Barker et al., 1994). Faults trend predominantly to the northeast and are downthrown to the southeast, with total offset of about 1,100 ft across the study area (Fig. 2). Dissolution along fractures, faults, and bedding plane partings, and within certain lithologic units, has created numerous sinkholes, sinking streams, springs, conduits, and caves.

It is estimated that 85% of recharge to the aquifer occurs along its six major (ephemeral to intermittent) losing streams that cross the recharge zone, including recharge from the Blanco River under certain hydrologic conditions. The remaining recharge occurs in the upland areas of the recharge zone (Slade et al., 1986). Recent studies (Hauwert, 2009) suggest that the amount of upland recharge is higher than earlier estimates. The amount of cross-formational flow (subsurface recharge) occurring through adjacent aquifers is unknown, although it is thought to be relatively small on the basis of water-budget analysis for surface recharge and discharge (Slade et al., 1985). Smith and Hunt (2004) have shown that in the western portion of the Barton Springs aquifer, heads are higher in the Edwards than in the underlying Trinity units. Therefore, it is unlikely that the Edwards receives any recharge from the deeper formations in this area. Higher heads in the saline Edwards to the east (Fig. 1) (Lambert et al., 2009) suggest the potential for flow from the saline zone into the freshwater zone, but faults and low permeability units along the saline-freshwater interface evidently limit the amount of saline water that can flow into the freshwater Edwards.

Groundwater generally flows west to east across the recharge zone, converging with preferential groundwater flow paths subparallel to major faulting, and then flowing northward toward Barton Springs. Rates of groundwater flow along preferential flow paths, determined from dye tracing, can be as fast as 4 to 7 miles per day under high-flow conditions or about 1 miles per day under low-flow conditions (Hauwert et al., 2002; Hunt et al., 2005).

DROUGHT IN CENTRAL TEXAS AND DROUGHT POLICIES

The climate of the study area is characterized as humid subtropical with an annual rainfall amount of 33.5 inches. Precipitation is fairly evenly distributed throughout the year with peaks of 4.4 inches and 3.5 inches occurring in May and September, respectively (Brune and Duffin, 1983). However, the region often receives a large portion of its annual rainfall in a very short period of time, resulting in flash flooding and periods of short, but intense recharge events. Based on studies of droughts in central Texas and sustainable yield of the Barton Springs aquifer, the District has implemented drought policies to protect the aquifer, Barton Springs, and the endangered salamanders from the impacts of drought to the extent practicable.

Barton Springs Aquifer and Drought

As a result of the climate, karstic nature of the aquifer, and pumping, the Edwards Aquifer is a very dynamic resource with rapid fluctuations in springflow, water levels, and storage. Figure 3 illustrates the correlation between rainfall, flow in the Blanco River, water levels in the aquifer, and Barton Springs discharge. Hydrographs for Barton Springs and the Blanco River show distinct increases in flow between 1958 and the present and the period before 1958. This suggests that rainfall amounts have been greater during the more recent period. Rainfall is presented in Figure 3 as 24-month running totals to show the cumulative effect of below average rainfall. Between 1950 and 1991, water levels were measured sporadically in the Lovelady monitor well. Since November 1991, water-level measurements have been made with a pressure transducer and data logger and recorded at 15-minute intervals.

The worst drought on record for the Barton Springs aquifer was a 10-year period from 1947 through 1957 commonly referred to as the drought of record (DOR) (Figs. 3 and 4). The lowest total annual rainfall for the Camp Mabry weather station in Austin in 1954 was 11.4 in. During this drought, water levels reached historic low levels and many springs stopped flowing completely, including Comal Springs (the largest spring in Texas). The annual mean discharge for Barton Springs was 13 cfs in 1956, with the lowest monthly mean discharge of 11 cfs occurring in July and August of 1956. The lowest single measurement of spring discharge was 9.6 cfs on March 26, 1956. Long-term average spring-flow values for Barton Springs are about 53 cfs (Scanlon et al., 2001).

Although all droughts originate with the absence of rainfall for a prolonged period of time, and impact the entire hydrologic cycle, drought is often discussed in terms of three physical effects characterized as meteorological, agricultural, and hydrological. A hydrological drought refers to deficiencies in surface and subsurface water supplies measured as streamflow, lake elevations, groundwater levels, and springflow. Hydrologic droughts generally lag behind meteorological and agricultural droughts. However, a karst aquifer system responds very quickly to stress in comparison to porous media equivalent aquifers (sands and gravels). A severe drought will eventually impact all these components (NDMC, 2006). Criteria for measuring hydrological droughts often focus on surface water rather than groundwater. Droughts that impact the Barton Springs aquifer can be best characterized as hydrological, but more specifically a groundwater drought. Groundwater droughts are a type of hydrologic drought, defined by Peters and van Lanen (2000) who stated that a groundwater drought occurs if groundwater heads have fallen below a critical level over a certain period of time, which results in adverse effects.

Causes of Drought

Understanding the cause of drought is important for making predictions and for development of a drought response program. However, the cause for “drier-than-normal conditions” is never the result of a single factor.

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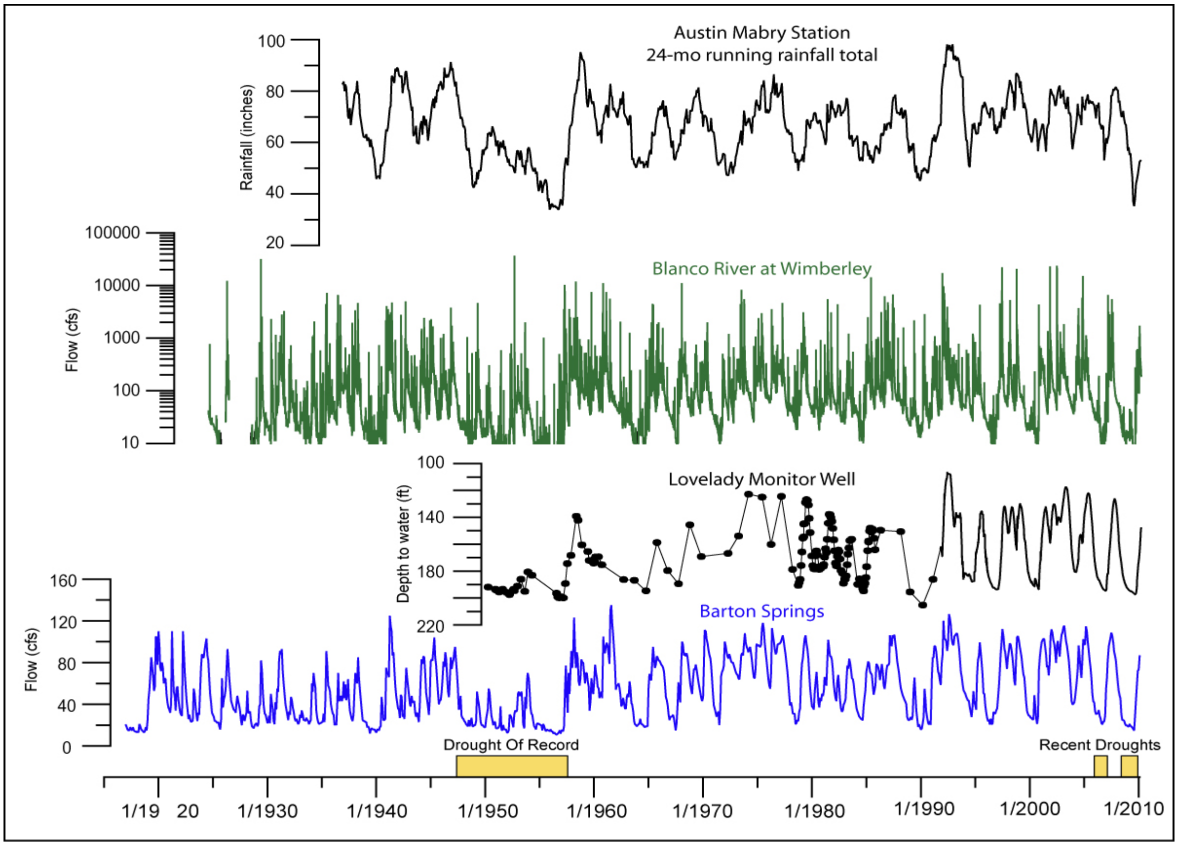

Figure 3. Long-term records of meteorological and hydrological data from the Barton Springs segment of the Edwards Aquifer, 1918-2010.

The immediate cause can be attributed to a large-scale persistent high (atmospheric) pressure that disrupts the global atmospheric circulation increasing sunshine, evaporation, and inhibiting the influx of moisture (NDMC, 2006). Multiyear droughts, such as that of the 1930s and 1950s, have been linked to several ocean-atmospheric processes such as El Niño/Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO) and other processes (Barlow et al., 2001; Schubert, 2004; Fye et al., 2004).

The El Niño/Southern Oscillation is a naturally occurring irregular cycle (occurring every 2-7 years) of the ocean-atmosphere system in the tropical Pacific Ocean. In particular, El Niño conditions arise during a warming of tropical Pacific sea surface temperatures, which contribute to a wetter than average period in Texas by influencing the position of the jet streams and therefore influx of moisture. La Niña conditions arise during a cooling of the tropical Pacific sea surface temperature and generally contribute to drier than average conditions in Texas (Barlow et al., 2001; Schubert, 2004).

Drought cannot be viewed solely as a natural event because the impacts often result from the combined natural event and the demand people place on a water supply. People often influence the timing and duration of droughts and exacerbate the impacts of drought (NDMC, 2006). Even without drought conditions, groundwater pumping can have profound negative effects on aquifers and surface waters (Glennon, 2002).

Sustainable Yield Analysis

Results of evaluations of sustainable yield of the Barton Springs aquifer indicate that water levels and springflow are significantly affected by 1950s drought conditions and increased pumping rates (Fig. 4) (Smith and Hunt, 2004). Simulations indicate that a given pumping rate applied under 1950s drought conditions would diminish Barton Springs flow by an amount equivalent to the pumping rate. At 10 cfs of aggregate pumping, a small amount of springflow (about 1 cfs monthly average) would be maintained. However, according to a minimum daily discharge of 9.6 cfs, such as that measured in 1956, springflow could temporarily cease for days or weeks. At 15 cfs of pumping, springflow would cease for at least 4 months. This same study indicates that as many as 19% of all water-supply wells in the District may experience adverse impacts under 1950s drought conditions and an aggregate pumping rate of 10 cfs.

Drought-Response Program

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To determine drought indices for the karstic Barton Springs aquifer the principal components of the hydrologic cycle (recharge, storage, and discharge) were evaluated. There is a wealth of historic rainfall, water-level, stream-flow, and spring-flow data for the Barton Springs aquifer. Methods employed to evaluate those data included simple statistical and graphical correlations, complex multivariate analysis, and numerical modeling.

Gauging recharge to an aquifer system would give the first indication of incipient drought conditions. However, results of the evaluation indicate that recharge, or its surrogates, is difficult to quantify and correlate to storage or discharge in the aquifer—both key components of the sustainable yield definition. Accordingly, storage and discharge are better-quantified drought indices for this karstic aquifer system. Multivariate analysis demonstrated that the aquifer is best characterized as having conduit and diffuse flow or storage (LBG-Guyton, 2005, personal communication). It was determined that the best measure of these components is discharge from Barton Springs and the water level in the Lovelady monitor well. Barton Springs discharge is a measure of the overall condition of the aquifer with dynamic responses integrating combined conduit, fracture, and matrix flow from the system. Water levels in the Lovelady well are muted, less influenced by conduit flow, and more indicative of diffuse flow and the overall amount of water in storage (Fig. 3).

Based on the drought studies described above, a drought trigger policy was developed to improve declarations of drought for implementation of mandated conservation measures by groundwater users (Smith et al., 2006). These conservation measures are the primary means of protecting water levels and springflow. The drought-trigger policy that was developed, and adopted by the District in January 2006, uses flow from Barton Springs and water levels in the Lovelady monitor well to determine drought status of the aquifer. Drought triggers were determined based upon sufficient margins of time for implementation of conservation measures that would be most protective of springflow (Smith et al., 2006)

Either water levels or springflow can trigger a drought on the basis of their respective trigger levels (Fig. 4). To exit a drought stage both water levels and springflow must be above their respective trigger levels. The point of entry to Alarm Stage Drought is when the 10-day average springflow is below 38 cfs, and the point of entry to Critical Stage Drought is when the 10-day average springflow is below 20 cfs. Extraordinary Stage Drought may be declared when the 10-day average springflow is below 14 cfs. If the water level in the Lovelady monitor well drops below a depth-to-water of 175 ft before a 10-day average springflow below 38 cfs is reached at Barton Springs, then Alarm Stage Drought may be declared. If the water level in the Lovelady monitor well drops below a depth-to-water of 192.1 ft before a 10-day average springflow below 20 cfs is reached, then Critical Stage Drought may be declared. During Alarm Stage Drought groundwater users within the District are required to reduce use by 20% compared to permitted values for non-drought conditions on a monthly basis. During Critical Stage Drought groundwater users are required to reduce use by 30%. A 40% reduction is groundwater use is required during an Extraordinary Stage Drought. A drought trigger for Extraordinary Stage Drought has not been set for the Lovelady monitor well owing to limited water-level data for extreme drought conditions.

The drought trigger policy will improve the timing of entering into drought stages which will minimize the impact of low water levels on water-supply wells and maintain flow at Barton Springs that will be protective of the endangered species (Smith et al., 2006).

COMPARISON OF DROUGHT OF RECORD TO 2009 DROUGHT

As various climatic and hydrological parameters were reaching record levels in central Texas during the summer of 2009, comparisons were being made with the DOR. However, it is clear from rainfall and hydrologic

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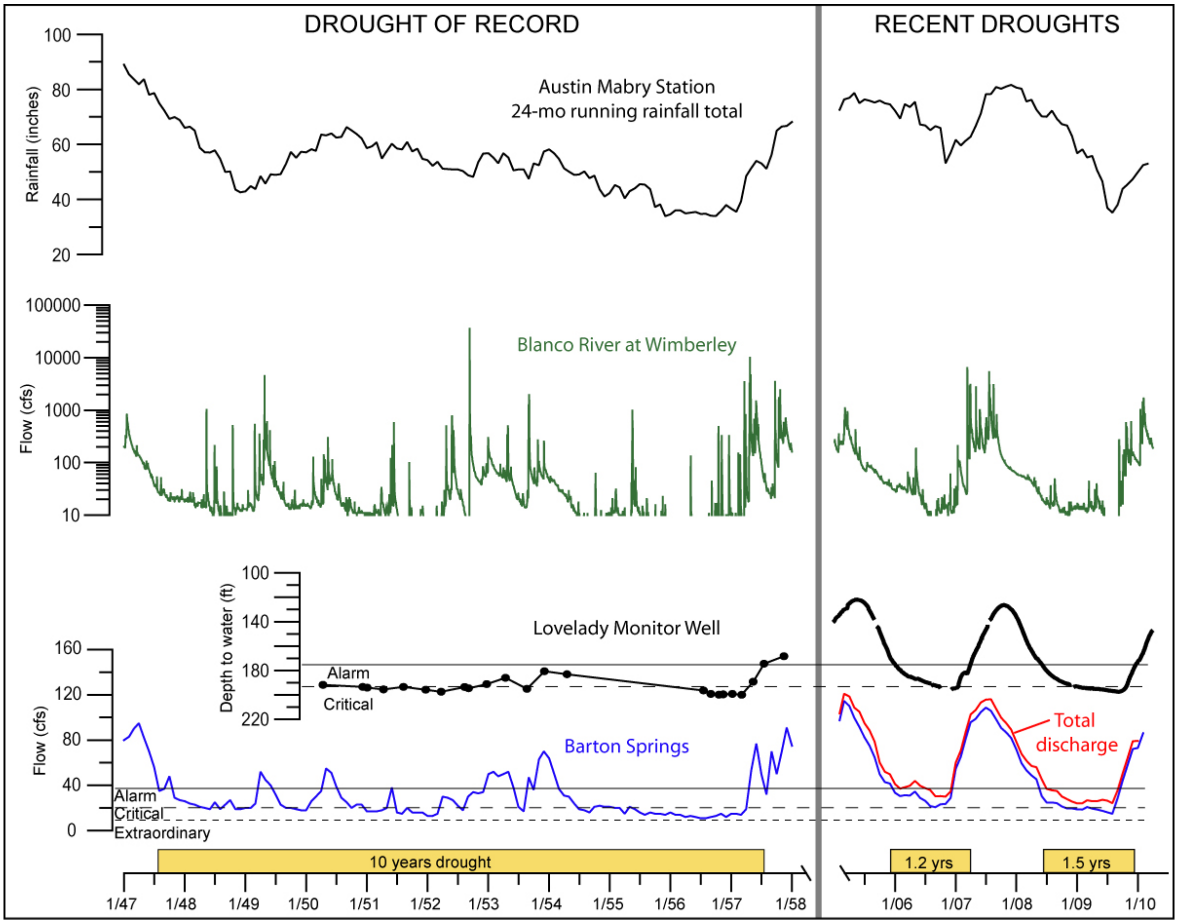

Figure 4. Meteorological and hydrological data from the Barton Springs segment of the Edwards Aquifer for the drought of record and 2006 and 2009 droughts.

data (Fig. 4) that the 2009 drought did not equal the severity of the DOR, but it was the most severe drought since 1957 (Fig. 3). A plot of 24-month running rainfall totals shows the amount of rainfall over the 2-year period prior to the end of the 2009 (35.2 inches) was only slightly less than the 2-year period prior to the end of the DOR (34.8 inches). However, the DOR lasted a total of 10 years compared to the 1.5-year 2009 drought.

Even though the Blanco River is outside of the District, it contributes recharge to the Barton Springs aquifer under severe drought conditions. Records for the Blanco River extend back before the DOR. Data from the DOR are not available for any of the streams that cross the recharge zone within the District. During the DOR, flow in the Blanco River at the Wimberley station dropped below 1 cfs briefly, and flow was frequently below 10 cfs. During the 2009 drought, flow at this station dropped to about 5 cfs, but was between 10 and 20 cfs for most of the drought.

The Lovelady monitor well is situated about 3 miles south of Barton Springs and does not appear to be connected to any significant conduits or flow paths that divert water to Barton Springs. Water levels in the well rise after long periods of recharge, but they do not respond to brief, but heavy rain events. As shown in Figures 3 and 4, response to climatic and recharge events is gradual. Because of this, water levels in the well are considered indicative of storage in the aquifer. The lowest depth-to-water measurement made in the Lovelady monitor well during the DOR was 199.9 feet. During the 2009 drought, the lowest depth-to-water measurement made in the well was 197.5 feet, a difference of 2.4 feet (Table 1). The maximum depth to water in the Johnson well was 3.9 feet lower during the DOR than during the 2009 drought. Water levels in the Gregg and Negley wells were lower

Table 1. Water-level differences between drought of record and the 2006 and 2009 droughts in selected monitor wells.

Monitor Well Name	August 1956 – August 2006	August 1956 – September 2009
Lovelady	8.8	2.4
Johnson	11.2	4
Gregg	5.8	-7.2
Negley	18.2	-1.7

Negative values indicate recent date has lower level; minimum daily value used.

during the 2009 drought than during the DOR. This is probably due to the effect of pumping from nearby pumping centers. Locations of these wells are shown in Figure 1. The cross section in Figure 2 shows the position of the potentiomentric surface in the DOR and during a high flow period in February 2002. Also shown in Figure 2 are water levels in certain wells from the drought of 2006, including the Negley well.

Unlike the Lovelady monitor well, Barton Springs responds quickly to minor rainfall and recharge events. But springflows decrease rapidly following rainfall events when the aquifer is under drought conditions. Monthly average flow values for Barton Springs look very similar to monthly average water-level data from the Lovelady monitor well (Fig. 3). A comparison of daily values (not shown) indicates that Barton Springs flow is very flashy in response to rainfall during drought conditions, but water levels in the Lovelady monitor well have minimal or no response to these events. Under drought conditions, conduits in the aquifer direct rainfall from recharge features, such as caves and sinkholes, to Barton Springs without any significant increase in storage. These same conduits help divert water in storage in the aquifer to the springs, quickly depleting the aquifer of stored water. During the DOR, average monthly springflow was estimated to be 11 cfs. The lowest average monthly springflow during the 2009 drought was 14.9 cfs.

If current drought rules were applied to the Barton Springs aquifer during the DOR, drought status would have been in effect from August 1947 until July 1957. Even though discharge from Barton Springs rose above the drought trigger threshold at times during the DOR, it is not likely that the water level in the Lovelady monitor well would have risen above a depth-to-water of 175 feet. Drought conditions would have intensified to Exceptional Drought Stage in early 1952, and again between early 1956 and May 1957. Following a brief rainy period in late 1953 the drought stage would have risen to Alarm, but this would have been limited by only a moderate increase in water levels in the Lovelady monitor well.

SUMMARY AND CONCLUSIONS

Almost all the data from the Barton Springs aquifer indicate that the DOR was more severe than the 2009 drought. Water levels in monitor wells were slightly lower during the DOR, except where recent pumping is increasing drawdown. Streamflow in creeks and rivers that contribute recharge to the aquifer were also slightly lower during the DOR. Springflow was about 5 cfs lower during the DOR than the 2009 drought. Twenty-four–month running totals for rainfall were virtually the same for the two droughts with a difference of about 0.4 inches at the most severe levels of drought. The largest difference between the two droughts is for total discharge from the aquifer. Total discharge is considered to be discharge from Barton Springs plus discharge by pumping. Pumping from the Barton Springs aquifer during the DOR was estimated to be less than 1 cfs (Brune and Duffin, 1983). Combined with the lowest monthly average springflow, total discharge for the most severe part of the DOR would have been about 12 cfs. With a monthly average pumping from permitted and exempt wells during September 2009 of 7 cfs, total discharge at the end of the 2009 drought would have been about 22 cfs. One possible explanation for this considerable difference in total discharge is that the DOR was considerably longer so the amount of water in storage was more depleted. Another possible factor in the difference in total discharge between the two droughts is that increased pumping since the 1950s could have been offset by an increase in recharge from streams that cross the recharge zone of the aquifer and an increase in flow from adjacent and underlying aquifers. With low amounts of recharge over a 10-year period, a significant reduction in storage would be expected compared to a 1.5-year period of drought. However, the best indicator of storage in the Barton Springs aquifer is the Lovelady monitor well, which did not exhibit significantly lower water levels in the DOR. Over long periods of time, aquifers tend to reach equilibrium with all the factors that affect the aquifers (Alley et al. 1999). With the gradual increase in pumping from the Barton Springs aquifer since the DOR, inflow from other sources, such as recharging streams and adjacent and underlying aquifers, could have increased enough that a new equilibrium has been reached.

Certainly more studies are needed to better understand recharge to the Barton Springs aquifer, both surface and subsurface derived recharge. As we look to future studies we need to factor in the potential for droughts worse than the DOR and changes that could come about from climate change. The last 30 years have been warming faster than the global average, and have been accompanied by a wetter period in Texas punctuated with more extreme events that are expected to continue into the future (Nielson-Gammon, 2008). It is expected that rapidly responding aquifers, such as the Edwards Aquifer, will be more sensitive to changes in climate (Mace, 2008). Increasing demand due to population growth and rising temperatures will be the dominant factor impacting springs and groundwater availability (Mace, 2008; Loaiciga, 2008). Climate change will likely exacerbate these impacts.

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REFERENCES CITED

Alley, W. M., T. E. Reilly, and O. L. Franke, 1999, Sustainable ground-water resources: U.S. Geological Survey Circular 1186, 79 p.

Barker, R., P. Bush, and E. Baker, 1994, Geologic history and hydrogeologic setting of the Edwards-Trinity Aquifer System, West-Central Texas: U.S. Geological Survey Water-Resources Investigations 94-4039, 51 p.

Barlow, M., S. Nigam, and E. H. Berbery, 2001, ENSO, Pacific decadal variability, and U.S. summertime precipitation, drought, and stream flow: Journal of Climate, v. 14, p. 2105-2128.

Brune, G., and G. Duffin, 1983, Occurrence, availability, and quality of ground water in Travis County, Texas: Texas Department of Water Resources Report 276, Austin, 219 p.

Ford, D., and P. Williams, 1992, Karst geomorphology and hydrology, 2nd ed.: Chapman and Hall, New York, New York, 600 p.

Fye, F. K., D. W. Stahle, and E. R. Cook, 2004, Twentieth-century sea surface temperature patterns in the Pacific during decadal moisture regimes over the United States: Earth Interactions, v. 8, issue 22 (December 2004), p. 1-22.

Glennon, R., 2002, Water follies: Groundwater pumping and the fate of America’s fresh waters: Island Press, Washington, D.C., 314 p.

Hauwert, N. M., D. A. Johns, J. W. Sansom, and T. J. Aley, 2002, Groundwater tracing of the Barton Springs Edwards Aquifer, Travis and Hays counties, Texas: Gulf Coast Associations of Geological Societies Transactions, v. 52, p. 377-384 .

Hauwert, N. M., D. A. Johns, J. W. Sansom, and T. J. Aley, 2004, Groundwater tracing of the Barton Springs Edwards Aquifer, southern Travis and northern Hays counties, Texas: Report by the Barton Springs/Edwards Aquifer Conservation District and the City of Austin Watershed Protection and Development Review Department, Texas,100 p. and appendices.

Hauwert, N., 2009, Groundwater flow and recharge within the Barton Springs segment of the Edwards Aquifer, southern Travis and northern Hays counties, Texas: Ph.D. dissertation, University of Texas at Austin, 328 p.

Hovorka, S., R. Mace, and E. Collins, 1995, Regional distribution of permeability in the Edwards Aquifer: Gulf Coast Association of Geological Societies Transactions, v. 45, p. 259-265.

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Hovorka, S., A. Dutton, S. Ruppel, and J. Yeh, 1996, Edwards Aquifer ground-water resources: geologic controls on porosity development in platform carbonates, south Texas: Texas Bureau of Economic Geology Report of Investigations 238, Austin, 75 p.

Hovorka, S., R. Mace, and E. Collins, 1998, Permeability structure of the Edwards Aquifer, south Texas—Implications for aquifer management: Texas Bureau of Economic Geology Report of Investigations 250, Austin, 55 p.

Hunt, B. B, B. A. Smith, J. Beery, N. Hauwert, and D. Johns, 2005, Structural influence on groundwater flow as evidenced by groundwater dye tracing in the Barton Springs segment of the Edwards Aquifer, central Texas: Implications for modeling conduits: Geological Society of America Abstracts with Programs.

Hunt, B. B, B. A. Smith, K. Holland, and J. Beery, 2006, Wells and pumping (1989-2006) in the Barton Springs/Edwards Aquifer Conservation District, central Texas: Barton Springs/Edwards Aquifer Conservation District Data Series Report 2006-1005, 46 p. and CD.

Lambert, R. B., A. G. Hunt, G. P. Stanton, and M. B. Nyman, 2009, Water-level, borehole geophysical log, and water-quality data from wells transecting the freshwater/saline-water interface of the San Antonio segment of the Edwards Aquifer, south-central Texas, 1999-2007: U.S. Geological Survey Data Series Report 403, 9 p.

Loaiciga, H., 2008, Climate change, growth, and managing the Edwards Aquifer: Proceedings from Climate Change Impacts on Texas Water, April 28-30, Texas State Capitol Extension, Austin, Texas.

Mace, R., 2008, Will climate change affect the aquifers of Texas?: Proceedings from Climate Change Impacts on Texas Water, April 28-30, 2008, Texas State Capitol Extension, Austin, Texas.

Maclay, R. W., and T. A. Small, 1986, Carbonate geology and hydrogeology of the Edwards Aquifer in the San Antonio area, Texas: Texas Water Development Board Report 296, Austin, 90 p.

National Drought Mitigation Center (NDMC), 2006, What is drought? Understanding and defining drought, <http://drought.unl.edu/whatis/predict.htm> Accessed February 9, 2010.

Nielsen-Gammon, J., 2008, What does the historic climate record in Texas say about future climate change?: Proceedings from Climate Change Impacts on Texas Water, April 28-30, Texas State Capitol Extension, Austin, Texas.

Palmer, A. N., M. V. Palmer, and I. D. Sasowsky, 1999, Karst modeling: Karst Waters Institute Special Publication 5, Leesburg, Virginia, 265 p.

Peters, E. and H. van Lanen, 2000, Hydrological drought—Groundwater, *in* H. Hisdal and L.M. Tallaksen, eds., Drought event definition: Assessment of the regional impact of droughts in Europe: Department of Geophysics, University of Oslo, , Technical Report 6, Blindern, Norway, p. 15-19.

Quinlan, J. F., G. J. Davies, S. W. Jones, and P. W. Huntoon, 1996, The applicability of numerical models to adequately characterize groundwater flow in karstic and other triple-porosity aquifers: American Society for Testing and Materials, Subsurface Fluid-Flow (Groundwater) Modeling, STP 1288.

Scanlon, B., R. Mace, B. Smith, S. Hovorka, A. Dutton, and R. Reedy, 2001, Groundwater availability of the Barton Springs aquifer, Texas—Numerical simulations through 2050: Report prepared by the Texas Bureau of Economic Geology, for the Lower Colorado River Authority, under Contract UTA99-0, Austin, 36 p., and figures, tables, and attachment.

Schubert S. D., M. J. Suarez, P. J. Pegion, R. D. Koster, and J. T. Bacmeister, 2004, Causes of long-term drought in the U.S. Great Plains: Journal of Climate, v. 17, p. 485-503.

Sharp, J. M., Jr., 1990, Stratigraphic, geomorphic and structural controls of the Edwards Aquifer, Texas, U.S.A., *in* E. S. Simpson, and J. M. Sharp, Jr., eds., Selected papers on Hydrogeology: International Association of Hydrogeologists, v. 1, Heise, Hannover, Germany, p. 67-82.

Slade, R., Jr., L. Ruiz, and D. Slagle, 1985, Simulation of the flow system of Barton Springs and associated Edwards Aquifer in the Austin area, Texas: U.S. Geological Survey Water-Resources Investigations Report 85-4299, 49 p.

Slade, R., Jr., M. Dorsey, and S. Stewart, 1986, Hydrology and water quality of the Edwards Aquifer associated with Barton Springs in the Austin area, Texas: U.S. Geological Survey Water-Resources Investigations Report 86-4036, 117 p.

Smith, B. A., and B. B. Hunt, 2004, Evaluation of sustainable yield of the Barton Springs aquifer, Hays and Travis counties, central Texas: Report by the Barton Springs/Edwards Aquifer Conservation District, Austin, Texas, 55 p. and appendices.

Smith, B. A., B. B. Hunt, I. Jones, R. Lindgren, and G. Schindel, 2005, Ground-water availability modeling of the three major segments of the Edwards Aquifer, central Texas: National Ground Water Association Abstract Book of the 2005 Ground Water Summit Program, San Antonio, Texas, April 17-20, p. 232-233.

Smith, B. A., B. B. Hunt, and W. F. Holland, 2006, Drought trigger methodology for a karst aquifer system: Barton Springs aquifer, central Texas: National Ground Water Association Abstract Book of the 2006 Groundwater Summit, April 22-27, San Antonio, Texas, p. 170.

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