Real and Apparent Daily Springflow Fluctuations during Drought Conditions in a Karst Aquifer, Barton Springs Segment of the Edwards Aquifer, Central Texas

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ABSTRACT

Flow from Barton Springs is one of the most important measures of the overall condition of the Barton Springs segment of the Edwards Aquifer. Resource management rules (e.g., drought declaration triggers) have been developed that depend on accurate springflow data. In 1978, the U.S. Geological Survey (USGS) established a stage-discharge relationship between a USGS monitor well near the main spring, and manual discharge measurements taken primarily below Barton Springs pool in Barton Creek near its confluence with Lady Bird Lake. The stage-discharge relationship is very sensitive to fluctuating water levels in the reservoir. During the summer of 2011, fluctuations of up to 1 ft from Lady Bird Lake appeared to influence the stage-discharge relationship and manual measurements, which varied up to 30% during low-flow conditions. This is an influence previously undocumented. To understand this influence the USGS and others manually measured flow over a 24-hr period beginning on September 2, 2011, using acoustic Doppler velocimeters. Nineteen manual measurements collected over a 24-hr period ranged from 15.6 to 21.8 ft^3/s (cfs), while lake levels fluctuated about 0.6 ft. Results indicate that the lake stage influences the depth of the profile in Barton Creek with high lake levels producing higher apparent discharge values. Rapid flux in lake stage also influences the velocity along the profile such that a rapid rise generally reduced the natural velocity, producing smaller apparent discharge values, and vice versa. Measurements can now be planned to occur during steady-state conditions (low lake level), usually in the early morning hours. In addition to influences on manual measurements, lake stage may be providing some backpressure on the pool and aquifer, producing daily fluctuations in the USGS well, and affecting the stage-discharge relationship in the monitor well.

INTRODUCTION

Springflow issuing from Barton Springs is one of the most important measures of the overall condition of this segment of the Edwards Aquifer. The aquifer is a sole- or primary source for more than 60,000 people and the springs are habitat for the endangered Barton Springs salamander. Resource management rules (e.g., drought declaration triggers) have been developed by the Barton Springs/Edwards Aquifer Conservation District (District) that depend on accurate and timely springflow data. The U.S. Geological Survey (USGS) has been measuring springflow at Barton Springs since the early 1900s. By 1978, a stage-discharge relationship (or rating curve) was

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developed for a well near the Main Spring of Barton Springs Pool. Manual measurements below the pool at the confluence with Lady Bird Lake are required to verify the stage-discharge relationship and to make any shifts or corrections to the data. As the 2011 drought conditions worsened, accurate springflow data became more important as drought trigger values (20 cfs) were approached and eventually reached. However, hourly variations in the web data of up to 30% of the median values were observed, which triggered a need for manual measurements from the USGS, District, and City of Austin (CoA). Manual measurements varied considerably from hour to hour and it was also observed that the level of Lady Bird Lake also fluctuated. It was hypothesized that the varying lake levels were influencing the manual measurements and possibly the stage in the well. The purpose of this study is to better understand the influence of the changing lake level on the manual measurements and stage-discharge relationship.

Hydrogeologic Setting

The Edwards Aquifer is a karst aquifer developed in faulted and fractured Cretaceous-age limestones and dolomites. The prolific karstic Edwards Aquifer system lies within the Miocene-age Balcones Fault Zone of Texas and provides water for some 2 million people. Hydrologic divides separate the Edwards Aquifer into three segments (Fig. 1). The reader is referred to Ryder (1996), Barker et al. (1994), and Lindgren et al. (2004), which provide detailed regional information on the Edwards Aquifer.

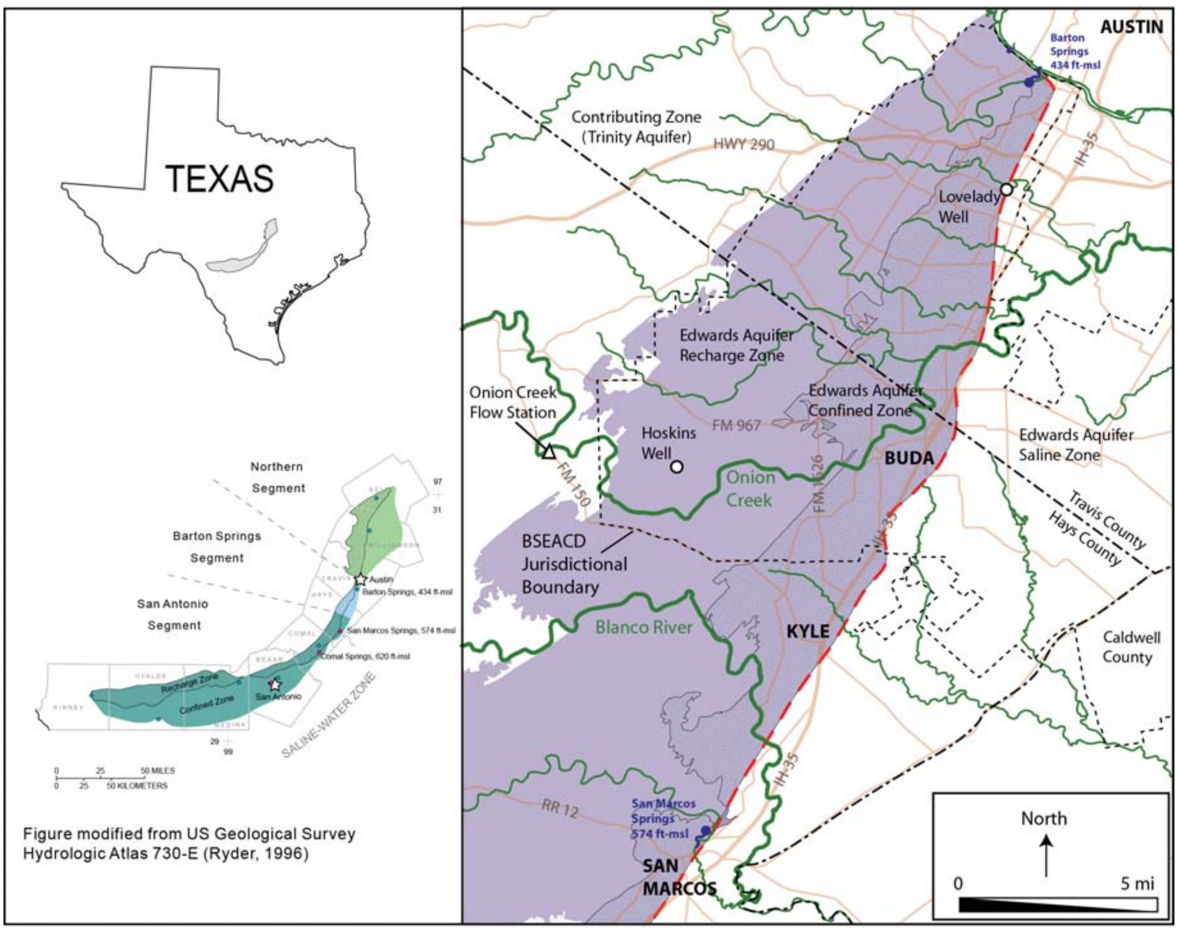

Figure 1. Location map of study area. This study is focused upon Barton Springs, the natural primary discharge point from the Barton Springs segment of the Edwards Aquifer.

The Barton Springs segment of the Edwards Aquifer is the smallest segment of the Edwards Aquifer (~155 mi^2), and is the subject of this paper. Hereafter, this segment is referred to as the Barton Springs aquifer. Barton Springs is the natural discharge point of the Barton Springs aquifer and is situated in Barton Creek about 1500 ft upstream of the main channel of the Colorado River, which is the northern hydrologic boundary of the aquifer. The Colorado River is dammed to create Lady Bird Lake (Fig. 2A). Barton Springs serves as habitat for federally-listed endangered species and provides water to Barton Springs Pool, a major recreation site (Fig. 2B). Barton Springs is the lowest point of discharge for the Barton Springs and San Antonio segments of the Edwards Aquifer (Figs. 1 and 3).

Recharge and Groundwater Flow

Ford (2004) defines karst as terrain with distinctive hydrology arising from the combination of high rock solubility and well-developed solution channel porosity underground. Karst terrains and aquifers are characterized by sinking streams, sinkholes, caves, springs, and an integrated system of pipe-like conduits that rapidly transmit groundwater from recharge features to springs (White, 1988; Todd and Mays, 2005). Although conduits dominate flow, the Edwards Aquifer can be further described as a triple porosity and permeability system consisting of matrix, fracture, and conduit (karstic) porosity (Hovorka et al., 1995; Halihan et al., 2000; Lindgren et al., 2004).

Figure 4 illustrates the hydrologic functioning of the Barton Springs aquifer. The majority of recharge to the aquifer is derived from rainfall and runoff into streams originating on the contributing zone, located up gradient and primarily west of the recharge zone (Figs. 1 and 2). Onion Creek is the largest source of recharge to the aquifer (Slade et al., 1986). Water flowing onto the recharge zone sinks into numerous caves, sinkholes, and fractures along numerous ephemeral to intermittent losing stream segments and builds up storage within the aquifer as indicated by rising water levels in wells (Fig. 4). Some of the recharge water quickly flows to Barton Springs as indicated by dye tracer studies (Hauwert et al., 2004), while other recharge water is stored in the secondary karstic and matrix porosity and flows to the springs more slowly, as recharge and heads decrease. Groundwater generally flows west to east across the recharge zone, then converges with preferential groundwater flow paths subparallel to major NE-trending faults toward the Barton Springs complex. Groundwater tracing and other studies demonstrate that a significant component of groundwater flow is discrete, occurring in a well integrated network of conduits, caves, and smaller dissolution features (Hauwert et al., 2004). Rates of groundwater flow along preferential flow paths, determined from dye tracing, can be as fast as 4 to 7 mi/day under high-flow conditions, and as low as about 1 mi/day under low-flow conditions (Hauwert et al., 2002; Hunt et al., 2005).

Barton Springs

Barton Springs flow is typical of a spring in a karst system with dynamic responses to recharge events and integration of conduit, fracture, and matrix flow from the system (Mahler et al., 2006). Although the relative contribution of the triple permeability system is unknown, dye tracer studies have proven that conduit-flow dominates the flow system in the Edwards under most conditions (Hauwert et al., 2004).

Barton Springs is the fourth largest spring in Texas (Brune, 2002) and consists of four major outlets: Main, Eliza, Old Mill, and Upper (Figs. 2B and 3). Main Spring has the largest discharge and flows directly into the Barton Springs Pool. Eliza Spring now discharges through a pipe into the pool bypass tunnel and then into Barton Creek at the downstream dam. Old Mill Spring flows overland into Barton Creek about 400 ft downstream of the pool. Upper Barton Springs is located in Barton Creek about 400 ft upstream of the pool (Fig. 2B). Flow from Upper Barton Springs, which is characterized as an 'overflow' spring, only flows when discharge at Barton Springs exceeds about 40 cfs (Hauwert et al., 2004). Each of the spring outlets provides habitat for the federally-listed Barton Springs salamander.

Springflow at Barton Springs is officially determined and reported by the USGS as site number 08155500. Discharge reported for Barton Springs is based on a stage-discharge (or rating-curve) relationship between gage height in the Barton Well (YD 58–42–903), and manual flow measurements of Barton Springs that include flow from Main, Eliza, and Old Mill. Daily mean springflow is computed from a stage-discharge relationship developed from daily mean gage height that is derived from 15-min observations of gage height. The stage-discharge

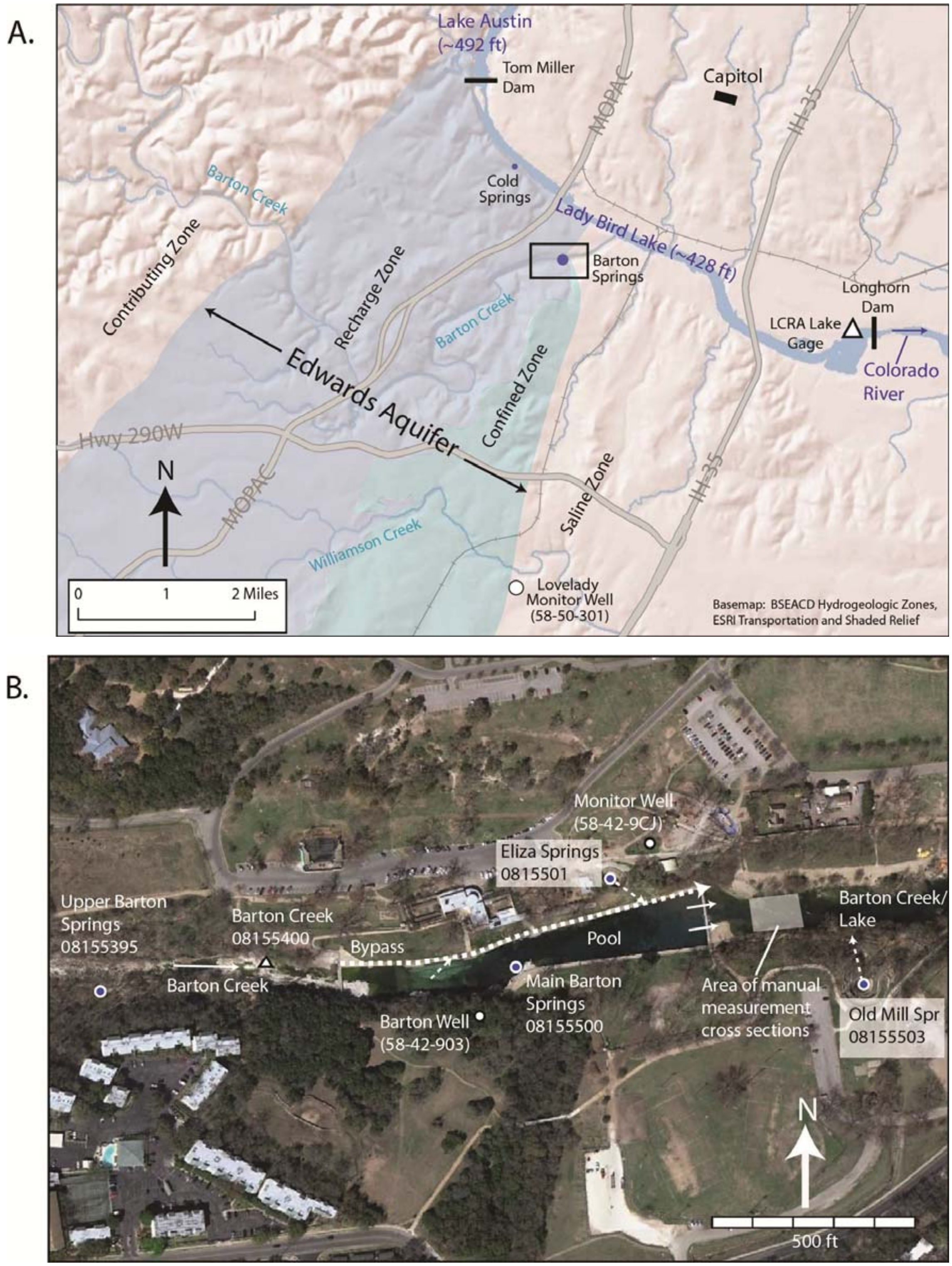

Figure 2. A) General location map of the region around the study area. B) Annotated aerial photograph of the Barton Springs Pool area. Aerial image is courtesy of Google Earth.

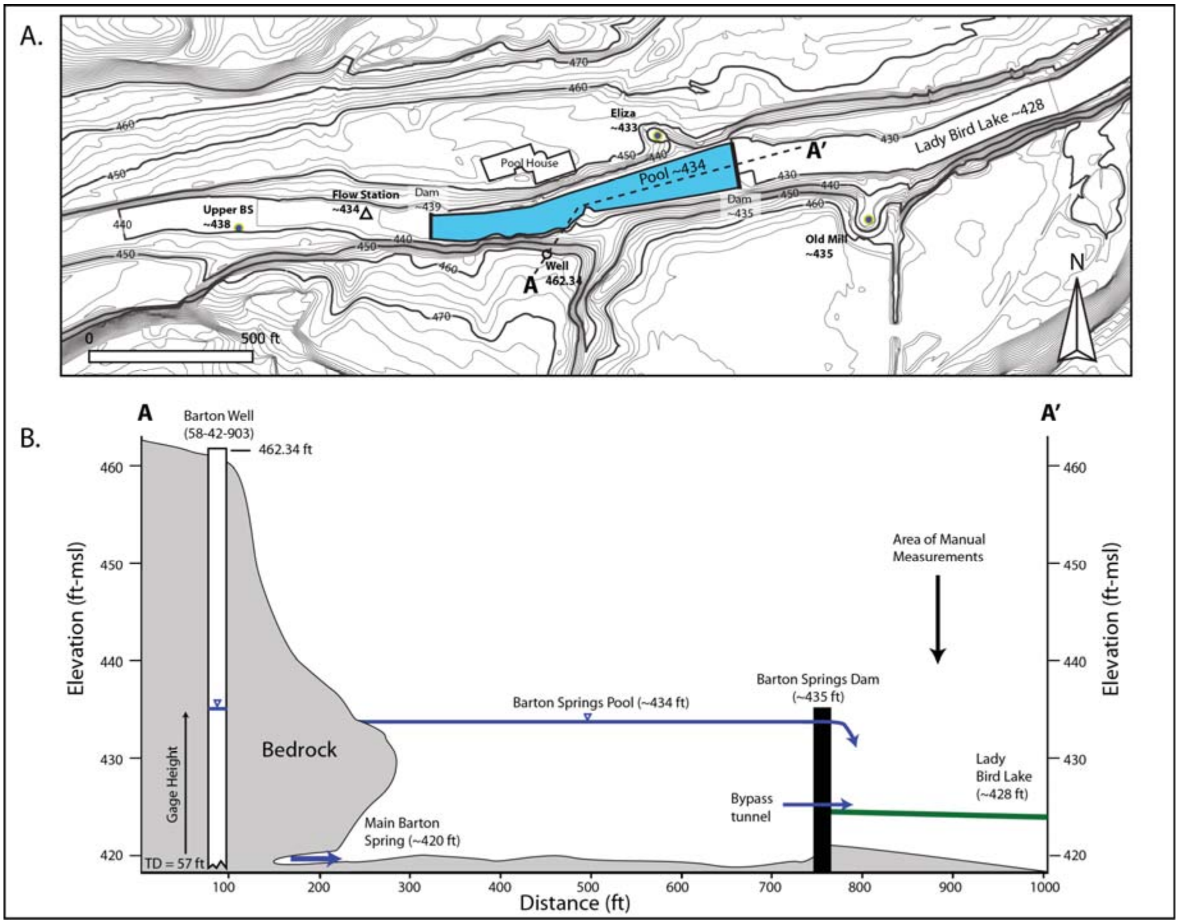

Figure 3. A) Topographic map of the pool area using 2003 City of Austin 2-ft contours. Note important elevations indicated. B) Cross section along A–A' illustrating the configuration of the stage-discharge relationship and important elevations.

relationship is an empirically derived relationship translating gage height (ft) into springflow (cfs). About 300 manual measurements have been recorded since 1958 to develop this relationship. Figure 5 illustrates the correlation of the Barton Springs flow derived by the rating curve to the Barton Well gage. The relationship is routinely verified with manual measurements of springflow and gage height (Fig. 6). Manual measurements of Barton Springs discharge require near synoptic measurements of discharge below Barton Springs Pool, discharge of Old Mill Spring, and flow of Barton Creek upstream of the pool (near USGS flow station 08155400). Barton Springs flow is derived by subtracting the measurement upstream of the pool from the downstream measurement, and then adding in flow from Old Mill. Upper Barton Springs is not included in springflows reported for Barton Springs (Asquith and Gary, 2005).

This stage-discharge relationship was developed for normal operational pool levels and any adjustment to the Barton Springs Pool level changes the hydraulic head of the spring, which influences hydraulic head in the aquifer. Indeed, draining the pool for cleaning has been shown to influence measured well water elevations 2.5 mi to the southeast (Slade et al., 1986). Thus, changes in pool elevation influence the Barton Well gage height and the rating curve. Changes in the pool level occur for cleaning, leaks into the bypass, pool-level adjustments for recreation, and opening dam gates in anticipation of flooding events. Therefore, the stage-discharge relation-

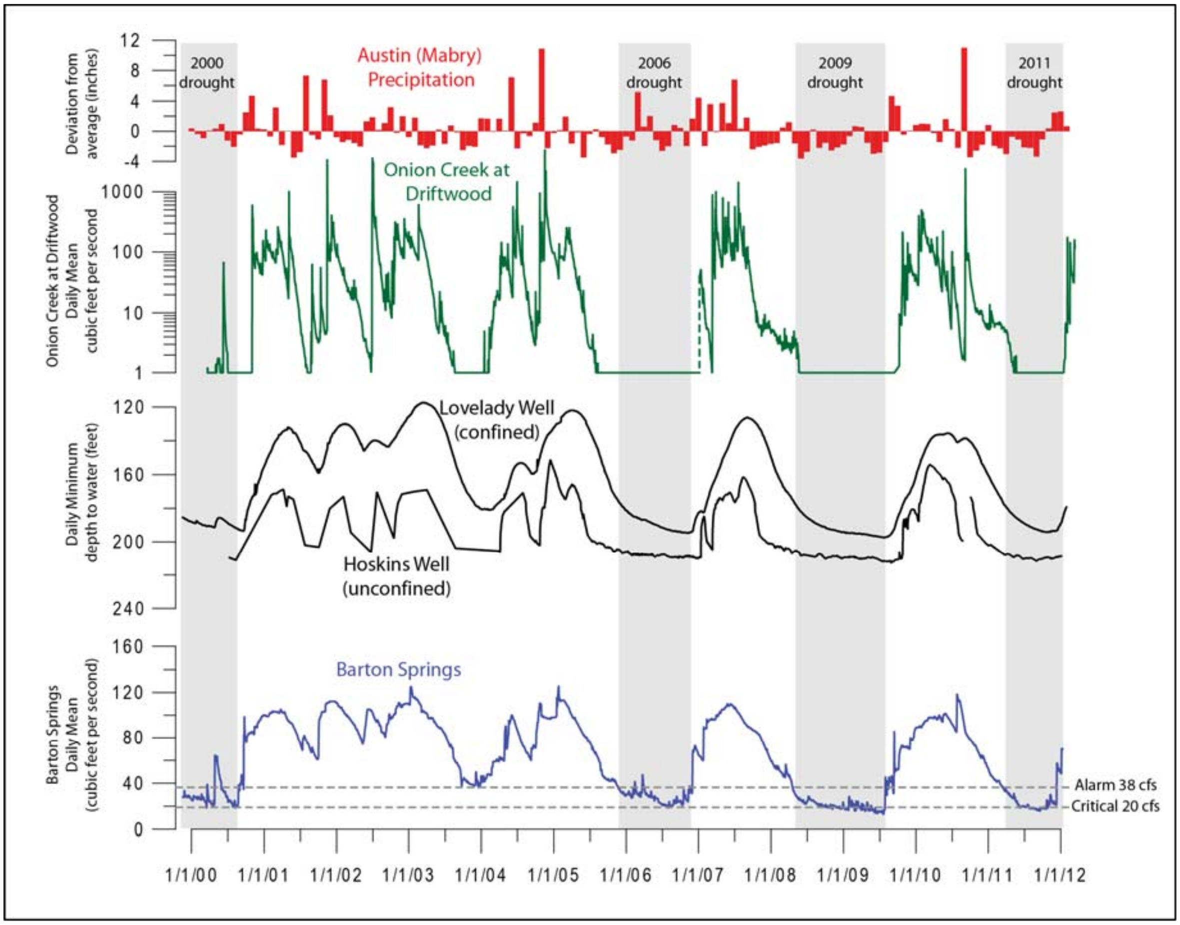

Figure 4. Hydrograph illustrating hydrologic functioning of the Barton Springs Aquifer. Rainfall generates flow in Onion Creek, which recharges the aquifer and increases storage as indicated by water levels in wells. Springflow mirrors the stream and water level trends. Note drought thresholds for Barton Springs and the recent droughts indicated. Source data: Onion Creek and Barton Springs data are from the U.S. Geological Survey (2012), well water level data are from the District (unpublished), and precipitation data are from the NOAA-NCDC (2012).

ship is not constant due to subtle changes in the pool elevation and a shift is often applied to the empirical relationship to maintain accurate data (Asquith and Gary, 2005).

Barton Springs has a long period of continuous discharge data beginning in 1917. Monthly mean data are available from 1917 to 1978 (Slade et al., 1986), and daily mean discharge data are available thereafter. The long-term average springflow at Barton Springs is 53 cfs based on data from 1917–1995 and is a widely reported value (Scanlon et al., 2001; Hauwert et al., 2004). The maximum and minimum measured instantaneous discharges are 166 and 9.6 cfs, respectively. The lowest measured spring discharge value occurred on March 26, 1956 during the 1950s drought (Brune, 2002; Slade et al., 1986). Mahler et al. (2006) and the CoA define low flow as below 40 cfs. The District declares Alarm Stage Drought when the 10-day average of Barton Springs is equal to or below 38 cfs.

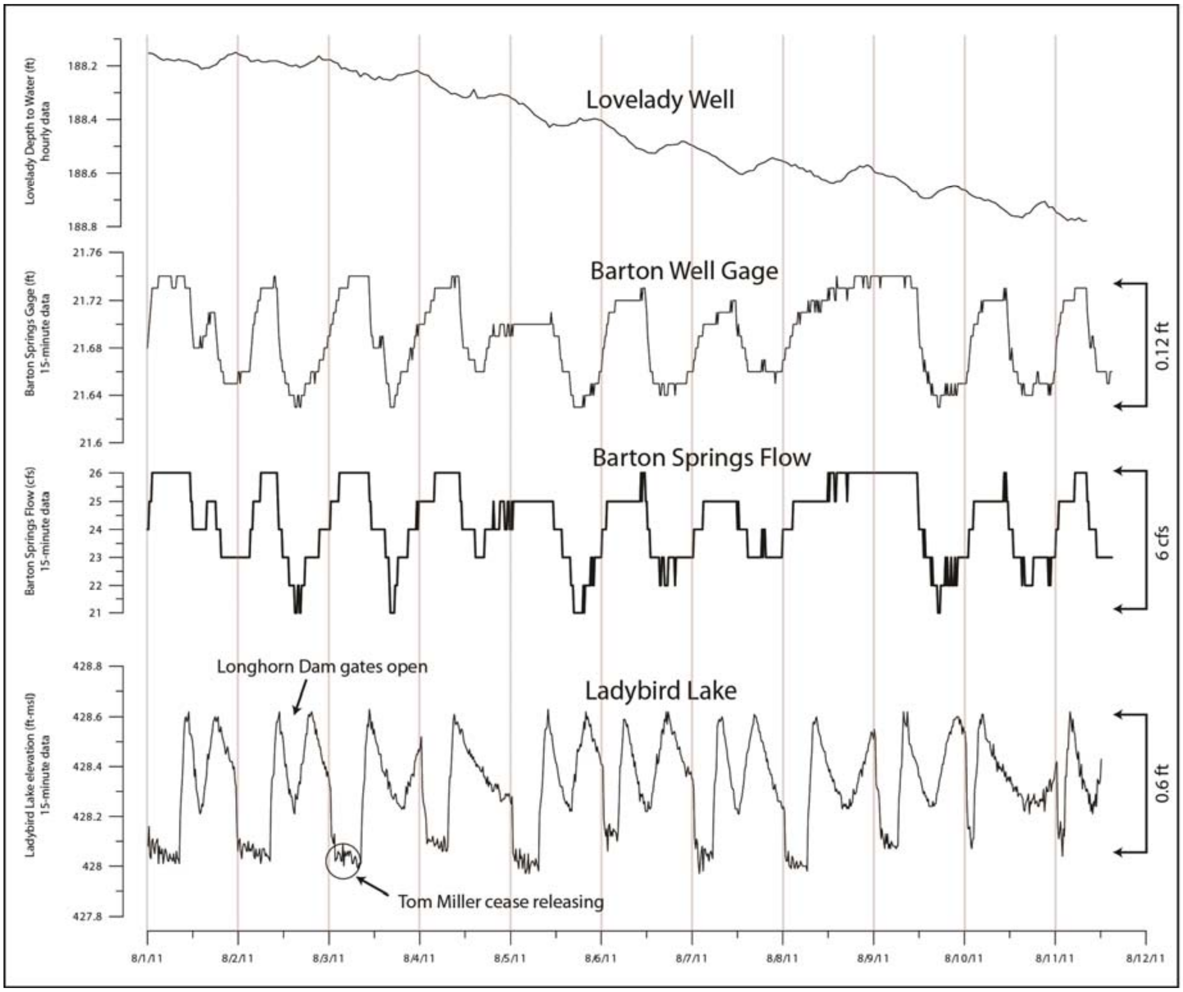

Figure 5. Hydrograph of August 2011 for hydrologic features discussed in this study. The drought is most apparent in the decline (recession) in water levels in the Lovelady well. Barton Springs gage data is used to compute Barton Springs springflow. The gage fluctuates in this hydrograph about 0.12 ft, which corresponds to about 6 cfs of springflow variation, or about 30% of the total flow. Lady Bird Lake fluctuates 0.6 ft due to releases from Tom Miller Dam and when gates on the Longhorn open and close.

Hydrologic Conditions and Drought

This study focused on springflow at Barton Springs during September 2011, as the region experienced an intense drought, and springflows were declining. During the study the District approached its Critical Stage Drought threshold at Barton Springs of 20 cfs (10-day average). However, daily fluctuations of up to 30% of flow were occurring as springflow approached 20 cfs, causing much uncertainty in the data used for aquifer management. It was noted that these fluctuations appeared to increase after June 2011. Figure 7 illustrates gage data, gaged springflow, manual measurements, and the drought triggers of the District.

The 2011 drought was the most intense (both driest and hottest) single year drought since 1895 when the historic record begins (Nielsen-Gammon, 2011). October 2010 to September 2011 was the driest 12-month period since records were kept in Austin since the 1860s. Austin received only 11.2 in of rainfall for that period,

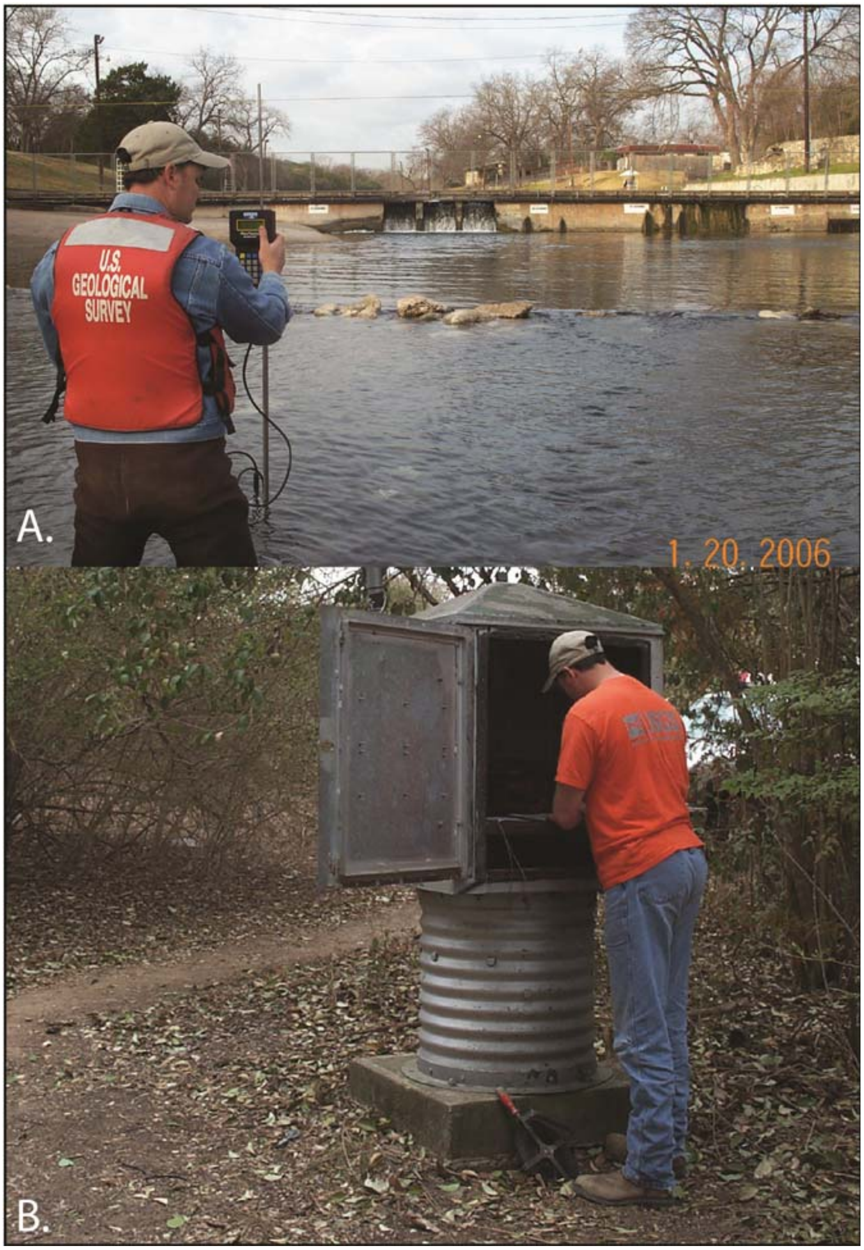

Figure 6. A) Photograph of USGS staff measuring flow about 250 ft downstream of Barton Springs Pool dam using a FlowTracker ADV®. Note the rock wall creating turbulence. B) USGS staff check equipment and make a manual stage measurement in the USGS Barton Well.

which is only 33% of its average annual total. As the rainfall diminished, so did flow in the creeks, which provide recharge to the Edwards Aquifer. Onion Creek, the largest contributor of recharge to the aquifer, stopped flowing by October 2010. Lack of recharge resulted in lower water levels, or storage, and decreasing springflow at Barton Springs. Figure 4 illustrates the intensity and depth of the 2011 drought relative to other recent droughts.

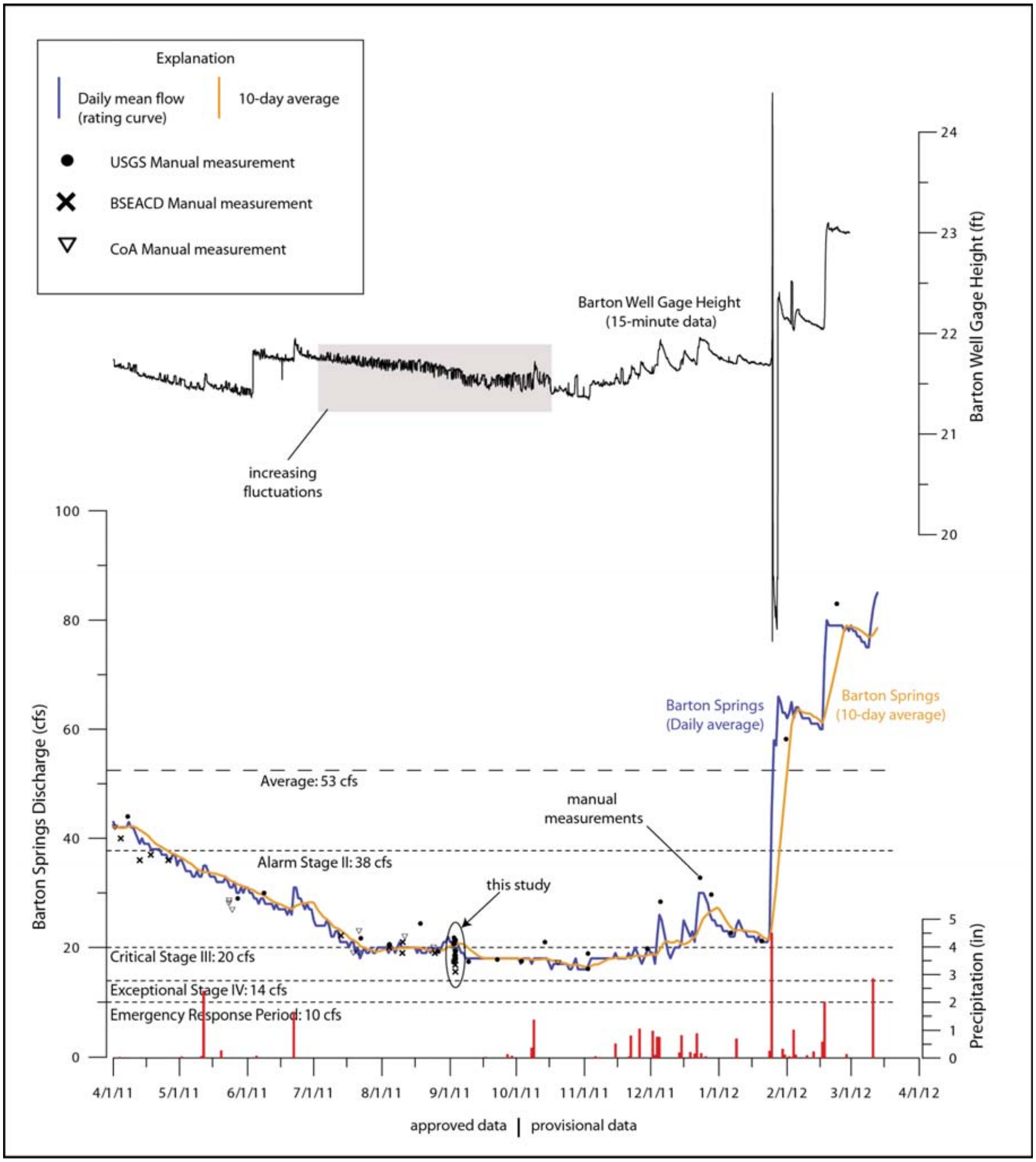

Figure 7. Barton Springs hydrograph with gage, computed springflow, and manual measurements indicated. Note the increasing variation in gage height (shaded area) after June 2011, and also the range in manual measurements around September 1, 2011 (this study).

The District developed a drought trigger methodology that uses both the Lovelady Well in South Austin and Barton Springs discharge to declare official groundwater droughts (Smith et al., 2006). The District Board declared Alarm Stage Drought on April 28, 2011, followed by a Critical Stage Drought declaration on September 8, 2011.

Dams, Pools, and Reservoirs

The upper and lower dam structures creating Barton Springs Pool were built in 1929 and 1928, respectively. The upper dam diverts streamflows of Barton Creek below 500 cfs into the bypass tunnel around Barton Springs Pool. There is also a small drain in the shallow end of the pool that drains directly into the bypass tunnel. Water leaking from the pool also flows directly into the bypass tunnel. The lower dam has several gates near the top that can control the elevation of water in the pool. The elevation of the pool is managed by the CoA Parks and Recreation Department in consultation with the CoA Watershed Protection Department in accordance with the City's Habitat Conservation Plan.

Lady Bird Lake was created in 1960 when Longhorn Dam was completed on the Colorado River downstream of Barton Creek. Longhorn Dam was originally built as a cooling lake for the Holly Power Plant in East Austin and is owned and operated by CoA. Lady Bird Lake has a relatively constant elevation of about 428 ft above mean sea level (ft-msl). Lake elevation data are available online at the Lower Colorado River Authority's (LCRA's) Hydromet system. Tom Miller Dam is located about 2.5 mi upstream of Barton Creek creating Lake Austin, and was completed in 1940 as a hydro-electric power generator. Lake Austin, above Tom Miller Dam, is also a relatively constant-level lake with an elevation of about 492 ft-msl. Releases from Tom Miller Dam are managed by the LCRA. The LCRA releases water from the Highland Lakes system which passes through Lake Austin and Lady Bird Lake. The LCRA releases water from the reservoirs during the summer months to maintain environmental flows and for agricultural needs downstream of Austin. These flows are pulsed to coincide with peak electric demand times (early morning hours). Lady Bird Lake serves as a pass-through lake with the elevation of water controlled by Tom Miller Dam releases and by gates on the top of Longhorn Dam that automatically open in response to increased flows (David Walker, 2011, personal communication). Lady Bird Lake was noted to vary in elevation about 0.6 ft prior and during the study period (Figs. 5 and 8). During the study the change in lake level corresponded to a release of about 1750 cfs for 16 hr (7 am to 11 pm) on September 2, and then a release of 1750 cfs for 15 hrs (8 am to 11 pm) on September 3 (LCRA, 2011a, 2011b). These fluctuating lake levels influence water levels in the Barton Springs Pool bypass tunnel (Nico Hauwert, 2008, pers. comm.). Figure 5 illustrates the fluctuation of the Barton Well gage of up to 0.12 ft. Low gage levels appear to have a 10- to 12-hr time-lag to the lowest Lady Bird Lake levels.

METHODS AND DATA

Techniques used for this study are primarily the manual collection of streamflow data using acoustic Doppler velocimeters (ADV). Results were compared with other readily available hydrologic data such as Barton Springs gage and flow (USGS site 0815550), and Lady Bird Lake elevations (LCRA Hydromet data).

A broad overview of stream gages is discussed in Lurry (2011). Techniques and standards for making discharge measurements at streamflow gaging stations are described in Turnipseed and Sauer (2010) and Nolan et al. (2007). These techniques are standard practice the USGS. In addition, recent technical memos by the USGS require an independent water temperature measurement prior to every measurement and certain quality assurance checks (Blanchard, 2010; Rehmel, 2010). A routine quality assurance program was established to track meters and verify and calibrate meter function (Blanchard, 2009). Data collected by District and CoA staff generally followed the standards and protocols cited above and are comparable to the data collected by the USGS in all material respects.

The USGS measured flow with the StreamPro ADCP (Acoustic Doppler Current Profiler) manufactured by RD Instruments. The StreamPro ADCP is mounted on a small float and is dragged across the section and can provide nearly continuous vertical and horizontal depth and velocity profiles. The District and the CoA used a hand-held FlowTracker ADV® manufactured by SonTek/YSI1. The FlowTracker ADV® is mounted on a standard wading rod and measures currents in 2D and provides discrete or point data on depth and velocity. For this study the FlowTracker ADV® traversed a section width of about 100 ft with about 27 stations during each measurement. The depths ranged from less than 1 ft up to 2.8 ft deep. The FlowTracker was used to collect data at each station using the 0.6 or the 0.2/0.8 methods, depending on water depth. Despite the difference in instruments used in this study, the data are comparable.

In order to verify the Lady Bird Lake stage-level data provided by the LCRA Hydromet system, we deployed an In-Situ Level Troll 300 in the stream during the study. The probe is unvented pressure transducer and

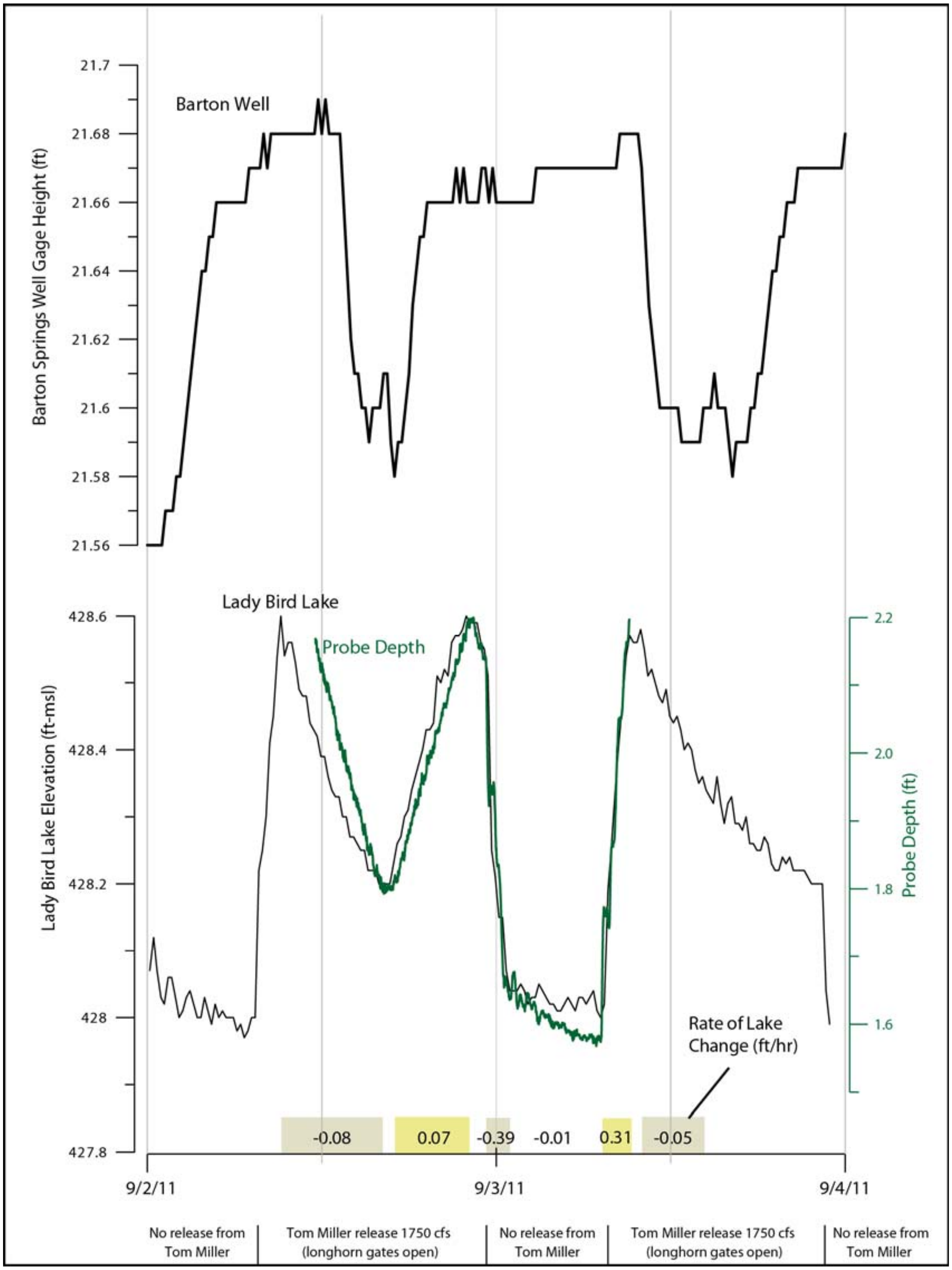

Figure 8. Hydrograph showing the Barton Well gage height compared to the Lady Bird Lake elevation and depth along profiled section as measured by a pressure transducer. The rate of change of the lake level is indicated along bottom axis as well as the functioning of the dams.

rated for 15 psi and recorded depth and temperature every minute during most of the data collection period. The data from the probe matched the lake stage data very well (Fig. 8).

Other challenges to measuring flows accurately include non-uniform cross-section floors (cobbles), public interference (rock dams and dogs), and equipment/operator errors.

RESULTS

The USGS, District, and CoA manually measured flow over a 24-hr period beginning on September 2, 2011, at 12:00. During this time, there was no flow above Barton Creek, and Old Mill was not flowing. Accordingly, only one measurement was needed below Barton Springs Pool that captured all of the flow from Barton Springs. Nineteen manual measurements collected over a 24-hr period ranged from 15.6 to 21.8 cfs, while lake levels fluctuated about 0.6 ft in magnitude (Figs 8 and 9; Table 1).

Results indicate that the Lady Bird Lake stage fluctuation influences the depth of the profile in Barton Creek below Barton Springs Pool. High lake levels produce higher apparent discharge values (Fig. 9; Table 1). Rapid flux in lake stage also influenced the velocity along the profile. A rapid rise generally reduced the natural velocity, producing smaller apparent discharge values. A rapid drop generally elevated the mean velocity, producing larger apparent discharge values (Fig. 9; Table 1). The fluctuations influence the Barton Well gage affecting the

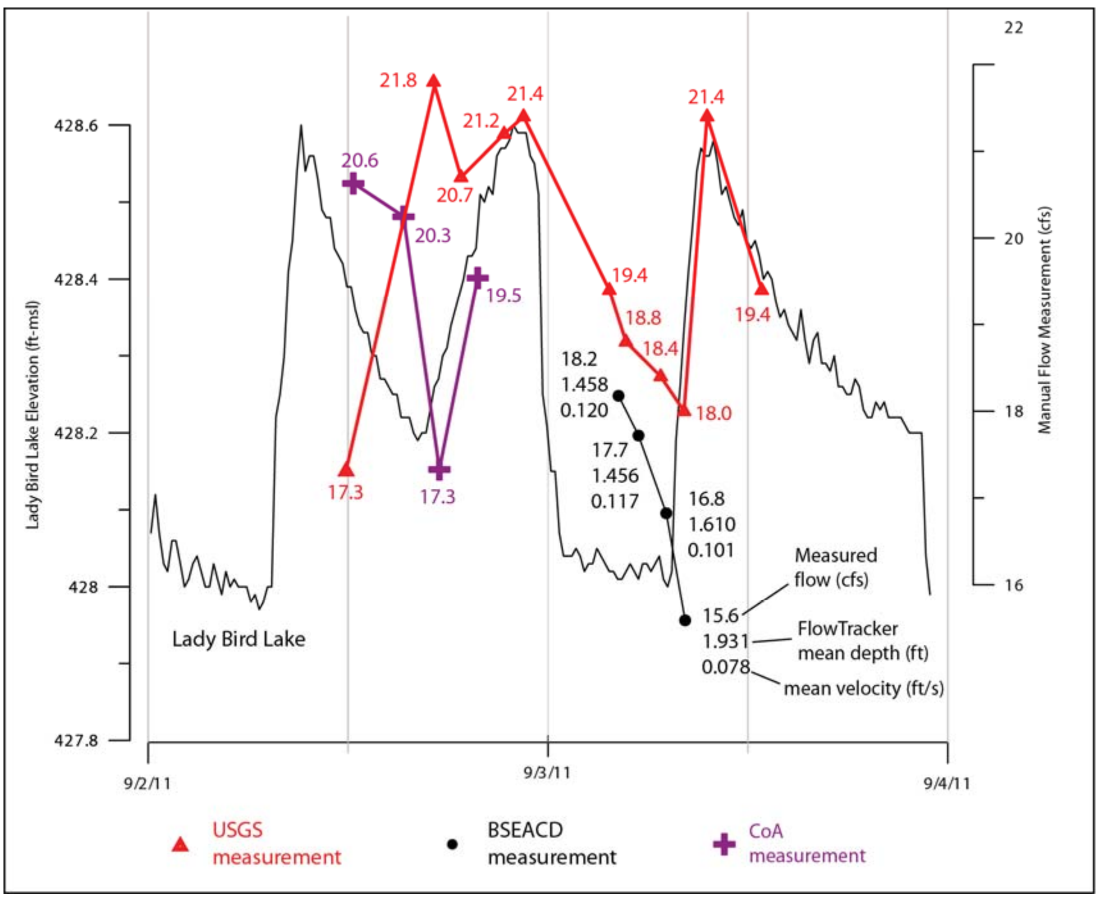

Figure 9. Hydrograph of the results of manual flow measurements compared with the elevation of Lady Bird Lake. Manual measurements by the District have mean depth (ft) and mean velocity (ft/s) indicated below discharge value.

Table 1. Manual discharge measurement data.

Agency Measure No.	Date and Time	USGS Stream-flow (cfs)	USGS Gage Height (ft)	Mean Depth (ft)	Mean Velocity (ft/s)	Distance Down-stream from Dam (ft)
USGS 275	9/2/11 11:50	17.3	21.7	nd	nd	100
USGS 276	9/2/11 17:08	21.8	21.6	nd	nd	100
USGS 277	9/2/11 18:47	20.7	21.7	nd	nd	100
USGS 278	9/2/11 21:22	21.2	21.7	nd	nd	100
USGS 279	9/2/11 22:32	21.4	21.7	nd	nd	100
USGS 280	9/3/11 03:41	19.4	21.7	nd	nd	100
USGS 281	9/3/11 04:41	18.8	21.7	nd	nd	100
USGS 282	9/3/11 06:46	18.4	21.7	nd	nd	100
USGS 283	9/3/11 08:10	18.0	21.7	nd	nd	100
USGS 284	9/3/11 09:33	21.4	21.7	nd	nd	100
USGS 285	9/3/11 12:50	19.4	21.7	nd	nd	100
CoA_2011_15	9/2/11 12:19	20.6	nd	1.80	0.11	250
CoA_2011_16	9/2/11 15:20	20.3	nd	1.62	0.14	100
CoA_2011_17	9/2/11 17:29	17.3	nd	1.85	0.09	250
CoA_2011_18	9/2/11 19:47	19.5	nd	1.67	0.12	150
BSEACD_2012_1	9/3/11 04:14	18.2	nd	1.46	0.12	250
BSEACD_2012_2	9/3/11 05:26	17.7	nd	1.46	0.12	250
BSEACD_2012_3	9/3/11 07:06	16.8	nd	1.61	0.10	250
BSEACD_2012_4	9/3/11 08:14	15.6	nd	1.93	0.08	250

nd = no data

stage-discharge relationship. This results in daily fluctuations in the calculated discharge. It appears that the most representative time to manually measure flow is when the lake levels are at low, steady-state elevations.

DISCUSSION

The results of this study have documented some of the challenges of measuring flow at Barton Springs during low-flow conditions. Low springflow conditions are when accurate flow data are most needed for resource management. The relationship between fluctuating lake levels and its influence on manual measurements and the aquifer is important to understand as the District approaches its various drought thresholds. This study suggests careful review of discharge data and concerted efforts to manually measure during steady-state conditions are needed.

Lake-level fluctuations appear to provide backpressure (with some lag time) on the aquifer. We recognized the water level in the bypass tunnel is influenced by the lake level fluctuations. We also recognized the pool has many leaks into the bypass tunnel and is therefore in hydraulic communication with the tunnel. Therefore, the pool level may also be influenced by fluctuating lake levels. The hydraulic connection between the pool and the Barton Well (and other wells) is also very well established. Therefore, it stands to reason that the lake levels are a likely source of the minor fluctuations within the aquifer, including the levels in the monitor (gage) well.

The well gage fluctuates about 0.12 ft, which in turn produces calculated springflow fluctuations up to 6 cfs based on the rating curve. An accurate manual measurement uninfluenced by lake levels should provide a median value for which the rating curve will oscillate above and below.

Not only is the Barton Springs gage fluctuating, but daily variations in springflow outlet velocity from Main Barton Spring were observed in velocity data during low-flow conditions during a study in 2004 (Asquith and Gary, 2005). These could be the result of barometric, tidal, and pumping effects. Fluctuations are also observed in the Lovelady well (Fig. 5) under high and low-flow conditions, and may be the result of barometric, and other, influences. A study by Cox et al. (2009) demonstrated that pumping explains about one third of the daily springflow discharge variability at Comal Springs—the largest of the Edwards Aquifer springs. Further work is needed to understand the various influences of these phenomena on water levels and springflow under varying conditions.

CONCLUSIONS

This study documents the influence of lake levels on manual measurements. Agencies measuring discharge are now aware of the issue. Measurements should be collected when low lake level, steady-state conditions exist to provide the most accurate manual measurements.

It also appears that minor fluctuations of the well gage are occurring from backpressure of lake levels during low-flow conditions. This can translate into significant calculated springflow variations of up to 30%.

FUTURE WORK

Future work could include investigation into the construction of a new control structure such as a weir that could isolate the system from lake-level influences and improve the cross section. In addition, another monitor well could be less sensitive to pool fluctuations and could be used in a stage-discharge relationship.

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