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

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

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

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

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

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INTRODUCTION

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

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

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

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

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

PREFERENTIAL GROUNDWATER FLOW ZONE BETWEEN SAN MARCOS SPRINGS AND BARTON SPRINGS

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

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

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

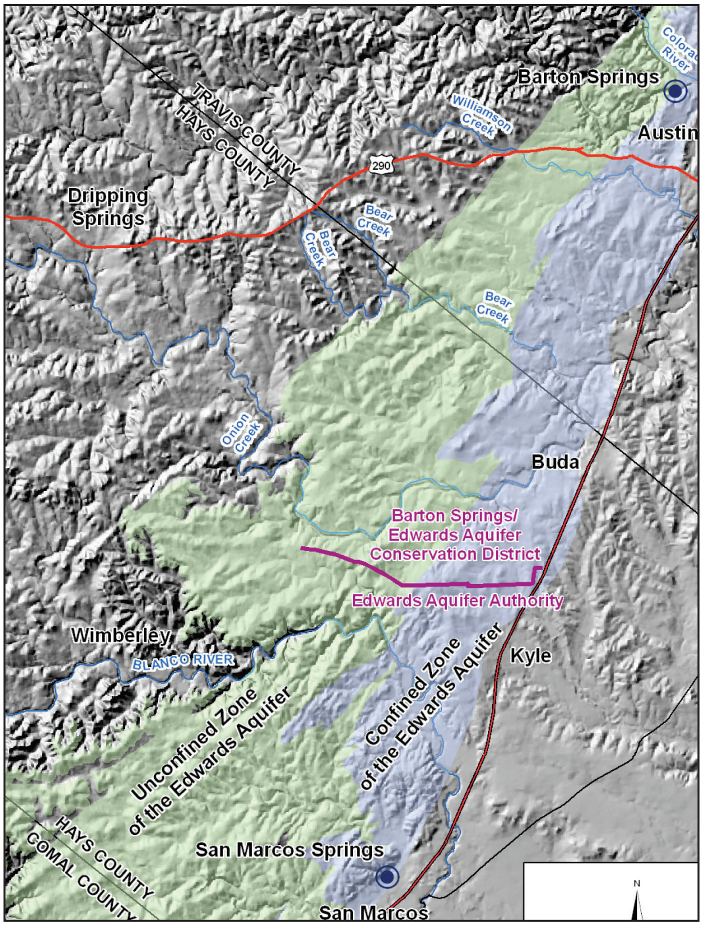

Fig. 1. Location of Study Area, Edwards Aquifer and Jurisdiction of Edwards Aquifer Authority and Barton Springs/Edwards Aquifer Conservation District.

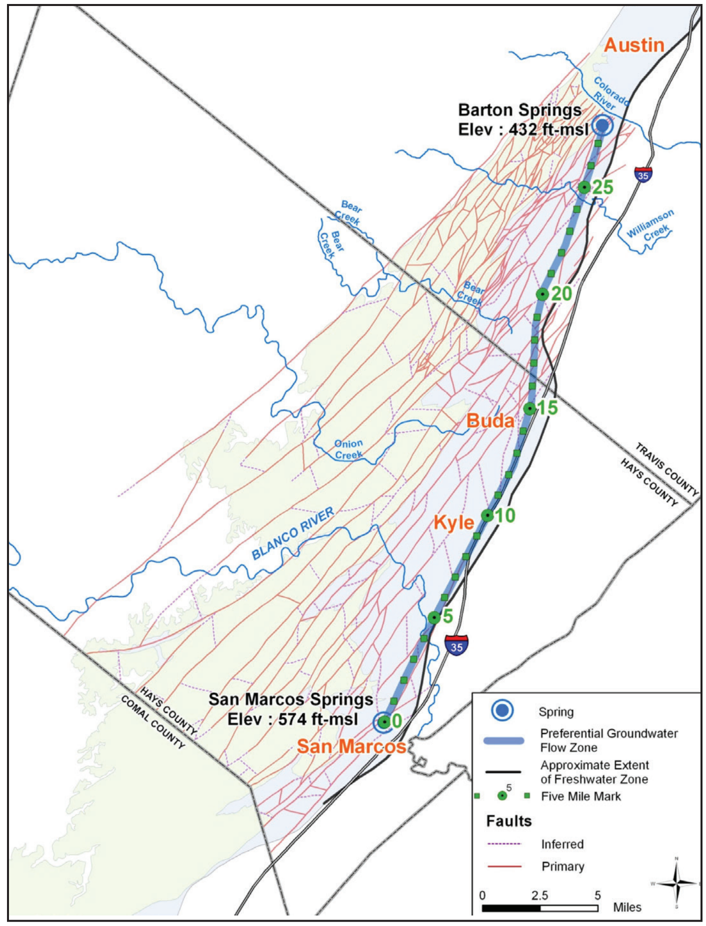

Fig. 2. Location of Preferential Groundwater Flow Zone.

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

OVERVIEW OF HYDROLOGIC CONDITIONS

1989-2009 Conditions

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

2009 Conditions

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

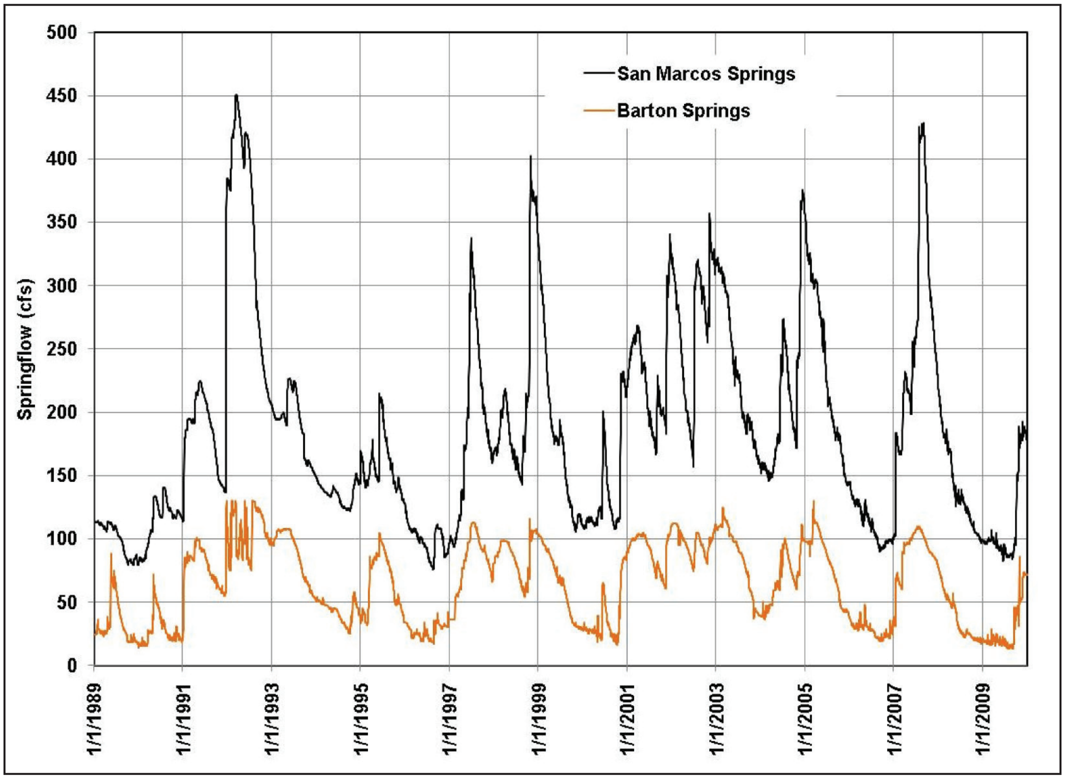

Fig. 3. Discharge hydrographs of San Marcos and Barton Springs (1989–2009).

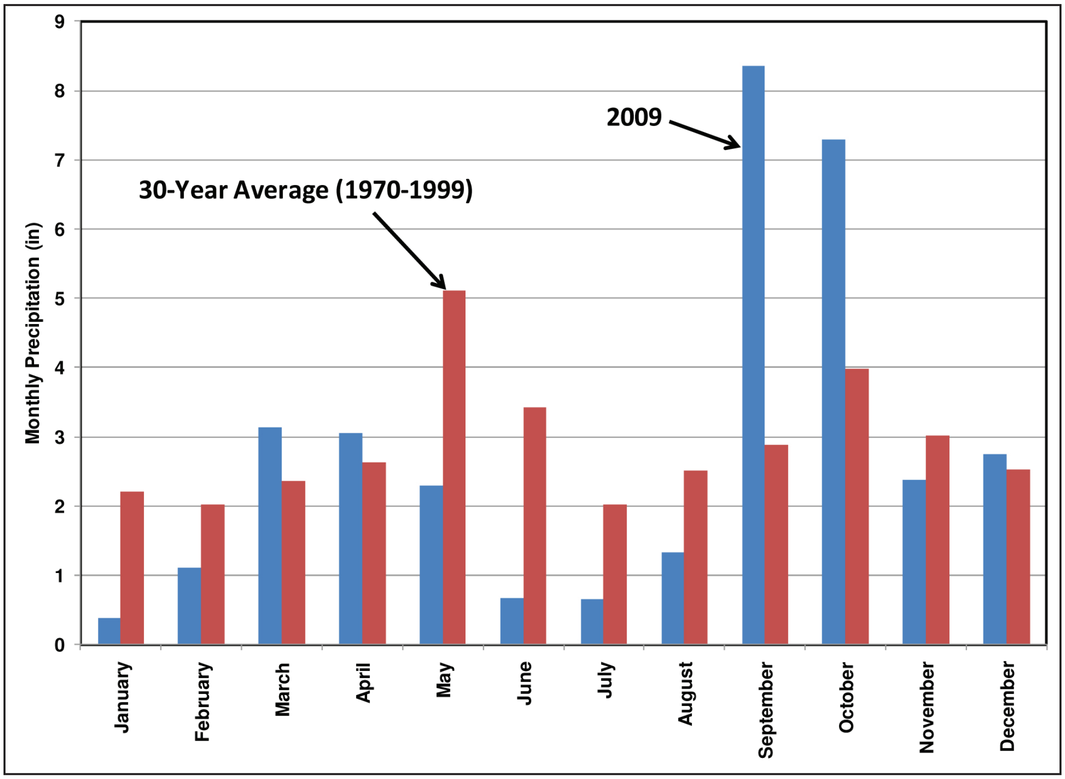

Fig. 4. Monthly precipitation, 2009 and 30-year average.

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

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

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

APPROACH

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

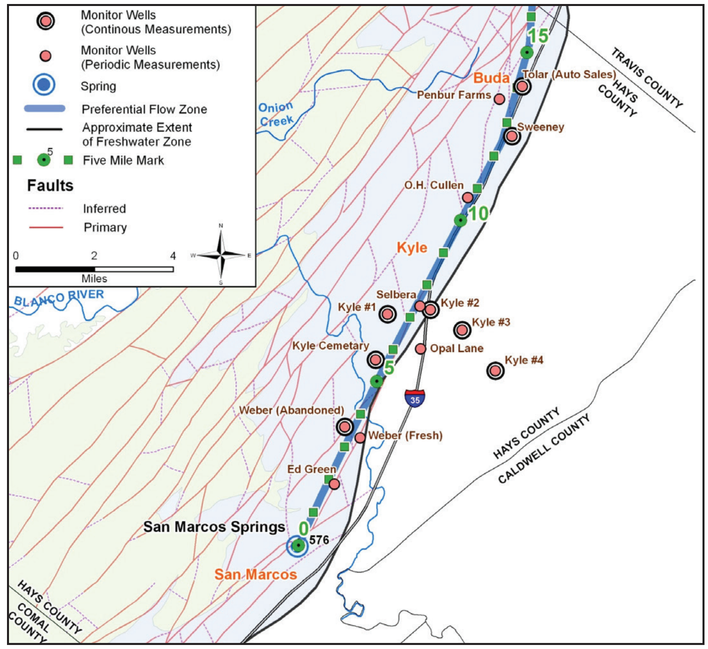

Fig. 5. Location of monitoring wells.

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

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

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

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

RESULTS: 2009 DATA

Periodic Measurements

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

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

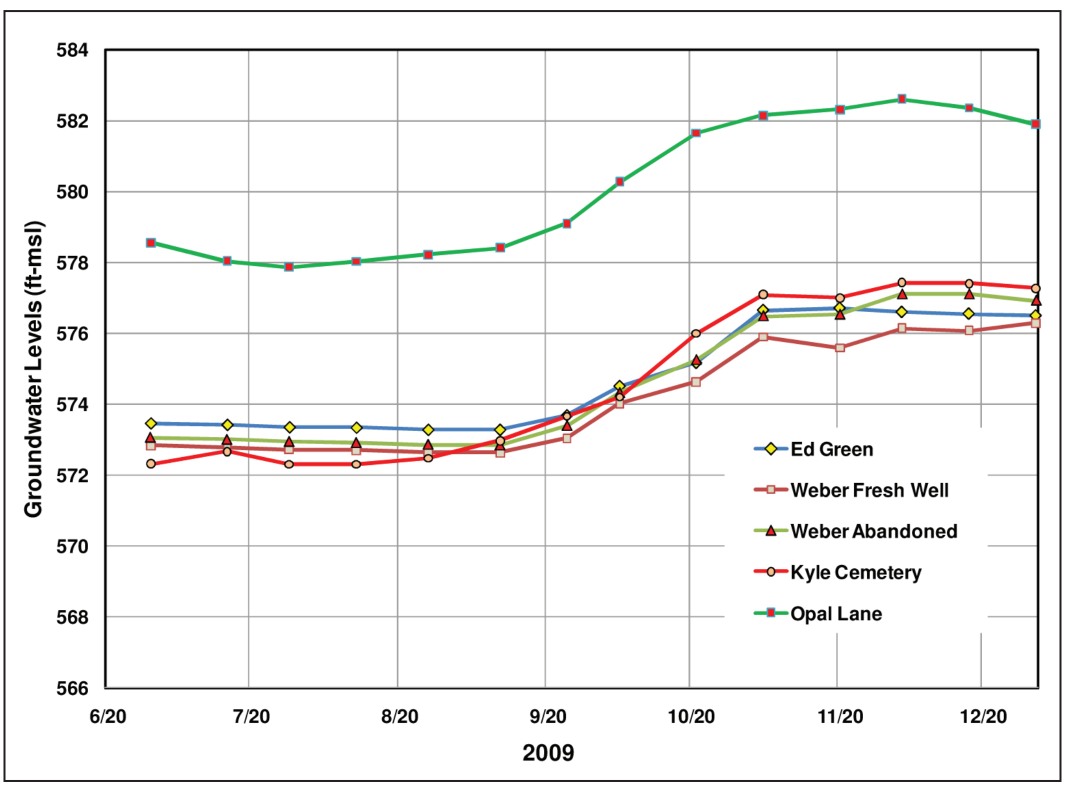

Fig. 6. Groundwater level hydrographs for monitoring wells: San Marcos Springs to Kyle.

Continuous Measurements

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

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

Pumping by City of Kyle

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

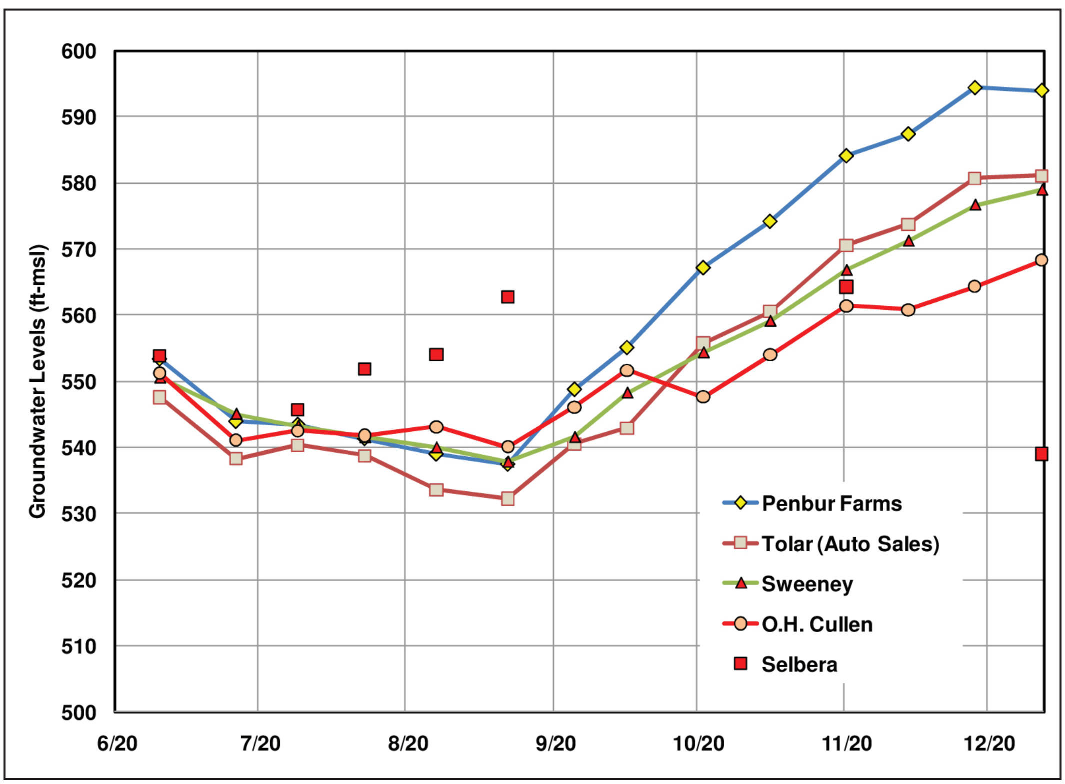

Fig. 7. Groundwater level hydrographs for 2009 study monitoring wells: Kyle to Buda.

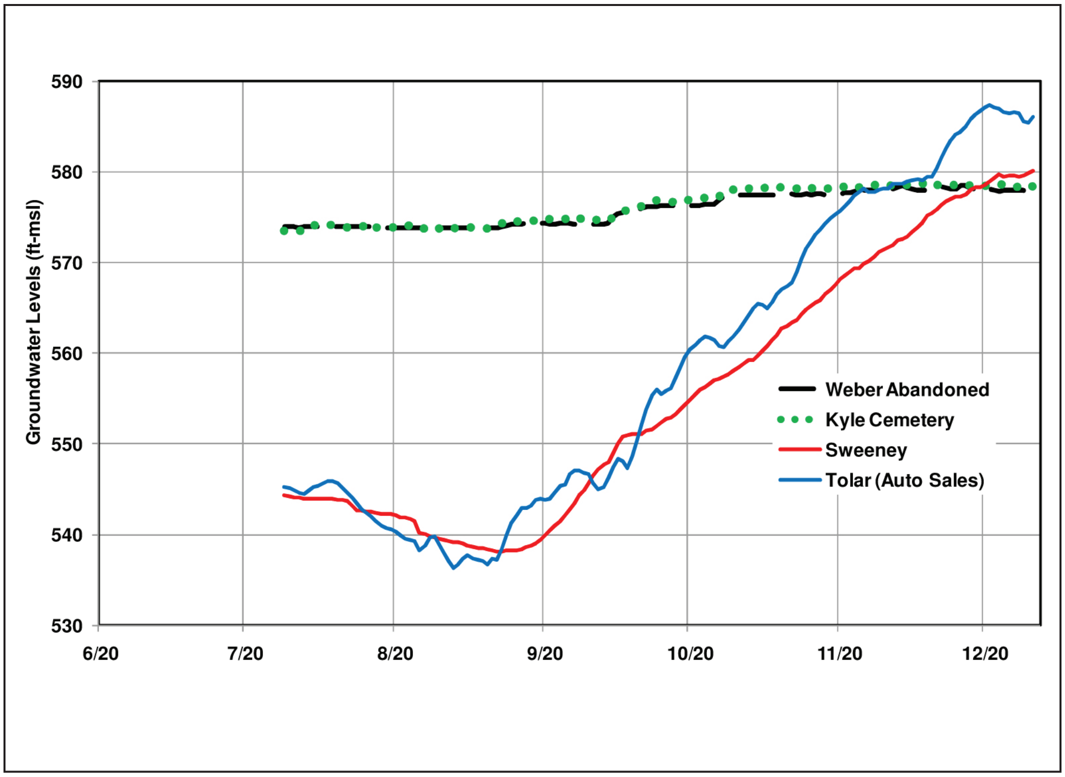

Fig. 8. Groundwater level hydrographs for monitoring wells with data loggers, 2009.

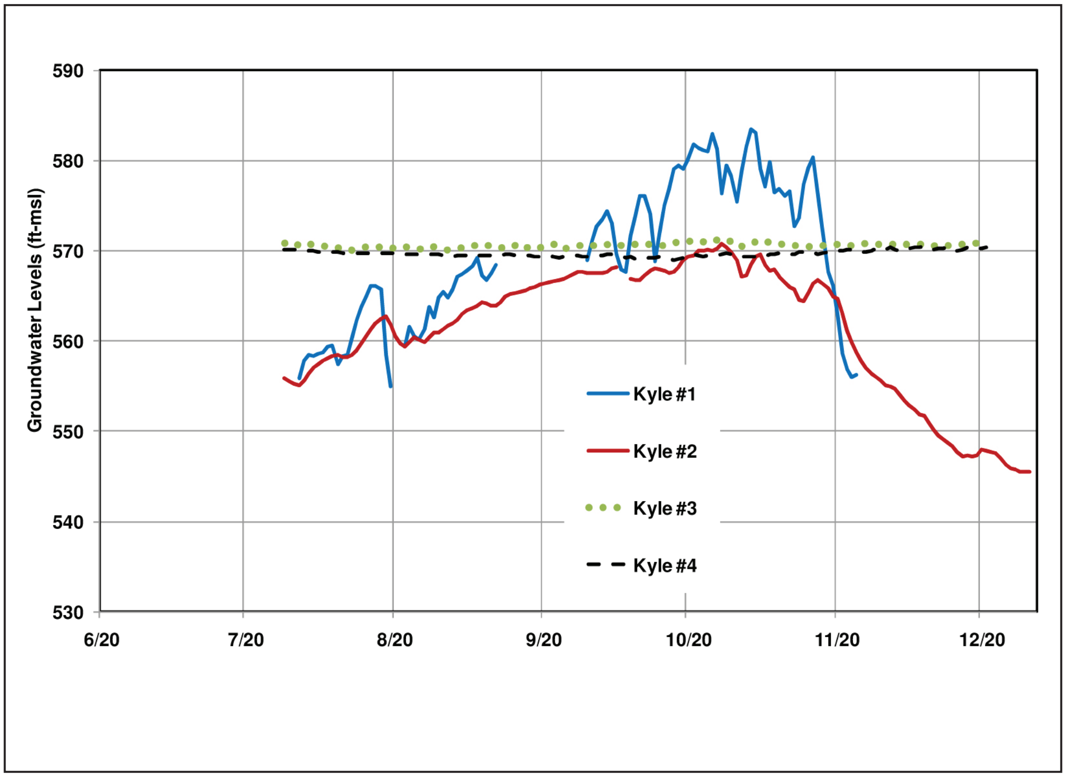

Fig. 9. Groundwater level hydrographs for SAWS monitoring wells along Kyle Transect, 2009.

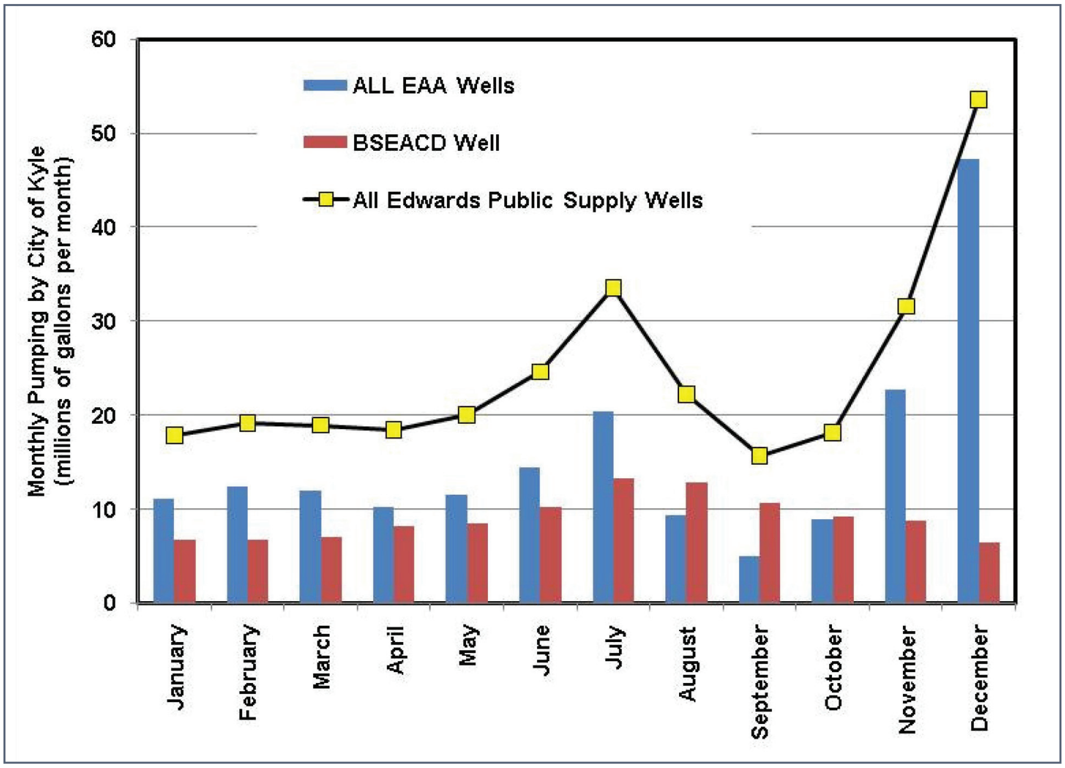

Fig. 10. Monthly pumping by the city of Kyle, 2009.

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

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

GROUNDWATER FLOW

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

February 2009 Conditions

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

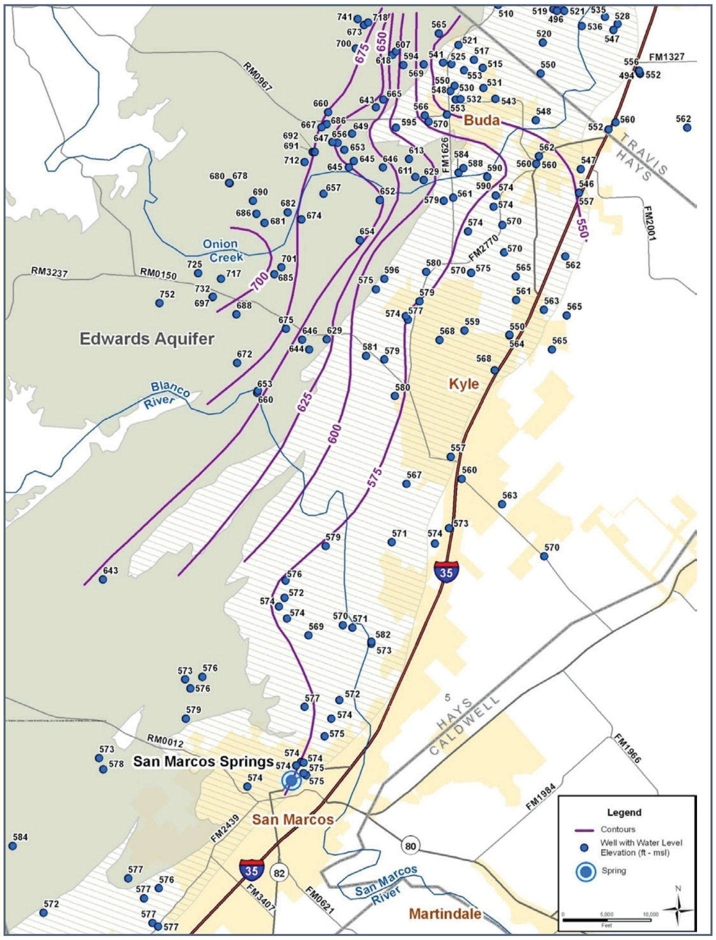

Fig. 11. Groundwater level map for mid-February to mid-March 2009 from synoptic survey by EAA and BSEACD in southern part of study area.

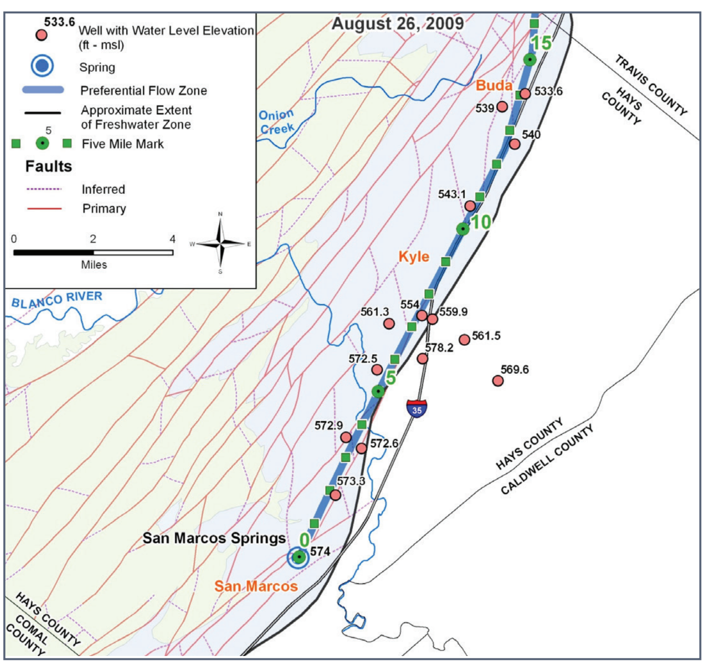

Fig. 12. Groundwater levels for 2009 drought conditions, August 26, 2009.

2009 Drought

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

Geologic Structures

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

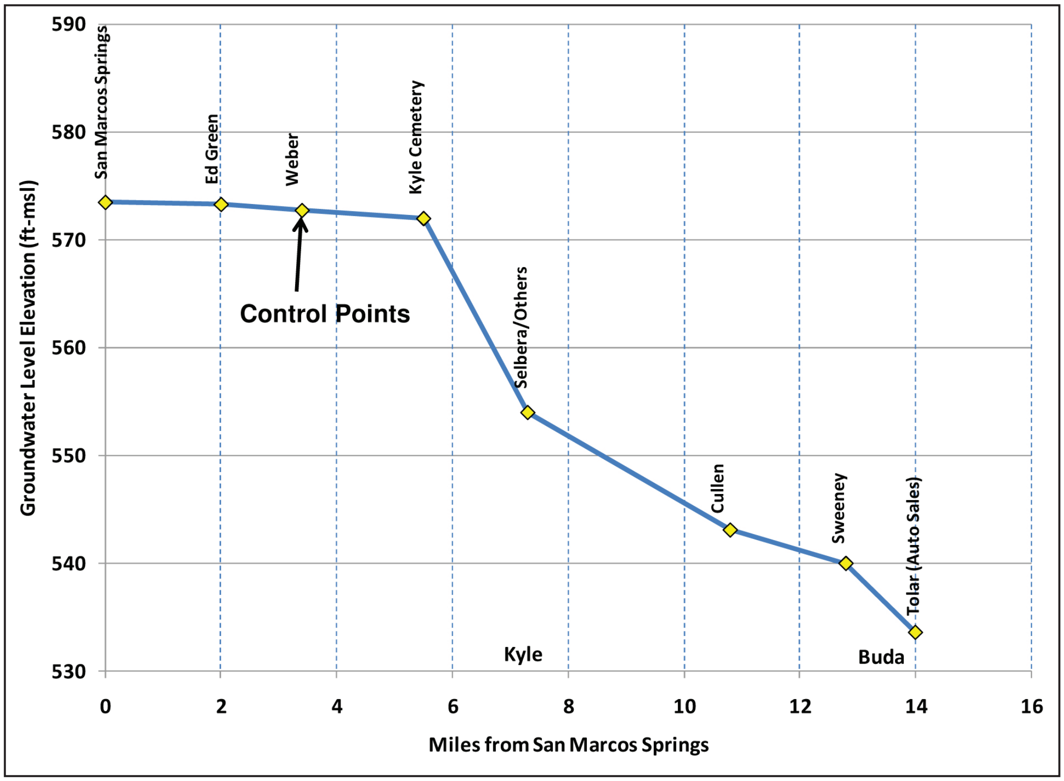

Fig. 13. Groundwater level profile along preferential groundwater flow zone during 2009 drought conditions, August 26, 2009.

Assessment with Groundwater Model

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

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

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

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

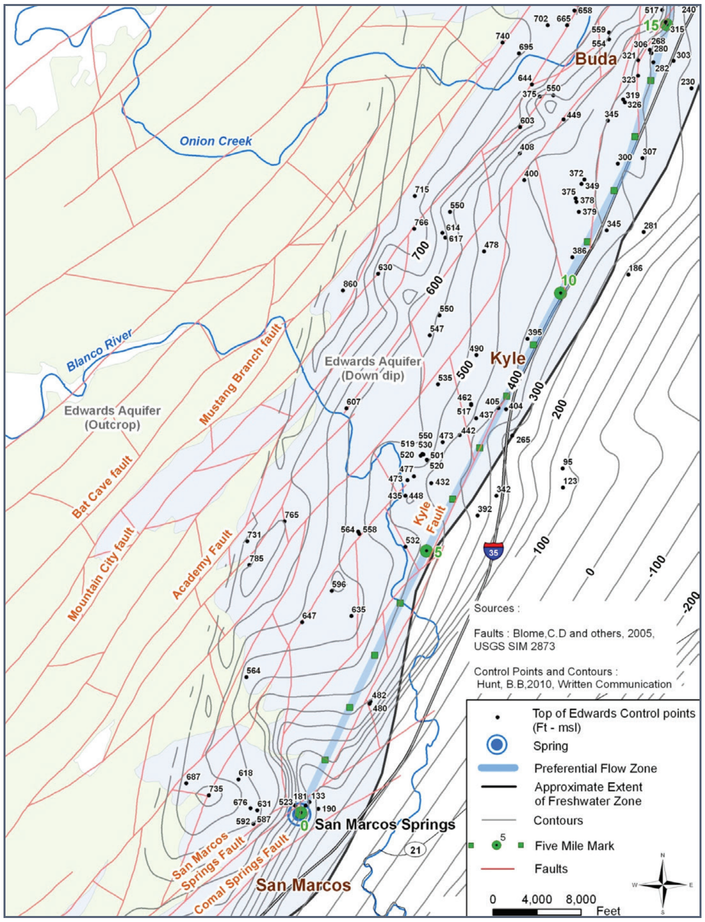

Fig. 14. Geologic structure of the top of the Edwards Aquifer in southern part of study area.

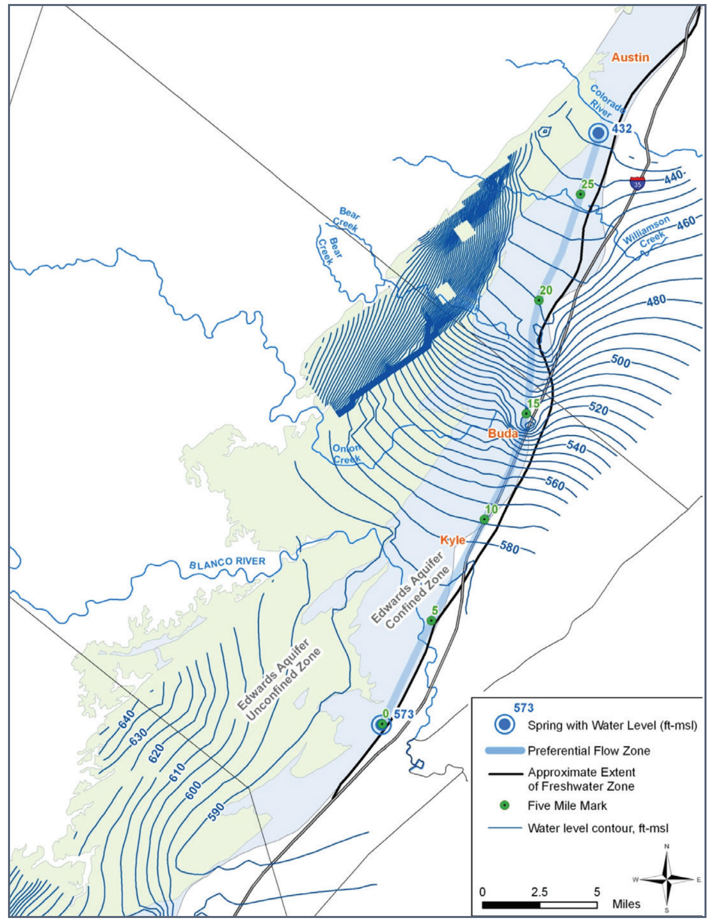

Fig. 15. Modeled groundwater level map from the Edwards Aquifer-San Antonio Segment Groundwater Availability Model for August 1996.

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

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

DISCUSSION

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

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

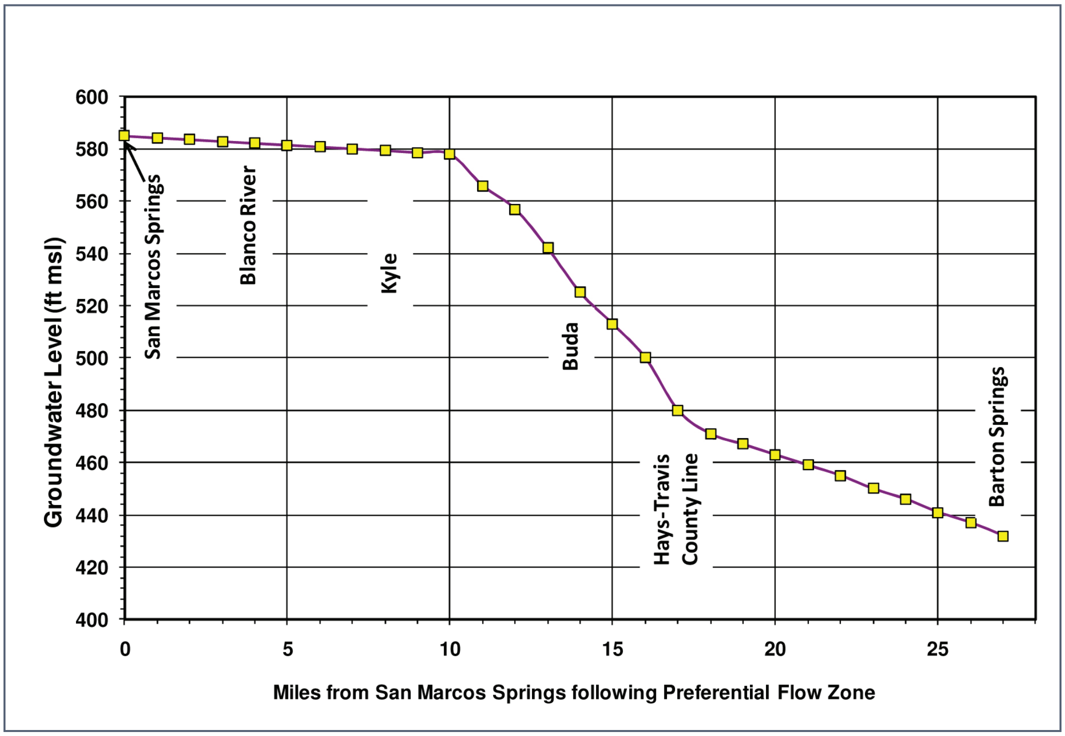

Fig. 16. Modeled groundwater level profile along preferential flow zone from the Edwards Aquifer-San Antonio Segment Groundwater Availability Model for August 1996.

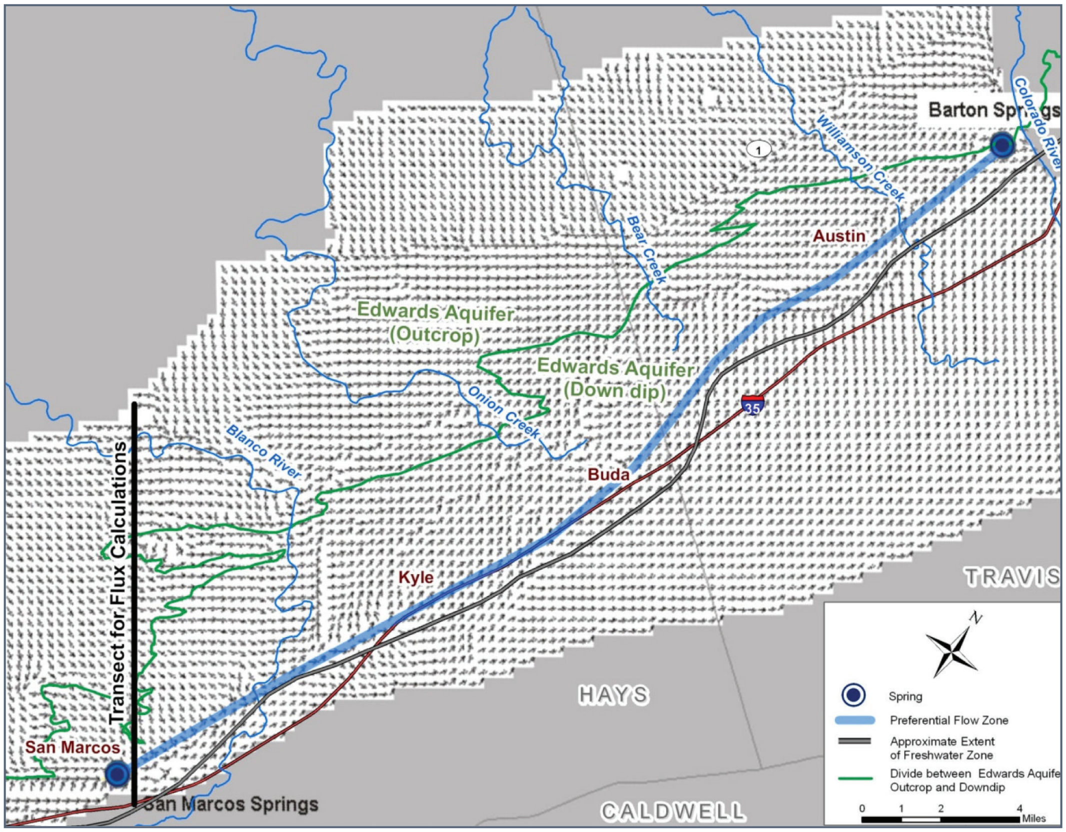

Fig. 17. Modeled groundwater flow direction vectors from the Edwards Aquifer-San Antonio Segment Groundwater Availability Model for August 1996.

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

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

CONCLUSIONS

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

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

FUTURE STUDIES

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

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

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