Evaluation of Hydrologic Connection between San Marcos Springs and Barton Springs through the Edwards Aquifer

Prepared for:

Guadalupe Blanco River Authority

Prepared by:

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Executive Summary

The Edwards Aquifer is the primary source of water for many needs in South-Central Texas and is the source for several major springs. In developing a plan to manage discharge from San Marcos Springs, the concept and characteristics of a persistent hydrologic divide between the San Antonio and Barton Springs segments of the Edwards Aquifer have been questioned. If this occurred, then there is a possibility for groundwater to bypass San Marcos Springs and flow toward the Barton Springs segment of the aquifer. To address these questions, a water-level data collection program was conducted.

Earlier studies and groundwater level data compiled during this study indicate that a groundwater divide exists in the vicinity of the surface drainage divide between Onion Creek and Blanco River during wet and normal hydrologic conditions. However, data collected during earlier droughts and this data collection program suggest that the groundwater divide dissipated and no longer hydrologically separates the two segments during major droughts and current levels of pumping. As a result, there is potential for some groundwater to bypass San Marcos Springs and flow toward Barton Springs during major droughts. The groundwater divide appears to be influenced by recharge along Onion Creek and Blanco River and vulnerable to extended periods of little or no recharge and extensive pumping.

The 2009 data set shows very low gradients in the potentiometric surface between San Marco Springs and Kyle with very little variation in levels between drought and non-drought periods. From Kyle northward, the potentiometric surface slopes significantly to the north and has dramatic changes in levels between drought and non-drought periods. Structural influences or hydraulic properties inherent in the aquifer appear to change significantly in the vicinity of Kyle, and may also influence the degree of hydrologic connection between San Marcos and Barton Springs.

There is not sufficient hydraulic property data of the Edwards Aquifer along the preferential groundwater flow zone to accurately calculate groundwater flow from the San Marcos Springs area to the Buda area. As an alternative, calculations of groundwater flow past San Marcos Springs were made with the USGS MODLFOW model (EA-SAR GAM). The amount of groundwater flow bypassing San Marcos Springs, if any, was calculated across a mile long transect that was drawn through a model column of cells immediately northeast of the model cell with San Marcos Springs. The flux (groundwater flow) across the transect was calculated for major droughts in 1956 and 1996. For drought conditions, the model calculates groundwater flow passing San Marcos Springs and moving toward Barton Springs at rates of 3.4 and 6.1 cfs for August 1956 and August 1996, respectively. Using these results as a guide, the 2009 drought was expected to cause about 5 cfs to bypass San Marcos Springs 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 bypassing San Marcos Springs actually discharges from Barton Springs. However, much of the groundwater bypassing San Marcos Springs probably becomes recharge to the Barton Springs segment of the Edwards Aquifer and supports both pumpage and discharge from Barton Springs. The response time between groundwater bypassing San Marcos Springs and entering the Barton Springs segment from the San Antonio segment is not known. Also, the effect of groundwater flow passing San Marcos Springs on discharge from Barton Springs is not known.

1.0 Introduction

The Edwards Aquifer is a prolific karst aquifer and the primary source of water for municipal, industrial, domestic, irrigation, livestock, and wildlife in much of South-Central Texas. It is also the source of water for several minor springs and the largest two springs in Texas, namely Comal Springs in New Braunfels and San Marcos Springs in San Marcos. These two springs are the primary sources of water in the Guadalupe and San Marcos Rivers during drought conditions. In addition, the Edwards Aquifer discharges to Barton Springs in the Colorado River Basin. Barton Springs in the fourth largest spring complex in Texas.

Eight species are federally-listed as threatened or endangered at or near Comal and San Marcos Springs and additional species are proposed for listing. At Barton Springs, one species is listed as endangered and one is proposed for listing. All of them depend directly on water issuing from the Edwards Aquifer. The primary threat to these species is the loss of habitat during periods of abnormally low springflows, which are attributed to droughts and pumping. An Edwards Aquifer-Recovery Implementation Program (EARIP) (http://earip.tamu.edu/) is being devised by a voluntary, multi-stakeholder group in response to the State Legislature to develop a management plan of the Edwards Aquifer to protect these federally-listed species. A federal Habitat Conservation Plan is also being developed for the endangered species at Barton Springs.

In 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 to occur, a groundwater divide (a ridge in the water table and potentiometric surface) must be sufficiently high to divert recharge and groundwater flow south of the divide to San Marcos Springs and recharge and groundwater flow north of the divide to Barton Springs. To address this question, data were collected during the severe 2009 drought to characterize groundwater levels in a study area between San Marcos Springs and Buda, which is in the Barton Springs segment. If the 2009 data show that the groundwater divide dissipates, then pumpage in either segment could theoretically affect water levels and springflows in the other segment during drought. If the groundwater divide persists during a major drought, then one can be reasonably assured that recharge and pumpage in one segment does not significantly affect aquifer conditions in the other segment.

For regulatory purposes, the Edwards Aquifer Authority (EAA) is responsible for the San Antonio segment; and, the Barton Springs/Edwards Aquifer Conservation District (BSEACD) is responsible for the Barton Springs segment. The dividing line between the two regulatory entities is generally along the watershed divide between Onion Creek and the Blanco River, which is also the watershed divide between the Colorado River Basin and the Guadalupe-San Antonio River Basin. Historically, it has been generally 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 and the regulatory divide between the two segments is shown in Figure 1-1. Historical estimates of the groundwater divide are shown in Figure 1-2 along with a generalized groundwater flow pattern.

The purposes of this report are to:

- Place the 2009 drought in perspective with recent hydrologic conditions.
- Present data summaries from a data collection program that was implemented during the 2009 drought.
- Provide an assessment of the potential for groundwater flow from the San Antonio segment of the Edwards Aquifer to bypass San Marcos Springs and flow toward the Barton Springs segment of the aquifer under 2009 and other recent drought and pumping conditions.
- If any, estimate the magnitude of the groundwater flow bypassing San Marcos Springs and flowing toward Barton Springs.
- Present and discuss other major findings.
- Present conclusions.

2.0 Preferential Groundwater Flow Zone between San Marcos Springs and Barton Springs

For purposes of this study, the primary hydrologic connection between San Marcos Springs and Barton Springs is believed to occur along a <u>preferential groundwater flow zone</u> between the two springs. For purposes of this report, the preferential groundwater flow zone coincides with the expected general pathway that groundwater would flow from San Marcos Springs to Barton Springs if a groundwater divide and a cone of depression did not exist. It is shown in Figure 2-1, but is not well constrained by data and may shift with variations in pumping and recharge.

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 and others (2004). This zone was delineated on the basis of geologic framework (Hanson and Small, 1995 and Small and others, 1996), hydrogeologic analyses (Baker and others, 1986 and Garza, 1962), dye tracing studies (Hunt and others, 2006), groundwater modeling study (Lindgren and others, 2004 and Scanlon and others, 2001), and water level data. It is generally located within about a mile of the ‘bad-water line’, which is locally defined as a hydrochemical boundary of Edwards groundwater at a total dissolved solids concentration of 1,000 milligrams per liter (mg/L). Inspection of the distribution of hydraulic conductivity in the USGS MODFLOW model (EA-SAR GAM) of the Edwards Aquifer shows a zone of relatively high transmissivity and a conduit between San Marcos Springs and Kyle (Lindgren and others, 2004). A study by Hunt and others (2006) shows groundwater flow paths connecting several recharge features to Barton Springs and possibly to San Marcos Springs. All major springs discharging from the Edwards (Balcones Fault Zone) Aquifer, and many large pumping centers, are in the vicinity of the ‘bad-water line’.

For clarification, the term preferential groundwater flow zone as it is used in this paper represents a much broader and diffuse area of relatively high rates of groundwater flow than the concept of conduits that was presented by Lindgren and others, (2004). As stated earlier, the preferential groundwater flow zone is intended to coincide with the expected general pathway that groundwater would flow from San Marcos Springs to Barton Springs if a groundwater divide and a cone of depression did not exist.

Analyses of the direction of groundwater flow are based primarily on water-level profiles that were drawn along the preferential groundwater flow zone from the data collected during this study. Although the study area is an anisotropic karst system, the hydraulic gradient does provide critical information into the potential for flow. Therefore, the slope of the profile (hydraulic gradient) along the preferential groundwater flow zone indicates the direction of groundwater flow along this line.

3.0 Overview of Hydrologic Conditions

3.1 1989-2009 Conditions

Springflow data for San Marcos Springs and Barton Springs were compiled from the USGS data base. Hydrographs of these data since 1989 are presented in Figure 3-1. These data show, from the perspective of springflow, that the 2009 drought had similar severity to the ones in 1989, 1996, 2000, and 2006, though 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.

Groundwater data for Edwards Aquifer wells in Hays County and Travis County were compiled from TWDB, USGS, and BSEACD databases and hydrographs were plotted for comparisons of the 2009 drought with the earlier droughts. These hydrographs are shown in Figure 3-2. The wells include the BSEACD's index well (Lovelady (5850301)) and three of their monitor wells: Negley (5857903), Porter (5858123), and Buda (5858101). The Buda and Porter wells show a water-level fluctuation range of about 100 ft. Also shown is an EAA monitor well 6701809, which is near San Marcos Springs and only 34 ft deep. It indicates a very flat water-level hydrograph in comparison with the monitor wells between Kyle and Barton Springs. These water-level data indicate that the effects of the 2009 drought are comparable to the 1996, 2000, and 2006 droughts. Profiles of groundwater levels along the preferential groundwater flow zone (Figure 2-1) during these drought periods were drawn with available groundwater level data and are shown in Figure 3-3.

3.2 2009 Conditions

The hydrologic conditions and rainfall during 2009 may be generally characterized with records from USGS streamflow gaging stations: 08158827 Onion Creek at Twin Creeks Road, 08171000 Blanco River at Wimberley, and 08171300 Blanco River near Kyle. Streamflow hydrographs for these stations are presented in Figure 3-4. Prior to September 10, these data show that the streamflow at Onion Creek and Blanco River-Kyle was zero except for occasional runoff events. The Blanco River-Wimberley record shows a stable flow of about 12-15 cubic feet per second (cfs) through April, decreasing streamflows until July, and about 5-6 cfs of flow in July and August. With the Blanco River-Kyle having no flow most all the time, it is generally understood that essentially all the Blanco River-Wimberley streamflow became recharge to the Edwards Aquifer.

LCRA's 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. Graphs of these rainfall data are shown in Figure 3-5. From May 25th to about September 12th, the total rainfall was about 2.5 inches. From September 12th to the end of the year, about 20 inches was recorded.

4.0 Approach

4.1 Data Collection and Compilation

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), Barton Springs/Edwards Aquifer Conservation District (BSEACD), U.S. Geological Survey (USGS), and HDR Engineering, Inc. (HDR). Data collection was performed by the USGS and BSEACD at the monitoring wells shown in Figure 4-1, which consisted of ten existing water wells. A summary of the well descriptions is provided in Table 4-1. From late June to December 2009, water levels were measured by the USGS at approximately two-week intervals. Four of the ten wells were instrumented with pressure transducers with electronic data loggers by BSAECD, which were programmed to provide measurements at one-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 USGS for four SAWS monitor wells along a northwest-southeast transect through Kyle. Data analyses were performed by HDR and included significant consultation with GBRA, BSEACD, and USGS scientists and engineers.

Other aquifer data were compiled from Texas Water Development Board (TWDB), BSEACD, EAA, and USGS data bases for a hydrologic perspective on the 2009 drought. These data included groundwater levels from wells in the study area, springflow from San Marcos 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 Lower Colorado River Authority (LCRA) gage near Onion Creek.

Analyses of the direction of groundwater flow are based primarily on water-level profiles that were drawn along the preferential groundwater flow zone from the data collected during this study. Although the study area is an anisotropic karst system, the hydraulic gradient does provide critical information into the potential for groundwater flow, which is based on the slope of the profile (hydraulic gradient) along the preferential groundwater flow zone.

4.2 Groundwater Flow Bypassing San Marcos Springs

Lacking site-specific aquifer transmissivity data in the study area, the USGS Edwards Aquifer-San Antonio Region Groundwater Availability Model (EA-SAR GAM) was used. This model extends from the Brackettville area to the Colorado River. A minor limitation of the model is that calibration procedures did not include the Travis County part of the model area. However, the hydrogeology in this area was represented with information from the Edwards Aquifer-Barton Springs Segment Groundwater Availability Model (EA-BS GAM) (Scanlon and others, 2001) and other sources. Groundwater flow that bypasses San Marcos Springs was calculated for selected months during two major droughts and two wet periods from the calibration simulation (1947-2000) with the EA-SAR GAM.

A detailed discussion on the EA-SAR-GAM limitations is presented by Lindgren and others, 2004. As a regional model with San Antonio and Barton Springs segments and with special emphasis on major springs, it is believed to be suitable in providing guidance on making an estimate of the groundwater flow that bypasses San Marcos Springs, if any, and flows toward Barton Springs.

5.0 2009 Data Summary

5.1 Periodic Measurements

Periodic water-level measurements were made in the network of ten existing monitor wells at approximately two-week intervals from late June through December of 2009. The preliminary data provided by the USGS were reviewed and some measurements were revised on the basis of: (1) data measurements by the pressure transducers, (2) consistency with nearby wells, and (3) hydrograph patterns. These data are summarized in Figure 5-1 for the monitor wells between San Marcos Springs and Kyle and in Figure 5-2 for wells between Kyle and Buda.

For the monitor 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 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) have slightly smaller fluctuations than wells near Kyle (Kyle Cemetery and Opal Lane).

Data from monitor wells between Kyle and Buda 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 mostly attributed to nearby pumping wells. 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. Pumping records for 2009 show the City of Kyle's five public supply wells had widely varying monthly pumping rates. A summary of monthly pumping for the City of Kyle wells in the EAA and BSEACD is shown in Figure 5-3. These data show that the well in the BSEACD has a typical demand pattern that trends from about 6,800,000 gallons in January to 13,200,000 gallons in July to 6,400,000 gallons in December. The EAA permitted wells range from 11,100,000 gallons in January to 20,300,000 gallons in July, abruptly declines to 9,400,000 and 5,000,000 gallons in August and September, respectively, and abruptly increases to 22,800,000 and 47,200,000 gallons in November and December, respectively. This unusual pumping pattern of the EAA permitted wells is believed to be the cause of the water-level fluctuations in the Selbera well and SAWS Kyle Wells #1 and #2 monitor wells.

5.2 Continuous Measurements

5.2.1 Study Data

Water-level measurements were recorded at hourly intervals at the Weber Abandoned, Kyle Cemetery, Sweeney, and Tolar (Auto Sales) monitor wells by digital data loggers and pressure transducers. These results are summarized in Figure 5-4 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 monitor wells between San Marcos Springs and Kyle.

5.2.2 SAWS Data

SAWS has conducted a test drilling program and installed four monitor wells in a northwest-southeast transect through Kyle and across the 'bad-water' line. These monitor wells are equipped with data loggers and pressure transducers. Kyle #1 monitor 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 Figure 5-5. Monitor wells Kyle #1 and #2 have a hydrograph pattern similar to the Selbera well where recovery occurs from late July to early November and rather rapid declines occur to the end of the year. Water levels for monitor wells in the saline zone were very flat and did not track with the dominant pattern in the freshwater zone. Gaps in the hydrographs are caused by missing data.

6.0 Groundwater Flow

6.1 Previous Drought and Wet Conditions

Historical groundwater-level data were reviewed to identify historic low and high water-level conditions. Using the hydrographs in Figure 3-2 as a reference, a major drought can be represented with year 2000 data; and, high water-level conditions can be represented with early 2003 conditions. Groundwater-level maps for these two periods are shown in Figures 6-1 and 6-2, respectively. The groundwater-level map for the major drought (Figure 6-1) indicates that groundwater levels continually become lower and lower along the preferential flow zone from San Marcos Springs to Barton Springs with the possible exception of a small cone of depression in the vicinity of Kyle. However, there is very limited data along the preferential groundwater flow zone between San Marcos Springs and Buda to verify this indication. A groundwater-level map for the wet conditions of 2003 (Figure 6-2) indicates a groundwater divide on the south side of Onion Creek. Near the preferential groundwater flow zone, this divide is at least 50 ft higher than groundwater levels near San Marcos Springs.

6.2 February-March 2009 Conditions

A synoptic survey of groundwater levels was conducted from mid-February to mid-March 2009 by the EAA, City of Austin (COA), and BSEACD from a large network of water wells to evaluate groundwater conditions throughout the aquifer and near the boundary between the two groundwater districts. The data were also used by the EAA to plan tracer testing projects in Hays County. These data were collected during a relatively short time to provide a snap-shot of hydrologic conditions. Conducting the survey in the winter minimizes the interference of pumping wells. A study of the precipitation and streamflow data during this period indicated no significant rainfall until March 12 when about 2 inches of rain was recorded. At this time, streamflow increased by only very minor rates. For purposes of this study, these data are considered to represent stable climatic and hydrologic conditions and do not require any adjustments. These water level data were mapped in the study area and groundwater-level contours were drawn (Figure 6-3). In the area of key interest, these data and contours suggest that there is a continuous slope in the hydraulic gradient from San Marcos Springs to Barton Springs along the preferential groundwater-flow zone with the exception of a possible small cone of depression in the vicinity of Kyle.

The EAA and COA were not involved in the data interpretation or any other aspects of developing this report by HDR.

6.3 2009 Drought and Wet Conditions

The 2009 water-level data sets that were collected have been studied to identify times when the data approximates the lowest (drought) and highest (wet) hydrologic conditions (see Figures 5-1 and 5-2). These conditions are strongly influenced by antecedent recharge and pumping. The hydrologic extremes during 2009 are represented by August 26 data for drought conditions and December 31 data for wet conditions. The groundwater levels for the selected drought and wet conditions are shown in Figure 6-4 and Figure 6-5, respectively. Figure 6-6 shows profiles of the groundwater levels along the preferential flow zone for these two conditions.

From mid-June to mid-September (drought conditions), 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 on toward Barton Springs. From mid-September to the end of the year (wet conditions) and along the preferential groundwater flow zone, the very mild slope of the hydraulic gradient from San Marcos Springs to Kyle was reversed and began to slope toward San Marcos Springs. Also, a cone of depression remained in the vicinity of Kyle which caused a rather steep hydraulic gradients to the north and south of Kyle. In summary, these data and analyses suggest that groundwater had the potential to bypass San Marcos Springs and flow toward Barton Springs during the 2009 drought. During wet conditions that flow potential to bypass San Marcos Springs was eliminated when a hydrologic divide, in the form of a ridge in the potentiometric surface, developed in the vicinity of Onion Creek and caused the hydraulic gradient to slope from Kyle to San Marcos Springs.

To illustrate the direction of groundwater flow, schematic diagrams have been prepared along the preferential flow zone for drought (August 26) and wet (December 31) conditions (Figures 6-7a and 6-7b). These diagrams show the approximate profile of the land surface, groundwater levels, the position of the Edwards Aquifer in the subsurface, and vectors of groundwater flow. The geometry of the Edwards Aquifer as shown is a major simplification of the structure of the Edwards Aquifer as provided by Lindgren and others (2004) and by Baker and others (1986). In general, the land surface topography ranges from about 575 ft-msl in the vicinity of San Marcos Springs, to a ridge of about 825 ft-msl in the vicinity of Bear Creek and Slaughter Creek, and to an elevation of about 450 ft-msl in the vicinity of Barton Springs. As discussed earlier, the groundwater profile for drought conditions (August 26) has a very mild slope from San Marcos Springs to Kyle, a noticeably greater slope from south to north through Kyle, and a moderate slope from Kyle to Buda. Additional water-level data from the BSEACD and TWDB data bases suggest a continuous slope in groundwater levels from Buda to Barton Springs. The groundwater profile for wet conditions shows a cone of depression in the vicinity of Kyle, a very mild slope in groundwater levels from south of Kyle to San Marcos Springs and a modest slope from north of Kyle to Barton Springs. A major fault immediately north of San Marcos Springs causes a vertical shift of the Edwards Aquifer along the preferential flow zone to be about 400 ft upward. However, the groundwater-level data do not show a noticeable discontinuity in the groundwater flow in this area. From Kyle to Barton Springs, the preferential flow zone crosses many faults with minor displacements.

6.4 Groundwater Flow Bypassing San Marcos Springs

There are not sufficient hydraulic property data on the Edwards Aquifer along the preferential groundwater flow zone to accurately calculate groundwater flow from the San Marcos Springs area to the Buda area. As an alternative, calculations of groundwater flow bypassing San Marcos Springs were made with the EA-SAR GAM. The underflow toward or away from San Marcos Springs was calculated across a mile long transect that was drawn through a model column of cells immediately northeast of the model cell with San Marcos Springs. The flux (groundwater flow) across this transect was calculated for two major droughts and two periods of high groundwater conditions. For drought conditions, the model calculates groundwater flow bypassing San Marcos Springs and moving toward Barton Springs at rates of 3.4 and 6.1 cfs for August 1956 and August 1996, respectively. For wet conditions, the model shows groundwater flow across the transect from the Kyle area to San Marcos Springs at rates of 46 and 150 cfs for July 1992 and May 1995, respectively. Using these 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 mean that groundwater bypassing San Marcos Springs actually discharges from Barton Springs. However, much of the groundwater bypassing San Marcos Springs probably becomes recharge to 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 not known. Also, the direct effect of groundwater flow bypassing San Marcos Springs on discharge from Barton Springs is not known.

7.0 Major Findings

A summary of the major findings of the 2009 data collection efforts and analyses follows:

1. Time trend in groundwater levels:
   a) From late-June to mid-September, which was during the most intense part of the 2009 drought, there was a general decline in groundwater levels within the study area.
   b) Since mid-September, water levels generally continued to rise until the end of the year.
   c) In the segment between San Marcos Springs and Kyle, the declines from late-June to mid-September were less than 0.5 ft. The recovery has been about 5 ft.
   d) In the segment between Kyle and Buda, the declines from late-June to mid-September were generally 10-15 ft and recovery has been about 50 ft.
   e) In the Selbera well and SAWS monitor wells #1 and #2 near Kyle, the water-level trend exhibited a very different pattern where groundwater levels tended to rise from late-July to October and declined to the end of the year. This is nearly opposite of the other water-level trends. The pattern is mostly attributed the 2009 pumping pattern of Kyle’s public supply wells.

2. Hydraulic gradients of groundwater levels along preferential groundwater flow zone:
   a) From mid-June to mid-September (drought conditions), 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 on toward Barton Springs.
   b) From mid-September to the end of the year (wet conditions) and along the preferential groundwater flow zone, the very mild slope of the hydraulic gradient from San Marcos Springs to Kyle was reversed and began to slope toward San Marcos Springs. Also, a cone of depression remained in the vicinity of Kyle which caused a rather steep hydraulic gradient from Buda to Kyle.
   c) A major break in hydraulic gradient profile exists under both wet and dry conditions in the general vicinity of Kyle.
3. Direction of groundwater flow:
   a) From late June to mid-September (drought conditions), groundwater flow had the potential to bypass San Marcos Springs and flow toward Buda, and in all likelihood, to Barton Springs. Data from a synoptic survey in late February 2009 suggests that the continual groundwater flow toward the Barton Springs segment began before June.
   b) Since mid-September, a groundwater divide has developed south of Onion Creek from major recharge events, and possibly reduced pumping, and is causing groundwater to flow from this area toward San Marcos Springs.
   c) A cone of depression formed in the vicinity of Kyle and has persisted during the recovery of groundwater levels since mid-September.
4. Highly transmissive zone from San Marcos Springs to south of Kyle (from mile marker 0 to 6.5):
   a) The water levels in this section of the Edwards Aquifer are very flat and generally rise and fall in unison, even when there are major recharge events in the area. This is characteristic of an aquifer with very high transmissivity (a measure of how readily groundwater flows in an aquifer). A review of the EA-

SAR GAM report (Lindgren and others, 2004) shows this area to have a relatively high transmissivity for the Edwards and shows a conduit near Kyle to San Marcos Springs.

b) The highly transmissive zone seems to end south of Kyle with a rapid transition to a zone with relatively low transmissivity. Studies of the geologic structure by Hanson, J.A. and Small, T.A. (1995), Small, T.A., Hanson, J.A., and Hauwert, N.M. (1996), and BSEACD, written communication (2010) does not show a major fault in the immediate vicinity of Kyle that could form a potential partial barrier of southwest-northeast groundwater flow.

5. Relatively low transmissive zone in vicinity of Kyle:
   a) Analyses of water-level data in the vicinity of Kyle suggest an area of relatively low transmissivity in comparison to areas to the southwest and northeast. This is indicated by irregular water-level hydrograph pattern, which are believed to be associated with local pumpage and rather abrupt transitions of the groundwater-level profile along the preferential groundwater flow zone.
   b) Absent major faults, this relatively low transmissivity zone appears to cause a significant resistance to groundwater flow along the preferential groundwater flow zone in the vicinity of Kyle. In effect, this low transmissivity zone creates a bottle-neck in the preferential groundwater flow zone but does not create a discontinuity. The magnitude and extent of this relatively low transmissivity zone is not known.
6. Direction and rate of groundwater movement beneath San Marcos Springs:
   a) The direction and rate of groundwater in the immediate vicinity of San Marcos Springs can't be accurately estimated with available data. However, an indirect estimate has been made with EA-SAR GAM modeling results during the calibration period from 1947-2000. For the severe droughts of the early to mid-1950s and 1996, the model computed groundwater flow bypassing San Marcos Springs to be about 3.4 cfs during August 1956 and 6.1 cfs during August 1996. Considering the intensity of the 2009 drought and the increases in recent pumpage in the vicinity of Kyle as a guide, a groundwater flow of 5 cfs bypassing San Marcos Springs is estimated for the most intense part of the 2009 drought. During these droughts, the approximate measured

discharges at Barton Springs were 13, 18, and 15 cfs in August 1956, August 1996 and August 2009, respectively.

b) During August 2009, the discharge from San Marcos Springs and Barton Springs averaged about 87 cfs and 15 cfs, respectively. An underflow of 5 cfs bypassing San Marcos Springs represents 6 percent of San Marcos Springs discharge and about a third of the Barton Springs discharge.

c) Following the recovery of groundwater levels in the Fall of 2009 and when San Marcos Springs and Barton Springs discharges increased to about 180 and 72 cfs, respectively, the direction of groundwater flow reversed on the northeast side of San Marcos Springs and began flowing toward San Marcos Springs. Using earlier groundwater modeling results as a guide, this magnitude could have ranged up to 50 cfs; but, the actual amount is unknown.

7. Connection between the freshwater and saline water zones:

   a) A comparison of water-level patterns among wells in the Kyle area shows a somewhat sluggish response in wells in the saline zone that are very near the freshwater zone.

   b) As the distance from the ‘bad water line’ increases to more than a mile, the water-level response from wells in the saline zone could not be clearly linked to water-level changes in the freshwater zone.

8.0 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 was continuity in the direction of groundwater flow along the preferential groundwater flow zone from San Marcos Springs to Barton Springs during the 2009 drought with the possible exception of a small cone of depression in the vicinity of Kyle. Thus, there is a potential for groundwater flow from San Marcos Springs to Barton Springs to exist during drought conditions.
- During the most intense part of the 2009 drought, the magnitude of the groundwater bypassing San Marcos Springs and flowing toward Barton Springs was estimated at about 5 cfs. This rate was estimated using calibration results in the EA-SARGAM.

- Following several major recharge events beginning in mid-September 2009, a groundwater divide was reestablished in the vicinity of Onion Creek. As a result, the direction of groundwater flow reversed and began flowing from the vicinity of Kyle to San Marcos Springs for these wetter conditions.
- Water levels in the vicinity of Buda recovered as much as 60 ft by the end of 2009, but are still much lower than historic high conditions and are only slightly higher than San Marcos Springs.
- 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.
- Mapped faults do not appear to be a strong controlling factor between the zones of relatively high and low transmissivity in the vicinity of Kyle.

9.0 Acknowledgments

This study was planned by Dr. Todd Votteler and Tommy Hill of the Guadalupe-Blanco River Authority, Brian Hunt and Brian Smith of the Barton Springs/Edwards Aquifer Conservation District, Mike Dorsey and Marylynn Musgrove of the U. S. Geological Survey, and Larry Land of HDR Engineering, Inc. Data collection was performed primarily by the Venezia Chavez of the USGS and Brian Hunt of the BSEACD. The study was greatly supported by existing data that were made available from the USGS, Texas Water Development Board, Edwards Aquifer Authority, and the San Antonio Water System data bases. Larry Land, P.E. prepared the initial data summaries, analyses and interpretations. This paper and the final report greatly benefitted from suggestions and review comments by all of the team members, Kirk Holland, P.G. of BSEACD, and Sam Vaugh, P.E. and Paula Jo Lemonds, P.E., P.G. of HDR.

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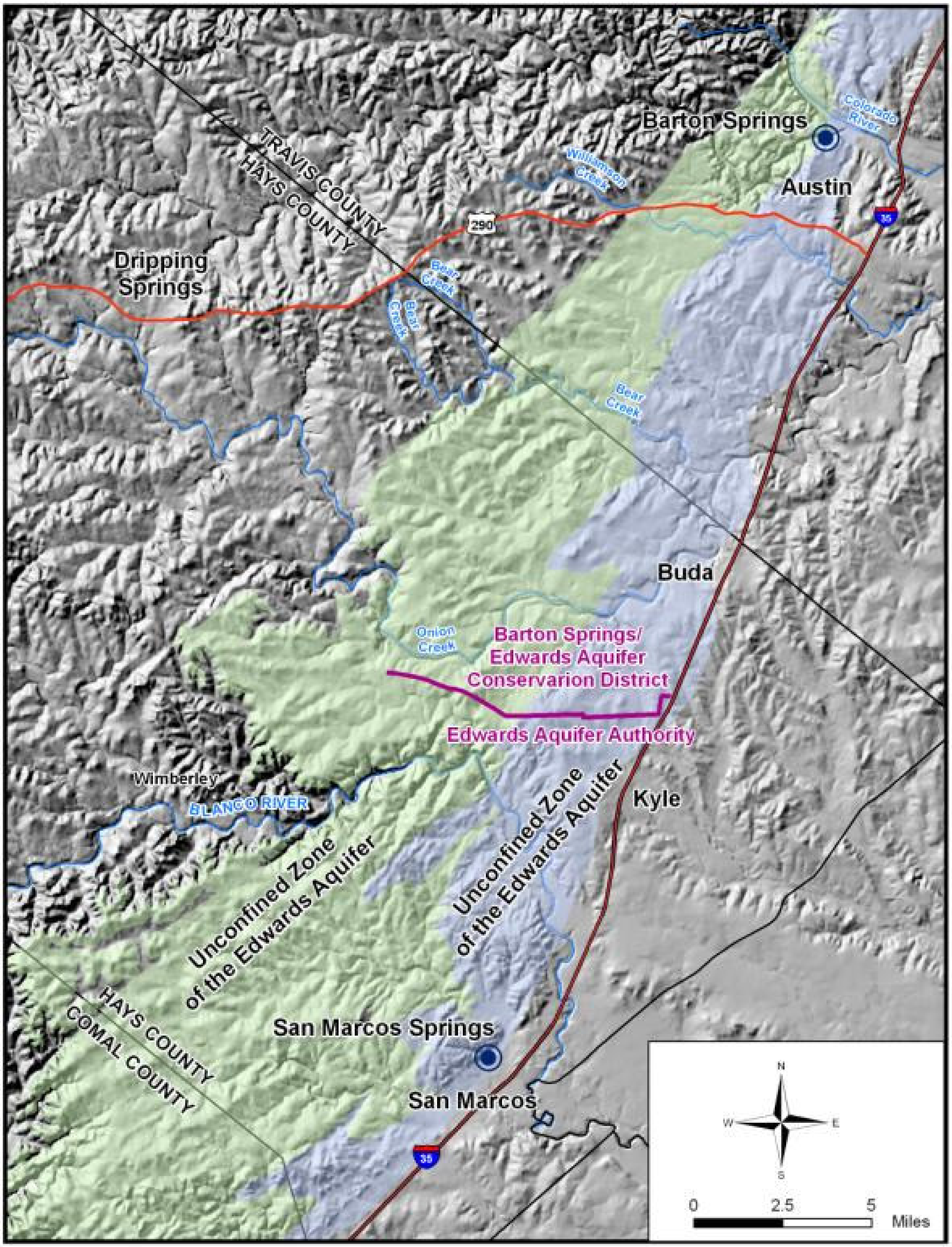

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Figure 1-1. Location of Study Area

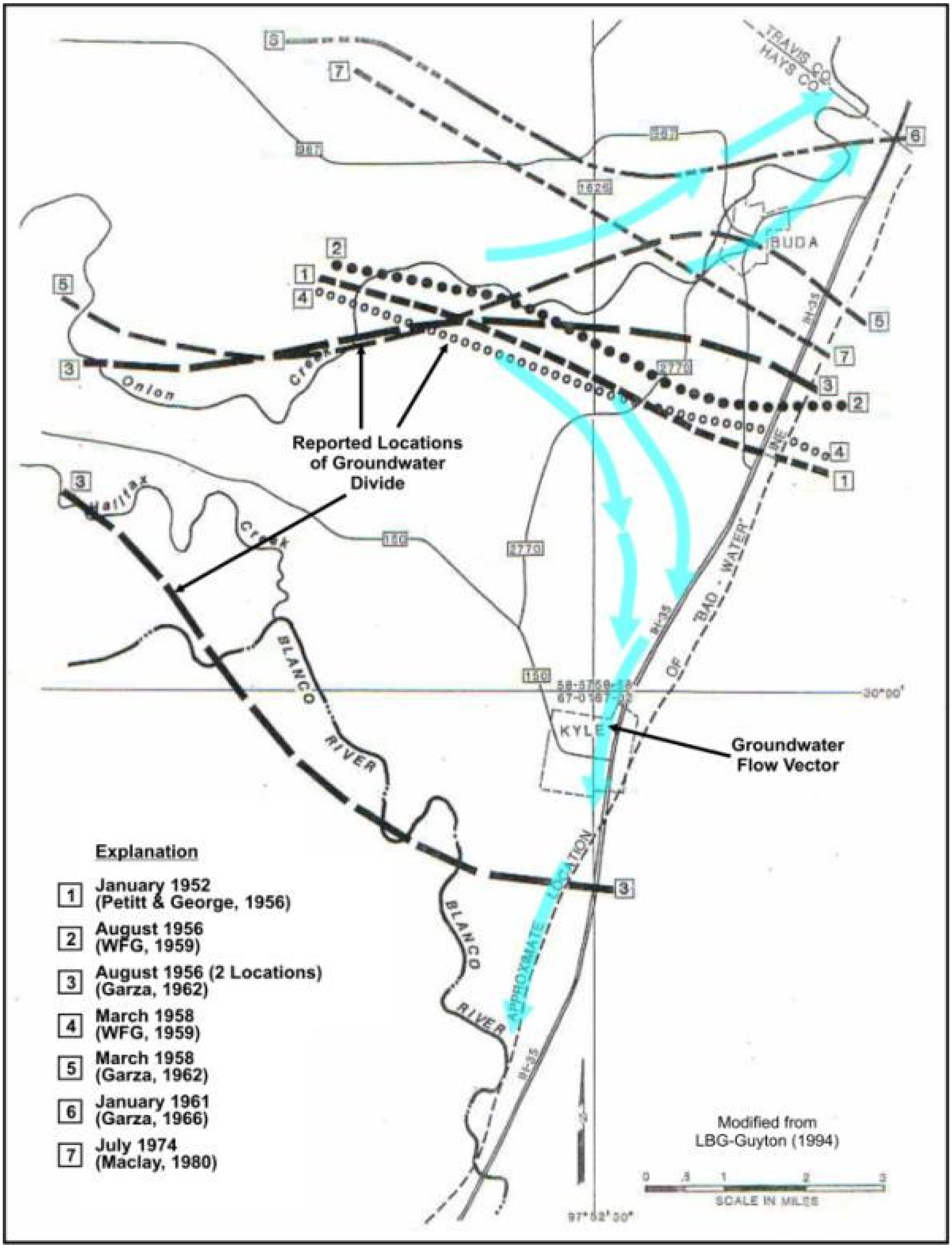

Figure 1-2. Reported Locations of Groundwater Divide between the San Antonio Segment and Barton Springs Segment of Edwards Aquifer

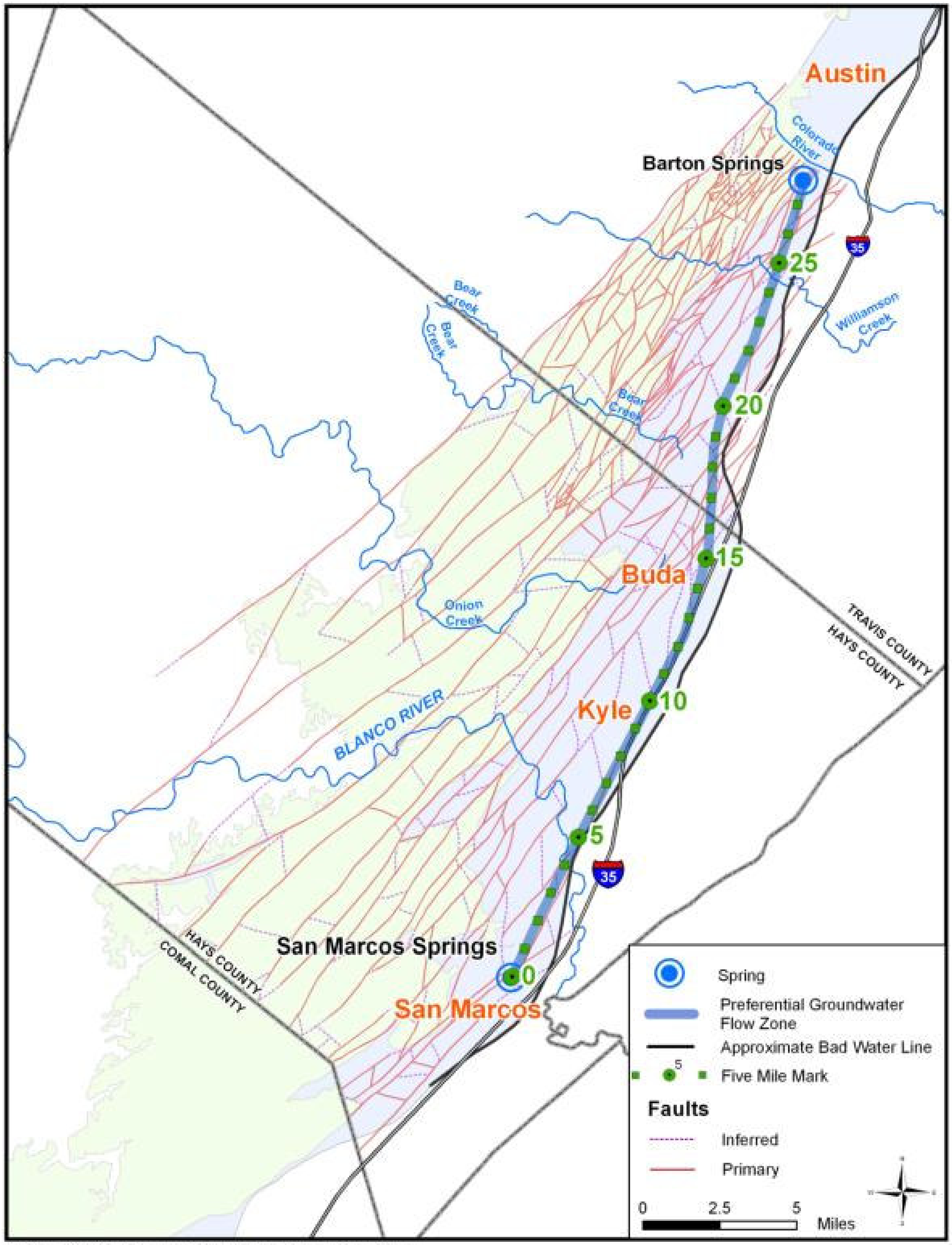

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Figure 2-1. Location of Preferential Groundwater Flow Zone

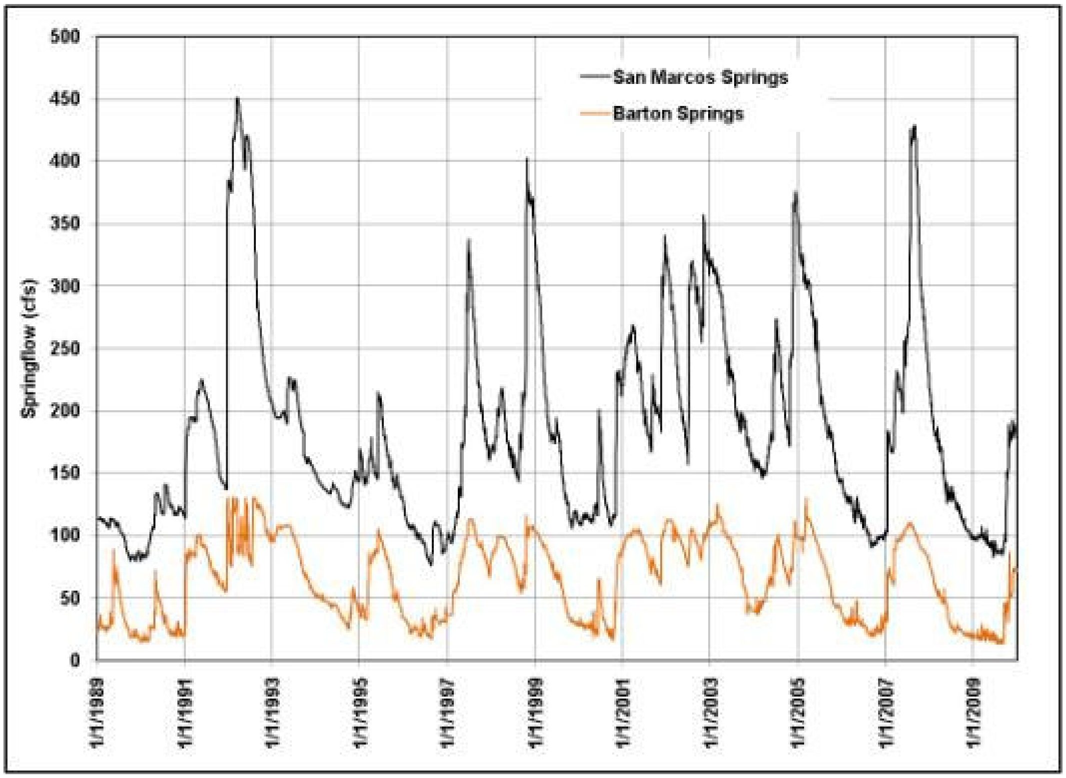

Figure 3-1. Discharge Hydrographs of San Marcos and Barton Springs: 1989 – 2009

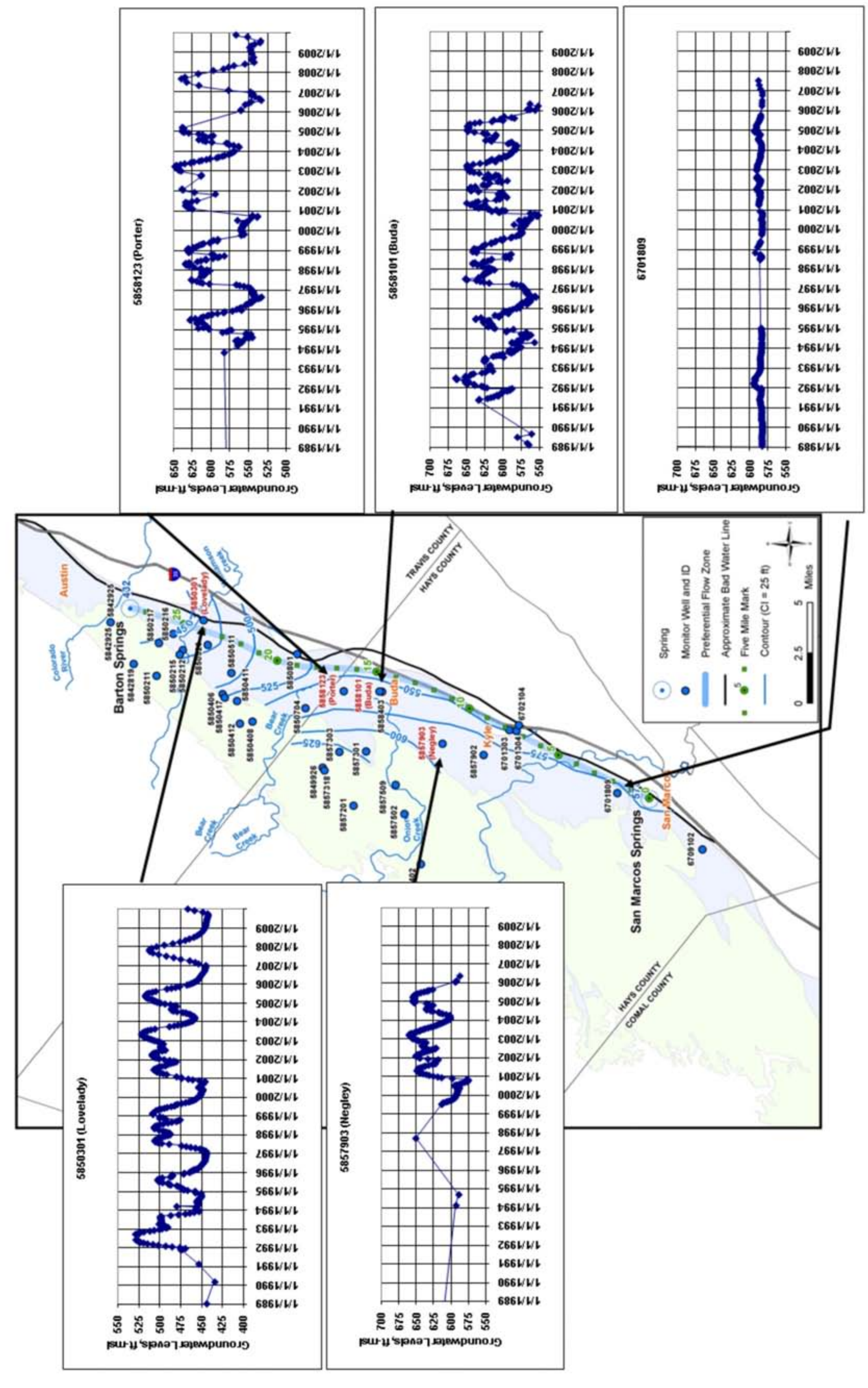

Figure 3-2. Groundwater Level Hydrographs of Selected Monitor Wells: 1989 - 2009

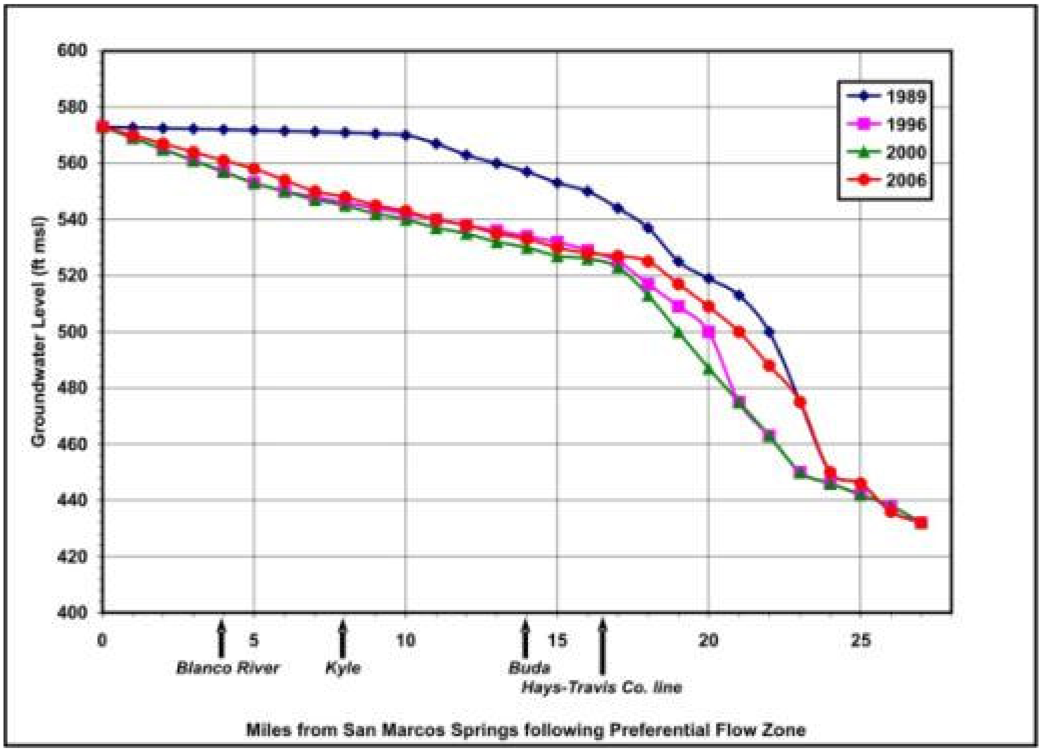

Figure 3-3. Estimated Profile of Groundwater Levels along Preferential Groundwater Flow Zone for Four Recent Droughts from Available Groundwater Data

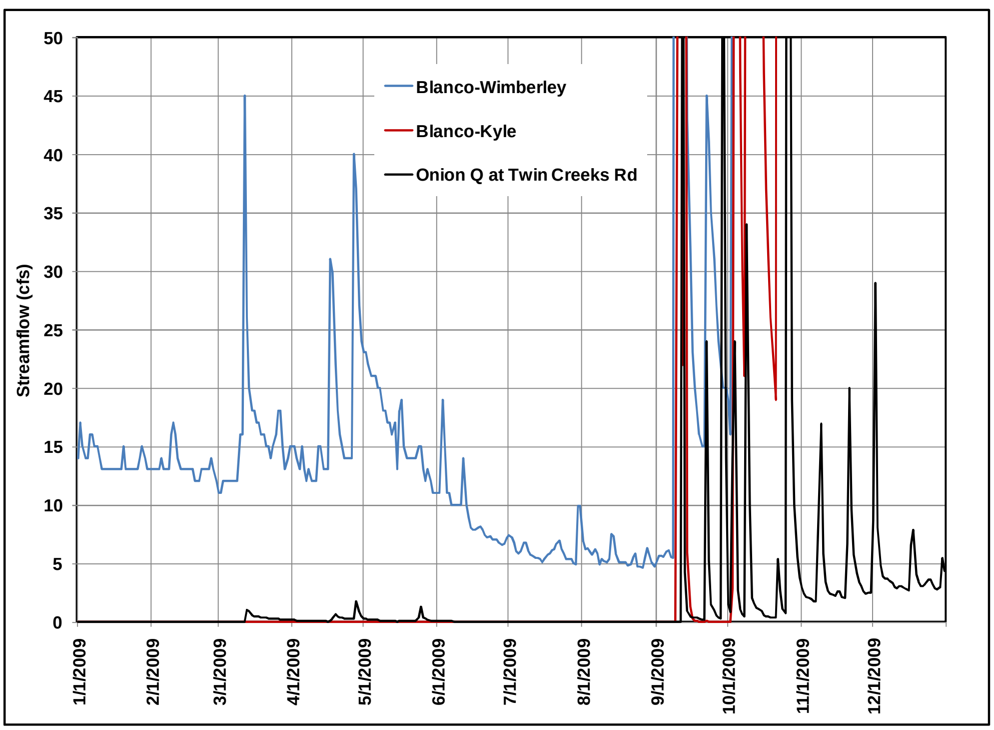

Figure 3-4. Discharge Hydrographs at Selected Streamflow Gaging Stations: 2009

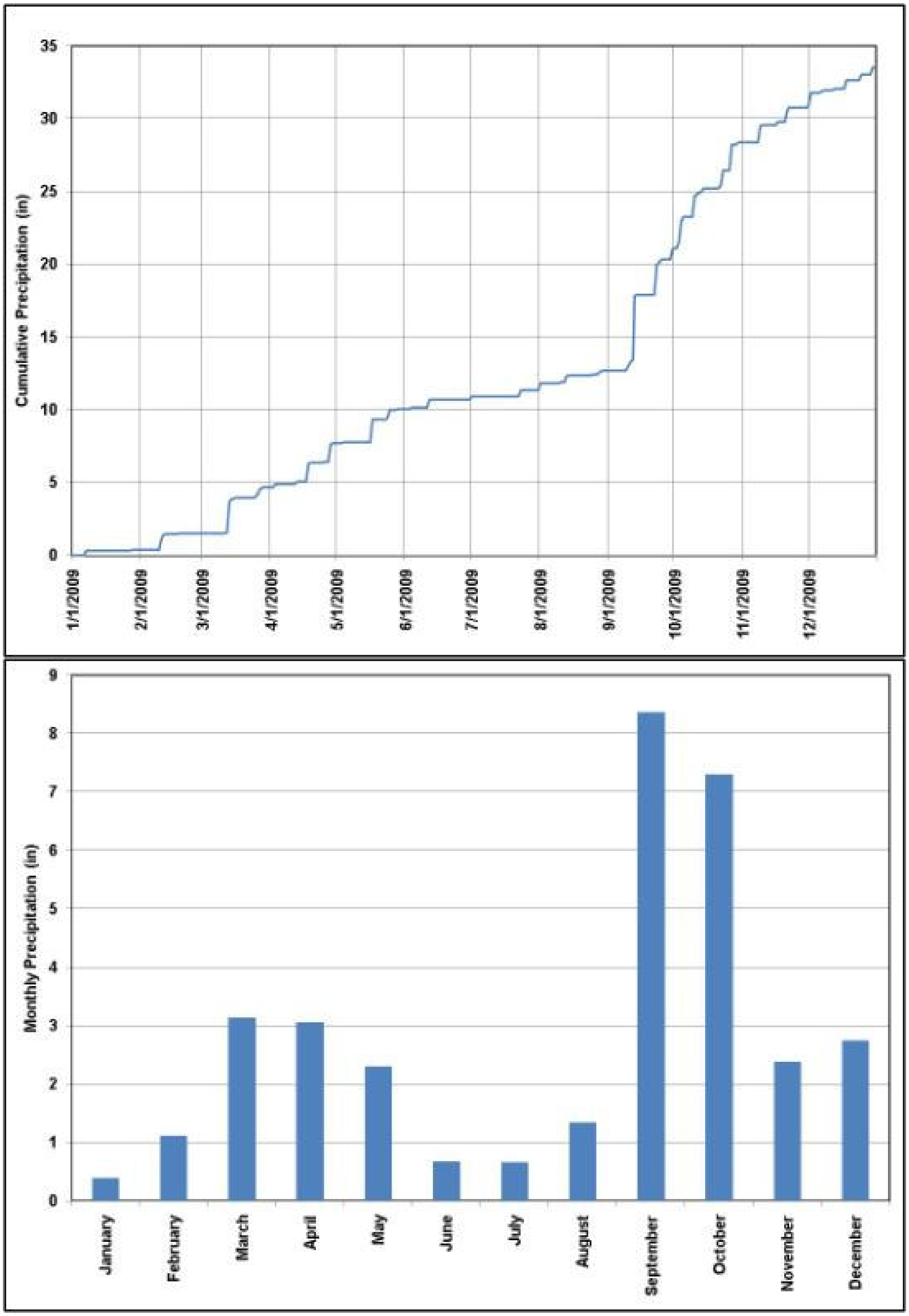

Figure 3-5. Cumulative Daily and Monthly Precipitation: 2009

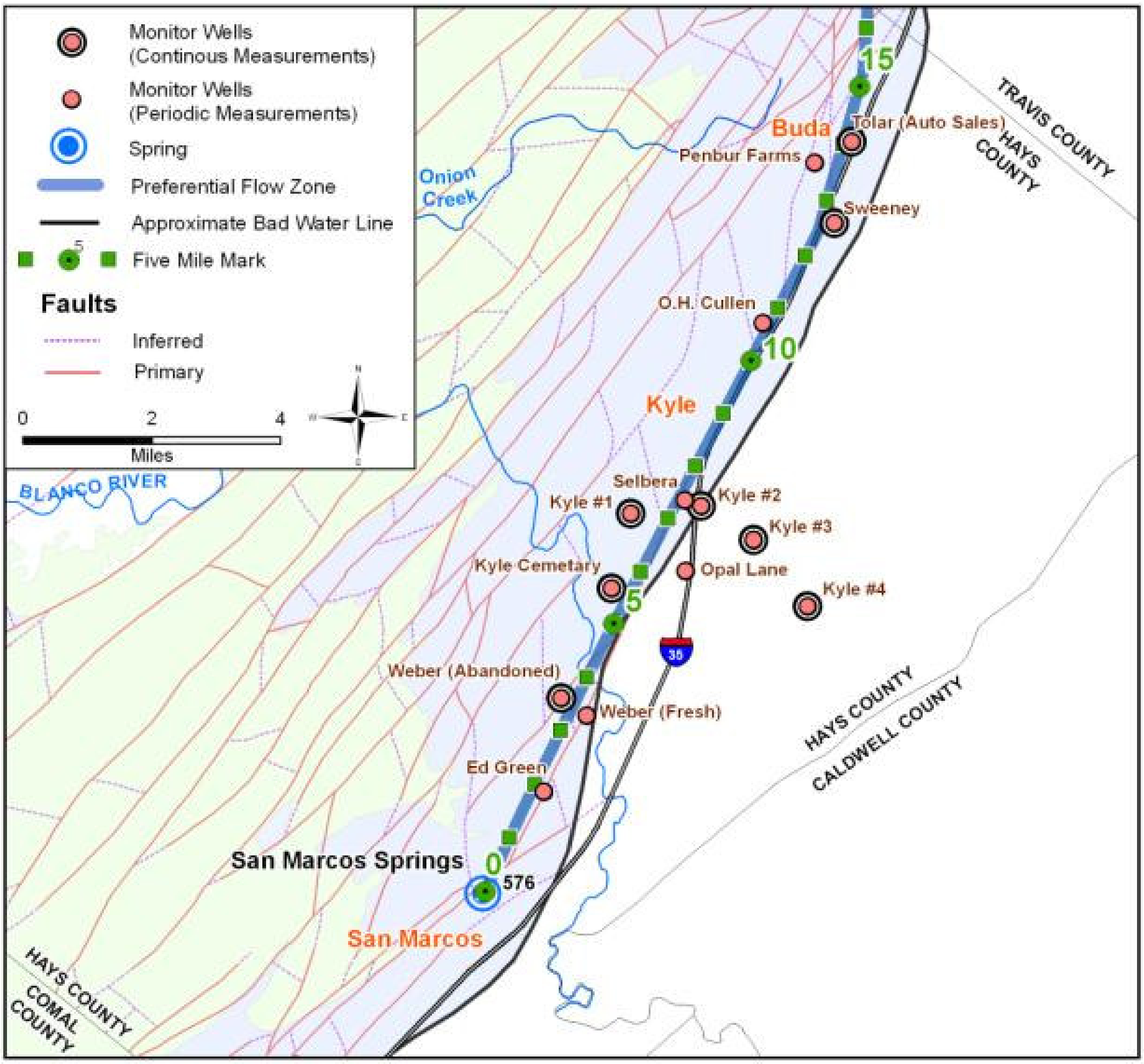

Figure 4-1. Location of Monitor Wells in 2009 Study

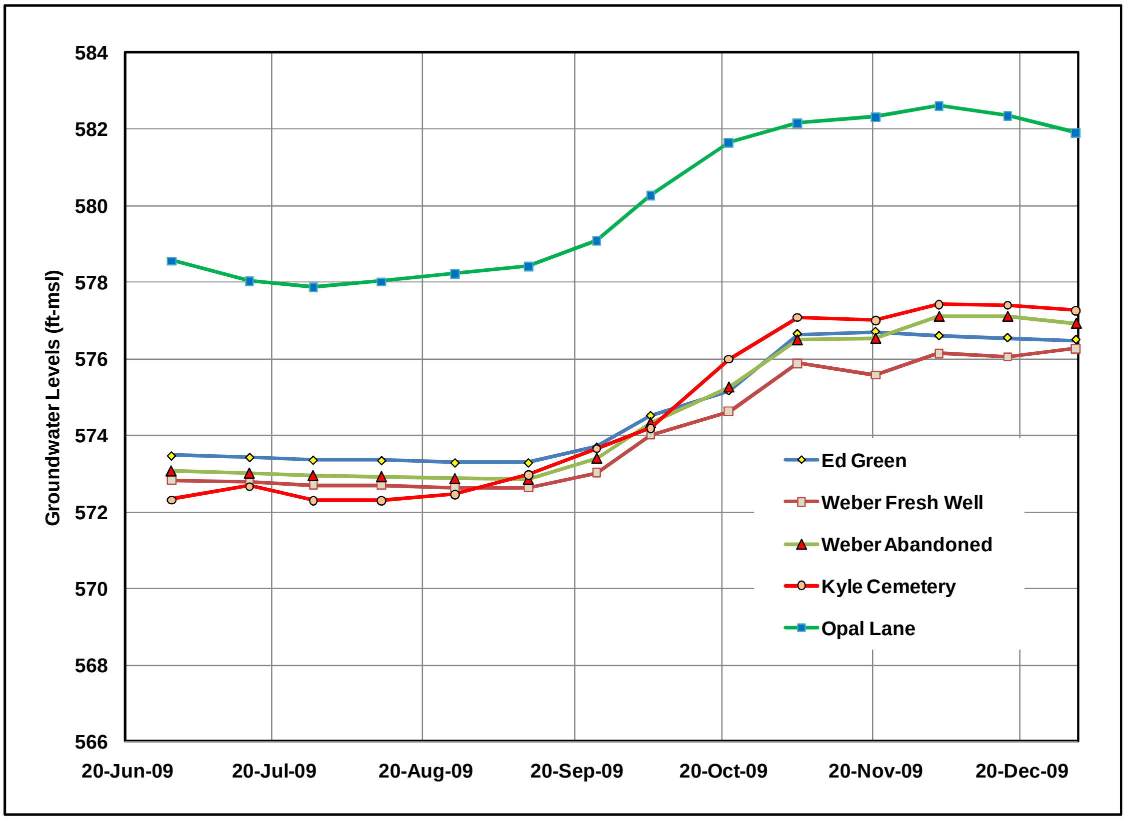

Figure 5-1. Groundwater-Level Hydrographs for 2009 Study Monitor Wells: San Marcos Springs to Kyle

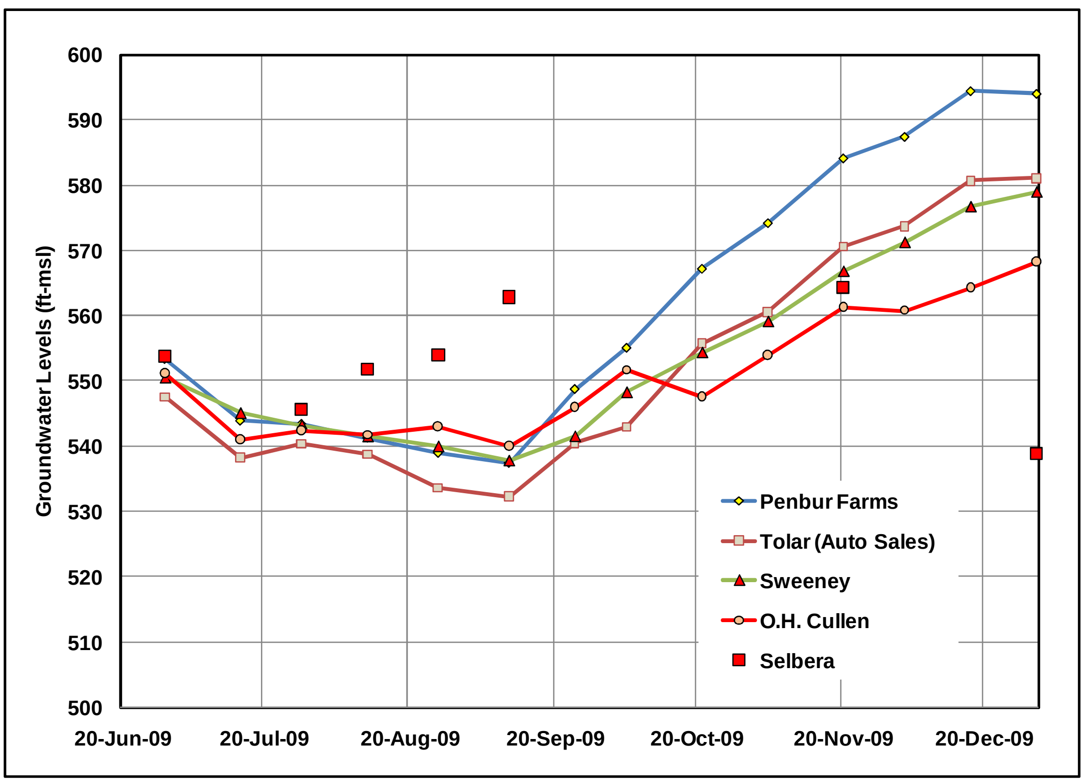

Figure 5-2. Groundwater-Level Hydrographs for 2009 Study Monitor Wells: Kyle to Buda

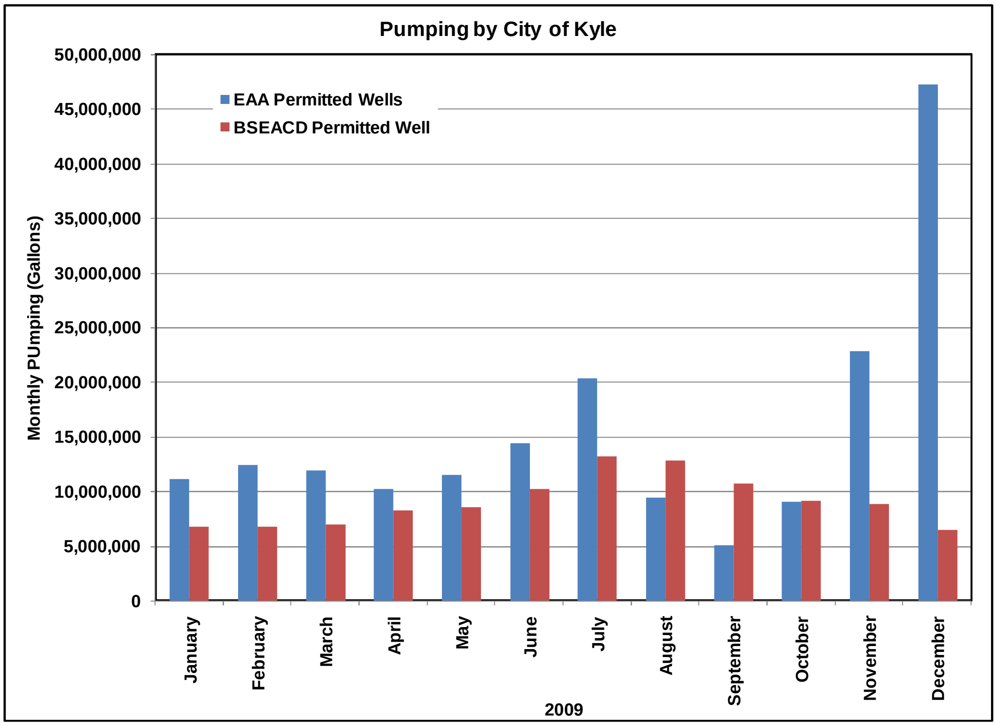

Figure 5-3. Groundwater Pumping by City of Kyle Supply Wells for 2009

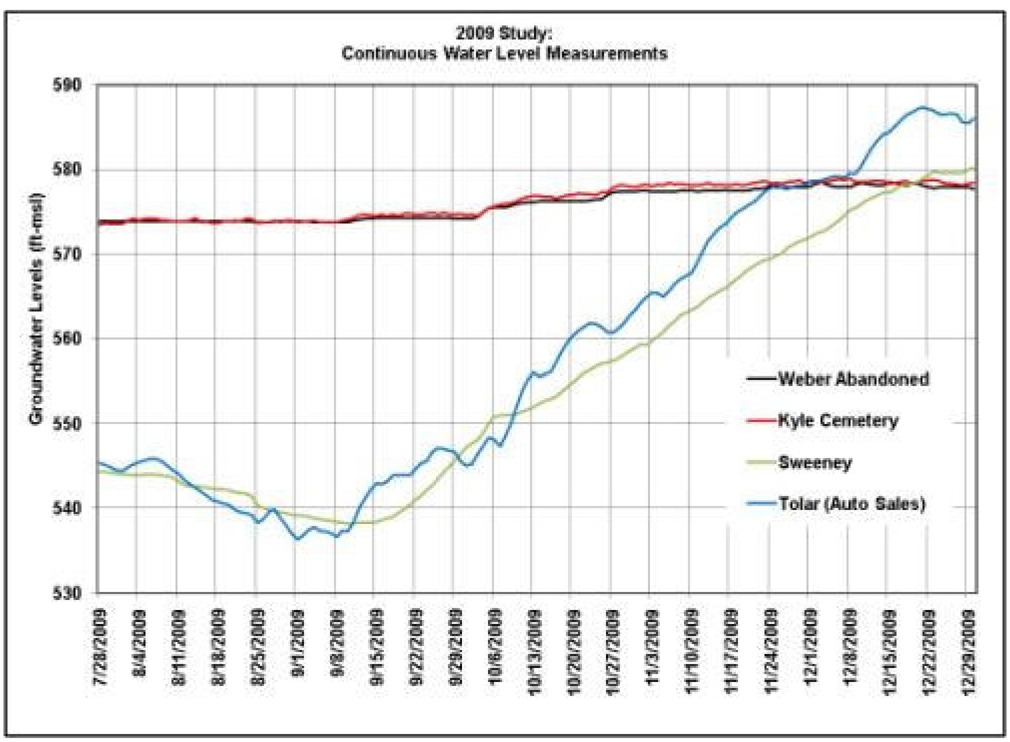

Figure 5-4. Groundwater-Level Hydrographs for 2009 Study Monitor Wells with Data Loggers

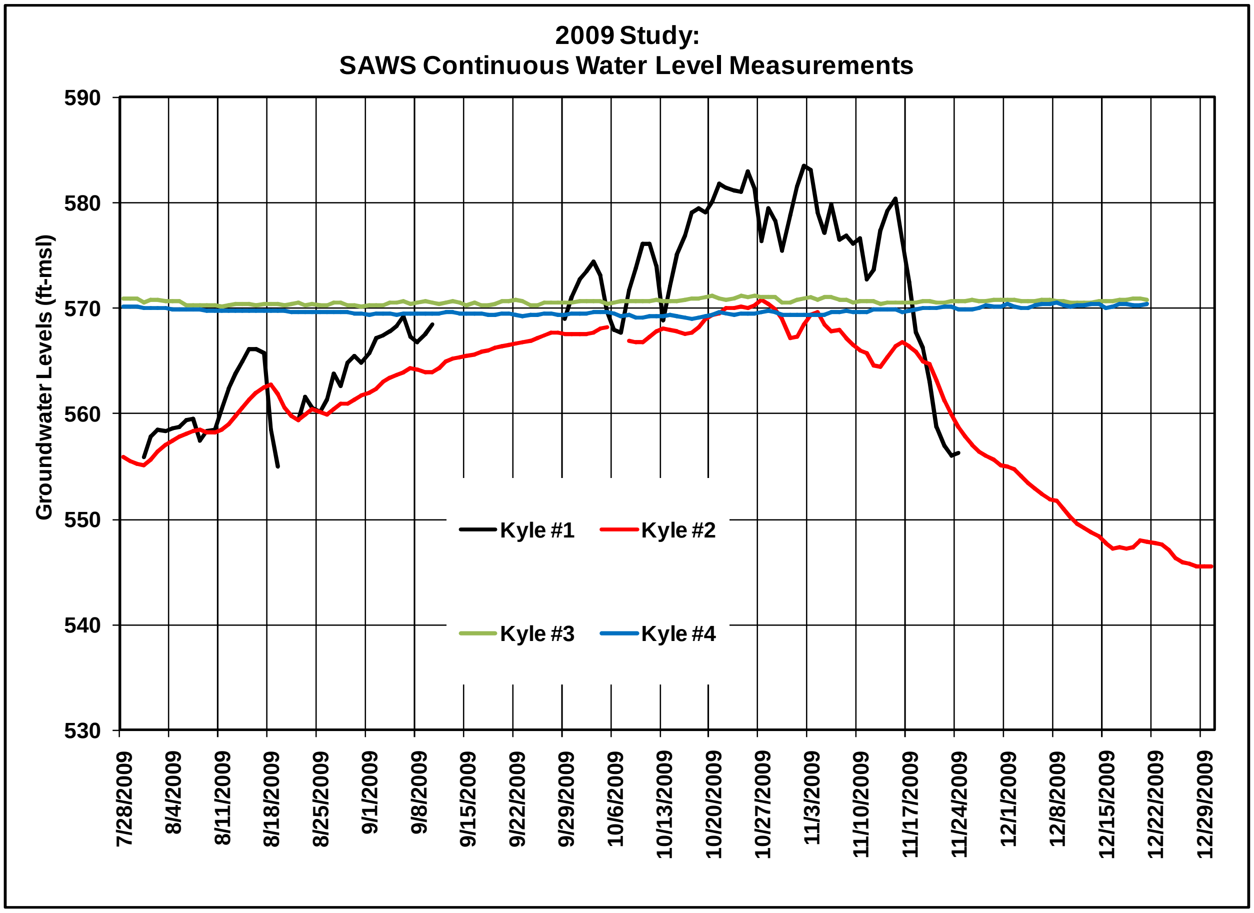

Figure 5-5. Groundwater-Level Hydrographs for SAWS Monitor Wells along Kyle Transect

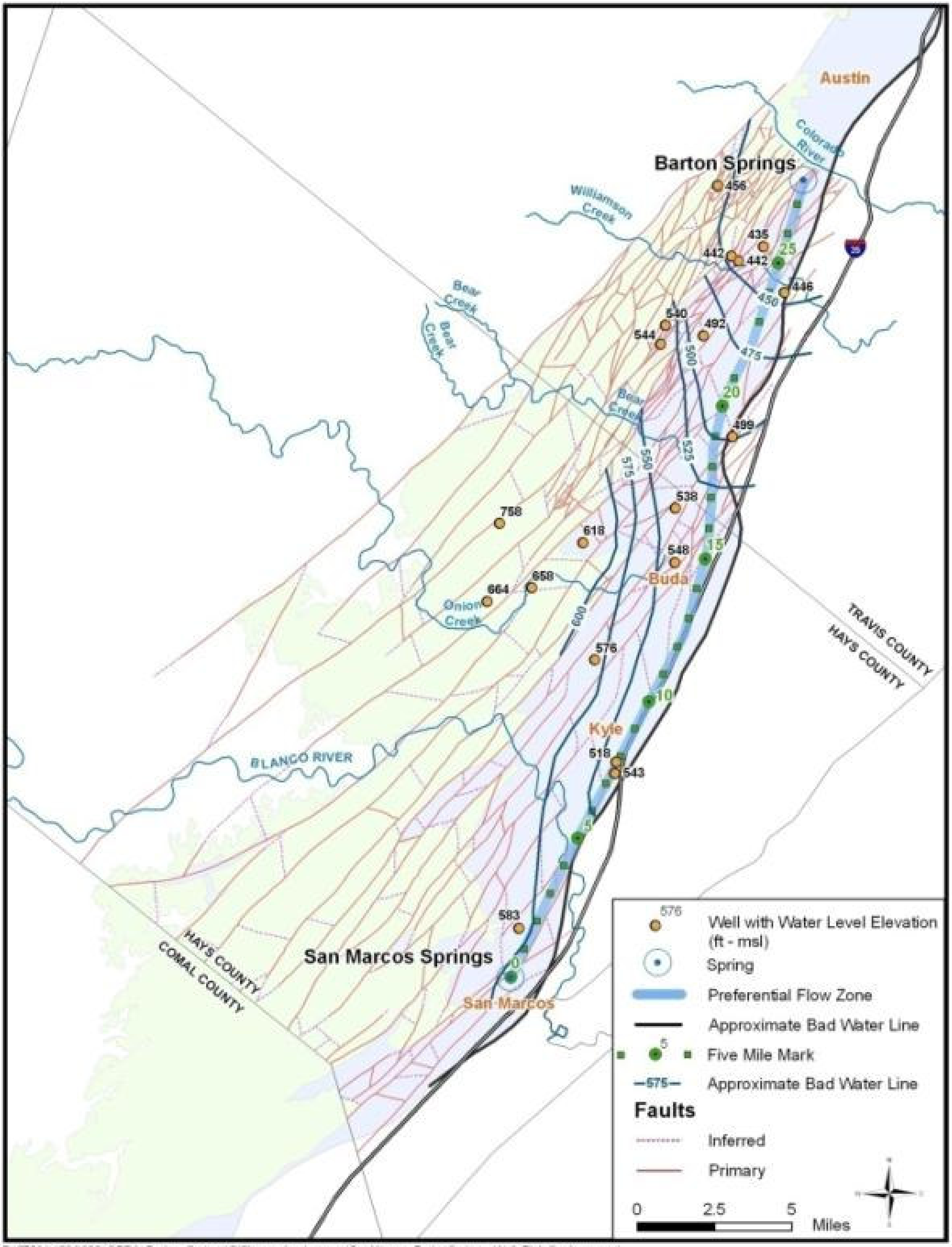

Figure 6-1. Groundwater-Level Map for Drought Conditions: 2000

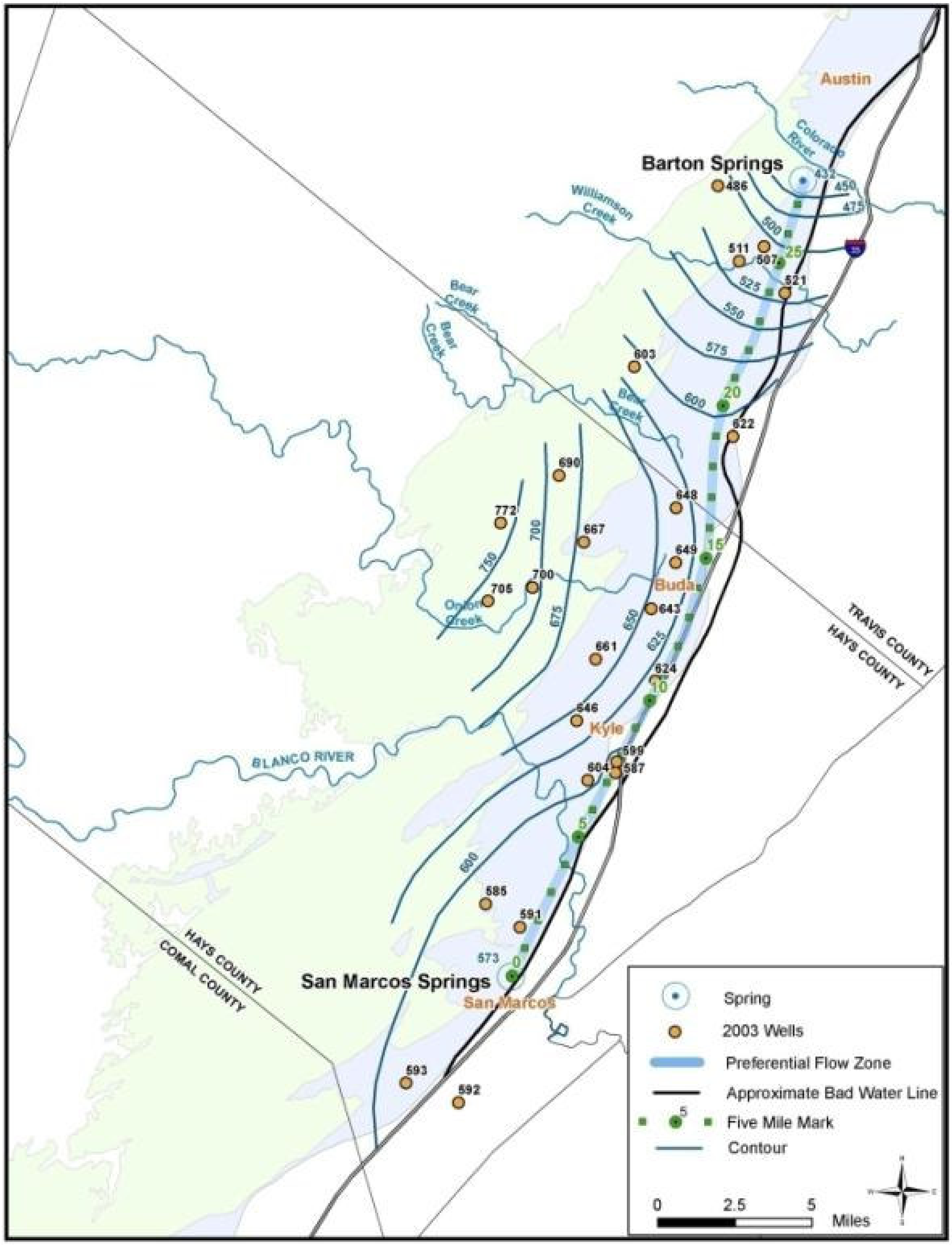

Figure 6-2. Groundwater-Level Map for Wet Conditions: 2003

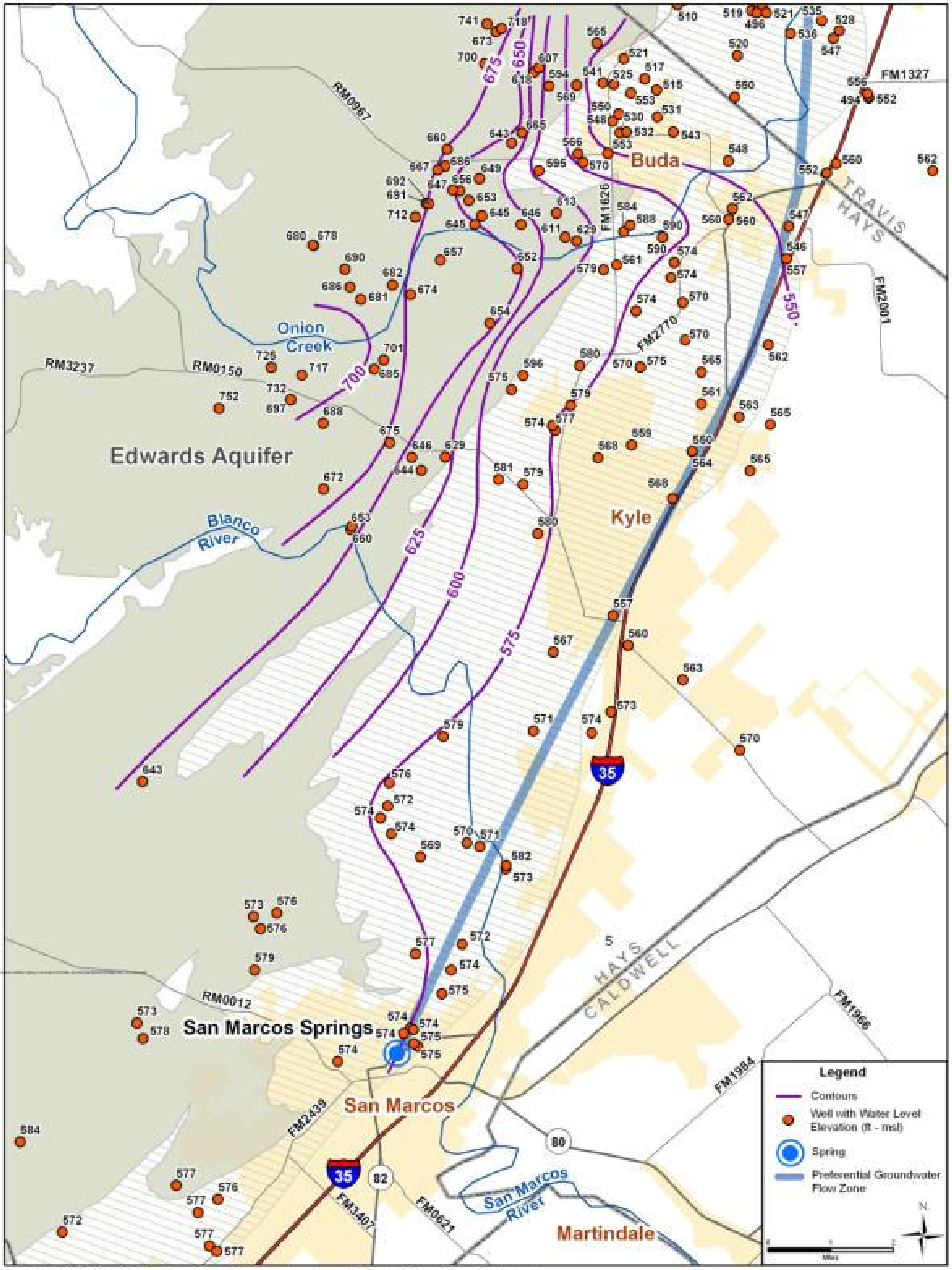

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Figure 6-3. Groundwater-Level Map for February-March 2009 from Synoptic Survey by EAA, BSEACD, and COA

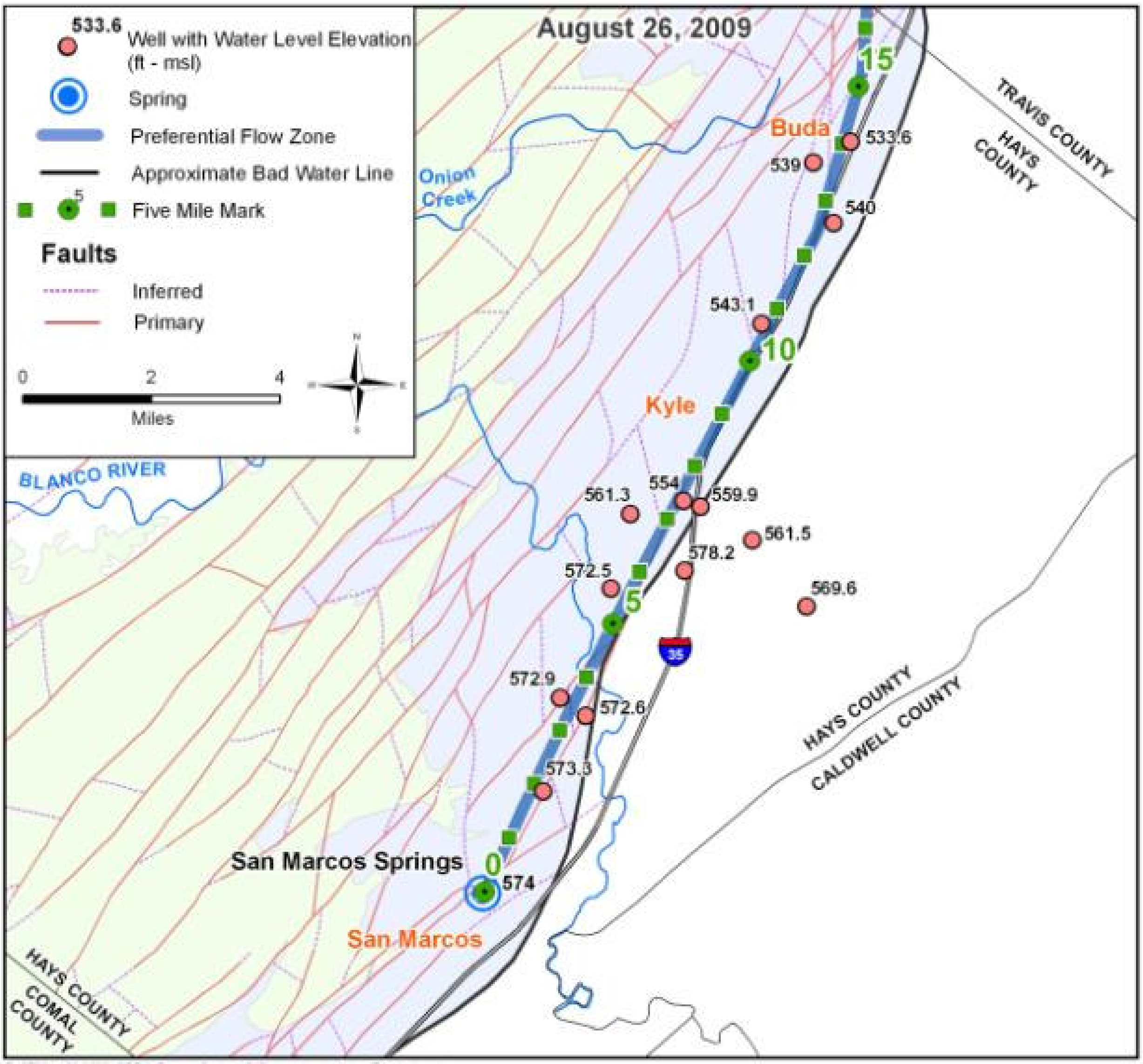

Figure 6-4. Groundwater Levels for Drought Conditions: August 26, 2009

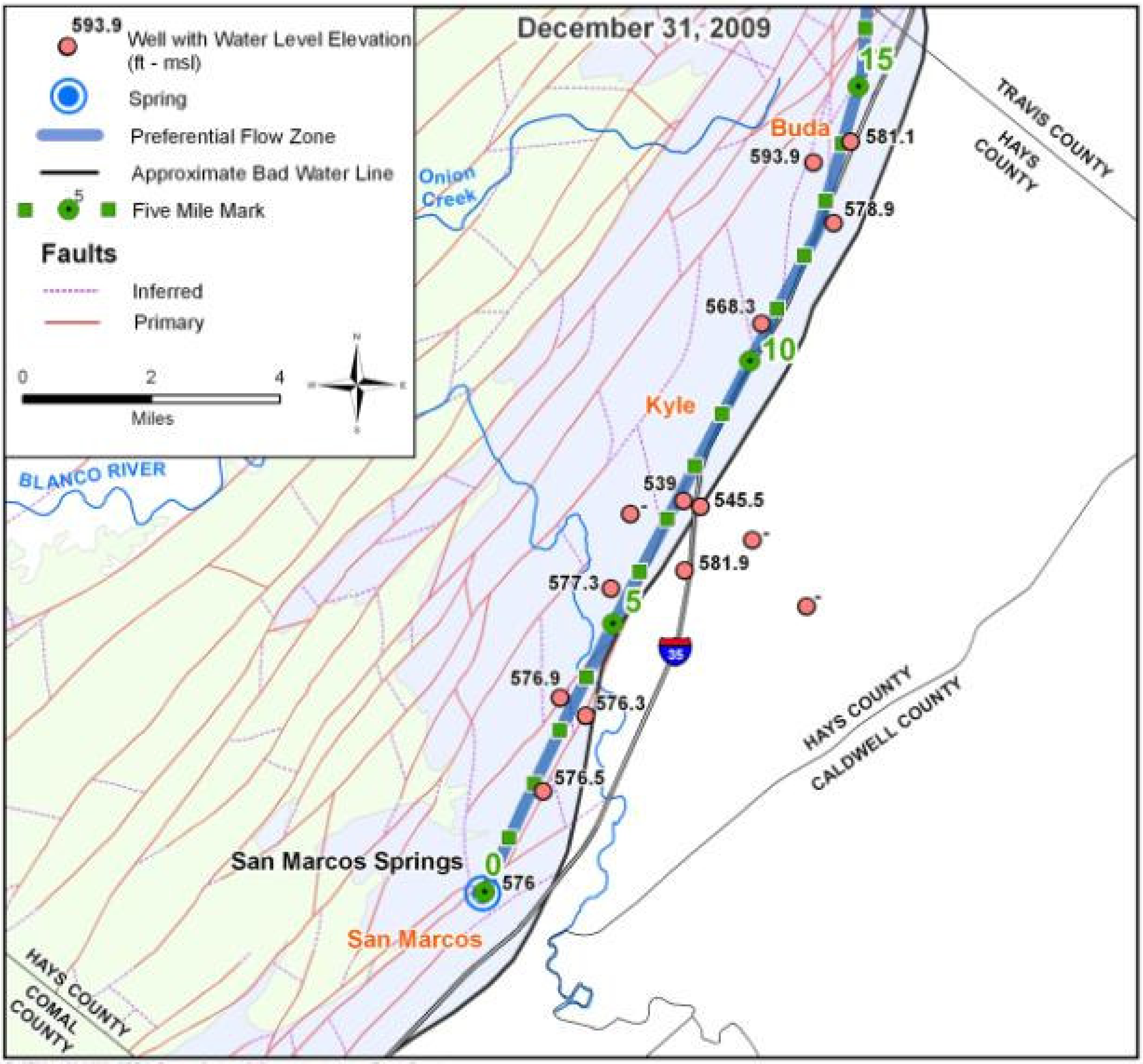

Figure 6-5. Groundwater Levels for Wet Conditions: December 31, 2009

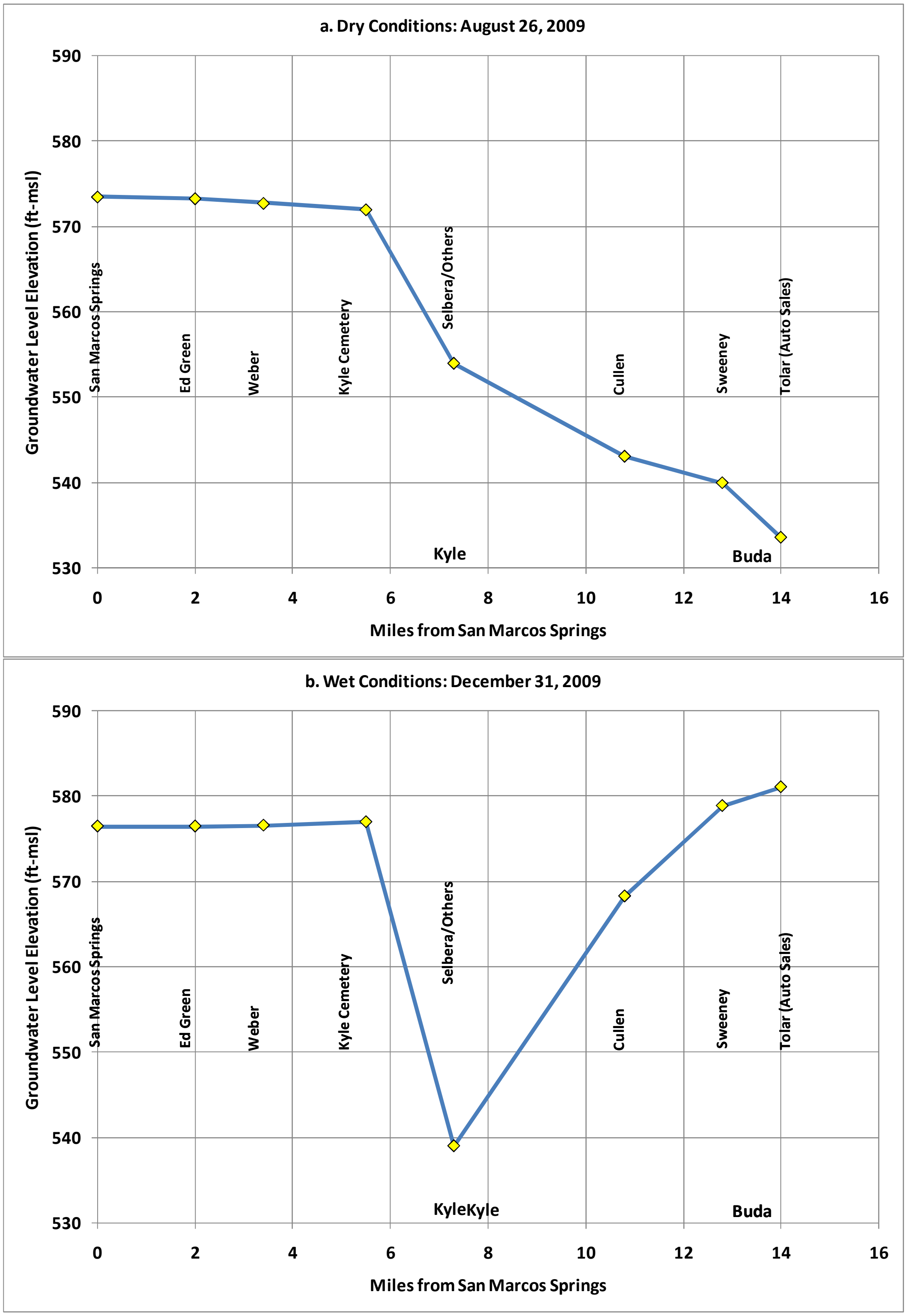

Figure 6-6. Groundwater-Level Profile along Preferential Groundwater Flow Zone

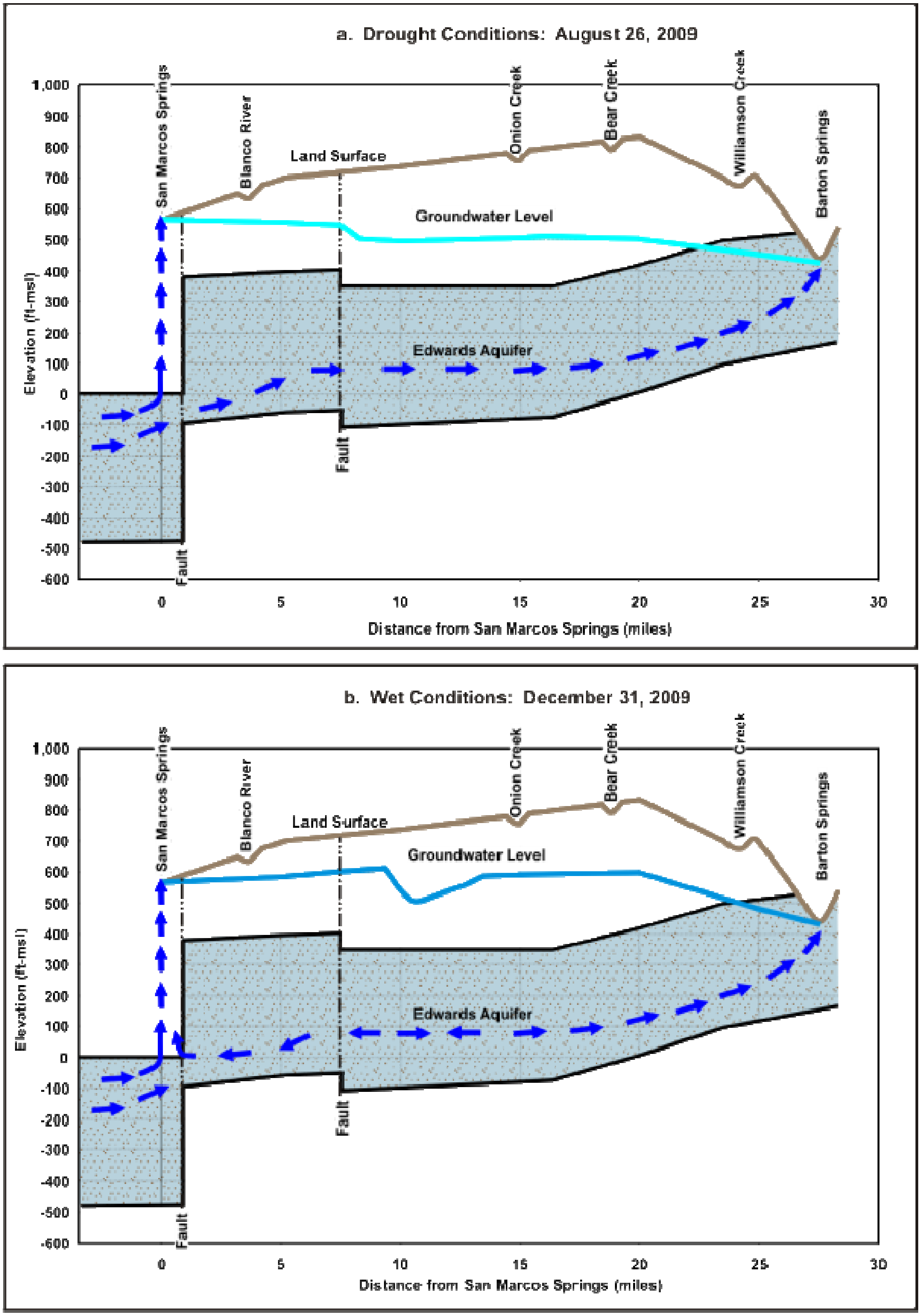

Figure 6-7. Schematics Showing Hydrogeologic Profile along Preferential Groundwater Flow Zone

Table 4-1. Description of Monitor Wells Used for 2009 Drought Study

Site Name	*State Well Number*	*Salinity*	*Latitude*	*Longitude*	*Well Depth (ft)*	*Land Surface Elevation (ft)*
2009 Study Monitor Wells						
Penbur Farms	5858410	Fresh	30.066905	-97.838912	584	765.39
Sweeney*	5858428	Fresh	30.052075	-97.833399	494	682.25
Tolar (Auto Sales)*	5858511	Fresh	30.071935	-97.828363	525	732.08
O.H. Cullen	5858704	Fresh	30.027707	-97.853915	532	745.65
Kyle Cemetery*	6701301	Fresh	29.963249	-97.897087	336	690.00
Opal Lane	67013AT	Saline	29.967388	-97.876221	unknown	697.00
Selbera	6701304	Fresh	29.98451	-97.876300	372	717.55
Weber Abandoned*	6701606	Fresh	29.936522	-97.911421	250.5	771.74
Weber Fresh Well	6701607	Fresh	29.932083	-97.904501	121	669.86
Ed Green	67019EG	Fresh	29.913665	-97.916541	unknown	645.29
SAWS Monitor Wells						
Kyle #1	6701311	Fresh	29.981388	-97.891388	810	770.52
Kyle #2	6702104	Transition	29.983054	-97.871666	975	674.32
Kyle #3	6702105	Saline	29.958333	-97.842221	970	678.28
Kyle #4	6702106	Saline	29.974721	-97.857222	1100	646.70

*Indicates pressure transducer installed as part of this study.