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REVISITING THE HYDROLOGIC DIVIDE BETWEEN THE SAN ANTONIO AND BARTON SPRINGS SEGMENTS OF THE EDWARDS AQUIFER: INSIGHTS FROM RECENT STUDIES

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ABSTRACT

Groundwater divides delineate the boundaries of aquifer systems and influence not only the local aquifer hydrodynamics but also the groundwater budget. The groundwater divide separating the San Antonio and Barton Springs segments of the Edwards Aquifer in Texas has historically been drawn along topographic or surface water divides between the Blanco River and Onion Creek in the recharge zone, and along potentiometric highs in the confined zone between the cities of Kyle and Buda in Hays County. The purpose of this study is to review the results of previous studies about the groundwater divide and to evaluate recently collected data that pertain to the groundwater divide. Studies have been conducted over the past five years using detailed potentiometric data, tracing techniques, and groundwater flow modeling to better characterize the Edwards Aquifer and to understand the relationship between the Barton Springs segment and the portion of the San Antonio segment north of San Marcos Springs. These studies reveal that during wet conditions the groundwater divide is located generally along Onion Creek in the recharge zone, extending easterly along a potentiometric ridge between the cities of Kyle and Buda toward the saline zone boundary. During dry conditions the hydrologic divide moves south and is located along the Blanco River in the recharge zone, extending southeasterly to San Marcos Springs. The groundwater divide is a hydrodynamic feature dependent upon the hydrologic conditions (wet versus dry) and the resulting hydraulic heads between Onion Creek and the Blanco River. The major influences on the position of the divides are groundwater mounds beneath the Blanco River and Onion Creek as the amount of recharge changes between wet and dry periods. During wet periods more water is recharged along Onion Creek because it has a greater potential for recharge through numerous recharge features. During dry periods, the Blanco River continues to flow and recharge the aquifer long after flow has ceased in Onion Creek and the Onion Creek mound has subsided. Under extreme drought conditions, some groundwater bypasses San Marcos Springs and flows toward Barton Springs.

INTRODUCTION

The concept of a groundwater divide in the Edwards Aquifer between San Marcos Springs and Barton Springs has been considered by researchers since at least 1956. The results of various studies have indicated the presence of a groundwater divide somewhere generally between Onion Creek and the Blanco River (Fig. 1). Some of these studies have acknowledged that the divide shifts over time and under varying hydrologic conditions. Earlier studies relied on potentiometric levels in monitor and water-supply wells. More recent studies have included tracing of organic dyes to determine direction, travel times, and pathways of groundwater flow. Together with detailed potentiometric level data from synoptic surveys, greater insight has been provided about the location and behavior of the groundwater divide between the Barton Springs and San Antonio segments of the Edwards Aquifer.

This study is a compilation of various studies and datasets relating to the location and nature of the groundwater divide. An assessment of the groundwater divide had not been made using all of these datasets. An understanding of the groundwater divide is needed for management of the Edwards Aquifer. To protect endangered species in Barton, Comal, and San Marcos springs, the amount of water permitted for pumping from the aquifer has

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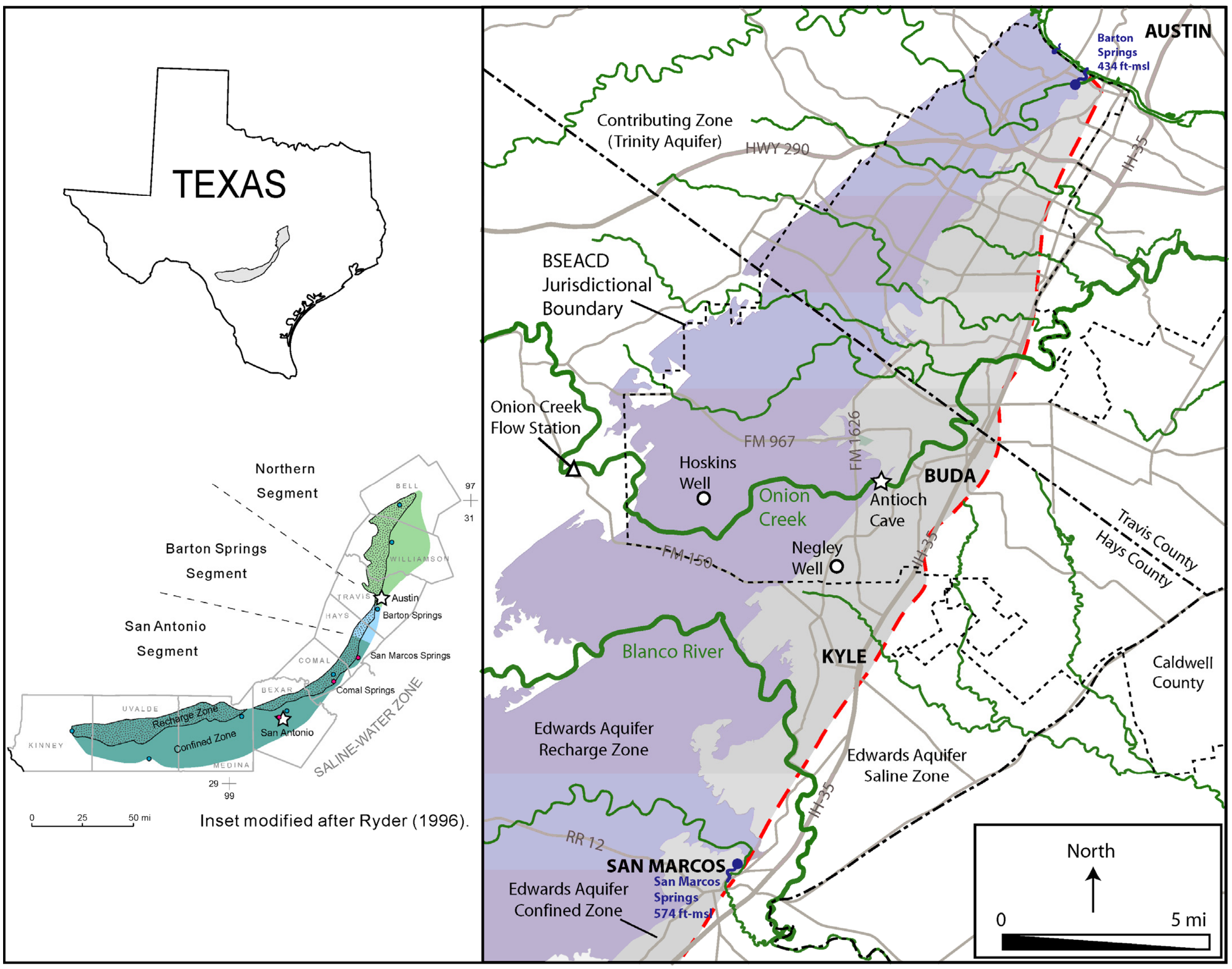


Figure 1. Location map of study area.

been limited by the Edwards Aquifer Authority (EAA) and the Barton Springs/Edwards Aquifer Conservation District (BSEACD). Extensive numerical groundwater modeling has been conducted for the various segments of the Edwards Aquifer. A firm understanding of the aquifer is important for development of useful models. A good understanding of flow directions and rates of flow are important for issues of contaminant transport within the aquifer. Numerous karst features in the recharge zone provide direct pathways to the aquifer for spills of contaminants. Estimating how these contaminants travel can be significant to protect users of the aquifer and the springs.

Study Area

The full extent of the Edwards Aquifer is shown in the inset to Figure 1. This study focused on that portion of the Edwards Aquifer between Barton Springs and San Marcos Springs. Barton Springs, situated in Barton Creek about 1500 ft (450 m) upstream of the Colorado River, is the lowest point of natural discharge for the Barton Springs and San Antonio segments of the Edwards Aquifer. The northern portion of the study area is heavily urbanized. Other than a limited urban area around San Marcos, most of the area is suburban to rural. The jurisdictional boundary of the BSEACD is shown in Figure 1. The jurisdictional boundary of the EAA begins immediately south of the BSEACD boundary.

Previous Studies

Figure 2 shows groundwater divides provided in some of the previous studies. The position of each line is largely a factor of the hydrologic conditions under which the studies were conducted.

One of the earliest studies to define a groundwater divide for the San Antonio segment of the Edwards Aquifer was conducted by Pettit and George (1956). That study used several potentiometric levels to define the groundwater divide between Buda and Kyle. DeCook (1960) published a potentiometric map of the San Marcos to Buda area using data from the drought of the 1950s and noted a groundwater divide in the vicinity of Buda.

Slagle et al. (1986) produced a map of the Barton Springs segment showing its southern boundary along the surface water divide between the Blanco River and Onion Creek. Subsequently, Slade et al. (1986) defined the first water budget of the Barton Springs segment. The water-budget elements associated with the Blanco River were not included in that budget although

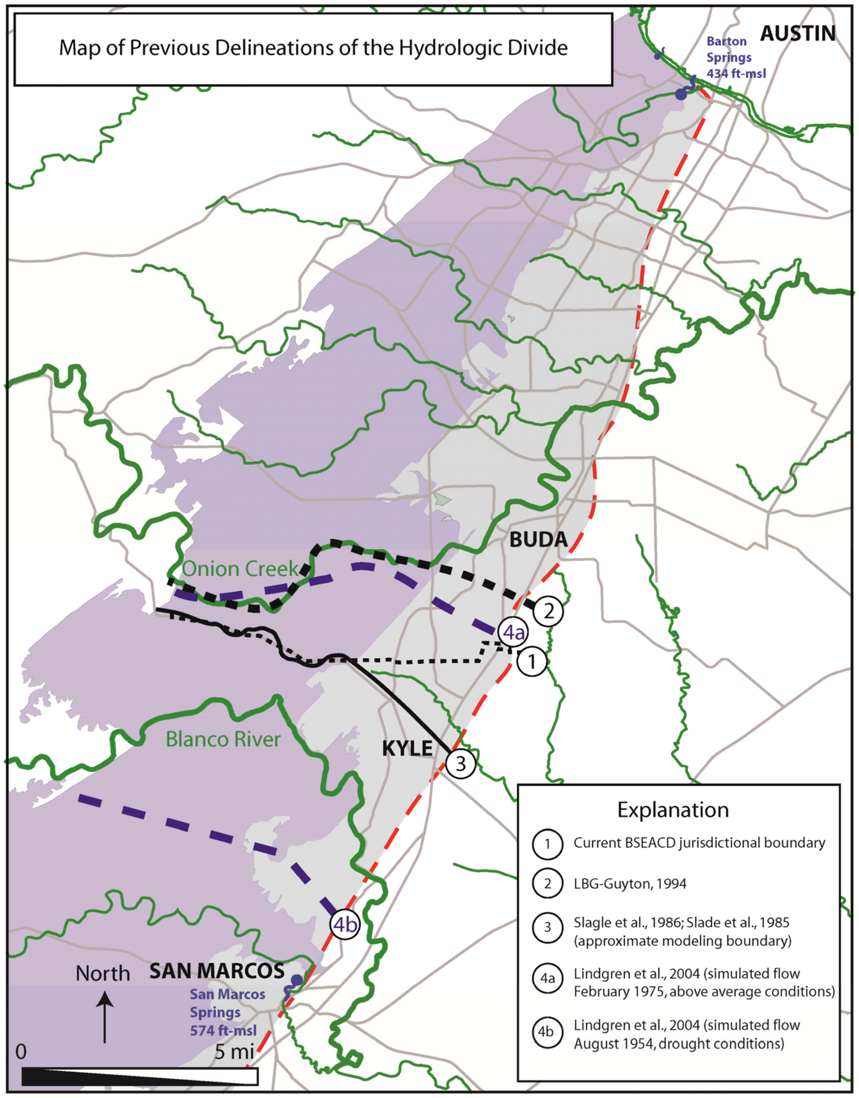


Figure 2. Map of previous delineations of the hydrologic divide.

lateral inflow and outflow (intra-aquifer) was mentioned to occur at times between the Barton Springs and San Antonio segments. However, the amount of lateral flow was not quantified. During the drought of the 1950s, the gradient between San Marcos and Buda indicated flow was to the north. All other datasets reviewed by Slade et al. (1986) indicated flow to the south in this area. Ogden et al. (1986) present the results of potentiometric, geochemical, and dye tracing studies in the vicinity of San Marcos Springs. This study demonstrated the hydrologic connection between the Blanco River and the northernmost spring orifices at San Marcos Springs.

A study focusing on the groundwater divide using potentiometric data under varying hydrologic conditions was conducted by LBG-Guyton (1994). The report also documents previously delineated boundaries—some of which are described above and included in Figure 2. Conclusions of the report indicate that the divide is located between Buda and Kyle in the artesian aquifer, and along Onion Creek in the recharge zone. Further discussions in the report state that during times of low water levels, the artesian part of the aquifer north of the Blanco River may supply water to water-supply wells near Kyle and Buda and ultimately to Barton Springs.

Numerical modeling of the Edwards Aquifer by Lindgren et al. (2004) includes the San Antonio and Barton Springs segments. The model did not contain a model boundary in the vicinity of Kyle. Instead, the northernmost boundary of the model was placed along the Colorado River near Barton Springs. Previous numerical models had specified model boundaries in the vicinity of Kyle and Onion creek (Slade et al. (1985) and Scanlon et al. (2001). Smith and Hunt (2004, their Appendix B) conducted a sensitivity analysis of the southern boundary of the Barton Springs model to compare a general-head boundary to the no-flow boundary that was used in previous models. This analysis showed that a general-head boundary could more accurately simulate flow to and from San Marcos Springs. Results of simulations in the Lindgren model suggest that the position of the groundwater divide varies depending on the hydrologic conditions. Under wet conditions the groundwater divide is located near Kyle in the confined zone and along Onion Creek in the recharge zone. During drought conditions the position of the groundwater divide shifts south and west to near San Marcos Springs in the confined zone, and south of the Blanco River in the recharge zone.

Hamilton et al. (2006) compiled regional-scale potentiometric surfaces focusing on the San Antonio segment with some data north of San Marcos Springs. A potentiometric map with data from December 2004, with the aquifer under high-flow conditions, shows a groundwater mound in the vicinity of Onion Creek and a gradient indicating flow from the Buda area southward to San Marcos Springs. Under low-flow conditions in October 1999, a northward gradient indicates flow from San Marcos Springs to the north.

A study by Johnson and Schindel (2008) focused on the contributions of flow to San Marcos Springs. In that report it was noted that under drought conditions potentiometric data suggest that some groundwater would flow past San Marcos Springs northward to Barton Springs. Further discussion suggested a groundwater divide along the Blanco River during drought conditions.

Hauwert (2011) conducted a water-budget analysis using streamflow and springflow data and concluded that under extreme low-flow conditions recharge from the Blanco River sustains at least half of the discharge from Barton Springs.

This report serves to integrate the studies mentioned above and some recent studies that involve dye tracing (Hauwert et al., 2004; Hunt et al., 2005 and 2006; and Johnson et al., 2011) and potentiometric data (Hunt et al., 2007; Land et al., 2011) in addition to some unpublished BSEACD data. Results of these studies are discussed below and presented in figures within this paper.

Hydrogeologic Setting

The Edwards Aquifer is a karst aquifer developed in faulted and fractured Cretaceous-age limestones and dolomites. Ford (2004) defines karst as terrain with distinctive hydrology resulting 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 transport groundwater from recharge features to springs (White, 1988; Todd and Mays, 2005).

The Edwards Aquifer system lies within the Miocene-age Balcones Fault Zone (BFZ) of south-central Texas and consists of an area of about 4,200 mi^2 (11,000 km^2) (Fig. 1). The aquifer extends about 250 mi (430 km) from Kinney County, west of San Antonio, to Bell County, north of Austin. Groundwater from the Edwards Aquifer is the primary source of water for about two million people plus numerous industrial, commercial, and irrigation users. The Edwards Aquifer system also supports 11 threatened or endangered species, aquatic habitats in rivers of the Gulf Coastal Plain, and coastal bays and estuaries. Hydrologic divides separate the Edwards Aquifer into three segments. North of the Colorado River is the Northern segment of the Edwards Aquifer, and south of the southern hydrologic divide near the City of Kyle is the San Antonio segment (Fig. 1). The Barton Springs segment is situated between the Northern and San Antonio segments. Ryder (1996) and Lindgren et al. (2004) provide detailed and regional information on the overall Edwards Aquifer.

Development of the Edwards Aquifer was influenced significantly by fracturing and faulting associated with Miocene-age tectonic activity and subsequent dissolution of limestone and dolomite units by infiltrating meteoric water (Sharp, 1990; Barker et al., 1994; Hovorka et al., 1995; Hovorka et al., 1998; Small et al., 1996). In addition, development of the aquifer is also thought to have been influenced by deep dissolution processes along the saline-fresh water interface, which is known as hypogene speleogenesis (Klimchouk, 2007; Schindel et al., 2008).

Numerous tracer tests have been performed on portions of the Edwards Aquifer demonstrating that rapid groundwater flow occurs in an integrated network of conduits discharging at wells and springs (Hauwert et al., 2004; BSEACD, 2003). During higher flow conditions, a portion of this groundwater flows from the conduits into the diffuse matrix of the aquifer thus increasing the amount of groundwater stored in the aquifer. Water from storage flows diffusely to wells or back into the conduit network during lower flow conditions (Mahler et al., 2006).

Recharge

The majority of recharge to the aquifer is derived from streams originating on the contributing zone, located up gradient and primarily west of the recharge zone. Water flowing onto the recharge zone sinks into numerous caves, sinkholes, and fractures along numerous (ephemeral to intermittent) losing streams. For the Barton Springs segment, Slade et al. (1986) estimated that as much as 85% of recharge to the aquifer is from water flowing in these streams. The remaining recharge (15%) occurs as infiltration through soils or direct flow into recharge features in the upland areas of the recharge zone (Slade et al., 1986). However, a recent study by Hauwert (2009) indicates that upland recharge may constitute a larger fraction of recharge than stated in the Slade et al. (1986) study. Both studies recognize that a significant amount of recharge to the Edwards Aquifer is from flow in the creeks that cross the recharge zone.

Mean surface recharge to the Barton Springs segment of the Edwards Aquifer should approximately equal mean discharge, or about 53 cubic feet per second (cfs) (1.5 m^3/s); however, maximum recharge rates during flooding may approach 400 cfs (11 m^3/s) (Slade et al., 1986). Studies have shown that recharge is highly variable in space and time and focused within discrete features (Smith et al., 2001). For example, Onion Creek is the largest contributor of recharge to the Barton Springs segment (34% of total creek recharge) with maximum recharge rates up to 160 cfs (4.5 m^3/s) (Slade et al., 1986). Antioch Cave, which is located within the Onion Creek channel, is the largest-capacity discrete recharge feature known in the Barton Springs segment with an average recharge of 46 cfs (1.3 m^3/s) and a maximum of 95 cfs (2.7 m^3/s) during a 100-day study (Fieseler, 1998). A more recent study (Smith et al., 2011) estimates that Antioch Cave is capable of recharging up to 100 cfs (2.8 m^3/s) and that the recharge portion of Onion Creek upstream of Antioch Cave is capable of recharging about 100 cfs (2.8 m^3/s).

The Blanco River has long been considered a minor contributor of recharge to the San Antonio segment of the Edwards Aquifer. Pettit and George (1956) suggest a ceiling of about 15 cfs (0.4 m^3/s), which is consistent with more recent studies (Johnson and Schindel, 2010).

Groundwater Flow

The Edwards Aquifer is inherently heterogeneous and anisotropic, characteristics that strongly influence groundwater flow and storage (Slade et al., 1985; Maclay and Small, 1986; Hovorka et al., 1996 and 1998; Hunt et al., 2005). The Edwards Aquifer can be described as a triple porosity and permeability system consisting of matrix, fracture, and conduit porosity (Hovorka et al., 1995; Halihan et al., 2000; Lindgren et al., 2004) reflecting an interaction between rock properties, structural history, and hydrologic evolution (Lindgren et al., 2004). In the Barton Springs segment groundwater generally flows from west to east across the recharge zone, converging with preferential groundwater flow paths subparallel to major faulting, and then flowing north toward Barton Springs. In the San Antonio segment, groundwater similarly flows downdip in the recharge zone then along strike in the confined zone toward the major springs of Comal and San Marcos (Hamilton et al., 2006; Pettit and George, 1956).

Groundwater tracing and other studies demonstrate that a significant component of groundwater flow in the Edwards Aquifer is discrete, occurring in an integrated network of conduits, caves, and smaller dissolution features (Hauwert et al., 2002a, 2002b; Hunt et al., 2005; Johnson et al., 2011). Interpreted flow paths from tracer testing generally coincide with troughs in the potentiometric surface. In karst aquifers with significant conduit flow, potentiometric levels can be influenced by head changes in the conduits. Where the conduits are close enough to influence water levels in wells, the mapped potentiometric surfaces may show v-shaped contour lines, or troughs, similar to contour lines on topographic maps that are indicative of valleys. The lower heads in the conduits are due to the high permeability of the conduits and, in some cases, their connection to the springs. In the Barton Springs segment these flow paths are parallel to the N40E (dominant) and N45W (secondary) fault and fracture trends presented on geologic maps, indicating the structural influence on groundwater flow. Rates of groundwater flow along preferential flow paths, determined from dye tracing, can be as fast as 4 to 7 mi/day (6 to 11 km/day) under high-flow conditions or about 1 mi/day (1.6 km/day) under low-flow conditions (Hauwert et al., 2002a). These values only apply to conditions under which the dye-trace studies were conducted.

Water Levels and Storage

Water levels in the Edwards Aquifer do not show long-term declines in storage, but generally recover quickly from low levels reached during drought to previous high conditions typical of wet periods (Fig. 3) (Smith et al., 2001). Water levels and discharge at the springs respond very quickly to recharge events and then decline at variable rates, influenced by both conduit and matrix permeability and storage (Lindgren et al., 2004; Worthington, 2003).

In the study area, Onion Creek and the Blanco River recharge conduits and matrix in the Edwards Aquifer. Figure 4A shows a potentiometric mound from recharge along Onion Creek and paths of dye injected into Antioch Cave. Figure 4B shows the difference in water levels between high- (February 2002) to low-flow conditions (August 2006) (Hunt et al., 2007). Even under low-flow conditions, the mound is still present. The greatest flux in water levels appears to extend from Antioch Cave to the north. The presence of a mound beneath Antioch and much of Onion Creek indicates that water recharging along Onion Creek is going into the aquifer matrix which consists of non-conduit dissolution features, fractures, and primary porosity. Some of that recharged water flows directly to Barton Springs through conduits that have been demonstrated with dye-trace studies. These conduits are not of sufficient capacity to carry all of the recharging water directly to Barton Springs. Therefore, the excess water must be entering the aquifer matrix as reflected in higher heads in monitor wells.

METHODS

Techniques used for this study of the groundwater divide are primarily collection of water-level data and generation of potentiometric maps and groundwater tracing studies using non-toxic, organic dyes.

Potentiometric Maps

Groundwater flow systems are three-dimensional with lateral and vertical flow components. The lateral and vertical driving force of water in an aquifer at a particular point is hydraulic head, which is the sum of elevation and water pressure divided by the weight density of water. Hydraulic head is determined by subtracting the measured depth to water from the elevation of the land surface elevation at a well. Water flows from areas of high head to areas of lower head, characterizing the flow of an aquifer system (Kresic, 2007).

Lateral flow can be described by determining the hydraulic head in a lateral distribution of wells and contouring lines of equal hydraulic head (or equipotential lines) resulting in a surface referred to as a water table or potentiometric map for unconfined and confined conditions, respectively (Domenico and Schwartz, 1990). This study presents contours of hydraulic head for both confined and unconfined conditions in a single surface, which is referred to as a potentiometric map.

Potentiometric maps describe the general direction of groundwater flow at a particular period of time. Additional uses of potentiometric maps, under the right conditions, include calculating (Darcian) flow velocity, gradients, total volumetric flow, or gaining a relative sense of the spatial distribution of transmissivity and hydraulic conductivity. According to Darcy's law, hydraulic gradients can reflect changes in hydraulic conductivity, changes in aquifer thickness, or cross-formational flow (Domenico and Schwartz, 1990; Kresic, 2007).

Conditions that influence hydraulic head and potentiometric surfaces include recharge, discharge (springs and pumping wells), and barometric fluctuations (for confined settings). Observing these conditions can lead to a greater understanding of an aquifer system.

Potentiometric Maps in Fractured Karst Aquifers

Potentiometric maps are commonly constructed for karst regions for understanding groundwater flow (see Previous Studies above). However, their use in evaluating directions and velocities of groundwater flow are limited. Potentiometric maps should be combined with hydrogeologic mapping and tracer studies for a more complete understanding of flow within a karst system (Quinlan, 1989; Kresic, 2007). However, Kresic (2007) pointed out that potentiometric maps showing regional flow patterns in karst aquifers may be justified in some cases since groundwater flow generally is from recharge areas to discharge areas and the regional hydraulic gradients will reflect this. Quinlan (1989) stated that it is often correct and conventional to interpret the direction of groundwater flow perpendicular to the potentiometric contours and down gradient. Sometimes, however, flow lines appear to be parallel to the contours rather than perpendicular to them, as has been demonstrated in the Edwards Aquifer (Maclay and Small, 1986). Flow parallel to potentiometric contours has also been documented for the Barton Springs segment (Hunt et al., 2006). This apparent discrepancy likely reflects two phenomena: 1) a lack of detailed potentiometric data in some areas; and 2) refraction of flow due to anisotropic and heterogenetic aquifer conditions.

Because flow occurs within fractures, conduits, and the matrix, hydraulic heads may not provide a unique answer to determining flow directions. Hydraulic gradient (head loss/flow distance) is very sensitive to the diameter of fractures and conduits. Conduits have much lower gradients and heads than in the sur-

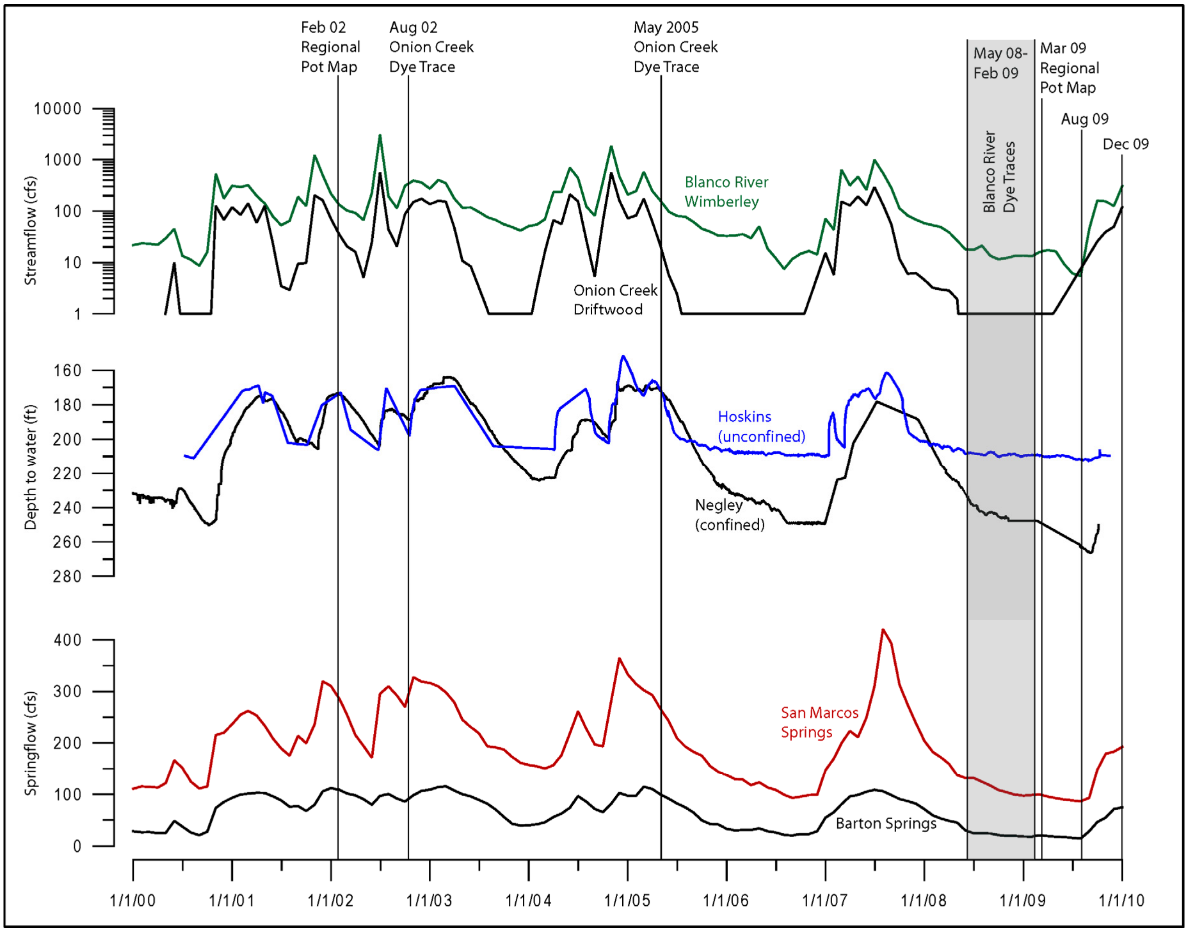


Figure 3. Hydrographs of key streams, monitor wells (Hoskins and Negley), and springs in the study area. Spring and streamflow data are monthly average from the U.S. Geological Survey. Water-level data are daily data from the BSEACD.

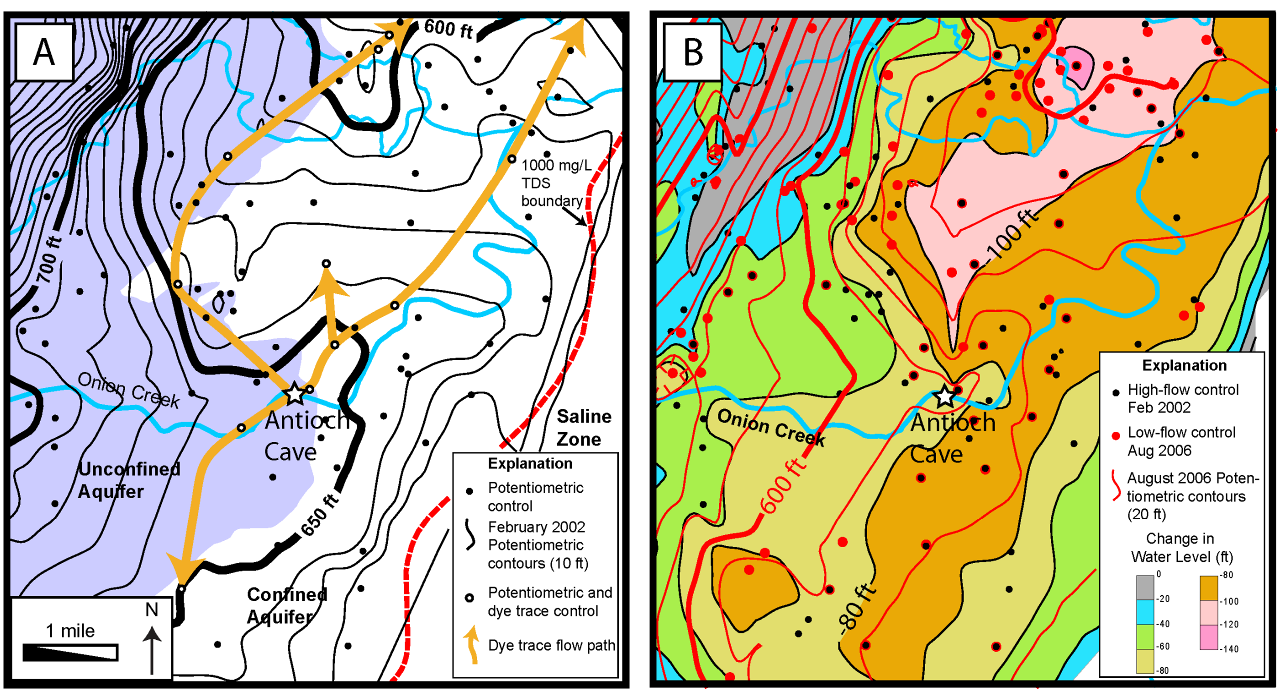


Figure 4. Map showing area around Onion Creek. A. Potentiometric map and inferred flow paths of dye injected into Antioch Cave in 2004. B. Differences in potentiometric levels between high-flow conditions and low-flow conditions. Figure modified from Hunt et al. (2007).

rounding matrix; therefore flow is convergent to conduits (or divergent depending on aquifer conditions). Convergent flow within karst aquifers are a common attribute and has been well documented in the Edwards Aquifer by the dye tracing work of Hauwert et al. (2002a), Johnson et al. (2010), and Johnson et al. (2011). Depending on the hydrologic conditions, a change in heads within a conduit can cause a reversal of flow direction. This has also been observed in the Barton Springs segment (Hunt et al., 2006). During periods of rapid recharge the aquifer can behave similar to bank storage phenomena in rising surface rivers (Palmer, 2004). Rapid flow through conduits can have an impact on hydraulic head measurements of wells completed in or near such a conduit. Kresic (2007) stated that the hydraulic head may vary up or down along the same conduit as the cross-sectional area increases or decreases, respectively.

Tracer Studies

Groundwater tracing with dyes involves the introduction of non-toxic, organic dyes into the subsurface via injection points, such as caves, sinkholes, and wells, and analyzing charcoal receptors and water samples taken from discharge points such as wells and springs. Alexander and Quinlan (1992) and Aley (1999) discussed the methodology of groundwater tracing with dyes. Field et al. (1996) discussed the safety of the dyes as tracers. Groundwater tracing techniques are recognized as the only direct method of locating groundwater flow paths and determining travel times in karst aquifers.

To monitor the movement of the dyes, charcoal receptors are placed in springs and many accessible wells. Receptor sites are monitored using a combination of charcoal receptors, which contain adsorbent activated charcoal in mesh packets, and water samples. Grab samples provide information on the instantaneous dye concentrations in the water. Charcoal receptors adsorb dye from the water and allow detection of dyes over extended periods of time. Charcoal receptors are placed at springs and wells and collected periodically to determine a positive or negative result.

RESULTS

Groundwater tracing studies and measurements of potentiometric levels from numerous monitor and water-supply wells were conducted in the study area during periods of high and low flow. Datasets from these two ends of the hydrologic spectrum provide an understanding of how water recharges the aquifer during wet times, how excess water is stored in the aquifer, and how the aquifer drains during dry periods. Figure 3 shows flow rates for stream gages upstream of the recharge zone for the Blanco River and Onion Creek, potentiometric levels in the Hoskins and Negley monitor wells, and discharge from Barton and San Marcos Springs between January 2000 and December 2009. Also shown in Figure 3 are dates for which water-level data were collected and when dye-trace studies were conducted. Patterns representing wet and dry conditions are fairly similar with the peaks and troughs lining up for each dataset.

Potentiometric Maps

Figures 5 and 6 show sets of potentiometric contours for the study area for a period of high flow in February 2002 and a period of low flow in March 2009, respectively. General patterns seen in the contour lines suggest that groundwater flow directions on the western side of the study area are from west to east. This area coincides approximately with the recharge zone. Near the north-south midline of the aquifer, approximately where the aquifer becomes confined, flow turns more to the north except in the area between Kyle and San Marcos where the flow either continues to the east or to the south.

High-Flow Conditions

During high-flow conditions, a significant groundwater mound can be seen to the west of Buda (Fig. 5) between the 640-ft and 660-ft contour lines. Considering high rates of recharge along Onion Creek, particularly recharge into Antioch Cave (Fig. 4A), a groundwater mound would be expected. The presence of a mound indicates that flow is likely to occur to the north, south and east, away from the recharge portion of Onion Creek. This concept of a semi-radial mound beneath Onion Creek is supported by the potentiometric contours shown in Figure 5. This mound is also seen in Figure 4A where it is delineated by the 650-ft contour line. Under high-flow conditions, this mound extends well to the northeast, beneath the confined zone. Under high-flow conditions the presence of a groundwater mound beneath the Blanco River is not as obvious as the one beneath Onion Creek.

Low-Flow Conditions

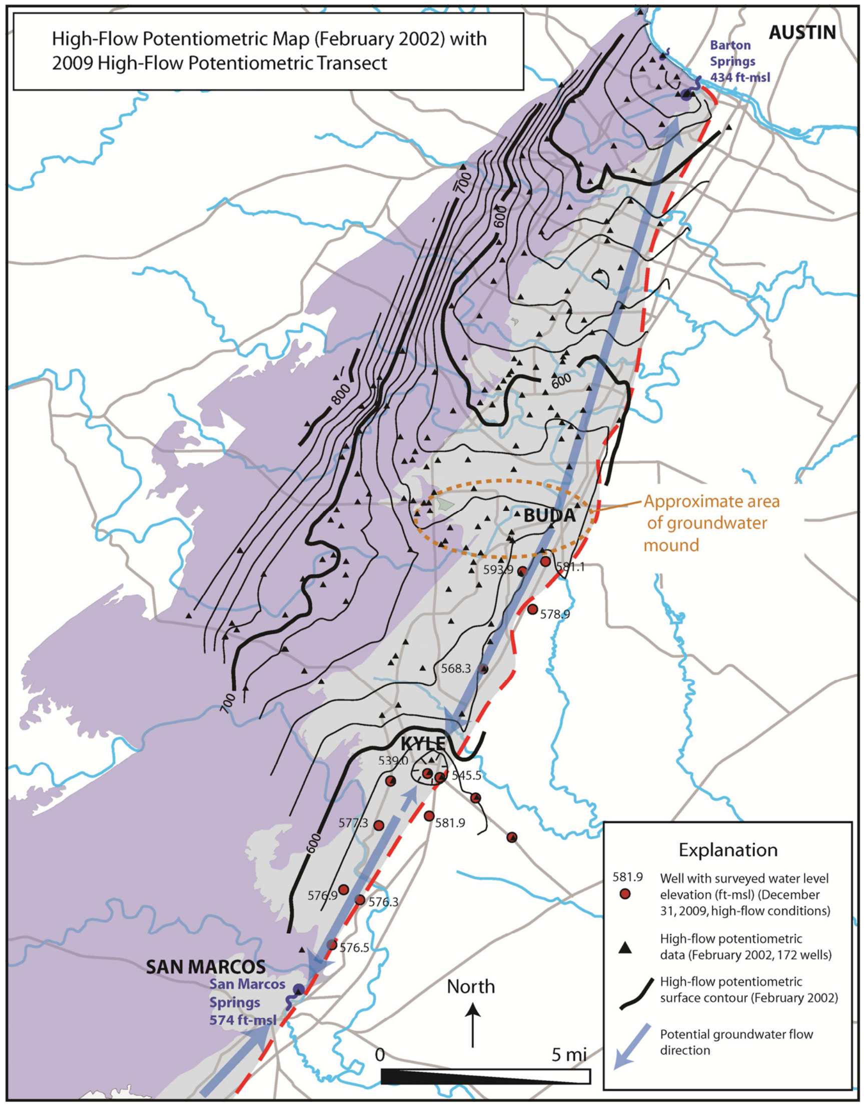
Under low-flow conditions in March 2009 (Fig. 6), a mound was still present beneath Onion Creek, although it was considerably diminished from high-flow conditions. The mound is best illustrated by the 580-ft contour line where it crosses Onion Creek west of Buda. A mound beneath the Blanco River is shown by the 620-ft, 600-ft, and 580-ft contour lines (Fig. 6). Troughs in the potentiometric surface are more evident during low-flow conditions than during high-flow conditions. These troughs are believed to be associated with conduits or zones of high permeability that allow groundwater to drain quickly to the springs, thereby reducing potentiometric levels in the vicinity of the conduits. These troughs are best illustrated by the 500-ft and 440-ft contour lines to the south of Barton Springs. Figure 4B, which shows the difference in potentiometric head between high- and low-flow conditions, indicates a trough immediately north of Antioch Cave where potentiometric levels vary by more than 100 ft (30 m). This trough likely represents one of the pathways through which groundwater drains from the vicinity of Antioch Cave. Dye-trace tests conducted in Antioch Cave indicate that flow from that area is to the north, and dye injected into Antioch Cave was detected in a well within this trough.

Temporal changes in the 600-ft contour line are shown in Figure 7. Under high-flow conditions, the 600-ft contour line swings to the east near where it crosses Bear Creek. Under low-flow conditions, the 600-ft contour line extends in a relatively straight line from a point west of Barton Springs to a point west of San Marco Springs.

Groundwater Tracing Studies

Various tracing studies have been conducted in the study area by the EAA, BSEACD, and the City of Austin. Figure 8 shows a limited set of results and inferred flow paths from a tracing study conducted by BSEACD and City of Austin in 2002 (Hauwert et al., 2004; Hunt et al., 2005). Dyes were injected into caves or sinkholes at three locations for this study. Arrows on the map show approximate pathways for the dyes based on detections in numerous monitor wells and various spring outlets. Dye

Figure 5. High-flow potentiometric map. Potentiometric contours modified from Hunt et al. (2007). Well and surveyed potentiometric-level data from Land et al. (2011).



injected into Crippled Crawfish Cave arrived at Barton Springs in less than 3 days. The straight-line distance between Crippled Crawfish Cave and Barton Springs is about 18 mi (29 km). Within 2 to 3 weeks the same dye was detected in two spring outlets at San Marcos Springs.

Under low-flow conditions a series of traces was conducted in the vicinity of the Blanco River (Johnson et al., 2011). Figure 9 shows a limited set of results and inferred flow paths from this low-flow, dye-trace study. For one trace, dye was injected into a swallet hole on the bank of the Blanco River. This dye was detected in wells to the north and south of the river and in Barton Springs. It was also detected in several individual orifices at San Marcos Springs. The results confirmed the prevailing conceptual model, in which San Marcos Springs receives local recharge as well as regional contributions from the Edwards Aquifer artesian zone (Ogden et al., 1986). Dye injected into Bull Pasture Sink was traced to wells to the east and north of the sinkhole (Fig. 9). This dye was also detected at Barton Springs, but not at San Marcos Springs. Bull Pasture Sink is located north of the Blanco River, so under low-flow conditions, it is likely that groundwater flow in this area is to the north due to the northern gradient developed by recharge along the Blanco River. If any of the dye from Bull Pasture Sink actually arrived at San Marcos Springs, it could have been too diluted to have been detected. Other than the wells and springs with verified detections of dye, the direction and velocity of flow from these injection points is unknown.

Potentiometric Cross Sections

To better visualize water levels in the aquifer under low- and high-flow conditions, two cross sections were constructed showing topographic surfaces, potentiometric levels for low- and high-flow conditions, and faults (Fig. 10). The western cross section (A–A') shows a gradient of about 0.002 with flow from the north to the south under both low- and high-flow conditions. However, groundwater flow in this area is largely from the west to the east as shown in Figures 5 and 6. The high-flow line shows a depression in the potentiometric surface near Kyle. This is presumably due to high rates of pumping in that area (Land et al., 2011).

Cross section B–B' (Fig. 10) extends from San Marcos Springs to Barton Springs. A distinct groundwater mound is present in the vicinity of Onion Creek during high-flow conditions. During low-flow conditions, the mound along this cross section dissipates and a down-to-the-north gradient develops indicating flow from San Marcos Springs to Barton Springs. This suggests that under extreme drought conditions, groundwa-

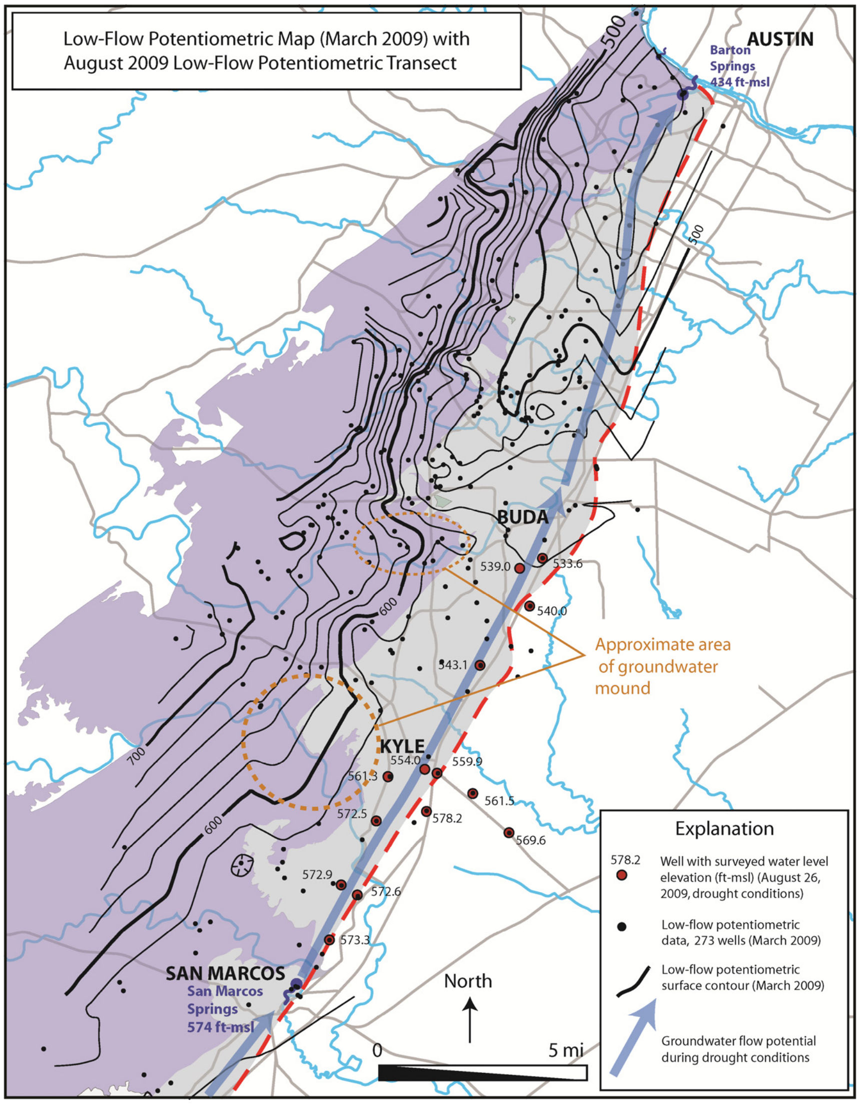


Figure 6. Low-flow potentiometric map. Potentiometric contours from BSEACD (unpublished data). Well and surveyed potentiometric-level data from Land et al. (2011).

ter flow may bypass San Marcos Springs and continue to Barton Springs. However, some of that flow is intercepted by water-supply wells along the way.

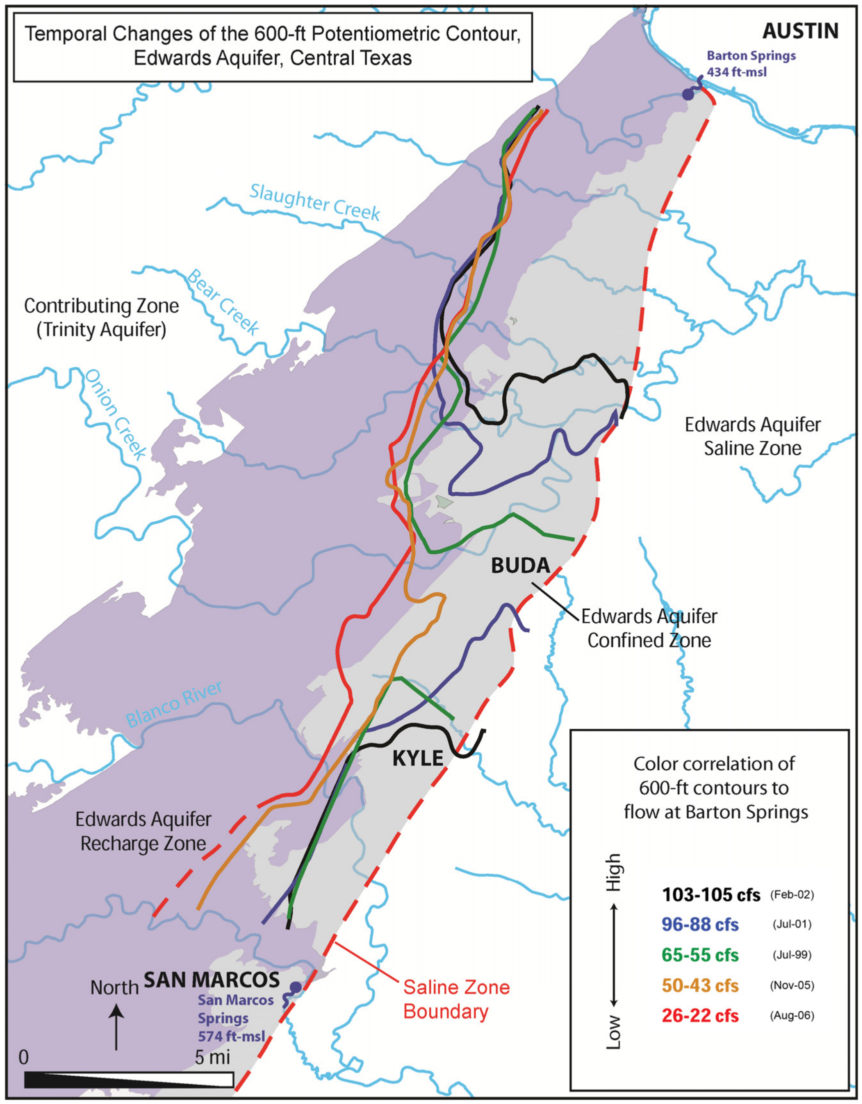
A study by Land et al. (2011), covering a period of drought in 2009, collected detailed water-level data from a series of wells between San Marcos Springs and Buda. These data show the potentiometric surface sloping down to the north of San Marcos Springs with a slight gradient (0.00005) (Fig. 10) during low-flow conditions. Near Kyle the gradient becomes much steeper (0.002) for a distance of about two miles before decreasing to a lesser gradient (0.001) from north of Kyle to Barton Springs. During high-flow conditions the gradient between San Marcos Springs and Kyle rises slightly from south to north with a gradient of about 0.0001.

In contrast, the potentiometric levels in the vicinity of San Marco Springs vary little between high-flow or low-flow conditions, as shown in Figure 10. Groundwater levels in the 67019EG well that is about 2 mi (3 km) north of San Marcos Springs declined about 3 ft (1 m) between high- and low-flow conditions. Well 5850824 (Fig. 10), situated near the peak of the Onion Creek groundwater mound, showed a water-level drop of about 100 ft (30 m) between high- and low-flow conditions.

DISCUSSION AND SUMMARY

The most significant influence on the divide is recharge from Onion Creek and the Blanco River. During wet periods, when Onion Creek is flowing, a groundwater mound develops beneath Onion Creek that directs some of that recharging water to the south, overcoming a smaller mound beneath the Blanco River. During dry periods, when flow in Onion Creek has ceased for some time and the groundwater mound has diminished, flow and recharge along the Blanco River continue and the mound beneath the Blanco River becomes the dominant influence on groundwater flow in the area (Figs. 6 and 9). Under more extreme drought conditions the Blanco River mound dissipates altogether and groundwater in the vicinity of San Marcos Springs will flow north toward Barton Springs (Fig. 10). Numerical groundwater modeling by Land et al. (2011) calculates groundwater flow during drought conditions passing San Marcos Springs and flowing to Barton Springs at a rate of 6.1 cfs (0.17 m^3/s). Considering that during the drought of record in 1956, the lowest flow measured at Barton Springs was about 10 cfs (0.28 m^3/s), the amount of flow coming from San Marcos Springs during extreme drought could account for more than half of Barton Springs discharge.

Figure 7. Temporal changes of the 600-ft potentiometric contour line (modified from Hunt et al., 2007).



The change in hydraulic gradients near Kyle (Fig. 10) occurs in the same vicinity as the depression in the potentiometric surface from pumping. This change in gradients is thought to represent a discontinuity in aquifer properties in that area (Land et al., 2011), and could influence the magnitude of flow to the north or south, depending on hydrologic conditions.

Delineations of a groundwater divide between the Barton Springs and San Antonio segments of the Edwards Aquifer are supported by the results of various studies. Previous interpretations have placed the divide anywhere from the vicinity of Onion Creek to near San Marcos Springs. A review of pertinent groundwater data from the study area indicates that the location of the divide varies depending on hydrologic conditions and that it shifts between Onion Creek to the north and to the Blanco River and San Marcos Springs to the south. During high-flow conditions a considerable amount of water recharges the aquifer through caves, sinkholes, and solutionally enlarged fractures in the bed of Onion Creek. Less recharge takes place in the Blanco River under high- and moderate-flow conditions. Under low-flow conditions, Onion Creek ceases to flow, yet the Blanco River continues to flow and only ceases to flow under extreme drought conditions.

The presence of a hydrologic boundary between the Barton Springs and San Antonio segments of the Edwards Aquifer is important for determining water budgets for each segment. Regulations of each respective groundwater management agency limit the amount of groundwater that can be pumped. Numerous numerical groundwater flow models have been developed to help determine how much groundwater can be pumped from the aquifer without causing harm to water-supply wells and to the endangered animal and plant species that live in or near the springs (Slade, 1985; Lindgren et al., 2004; Smith and Hunt, 2004). Even though the amount of water moving across the boundary might be small, under extreme drought conditions that amount of groundwater could determine the fate of the endangered species. Future groundwater flow models should consider the nature of the shifting groundwater divide so that the models will yield more accurate and useful results. Current models of the Barton Springs segment do not account for flow from the San Marcos area. If there is a contribution of groundwater from the south during extreme drought, there could be more discharge from Barton Springs than is currently predicted. Furthermore, knowing the direction of groundwater flow is important for predicting contaminant transport in the event of a spill of hazardous materials over the recharge zone.

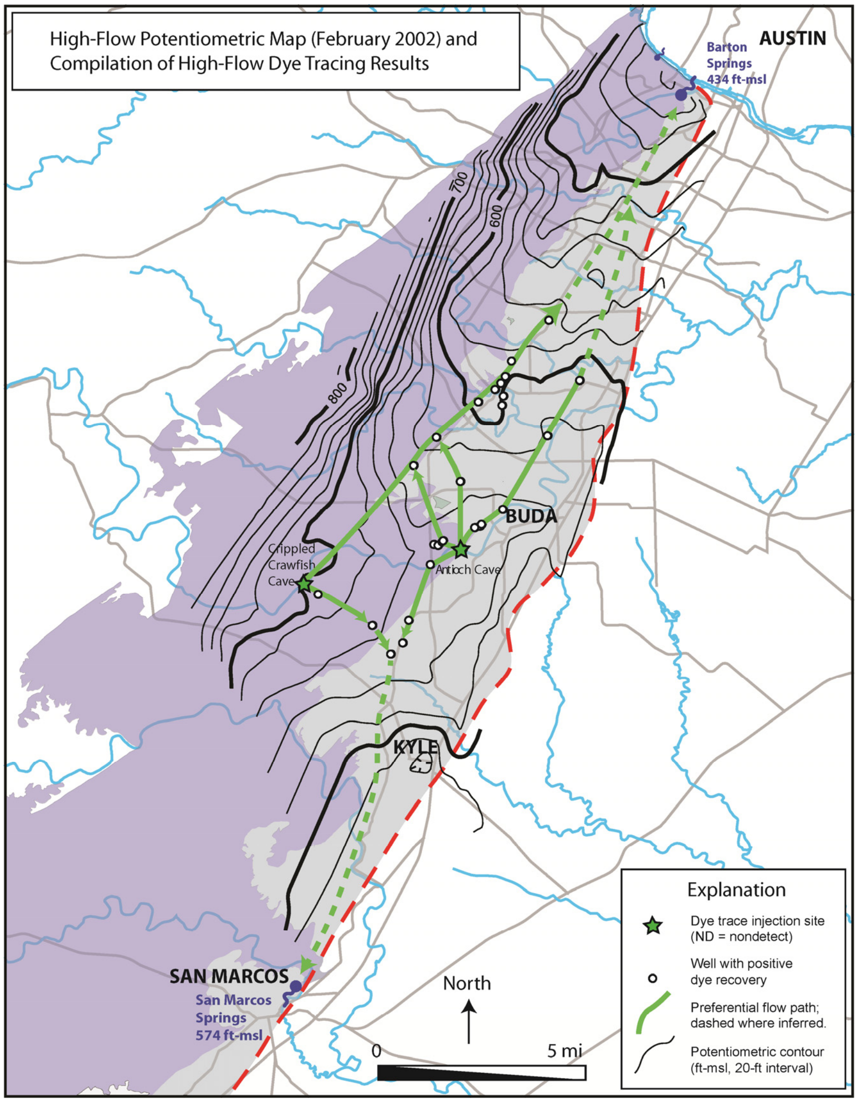


Figure 8. High-flow potentiometric map with high-flow dye tracing results. Potentiometric contours modified from Hunt et al. (2007). Dye tracing results from Hauwert et al. (2004), Hunt et al. (2005), and Hunt et al. (2006).

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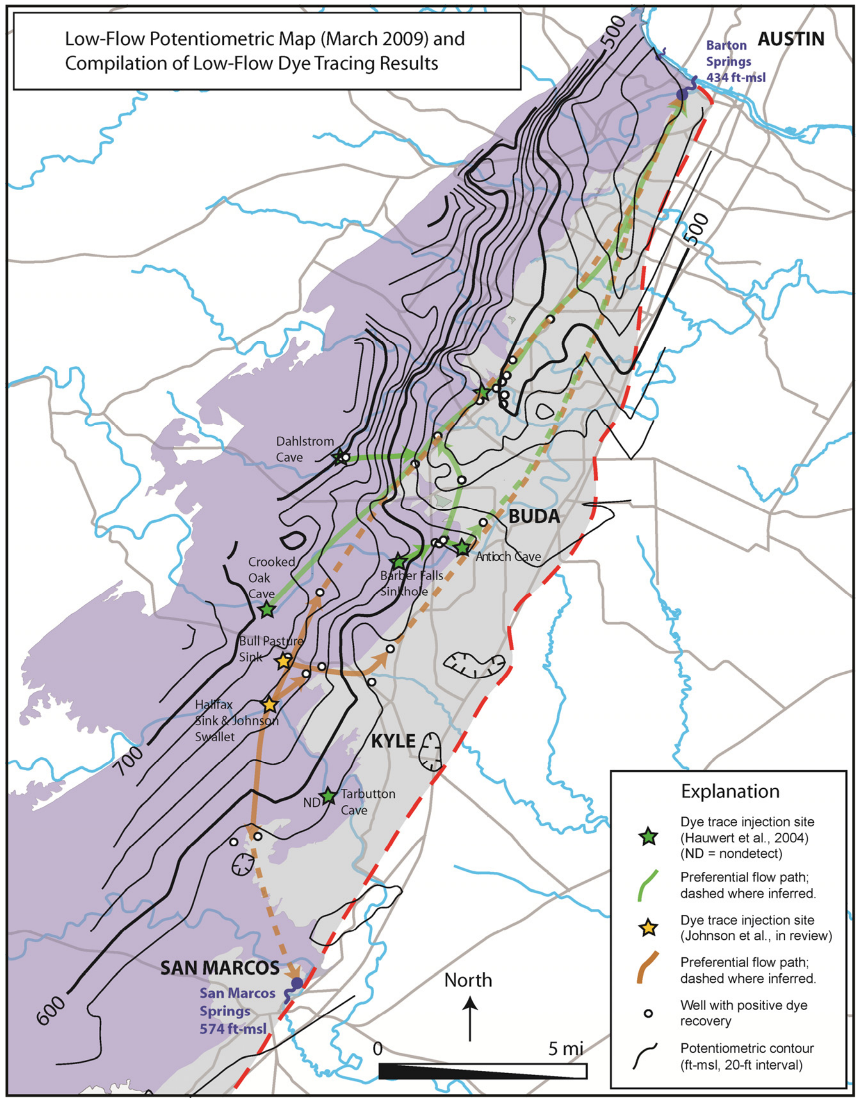
Figure 9. Low-flow potentiometric map with low-flow dye tracing results. Potentiometric contours from BSEACD (unpublished data). Dye tracing results from Hauwert et al. (2004) and Johnson et al. (2011).



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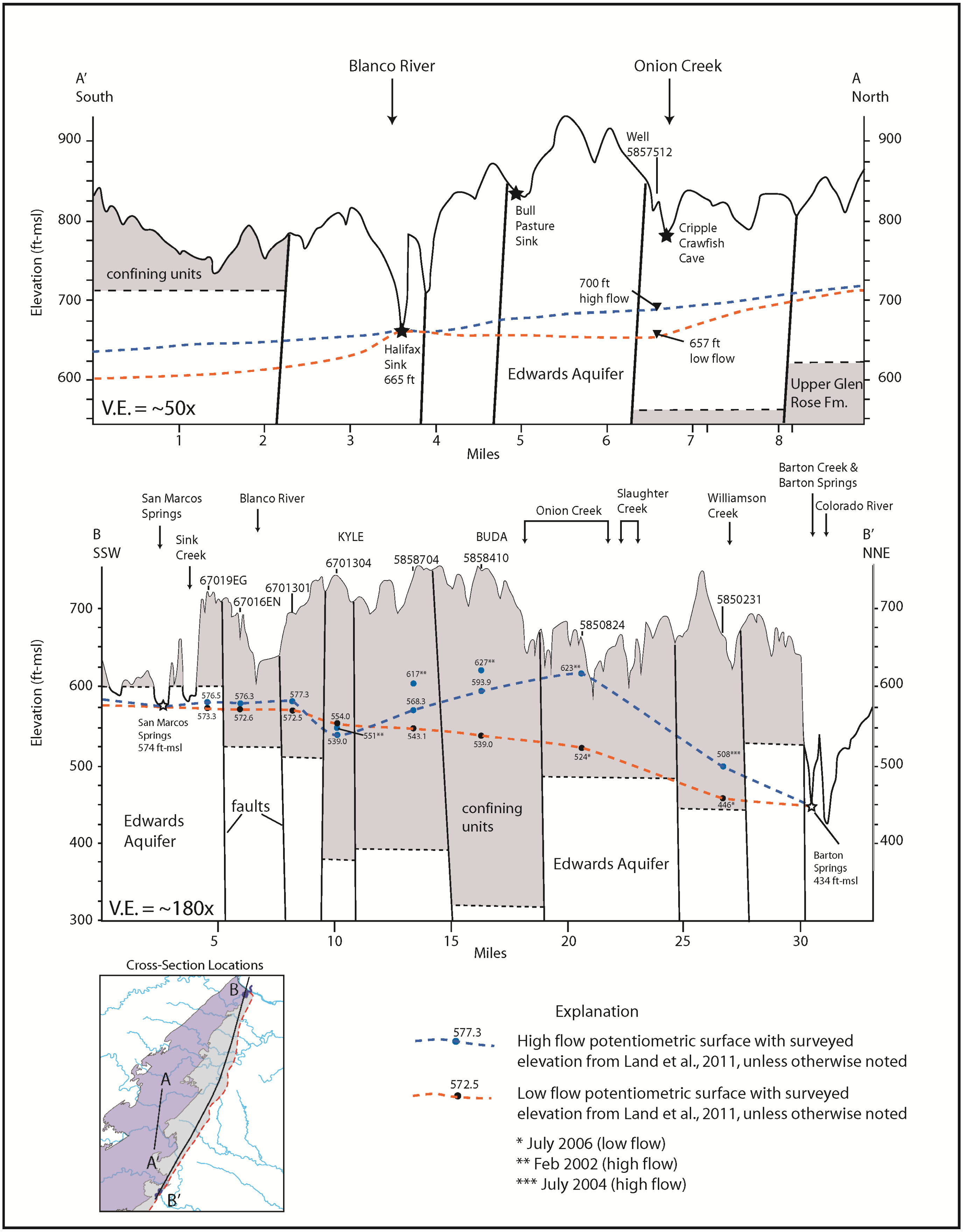

Figure 10. **North-south cross sections showing topography, potentiometric levels, and generalized hydrogeologic units with faults. Source data include: Google Earth for topographic profile; Land et al. (2011), and Hunt et al. (2007), for potentiometric data; and Small et al. (1996), and LBG-Guyton (1979) for generalized hydrogeology and faulting.**

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