Groundwater Flow in the Edwards Aquifer:
Comparison of Groundwater Modeling and Dye Trace Results

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Abstract

The Edwards Aquifer of central Texas is a karst aquifer developed in faulted and fractured Cretaceous-age limestones and dolomites. Numerous groundwater models have been developed for the three segments of the Edwards Aquifer since completion of the first major flow model in 1979. Groundwater models have helped refine our understanding of the relationships among flowpaths, recharge, groundwater pumping, and springflow. Tracer test studies have been performed on the Edwards Aquifer since 1982. These studies have also brought about a better understanding of aquifer flowpaths, yet the results of groundwater modeling and dye trace studies do not have a high level of agreement. A comparison of the two types of studies has indicated the strengths and weaknesses of each method. Groundwater models of the Edwards Aquifer have been effective in simulating spring discharge and determining water budgets. The models have simulated water levels reasonably well, but there are significant discrepancies between measured and simulated water levels in areas that are more strongly influenced by conduit flow. Tracer testing is the best method for measuring rates of flow from a recharge feature, or a well, to springs and other wells. However, tracer tests provide little useful information about water levels or water budgets. Traditional groundwater models are poor tools for simulating contaminant transport and delineating areas for source-water protection of mature karst aquifers with well-developed conduit networks.

Introduction

The Edwards Aquifer, located in south-central Texas, is one of the most prolific karst aquifers in the United States. The aquifer extends about 270 miles from the Rio Grande River along the Mexico/United States border at Del Rio, east to San Antonio, then northeast through Austin to Salado (Figure 1). The aquifer ranges in width from 2 to almost 40 miles and from 400 to more than 600 feet in thickness. The total area of the Edwards Aquifer is about 4,350 square miles, with about 1,700 square miles of recharge zone and 2,650 square miles of confined, or artesian, zone. The Edwards Aquifer is divided into three major segments: the San Antonio, Barton Springs, and Northern segments and numerous subsections. The areas for each segment are 3,600, 155, and 600 square miles, respectively. Public and private water-supply systems provide water to about 1.7 million people in the San Antonio segment. In addition, about 30 percent of water extracted from the San Antonio segment is used for agricultural purposes. More than 50,000 people depend on the Barton Springs segment and about 230,000 people depend upon the Northern segment as their sole source of drinking water (Smith et al., 2005). In addition, the springs that drain the aquifer provide habitat for a number of Federally listed endangered species.

The U.S. Environmental Protection Agency (USEPA) has identified karst aquifers as one of the aquifer types most vulnerable to pollution (Schindel et al., 1996). Karst aquifers are noted for their rapid groundwater velocities and limited ability to filter contaminants. Traditional groundwater flow models have proven effective at predicting water levels and discharge in some karst aquifers (Scanlon et al., 2003; Smith and Scanlon, 2003). However, traditional groundwater flow models have not proven to be very effective in predicting travel times and pathways for flow in mature karst aquifers with well-developed conduit networks. Tracer testing techniques, if conducted properly, are able to provide accurate information on travel times, and if multiple monitoring points (wells) are available, locations of pathways can be determined. Groundwater flow models have been developed for the San Antonio and Barton Springs segment of the aquifer. In addition, numerous tracer tests have been performed on the Barton

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Springs segment, and to a more limited degree, the San Antonio segment. Having accurate data on groundwater velocities and flowpaths is important in determining the vulnerability of water-supply systems and in developing source-water protection strategies and hazardous-materials response actions. While groundwater models and tracer test data provide useful information about the aquifer, both methods have limitations on their usefulness as predictive tools.

Hydrogeology

The Edwards Aquifer is composed of limestone and dolomite of the Cretaceous-age Edwards Group and Georgetown Formation. The carbonate sediments that make up the Edwards Group accumulated on the Comanche Shelf as shallow marine, intertidal, and supratidal deposits. The Georgetown Formation, disconformably overlying the Edwards Group, was deposited in a more openly circulated, shallow-marine environment (Rose, 1972).

The Edwards Aquifer evolved over millions of years as the result of numerous geologic processes including deposition, diagenesis, faulting, erosion, volcanism, and dissolution. The formation of the aquifer was influenced significantly by fracturing and faulting associated with the Balcones Fault Zone (BFZ) and dissolution of limestone and dolomite units by infiltrating meteoric water (Sharp, 1990; Barker et al., 1994; Sharp and Banner, 1997). In places, faulting has dropped the Edwards Aquifer more than 2,000 feet below the surface. Dissolution along fractures, faults, bedding plane partings, and within certain lithologic units has created numerous sinkholes, sinking streams, springs, conduits, and caves. Groundwater flow occurs in a well integrated network of conduits, caves, and smaller dissolution features. This network of dissolution features is situated in a matrix of limestone and dolomite through which flow is diffuse. The majority of storage in the aquifer is in this matrix. Discharge occurs at some of the largest springs in the southwestern United States and from water-supply wells. Hovorka and others (1998) have described the Edwards Aquifer as having over eight orders of magnitude of permeability. Hydraulic conductivities along major conduits may be about 1,000,000 feet per day (ft/d). Intermediate values of hydraulic conductivity are associated with solution-enhanced fractures and stratigraphically controlled karst features. Hydraulic conductivity of the porous carbonate matrix is between 0.001 and 10 ft/d.

Mapping of the Barton Springs segment has delineated faults and several informal stratigraphic members of the Edwards Group (Rose, 1972), each having distinctive hydrogeologic characteristics (Small et al., 1996; Barton Springs/Edwards Aquifer Conservation District (BSEACD), 2002). The limestone units generally step down to the east, primarily because of faulting. Most faults trend north and northeast and are downthrown to the southeast, with total vertical displacement of about 1,100 ft across the area (Figure 2).

Mapping of the San Antonio segment has also defined several informal stratigraphic members of the Edwards Group (Stein and Ozuna, 1996). Numerous faults, some with more than 600 feet of vertical displacement, generally trending in east/west and northeast/southwest directions, have also been identified (Collins and Hovorka, 1997). Faulting is generally down to the south and southeast toward the Gulf of Mexico. Total vertical displacement of the San Antonio segment, from north to south in Medina County (west of San Antonio), exceeds 2,000 feet.

Hydrologic divides separate the three segments of the Edwards Aquifer. The hydrologic divide between the Barton Springs segment and the San Antonio segment is approximately located between Onion Creek and the Blanco River, as supported by potentiometric-surface elevations and recent tracer testing results (LBG-Guyton Associates, 1994; Hauwert et. al, 2004). The hydrologic divide between the Barton Springs segment and the Northern segment is the Colorado River, a major surface water feature flowing from northwest to southeast through Austin, Texas. The western hydrologic divide for the San Antonio segment is not well defined and appears to occur in the area of Brackettville, in Kinney County, Texas. Groundwater to the west of this divide flows toward large springs located in the Del Rio area.

From 50 to 85 percent of recharge to the aquifer is derived from streams originating on the contributing zone, located up gradient to the north and west of the recharge zone. Water flowing onto the recharge zone sinks into numerous caves, sinkholes, and fractures. Recent tracer testing data along with groundwater model data indicate that in portions of the San Antonio segment there is also a significant component of lateral interformational flow from the Trinity/Glen Rose Formation, located stratigraphically below the Edwards Aquifer.

Major springs in the Edwards Aquifer are San Felipe, Ft. Clark, Leona, Hueco, Comal, San Marcos, Barton, and Salado Springs. Comal, San Marcos, Barton, and Salado Springs discharge an average of about 280, 170, 50, and 30 cubic feet per second (cfs), respectively (Figure 1).

Groundwater Modeling

Numerous groundwater models of the Edwards Aquifer have been developed since 1979 (Land, 2004). Recent groundwater modeling efforts of each segment of the Edwards Aquifer (Northern, Barton Springs, and San Antonio segments) have used the U.S. Geological Survey (USGS) MODFLOW code to simulate groundwater flow (Harbaugh and McDonald, 1996). MODFLOW was developed within the public domain and is an equivalent porous media model that assumes that groundwater flow is diffuse and laminar. It has been used to characterize karst aquifers with the assumption that, on a regional scale, karst aquifers behave as equivalent porous media aquifers.

A numerical model was developed for the Barton Springs segment (Scanlon et al., 2001) as an aquifer-management tool to help evaluate the effects of pumping on the aquifer. The numerical model was developed by the Bureau of Economic Geology at The University of Texas at Austin (BEG) and the BSEACD as part of the Groundwater Availability Model (GAM) initiative of the Texas Water Development Board (TWDB). The 2001 GAM was recalibrated to better match spring-flow and water-level data from the 1950's drought and was used to predict spring-flow and water-level declines under 1950's drought conditions and various rates of pumping (Smith and Hunt, 2004). The GAM is a two-dimensional, finite-difference model consisting of a single layer with 120 rows, 120 columns, and 7,043 active rectangular cells, each 1,000 ft long and 500 ft wide. Twelve zones of hydraulic conductivity were set with values ranging from 0.3 ft/d to 740 ft/d (Figure 3). To simulate the effects of conduits, zones of high hydraulic conductivity were placed close to Barton Springs with zones of intermediate hydraulic conductivity extending south-southwest to the southern model boundary. This smeared-conduit approach distributes the effects of a conduit or conduits over the area of a model cell or cells (Painter et al., 2004).

Model results agree reasonably well with actual field measurements for water levels and spring discharge. Figures 4 and 5 show the measured and simulated potentiometric surfaces, respectively. The root mean square (RMS) error between simulated and measured water levels is about 11 percent. The RMS error for spring discharge with the 2001 GAM for a period from 1989 to 1998 was 11 percent. With the recalibrated GAM, the RMS error for spring discharge during periods of flow of less than 18 cfs was 10 percent.

Numerous groundwater models have been developed for the San Antonio segment. The most recent model (Lindgren et al., 2004) was developed by the U.S. Geological Survey (USGS) and BEG in cooperation with the U.S. Department of Defense (DOD) and the Edwards Aquifer Authority (EAA). The model covers the area from the estimated groundwater divide in Kinney County to the Colorado River and includes the recharge zone and artesian zone. The model is a two-dimensional, finite-difference model and contains 259,000 cells, of which 85,000 are active. The dimensions of the grid cells are uniformly 0.25 mi (1,320 ft) along rows and columns. The model contains a "matrix" hydraulic conductivity that ranges from less than 20 feet per day to 7,347 feet per day. Embedded in the model are interconnected high hydraulic conductivity cells that mimic discrete conduits within the aquifer. These cells have a hydraulic conductivity that ranges from 1,000 feet per day to 300,000 feet per day with hydraulic conductivities increasing from the recharge zone to Comal and San Marcos Springs (Figure 6).

Model results agree reasonably well with field measurements for water levels and spring discharges. Figure 7 shows the measured potentiometric surface of the San Antonio segment. The root mean square (RMS) error for the simulated water levels is about 8 percent of the total head difference across the model. The RMS errors for the five springs (Leona, San Marcos, San Antonio, San Pedro, and Comal) varied from 7.0 percent for San Marcos Springs to 36.6 percent for Leona Springs and were less than 10 percent for all but Leona Springs.

Tracer Testing in the Barton Springs Segment

Tracer tests performed in the Barton Springs segment have delineated a flowpath system composed of interconnected conduits that extend from recharge features within the outcrop of the Edwards Aquifer units to springs along Barton Creek and the Colorado River. A total of 22 injections were conducted in all major contributing watersheds that supply water to Barton Springs (Figure 4)(Hauwert et al., 2002; BSEACD, 2003). Five traditional, well-documented, and distinct organic dyes were used in this study: uranine (fluorescein), rhodamine WT, eosine, sulforhodamine B, and pyranine. The dyes were injected into 19 different natural recharge features, such as caves and sinkholes, and one well within the Barton Springs segment. Injections were conducted twice at site A and three times at site M. All dyes were either flushed into the aquifer with about 10,000 gallons of water to carry the dye to the water table or were injected into creek water flowing into recharge features. To monitor the movement of the dyes, charcoal receptors were placed in springs, creeks, river sites, and many accessible wells. Receptor sites were monitored using a combination of charcoal receptors, which contain adsorbent activated charcoal in mesh packets, and water samples. Charcoal receptors absorb dye from the water and allow detection of dyes over extended periods of time. Water samples, known as grab samples, were collected in plastic bottles at the time the receptors were replaced. Grab samples provide information on the instantaneous dye concentrations in the water. Receptor sites were monitored for 2 weeks prior to dye injection to detect any background presence of dyes. After injection of the dyes, receptors were collected at intervals ranging from several hours to 3 weeks.

Results of the Barton Springs tracer testing are included in Table 1 and Figure 4 (Hauwert et al., 2002; BSEACD, 2003). A subbasin was identified from which groundwater discharges primarily to Cold Springs on the Colorado River. Dyes injected in locations F and A discharged at Cold Springs, whereas dye injected at location D discharged at Barton Springs, indicating a groundwater divide under the conditions at the time of the traces. Travel times from injection to initial discharge range from less than a day to as much as 43 days. Groundwater velocities range from 3,000 ft/d to about 30,000 ft/d. Travel times vary depending on flow conditions in the aquifer with faster travel times during periods of high flow (high water levels and high rates of spring discharge) (Hauwert et al., 2002). Groundwater flow velocities are generally slower in the recharge zone where flow is primarily to the east, and greater near the boundary between the recharge and confined zones where flow is primarily north-northeast, directly to Barton Springs.

Tracer Tracing in the San Antonio Segment

Tracer testing in the San Antonio segment has occurred in the area surrounding Comal and San Marcos Springs and in the recharge zone of northern Bexar County (San Antonio). A total of 14 tracer tests have been performed, with seven traces occurring from six locations in Bexar County, two traces from two locations near Comal Springs and five traces from three locations near San Marcos Springs. Three fluorescent organic dyes were used in these studies: uranine (fluorescein), eosine, and Phloxine B. All of the tracer tests were run as quantitative traces using water samples for analysis. Analytical results were obtained from the EAA’s tracer testing laboratory using a Perkin-Elmer LS-50B Luminescence Spectrometer. The dyes were injected into caves, sinkholes, and monitoring wells and generally flushed with about 2,000 to 5,000 gallons of water to carry the dye to the water table. Samples were collected at intervals of 2 to 8 hours using automatic water samplers and grab samples from public, domestic, and monitoring wells, springs, and caves. Travel times from injection to initial discharge ranged from less than a day to 8 days over a range of 1,000 feet to 26,000 feet. Groundwater velocities ranged from as little as 80 ft/d to about 13,000 ft/d with all but one tracer test exceeding 1,000 ft/d. Travel times vary depending on aquifer stage and whether the tracer test was occurring in the recharge or artesian portions of the aquifer.

Comparison of Results

The presence of preferential flow in conduits in the Edwards Aquifer has been inferred for many years from geologic data such as the presence of caves in the recharge zone, water chemistry data, drill bit drops in the artesian zone during construction of water wells, and from down-hole video logs. Biologic data are also an excellent indicator of the interconnection of conduits in the aquifer. The Edwards Aquifer contains more than 40 species of highly specialized endemic biota including salamanders, fish, and shrimp.

Tracer tests have identified some of these conduits and have quantified the rate of flow in the conduits. Flow rates determined by dye tracing within the Barton Springs segment are as high as 30,000 ft/d for major flowpaths under high water-level conditions. Traces of secondary flowpaths are generally about 3,000 to 5,000 ft/d. Groundwater models give flow rates in the Barton Springs segment up to about 60 ft/d under high water-level conditions. The highest flow rates are close to the springs where zones of hydraulic conductivity have been set higher than other parts of the aquifer. Simulated flow rates farther from Barton Springs are generally less than 1 ft/d, with flow rates in some parts of the aquifer at about 0.1 to 0.01 ft/d.

Groundwater flow directions, delineated by the dye-trace results, generally match flow directions that would be estimated by the potentiometric-surface maps (Figure 4). To compare simulated flowpaths with flowpaths determined from tracer testing in the Barton Springs segment, a particle-tracking program was used. Starting points for particles were set in the same location in the model as the actual dye injection points. A comparison of the flowpaths shown in Figures 4 and 5 indicates that particle tracking generates flowpaths that are similar to flowpaths determined by tracer tests, with a few exceptions. A tracer test from Crippled Crawfish Cave on Onion Creek (Point S) determined that there is a flowpath that goes directly from the cave to Barton Springs. Tracer detections in numerous wells support the path shown in Figure 4. Particle tracking does not indicate any direct flowpath from Crippled Crawfish Cave to Barton Springs. Tracer tests in Antioch Cave (Point M) show that dyes injected in the cave flow both to the north and south of the cave. Particle tracking shows groundwater flowing only to the north of that point. Using more accurate recharge data in the model might develop groundwater mounds beneath these recharge features from which the model would show divergent flow. In the current model, recharge is spread evenly along the creeks over the recharge zone rather than concentrated in major recharge features.

Tracer testing in the San Antonio segment has yielded flow rates between 80 and 13,000 ft/d with all but one tracer test exceeding 1,000 ft/d. In the San Antonio model, flow rates as high as 400 ft/d have been determined along lines of model cells that have been assigned high hydraulic conductivity values to simulate conduits (Lindgren et al., 2004).

In both cases, the groundwater models underestimate groundwater velocities and would provide unrealistic values for determining vulnerability of public water-supply wells based on time-of-travel estimates. In addition, groundwater flowpaths from model data and potentiometric data were close, but did not exactly match flowpaths determined from the empirical data of tracer testing.

Conclusions

Tracer test studies have provided very accurate information about the direction and velocity of flow in the limited portions of the aquifer that have been traced. In general, these flow directions agree with flow directions determined from potentiometric surface maps and from particle tracking based on groundwater model results. However, the model results do not show the divergent and convergent flow directions that tracer test studies have provided.

Clearly, the tracer test studies are biased towards the major flow routes since dyes are usually injected into recharge features that are directly connected to conduits. The groundwater flow models are biased toward flow in the aquifer matrix, although the Barton Springs and the San Antonio models have used different methods to implicitly simulate the effects of conduit flow in the aquifer. Despite the fact that there is significant conduit flow in the Edwards Aquifer, the models have done a reasonable job of simulating water levels, spring flow, and water budgets. The current models are not adequate for simulation of contaminant transport or for predicting water levels in those parts of the aquifer that are more directly influenced by conduits. Models should not be used to calculate time-of-travel for source-water protection programs in karst aquifers until their accuracy can be proven with tracer tests. Models that can explicitly simulate conduits are needed to more accurately determine groundwater availability of the

Edwards Aquifer. More tracer studies are needed to locate additional conduits and to determine travel times under various aquifer conditions.

Acknowledgements

The authors wish to thank Ron Green (Southwest Research Institute), Kirk Holland (General Manager, BSEACD), and two anonymous reviewers for their constructive review of this paper.

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Table 1: Summary of dye tracing in the Barton Springs segment (Modified from Hauwert et al. 2002; BSEACD, 2003).

Site	Site Name	Recovery Site	Min. est. flow path to recovery site (miles)	*First Arrival Time (days)
A	Mopac Bridge	Cold Springs	3.4	5
A'	Mopac Bridge	Cold Springs	3.4	0.8
B	Mnt. Bonnell Fault	Colorado River	2.7	6
C	Dry Fork Sink	Barton Springs	4.8	1.3
D	Whirlpool Cave	Barton Springs	5.7	3 to 4
E	Westhill Drive	Barton Springs	2.0	0.4
F	Brush Country	Cold Springs	5.3	< 8
G	Loop 360	Cold Springs	3.3	< 2
H	Brodie Sink	Barton Springs	8.6	1 to 2
I	Hobbit Hole	unrecovered	-	-
J	Midnight Cave	Barton Springs	11.0	7 to 8
K	Spillar Ranch Sink	nearby well only	-	-
L	Dahlstrom Cave	Barton Springs	14.9	14 to 29
M	Antioch Cave	Barton Springs	17.5	7 to 8
N	Barber Falls	Barton Springs	15.7	14 to 18
O	Crooked Oak Cave	Barton Springs	18.6	23 to 32
P	Marbridge Sink	Barton Springs	11.0	36 to 43
Q	Tarbutton Cave	unrecovered	-	-
R	Recharge Sink	unrecovered	-	-
S	Cripple Crawfish Cave	Barton Springs	17.5	< 3

* First arrival times are presented as a range

** Arrival inferred, but obscured by background data

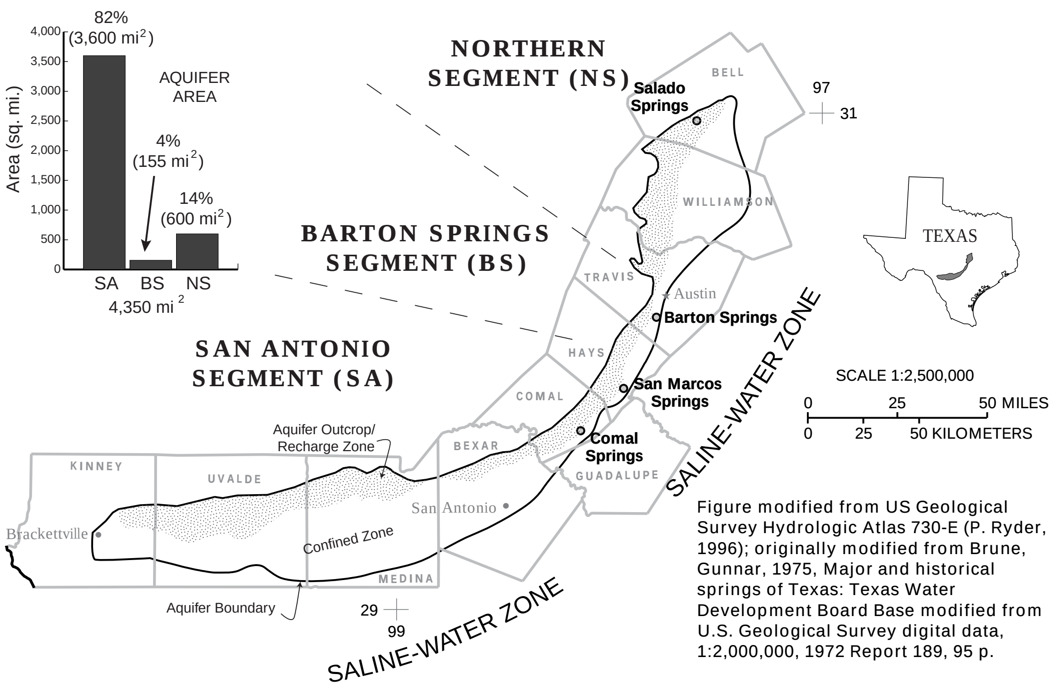

Figure 1: Location map of the Edwards Aquifer and its primary segments.

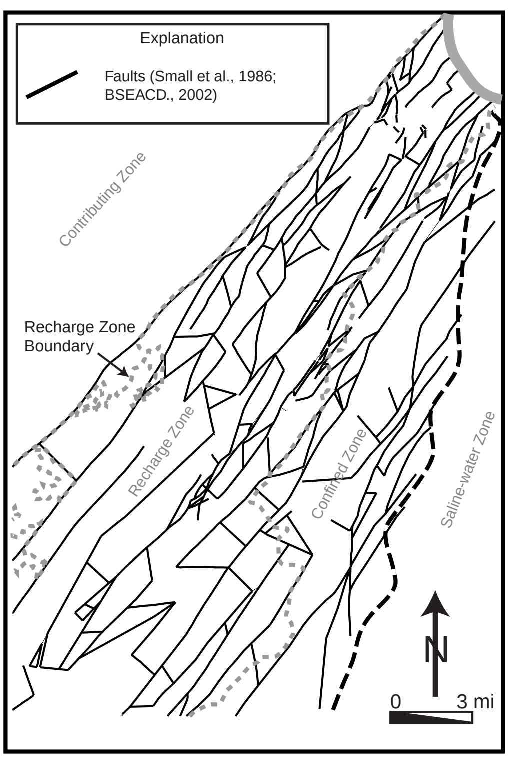

Figure 2: Map showing faulting in the Barton Springs segment of the Edwards Aquifer.

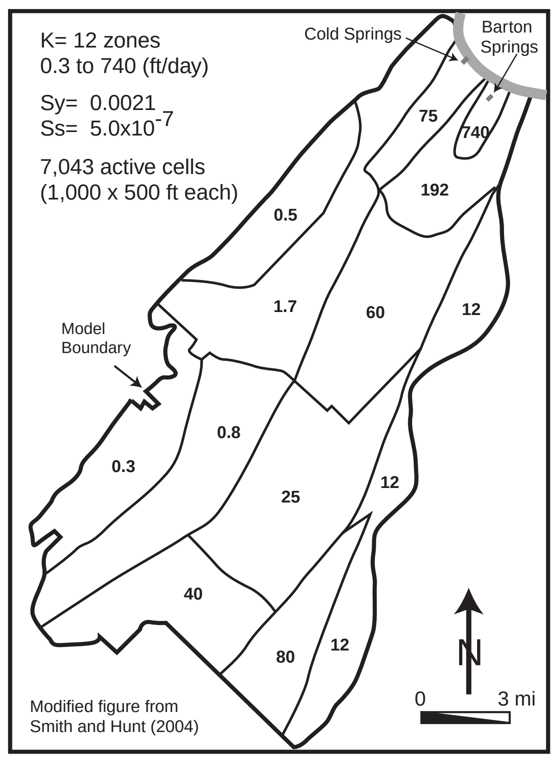

Figure 3: Map showing the zonal distribution of hydraulic conductivity in the Barton Springs model.

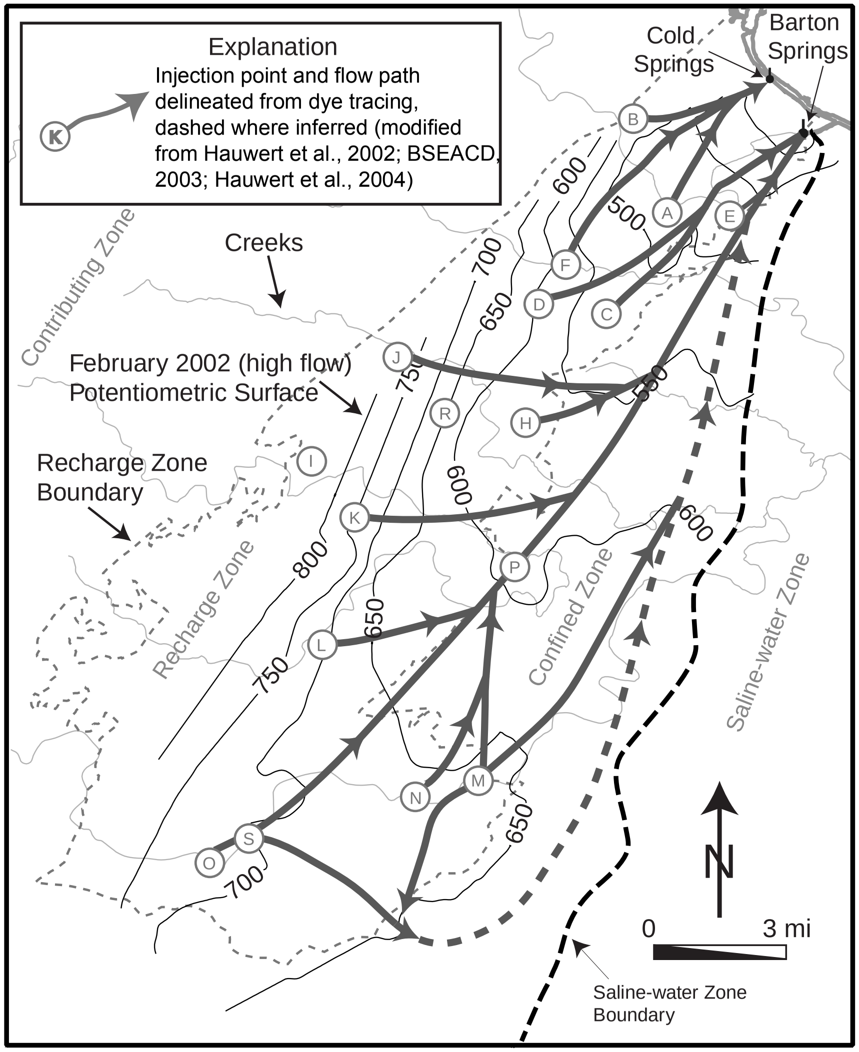

Figure 4: Map showing flowpaths from injection sites to Barton and Cold Springs. Note that flowpaths are generally parallel to the primary and secondary structural grain shown in Figure 2.

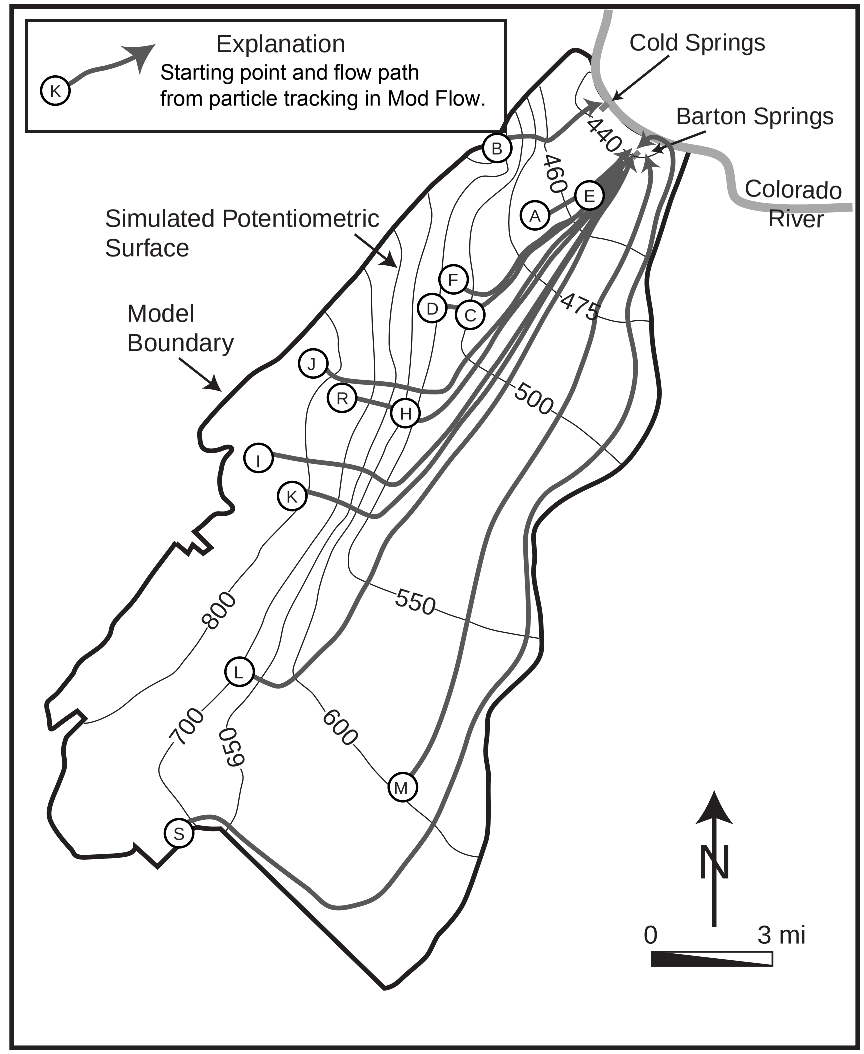

Figure 5: Map showing simulated flowpaths from starting points placed near the corresponding dye trace injection sites to Barton and Cold Springs.

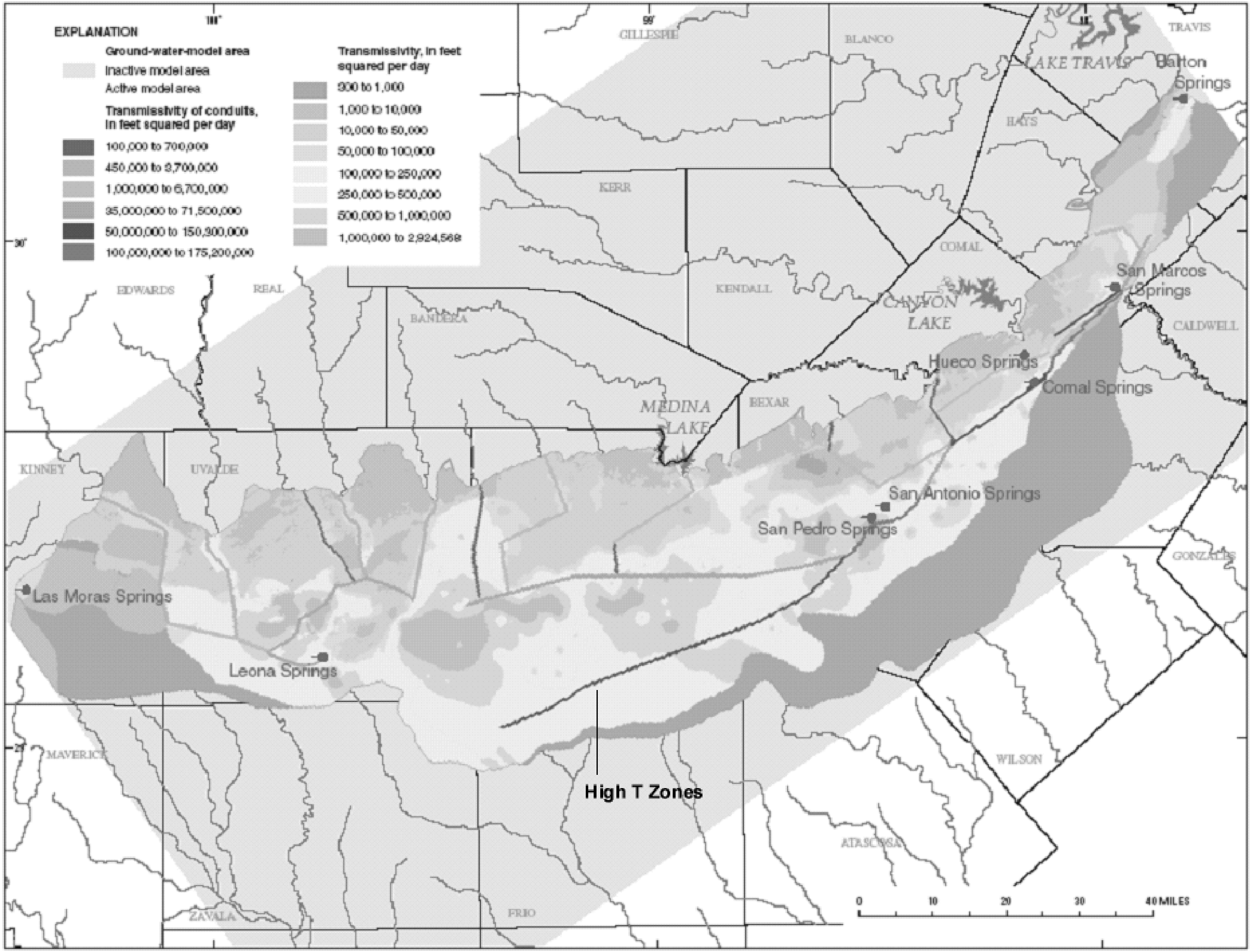

Figure 6: Map showing distribution of transmissivity in the model of the San Antonio segment of the Edwards Aquifer (figure modified from Lindgren et al., 2004).

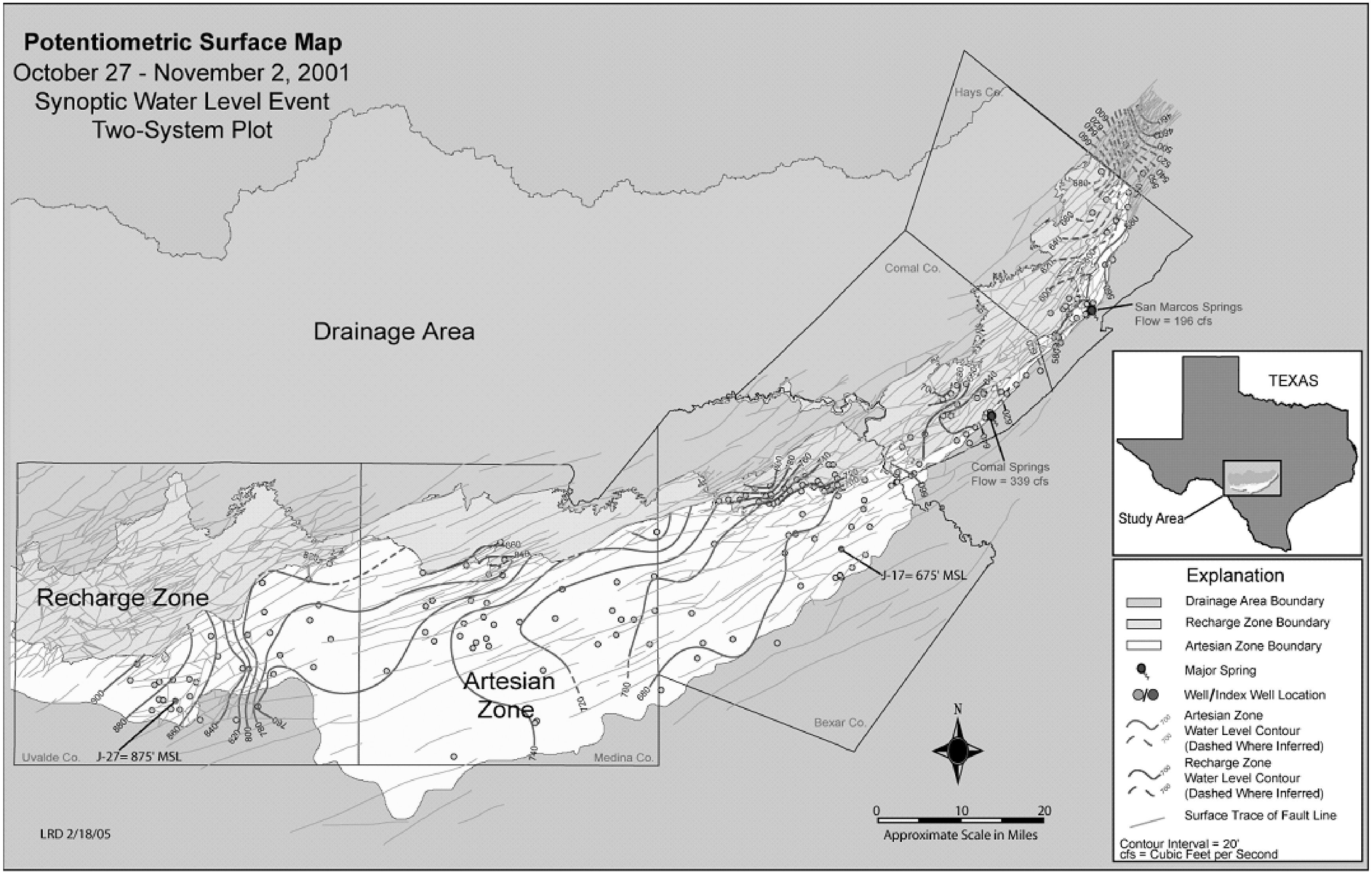

Figure 7. Potentiometric surface map and inferred regional groundwater flow pattern of the San Antonio segment of the Edwards Aquifer based on measured values from October 27 – November 2, 2001 (EAA Synoptic Water Level Data).