SUSTAINABLE YIELD OF A KARST AQUIFER IN CENTRAL TEXAS

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ABSTRACT

In recent years, various hydrogeologic studies have been conducted to characterize the Barton Springs segment of the Edwards Aquifer and to support sustainable yield determination. These studies include: geologic mapping, pumping tests, tracer tests, evaluation of historical data, numerical ground-water modeling, well-impact analysis, and biological studies. A broad definition of sustainable yield considers that water can be extracted from an aquifer only to the extent that no undesired results take place. The Barton Springs/Edwards Aquifer Conservation District has determined that undesired results for the aquifer are sole-source water-supply wells' going dry and jeopardy of the endangered salamander population at Barton Springs.

Historical data show that during the 1950's drought of record, flow from Barton Springs reached a low of 9.6 cubic feet per second (cfs). Currently, permitted and exempt annual pumpage from the aquifer is 11.3 cfs, and actual pumpage from the aquifer in 2006 is estimated to have been 9.6 cfs. If drought-of-record conditions recur, and actual pumpage is 9.6 cfs or greater, it is likely that flow from Barton Springs will cease for some period of time. Considering that water quality is also expected to decrease as spring flow decreases, it is not likely that the endangered salamanders will survive. Additional studies based on historical water levels, ground-water modeling, and well-completion data indicate that as many as 20% of the wells in the District will experience yield problems under these conditions.

To address these concerns, the District has implemented a conditional permit policy and has set drought trigger levels for the aquifer. Additional studies are being conducted on potential impacts to the endangered salamanders and on possible use of alternative water sources. When results are available from these studies, the District's ground-water management plan will likely be further revised to reflect changes to our definition of sustainable yield.

DEFINITION OF SUSTAINABLE YIELD

The District and other researchers have been studying ground-water availability of the Barton Springs segment of the Edwards Aquifer for many years (Slade et al. 1985, Barrett and Charbeneau 1996, Wanakule 1989, Scanlon et al. 2001, Smith et al. 2004). Ground-water availability studies by the District have been considered largely as a quantification of recharge to the aquifer, flow within the aquifer, and discharge at springs and water-supply wells. Sustainable yield is a concept that has evolved from earlier definitions of safe yield. Some of the definitions focused on recharge to the aquifer as the key limitation on pumping from an aquifer (Alley and Leake 2004; Kalf and Woolley 2005). The idea that ground-water extraction up to the amount of average annual basin recharge was "safe" has brought about unintended consequences such as drying of springs and rivers, saline-water intrusion, land subsidence, among others. Todd (1959) tied safe yield to the idea that "undesired results" need to be considered as a consequence of over pumping. It is the recognition of the complexity of water systems and society's exploitation of water resources that has led to the use of the term "sustainable yield" rather than safe yield. Alley et al. (1999) defines ground-water sustainability as "development and use of ground water in a manner that can be maintained for an indefinite period of time without causing unacceptable environmental, economic, or social consequences." Their concept of "unacceptable consequences" is similar to the "undesired results" of Todd (1959). Alley et al. (1999) acknowledges that a determination of "unacceptable consequences" is very subjective and involves a large number of criteria. Establishing these criteria requires discussions between scientists and policy makers, and between the regulating entities and the various stakeholders.

The Texas Water Development Board (TWDB) recommends a series of steps to be taken to arrive at a consensus on ground-water availability (Mace et al. 2001). These steps include education of stakeholders, defining socio-economic and environmental goals, and estimation of availability based on socio-economic and environmental goals. The District has used these steps to help determine the sustainable yield of the Barton Springs segment of the Edwards Aquifer (Smith and Hunt, 2004). The District defines sustainable yield as: *the amount of water that can be pumped for beneficial use from the aquifer under drought-of-record conditions after considering adequate water levels in water-supply wells and degradation of water quality that could result from low water levels and low spring discharge* (BSEACD, 2003). During periods of severe drought the District is concerned about sufficient yield from water-supply wells, quality of ground water, and quantity and quality of ground water discharging from Barton Springs. Low water-level conditions brought about by 1950's drought conditions combined with high rates of future pumping could cause Barton Springs and some water-supply wells to undergo water-quality degradation because of migration of saline water from the saline-water zone into the freshwater part of the aquifer. The amount and quality of water flowing from Barton Springs is of concern for the viability of the endangered salamanders that live at Barton Springs. Very low flow or no flow from the springs combined with lower water quality could bring about the extinction of two species of salamanders. Therefore, the undesired results identified by the District and stakeholders are sole-source water-supply wells going dry and extinction of the endangered salamanders.

BACKGROUND

Regional Setting

The Edwards Aquifer of Central Texas is a karst aquifer developed in faulted and fractured Cretaceous-age limestones and dolomites. The aquifer system lies within the

Miocene-age Balcones Fault Zone (BFZ), or Balcones Escarpment, of Central Texas. The aquifer contains hydrologic divides that separate the aquifer into three major segments: San Antonio, Barton Springs, and Northern segments (Figure 1). The entire aquifer system is about 270 miles long covering an area of about 4,350 mi^2 with about 1,700 square miles of recharge zone and 2,650 square miles of confined, or artesian, zone. The aquifer ranges in width from 2 to almost 40 miles and from 400 to more than 600 feet in thickness.

Discharge from the aquifer occurs at some of the largest springs and water-supply wells in the southwestern United States. The aquifer system is the sole-source of water for 2 million people with pumping totaling about 474,400 acre-ft/yr (155 billion gallons, 655 cfs) (Smith et al., 2005). The three largest springs in Texas issue from the Edwards Aquifer and include Comal, San Marcos, and Barton Springs. These springs have a mean annual historical flow of 200,900 (277 cfs) and 114,300 (199 cfs), and 38,400 (53 cfs) acre-ft/yr, respectively. Each of these springs provide habitat for federally-listed endangered aquatic species.

Barton Springs Segment of the Edwards Aquifer

The Barton Springs segment of the Edward Aquifer is bounded to the north by the Colorado River, by a ground-water divide to the south, by the interface between the fresh- and saline-water zones to the east, and by the outcrop and saturated thickness of the Edwards Group to the west (Figures 2 and 3). The Barton Springs segment is 155 mi^2 in area (Figure 1), with about 80% of the area under unconfined conditions, and a maximum thickness of about 450 feet (Figure 3).

The Barton Springs segment provides water for about 60,000 people and currently has about 7,800 acre-ft/yr (2.5 billion gallons; 11 cfs) of authorized pumping from 94 permit holders. Ground water use is characterized as 80% public-supply, 13% industrial (quarry operations), and 7% irrigation (golf courses). The District contains about 1,230 operational wells, with the majority producing water from the Edwards (Hunt et al., 2006).

The largest natural discharge point of the Barton Springs segment of the Edwards Aquifer is Barton Springs, located in Barton Creek about ¼ mi upstream of its confluence with the Colorado River (Figure 2). Barton Springs consists of four major outlets, the largest discharging directly into Barton Springs pool, a major recreational attraction of the City of Austin. Each of the spring outlets provides habitat for the federally-listed Barton Springs Salamander.

The formation of the aquifer was influenced significantly by fracturing and faulting associated with the Miocene-age BFZ and dissolution of limestone and dolomite units by infiltrating meteoric water (Sharp, 1990; Barker et al., 1994). Faults trend predominantly to the northeast and are downthrown to the southeast, with total offset of about 1,100 ft across the study area (Figures 2 and 3). Dissolution along fractures, faults, and bedding plane partings and within certain lithologic units has created numerous sinkholes, sinking streams, springs, conduits, and caves.

It is estimated that 85% of recharge to the aquifer occurs along its six major (ephemeral) losing streams that cross the recharge zone, and the remaining recharge occurring in the upland areas of the recharge zone (Slade et al., 1986). The amount of cross-formational flow (sub-surface recharge) occurring through adjacent aquifers is unknown, although it is thought to be relatively small on the basis of water-budget analysis for surface recharge and discharge (Slade et al., 1985). Current investigations are underway to estimate the potential for cross-formational flow to the aquifer from the Trinity and the saline-zone of the Edwards units.

The Edwards Aquifer is geologically and hydraulically heterogeneous and anisotropic, both of which strongly influence ground-water flow and storage (Slade et al., 1985; Maclay and Small, 1986; Hovorka et al., 1996; Hovorka et al., 1998; Hunt et al., 2005). Karst aquifers such as the Barton Springs segment are commonly described as triple porosity (and permeability) systems consisting of matrix, fracture, and conduit porosity (Ford and Williams, 1992; Quinlan et al., 1996; Palmer et al., 1999). Hovorka and others (1998) has described the Edwards Aquifer as having permeability ranging over eight orders of magnitude. Most storage of water in the Edwards Aquifer is within the matrix porosity (Hovorka et al., 1998); therefore, volumetrically, flow through the aquifer is dominantly diffuse. However, ground-water dye-tracing studies demonstrate that significant components of ground-water flow occur in a well integrated network of conduits, caves, and smaller dissolution features (BSEACD/COA, 2001; Hauwert et al., 2002). Ground water generally flows west to east across the recharge zone, converging with preferential ground water flow paths subparallel to major faulting, and then flowing north toward Barton Springs. Rates of ground-water flow along preferential flow paths, determined from dye tracing, can be as fast as 4 to 7 mi/day under high-flow conditions or about 1 mi/day under low-flow conditions (Figure 2; Hauwert et al., 2002).

Water Quality

Water quality of the Barton Springs segment is very good (BSEACD/COA, 2001). However, the study area is located in one of the most rapidly urbanizing regions of the State; therefore there is an increasing potential for a variety of anthropogenic sources of contamination. Impacts to water quality from anthropogenic sources are currently observed at Barton Springs (City of Austin, 1997; Barbara Mahler, USGS, personal communication).

Aqueous chemistry of ground water discharging from Barton Springs varies with aquifer conditions, with the most substantial decrease in water quality occurring under low-flow conditions. Increases in chloride, sodium, sulfate, and strontium concentrations are reported for low-flow conditions that result from an influx from the Edwards saline-water zone and the underlying Trinity Aquifer (Senger and Kreitler, 1984). Increasing pumping under drought conditions may increase the potential for subsurface recharge from these undesirable ground water sources. Such degradation of water quality could affect potable water supplies and the habitat for federally-listed endangered species at Barton Springs.

Aquifer Conditions

The climate of the study area is characterized as humid subtropical with an annual rainfall amount of 33.5 inches. Precipitation is fairly evenly distributed throughout the year with peaks occurring in May and September (Brune and Duffin, 1983). However, the region often receives a large portion of its annual rainfall in a very short period of time, resulting in flash flooding and periods of short, but intense recharge events. As a result of the climate, karstic nature, and pumping, the Edwards Aquifer is a very dynamic resource with rapid fluctuations in spring flow, water levels, and storage. Figure 4 illustrates the excellent correlation between peak rainfall, flow in Onion Creek, Barton Springs discharge, and water levels in the aquifer.

Central Texas' worst drought on record was a 7-year period from 1950 through 1956 (Figure 4A). The lowest total annual rainfall for Austin's Camp Mabry in 1954 was 11.42 inches. During this drought, water levels reached historic low levels and many springs stopped flowing completely, including Comal Springs. The annual mean discharge for Barton Springs was 13 cubic feet per second (cfs) in 1956, with the lowest monthly mean discharge of 11 cfs occurring in July and August of 1956. The lowest measured spring discharge value was 9.6 cfs on March 26, 1956. Long-term average spring-flow values for Barton Springs are about 53 cfs (Scanlon et al., 2001).

SUMMARY OF SCIENTIFIC STUDIES

Sustainable Yield Analysis

Texas state law requires water planning for drought-of-record conditions and use of ground-water modeling information in conjunction with other studies or data about the aquifer. Results of the District's sustainable yield studies are presented in Smith and Hunt (2004) and generally followed the approach outlined by the TWDB (Mace et al., 2001).

Evaluation of sustainable yield was based on modification of a Groundwater Availability Model (GAM) developed for the Barton Springs segment by Scanlon et al. (2001). The model was recalibrated to better match simulated and measured spring-flow and water-level data from the 1950's drought (Smith and Hunt, 2004). The recalibrated model was then used to predict spring-flow and water-level declines under 1950's drought conditions and various future (increasing) pumping scenarios. Hydrogeological data, such as saturated-thickness maps, potentiometric-surface maps, and well-construction and yield data, were evaluated along with the model results so that impacts to water-supply wells under 1950's drought conditions and various rates of pumping could be estimated (Hunt and Smith, 2004).

Results of the evaluations indicate that water levels and spring flow are significantly affected by 1950's drought conditions and increased pumping rates (Figure 5). Simulations indicate that a given pumping rate applied under 1950's drought conditions would diminish Barton Springs flow by an amount equivalent to the pumping rate. At 10 cfs of pumping a small amount of spring flow (~2 cfs monthly average) would be maintained. However, according to a minimum daily discharge of 9.6 cfs, such as that measured in 1956, spring flow could temporarily cease for days or weeks. At 15 cfs of pumping, spring flow would cease for at least 4 months. As many as 19% of all water-supply wells in the District may have adverse impacts under 1950's drought conditions and a pumping rate of 10 cfs (Figure 5).

Drought-Trigger Methodology

To determine drought indices for the karstic Barton Springs segment of the Edwards Aquifer the principal components of the hydrologic cycle (recharge, storage, and discharge) were evaluated. The Barton Springs segment has a wealth of historic rainfall, water-level, creek-flow, and spring-flow data. Methods employed to evaluate those data included simple statistical and graphical correlations, complex multivariate analysis, and numerical modeling.

Gauging recharge to an aquifer system would give the first indication of incipient drought conditions. However, results of the evaluation indicates that recharge, or its surrogates, is difficult to quantify and correlate to storage or discharge in the aquifer—both key components of the sustainable yield definition. Accordingly, storage and discharge are better-quantified drought indices for this karstic aquifer system. Multivariate analysis demonstrated that the aquifer is best characterized as having conduit and diffuse flow or storage (LBG-Guyton, 2005). It was determined that the best measure of these components is flow at Barton Springs and the water level at the Lovelady monitor well. Barton Springs is a measure of the overall condition of the aquifer with dynamic responses integrating combined conduit, fracture, and matrix flow from the system. Water levels in the Lovelady well are muted, less influenced by conduit flow, and more indicative of diffuse flow and the overall amount of water in storage (Figure 6).

The initial Alarm Stage drought trigger generally corresponds to levels when overflow springs within the Barton Springs complex cease flowing, and precedes a prominent break in the spring-flow recession (Figure 6). Critical Stage triggers were determined based upon sufficient margins of time for implementation of conservation measures that would be most protective of spring flow.

REGULATORY RESPONSES OF THE DISTRICT

Sustainable Yield Policy

Under Chapter 36 of the Texas Water Code, the District has authority to regulate ground water pumping within District boundaries. In response to studies conducted by District staff and other researchers, and according to its definition of sustainable yield, the District's Board of Directors adopted a sustainable yield value of 7,239 acre-ft/yr (2.4 billion gallons, 10 cfs) in its most recent management plan (BSEACD, 2003). This is the amount of water that is available for production during drought conditions. This plan was accepted by the TWDB and incorporated into the State Water Plan.

To achieve the sustainable yield value set in its management plan, the District's Board of Directors adopted two key policies that will regulate pumping from the aquifer during drought. The Drought Trigger policy sets specific aquifer conditions at which permittees are required to implement pre-established, mandatory conservation measures and usage restrictions. The Conditional Permitting policy is a way to further limit pumping during a drought and to slow the rate of additional permitting without setting a fixed cap on pumping.

Drought Trigger Policy

Based on the drought studies described above, a drought trigger policy was developed to improve declarations of drought for implementation of mandated conservation measures by ground-water users (Smith et al., 2006). These conservation measures are the primary means of protecting water levels and spring flow. The drought trigger policy that was developed, and adopted by the District in January 2006, uses flow from Barton Springs and water levels in the Lovelady monitor well to determine drought status of the aquifer. Either water levels or spring flow can trigger a drought on the basis of their respective trigger levels (Figure 4B). However, both water levels and spring flow must be above their respective trigger levels to exit a drought stage.

The drought trigger policy will improve the timing of entering into drought stages which will minimize the impact of low water levels on water-supply wells and maintain flow at Barton Springs that will be protective of the endangered species (Smith et al., 2006).

Conditional Permitting Policy

To address concerns about over pumping the aquifer due to significantly increasing demand, the District implemented a conditional permit policy in 2004 that would allow for some increases in pumping under non-drought conditions. Limits have not been set on the amount of ground water that can be pumped under these conditional permits, but they do limit pumping under drought conditions. Under Alarm Stage drought and the early phase of Critical Stage drought conditional permit holders are required to reduce pumping by 20% and 30%, respectively, similar to traditional permits. However, under more extreme drought conditions, pumping will be cut back to 50%, 75%, and even 100% of the amount under the conditional permit. Investigations are currently underway to determine what thresholds (e.g., flows at Barton Springs) are optimal for triggering these more stringent curtailments for the conditional permits. Applicants for conditional permits are required to demonstrate alternative sources of water for those times when their use of the aquifer will be sharply restricted.

FUTURE CONSIDERATIONS

To improve our knowledge of the aquifer and to support District policy development, District scientists continue to conduct aquifer studies. In 2004, the District was awarded a 3-

year grant from the U.S. Fish and Wildlife Service (USFW) to develop a Habitat Conservation Plan (HCP) for the Barton Springs salamander. Results of these various studies will help refine the sustainable yield values.

Recent legislative initiatives require that ground-water districts in Texas that share an interest in a specific aquifer will collectively determine desired future conditions (DFCs) of the aquifer. TWDB will work with the districts to determine the amount of managed available ground water (MAG). Districts will than develop management policies to meet the requirements set forth by the DFCs and MAGs.

The Barton Springs/Edwards Aquifer Conservation District will use the results of the HCP studies, additional ground water modeling, and other aquifer studies to develop policies that will achieve the goals set forth by the TWDB for aquifer management.

CONCLUSIONS

Evaluations of the sustainable yield of the Barton Springs segment of the Edwards Aquifer have indicated that at high rates of pumping during drought-of-record conditions, numerous water-supply wells will go dry and low flow or no flow from Barton Springs will jeopardize the endangered salamanders. The District's Board of Directors determined that policies were needed to minimize these undesired results of ground-water exploitation. A sustainable yield policy was implemented that sets a pumping limit of 10 cfs during periods of extreme drought. A drought trigger policy was implemented that sets spring-flow rates and water levels in a monitor well that will trigger declarations of drought stages. The enactment of conservation measures and reduction of pumping under conditional permits will minimize adverse impacts to water-supply wells and the endangered salamanders.

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Biographical Sketches

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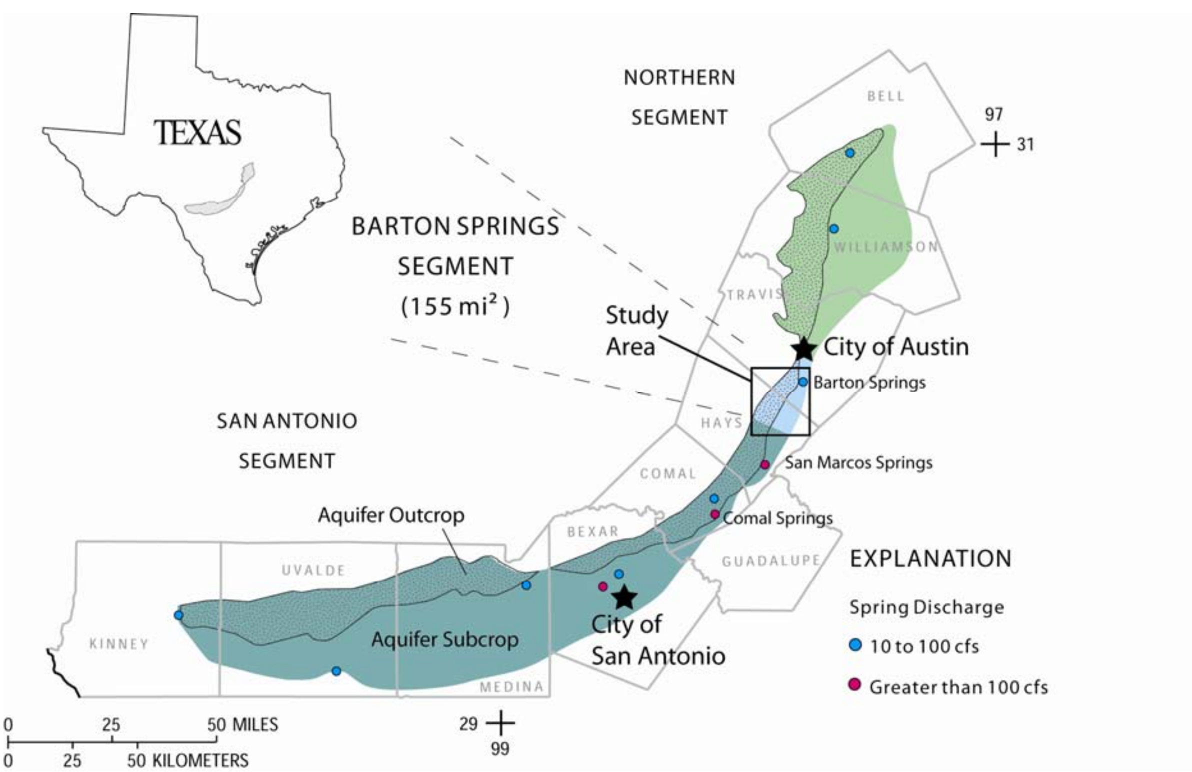


Figure 1. Regional setting of the Edwards Aquifer in Texas. Figure modified from Ryder (1996).

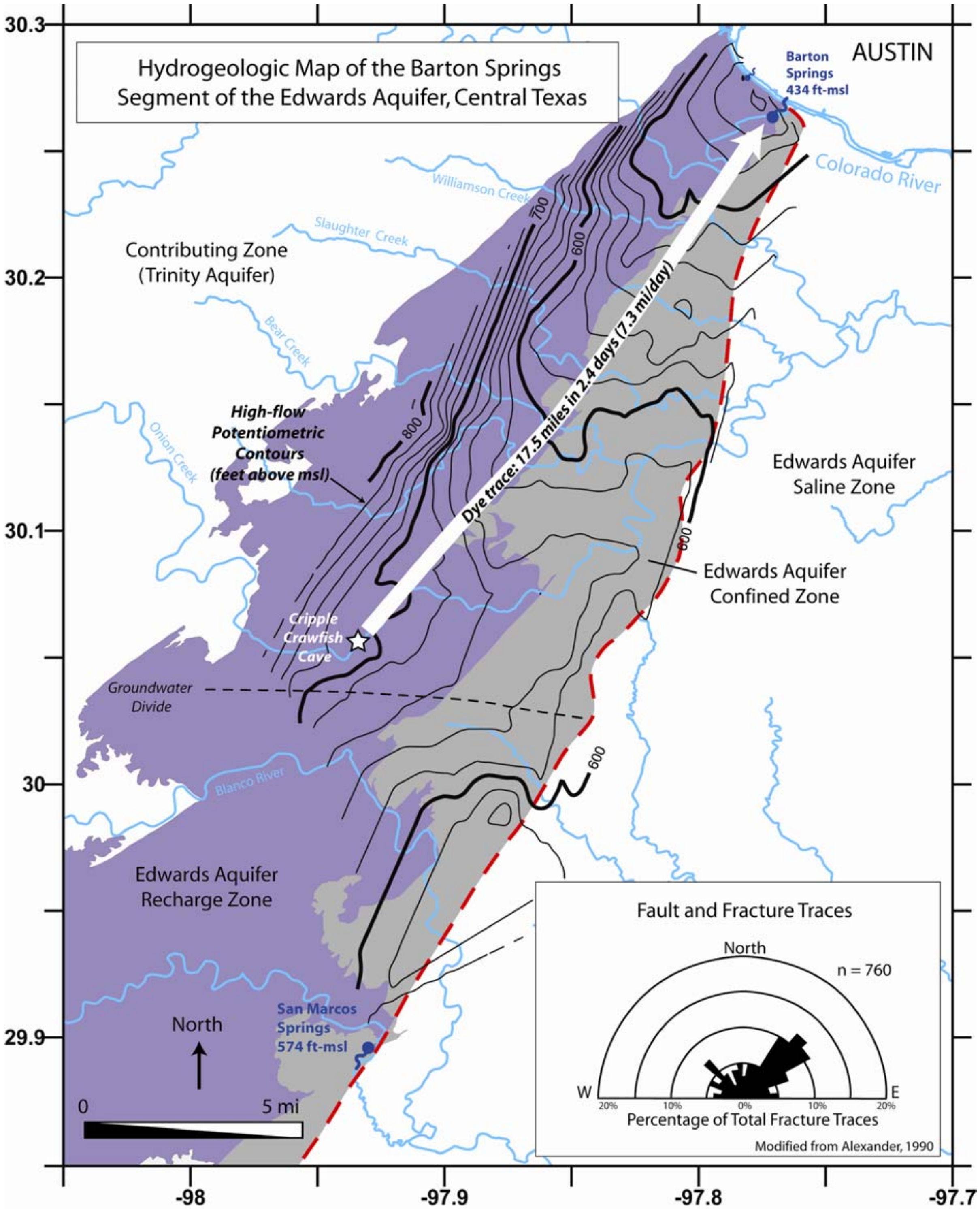


Figure 2. Hydrogeologic map of the Barton Springs segment of the Edwards Aquifer. High-flow potentiometric contours and a sample dye trace injection result illustrate the complexity of ground-water flow in the aquifer. Note that fault and fracture traces shown on the rose diagram are generally to the northeast and parallel to ground-water flow.

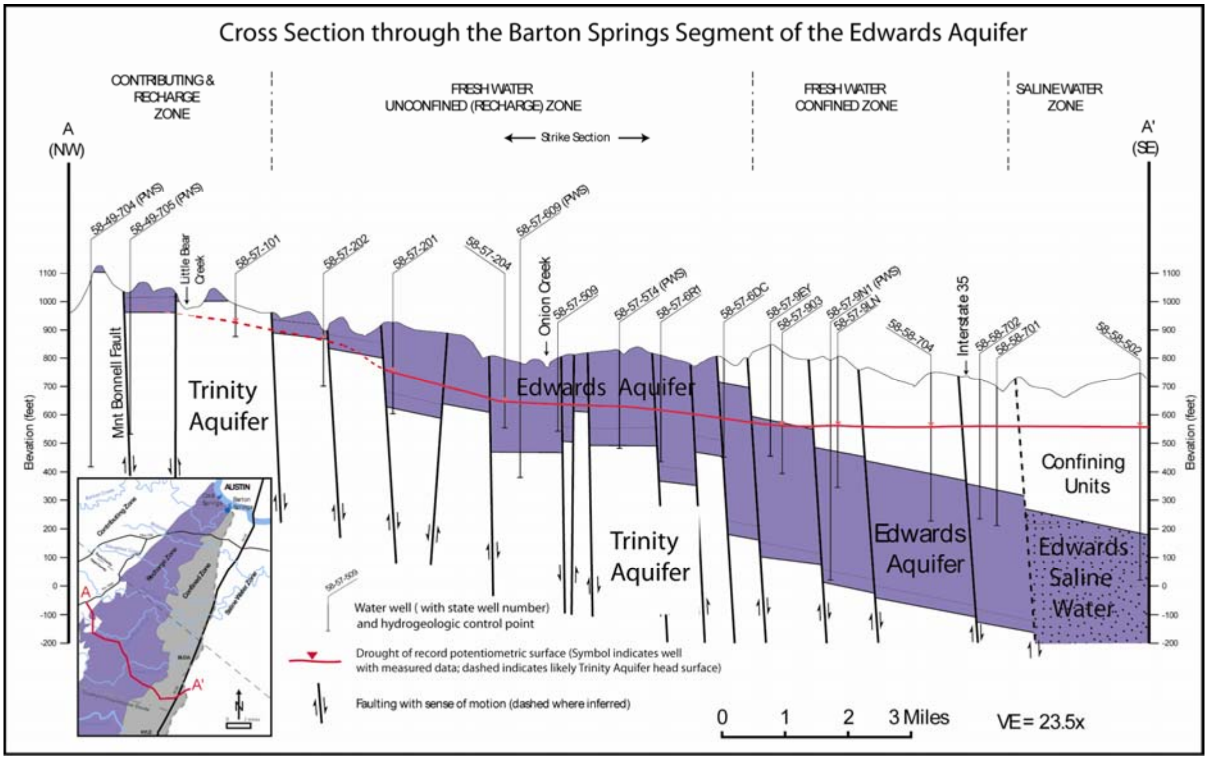


Figure 3. Cross section through the Barton Springs segment of the Edwards Aquifer. Modified from Smith and Hunt (2004).

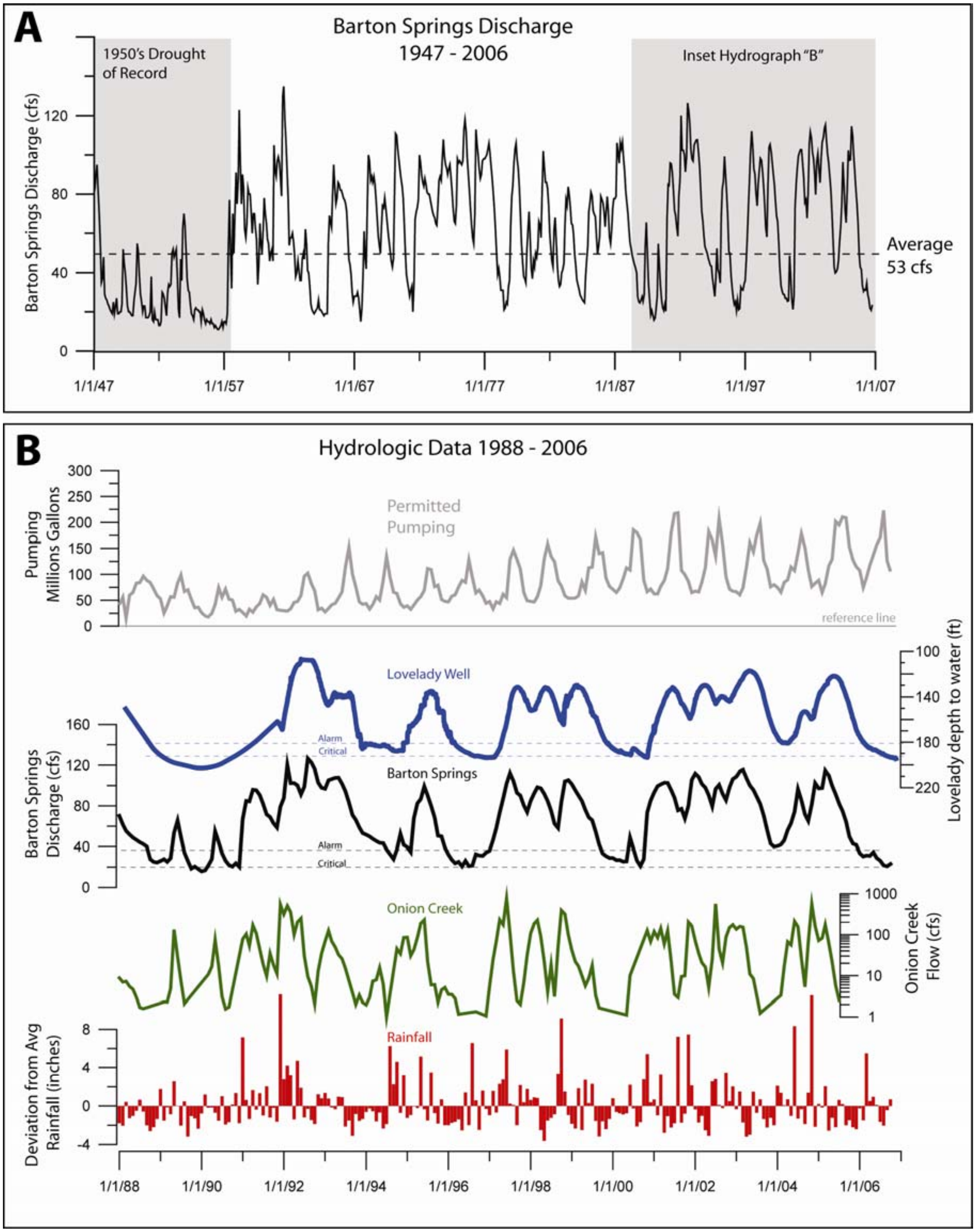
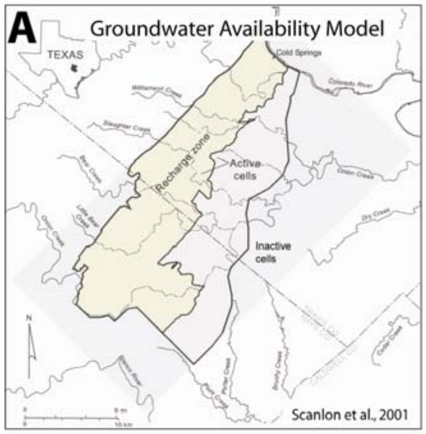


Figure 4. Hydrograph from the Barton Springs segment of the Edwards Aquifer. A) Hydrograph of Barton Springs discharge since 1947 illustrating the dynamic nature of the aquifer system and the 1950's drought of record; B) Hydrograph illustrating some of the major hydrologic components of the aquifer since 1988. Note the excellent correlation between large rainfall events, creek, water levels, and spring flow. Drought indices (Alarm and Critical Stages) are triggered by water levels and spring flow. Data source for Barton Springs and Onion Creek is the U.S. Geological Survey, precipitation data from Camp Mabry in Austin, Texas and provided by the National Weather Service Forecast Office.



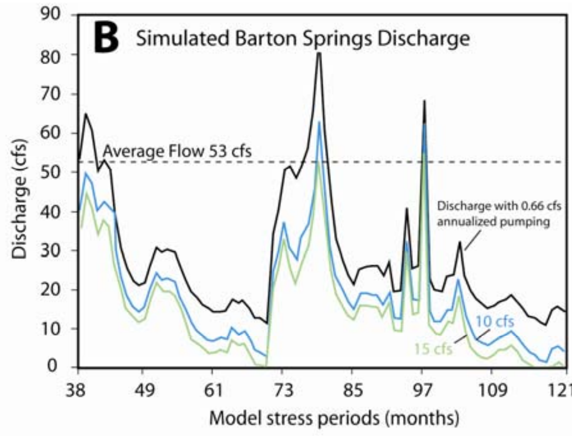
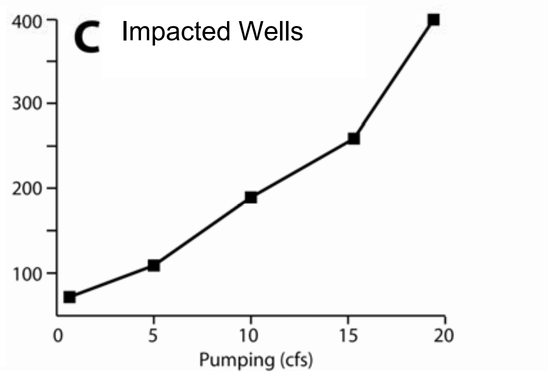


Figure 5. Results of Sustainable Yield Studies. A) Model boundaries of the Barton Springs GAM; B) Results of simulated Barton Springs discharge with 0.66, 10, and 15 cfs of pumping superimposed on the 7-year drought of record (from Smith and Hunt, 2004); C) chart showing the estimated impacts to wells under drought conditions and increasing pumping (from Smith and Hunt, 2004).



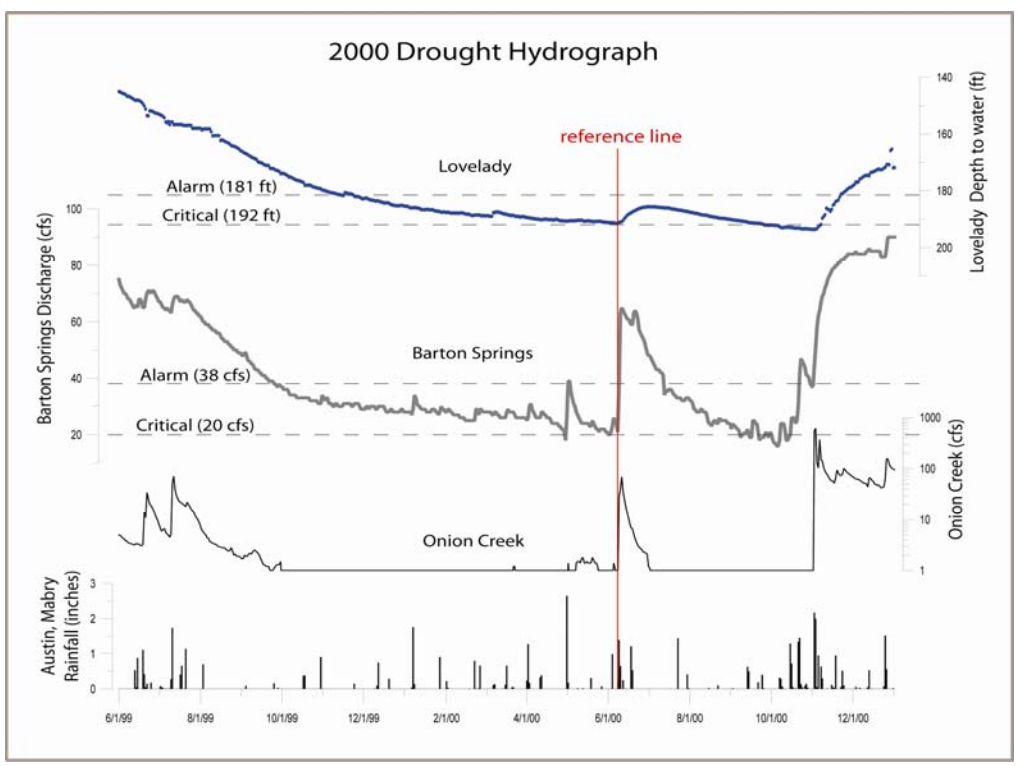


Figure 6. Hydrograph from the 2000 drought. Depth to water in the Lovelady monitor well and discharge from Barton Springs are used for drought declarations.