Groundwater Availability during Drought Conditions in the Edwards Aquifer, Hays and Travis Counties, Texas

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Abstract

The Barton Springs segment of the Edwards Aquifer is an important water resource for municipal, industrial, domestic, recreational, and ecological needs. Recent studies have given us a better understanding of the amount of groundwater that will be available during a severe drought with increased demand. This paper describes the methods used to characterize and quantify the impacts to water-supply wells during drought-of-record conditions (e.g., 1950s) and with increasing demand on groundwater. Potentiometric and saturated thickness maps of the aquifer representing drought conditions and computer-simulated drawdown from pumping were created. Well productivity (specific capacity) and construction data were compiled and evaluated with saturated thickness and potentiometric maps to estimate the number of wells that could be negatively impacted. Results indicate that the southwestern, unconfined portion of the aquifer is the most susceptible to decreased saturated thickness under drought and is further reduced with increased pumping. Up to 7% of water-supply wells in the District may have yield problems under drought alone. The combined effects of drought and pumping at an annualized rate of 10 cubic feet per second, currently permitted by the District, could result in negative impacts of up to 19% of the total water-supply wells in the District. Severe drought and high pumping rates will increase the potential for flow from the saline to fresh-water zone. These studies are a critical component of the management of the Edwards Aquifer and will be used to set sustainable yield policies for resource management by the District.

Introduction

The Barton Springs segment of the Edwards aquifer is an important groundwater resource providing for municipal, industrial, domestic, recreational, and ecological needs. The Barton Springs segment is located south of the Colorado River, extending south to the city of Kyle, and between Interstate 35 and FM 1826 (Fig. 1). Approximately 50,000 people depend upon water from the Barton Springs segment, and Barton Springs are the only known habitat for the endangered Barton Springs salamander. However, the amount of groundwater that will be available to meet those, and future needs during a drought of record, and increased demand (pumping) is limited. In order to properly manage the resource for sustainable use, the District is performing studies to determine the sustainable yield of water for the Barton Springs segment of the Edwards Aquifer. 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.*

The purpose of this paper is to characterize and quantify the effects of drought-of-record conditions and increasing demand (pumping) on groundwater levels and the impacts to wells. Well productivity and construction data were compiled and evaluated with saturated thickness and potentiometric maps to estimate the number of wells that could be impacted. Results indicate that the southwestern, unconfined portion of the aquifer is the most susceptible to decreased saturated thickness under drought and is further reduced with increased pumping. Drought and pumping also decrease heads in the eastern, confined portion of the aquifer. Up to 7% of water-supply wells in the District may have yield problems under drought alone. The combined effects of drought and pumping at an annualized rate of 10 cubic feet per second (cfs), currently permitted by the District, could result in negative impacts of up to 19% of the total water-supply wells in the District. These studies are a critical component of the management of the Edwards Aquifer and will be used to set sustainable yield policies for resource management by the District

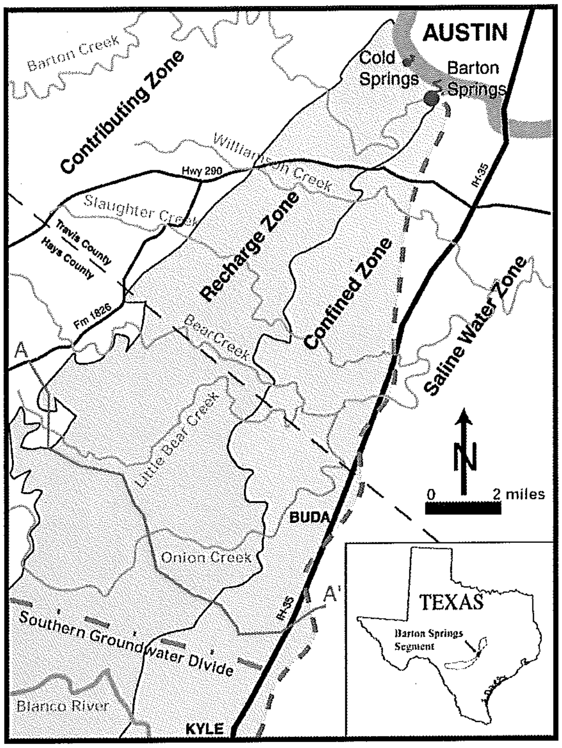

Figure 1. Location map and major hydrologic features of the study area.

Previous Work

Previous investigations of the Barton Springs segment of the Edwards Aquifer have primarily concentrated on characterizing and understanding the geology and hydrogeology of the Edwards Aquifer system (Senger and Kreitler, 1984; Baker et al., 1986; Slade et al., 1986; Small et al., 1996; Hauwert et al., 2002). Brune and Duffin (1983) discuss the availability of groundwater during a drought in terms of springflow, and recognize that withdrawls (pumping) equal to, or greater than, the lowest recorded springflow measurement of 9.6 cfs would dry up all stream flow (Barton Springs). Slade et al. (1986) present a series of potentiometric maps, including two that represent drought from 1956 and 1978.

Slade et al. (1985) used a numerical groundwater-flow model calibrated to average flow conditions to simulate the effects of pumping on groundwater availability. Their results showed that with increased demand, portions of the aquifer would be dewatered due to large declines in head.

Groundwater Availability Modeling (GAM), an initiative by the Texas Water Development Board (TWDB) to develop state-of-the-art, publicly available, numerical groundwater flow models, was developed for the Barton Springs segment by several agencies (Scanlon et al., 2001). The purpose of the GAM model was to evaluate groundwater availability and predict water levels and springflow in response to increased pumpage and the drought of record. Good agreement was found between measured and simulated flow at Barton Springs and between measured and simulated water levels. However, the GAM model was calibrated to data from non-drought conditions of the 1990s, and when compared to the drought-of-record data, GAM results generally overestimated springflow, and underpredicted head elevations (Smith and Hunt, in press).

Geologic Setting

The Edwards Aquifer is composed of the Cretaceous-age Edwards Group limestone sediments, composed of the Kainer and Person Formations, and the Georgetown Formation (Fig. 2). The Edwards Group accumulated on the Comanche Shelf as shallow marine, intertidal, and supratidal deposits. The Georgetown Formation disconformably overlies the Edwards Group and was deposited in more openly circulated, shallow, marine environment (Rose, 1972). These units have been fractured and faulted, associated with the Balcones Fault Zone (BFZ), and partially dissolved by infiltrating rainwater, resulting in the development of a prolific karst aquifer that has both conduit and diffuse flow components. Recent mapping of the Barton Springs segment has delineated geologic faults and several informal stratigraphic members within the Edwards Group defined by Rose (1972), each having distinctive hydrogeologic characteristics (Small et al., 1996). The majority of faults trend to the northeast and are downthrown to the southeast, with total offset of about 1,100 ft across the study area. Due to faulting and erosion, the aquifer ranges from its full thickness of about 450 ft along the eastern side, to zero along the western side of the recharge zone (Slade et al., 1986).

Hydrogeology

Water-supply wells in the Barton Springs segment of the Edwards aquifer include about 971 active Edwards wells including: public, domestic, industrial, commercial, irrigation, and agricultural. About 10% of these wells have annual permitted pumping volumes that total about 2.3 billion gallons of water in 2004. These wells supply water for primarily commercial and municipal use. Non-permitted pumpage, such as agricultural- and domestic-supply, is estimated to pump about 198 million gallons per year. Combined, these pumping volumes are about 2.5 billion gallons and equate to about 10.8 cfs for 2004. Most permitted pumping occurs in the thick southeastern portion of the aquifer.

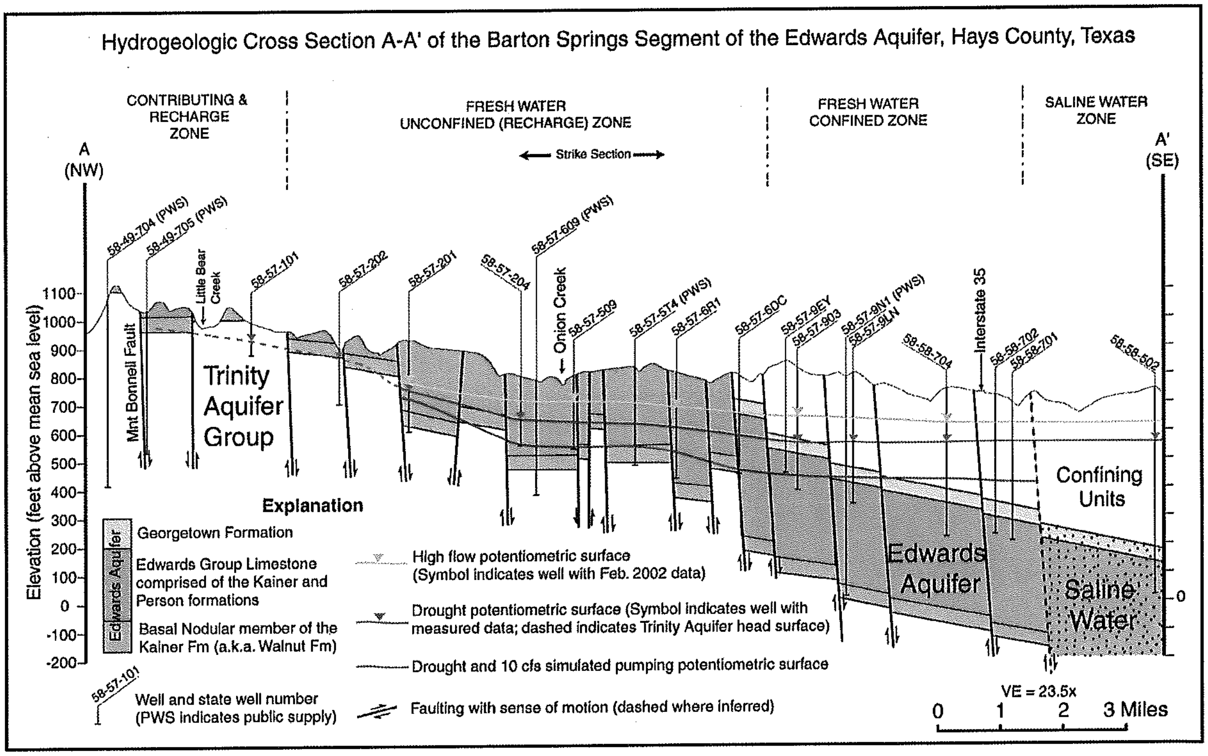

Figure 2. Cross section of the Barton Springs segment of the Edwards Aquifer in Hays County. Line of cross section A to A' shown on Figure 1.

The aerial extent of the Barton Springs segment is about 155 square miles and is bounded on the north by the Colorado River, the location of regional base level and spring discharge (Fig. 1). The eastern boundary is known as the saline or "bad water" zone of the aquifer, characterized by a sharp increase in dissolved constituents (greater than 1,000 mg/l) and a decrease in permeability (Flores, 1990). Leakage from the bad-water zone is thought to influence water quality at Barton Springs during low springflow conditions (Senger and Kreitler, 1984; Slade et al., 1986). The western boundary of the aquifer is poorly defined and is limited by the saturated thickness, and may be leaky due to lateral subsurface flow from the adjacent Trinity Aquifer. Evidence for this leakage is based on water quality influences attributed to the Trinity Aquifer, and the similarity of water-levels between the aquifers along the western boundary (Slate et al., 1986). A recent groundwater model for the Trinity Aquifer shows lateral groundwater leakage into the Edwards Aquifer in the San Antonio area in order to simulate observed hydrogeologic conditions in the Trinity (Mace, 2000). Where the Trinity Aquifer is in contact with the Barton Springs segment, the model indicates little or no flow into the Edwards. The southern groundwater hydrologic divide between the Barton Springs segment and the San Antonio segment is estimated to occur between Onion Creek and Blanco River basins based on potentiometric-surface elevations and recent dye tracing information (Hauwert et. al, in press). Flow across the southern boundary is likely insignificant (Hauwert et al., in press).

It is estimated that 85% of the water that recharges the Barton Springs segment infiltrates via caves, sinkholes, fractures, and solution cavities within stream channels. The remaining recharge enters the upland areas of the recharge zone through soil-covered bedrock and other sinkholes and caves (Slade et al., 1986). East of the recharge zone, the aquifer is overlain by less permeable limestone and clay units, which serve to confine the aquifer, and is called the Confined or Artesian Zone (Figs. 1 and 2).

The Edwards Aquifer is very dynamic with rapid fluctuations in springflow and water levels, reflecting changes in storage due to recharge (climatic conditions) and pumpage (demand). Without major pumping, the majority of groundwater in the aquifer discharges to Barton Springs, located in Barton Creek about ¼ mile upstream of its confluence with the Colorado River. Barton Springs consists of major 4 outlets, with the largest discharging directly into Barton Springs pool, a major recreational attraction for the city. Discharge from Barton Springs has a long-term average of 53 cfs with highest values greater than 160 cfs (Scanlon et al., 2001). The lowest instantaneous springflow measurement of 9.6 cfs was taken March 29, 1956 (Brune, 2002). The lowest monthly average springflow of 11 cfs is reported at the end of the 7-year drought of record during July and August of 1956 (Slade et al., 1986).

The Edwards Aquifer is geologically and hydraulically heterogeneous and anisotropic, which strongly influences groundwater flow and storage. Karst aquifers, such as the Barton Springs segment, are often described as triple porosity systems consisting of matrix, fracture, and conduit porosity (Ford and Williams, 1992; Quinlan et al., 1996). Though most of the storage of water in the Edwards Aquifer is within the matrix porosity (Hovorka et al., 1998), recent groundwater dye tracing studies indicate that some components of groundwater flow are very rapid and strongly influenced by conduit flow (Hauwert et al., 2002). The heterogeneity of the aquifer is further expressed in terms of well yields, which range from less than 10 gallons per minute (gpm), to greater than 1000 gpm.

The Edwards Aquifer is very dynamic with rapid fluctuations in springflow and water levels reflecting changes in recharge and pumping. Groundwater generally flows east to west across the recharge zone and then converges with preferential groundwater flow paths, flows north and discharges at either Barton or Cold Springs. Flow paths were repeatedly traced along troughs in the potentiometric surface, indicating high permeability areas and preferential flow paths. Rates of groundwater flow from recharge features to the springs determined from dye tracing were very rapid under high flow conditions (4 to 7 miles per day), and less rapid (up to 1 mile per day) under low flow (Hauwert et al., 2002).

The Edwards Aquifer overlies the Trinity Aquifer system in the BFZ (Fig. 2). The Upper Trinity Aquifer is comprised of the upper Glen Rose Formation. The Upper Trinity supplies, almost exclusively, domestic and livestock needs with very small (0-5 gpm) to small (5-20 gpm) yields of mineralized water in the central Texas Hill Country west of the BFZ (DeCook, 1960; Ashworth, 1983; Muller, 1987). Almost no new wells are being completed exclusively within the Upper Trinity Aquifer in the Hill Country (Ashworth, 1983). The Upper Trinity Aquifer is consistently about 350-400 ft thick in Hays County, and has significantly lower hydraulic properties than the Edwards Aquifer (Ashworth, 1983; Barker, 1994). Seasonal variations in the in the Upper Trinity are most dramatic in wells less than 250 ft deep. These aspects make the Trinity Aquifer more susceptible to the effects of drought than the Edwards Aquifer (Barker, 1994).

Methods (Approach)

Water-supply wells in this study include about 970 active Edwards-producing wells including: public, domestic, industrial, commercial, irrigation, and agricultural. In general terms, "negative impacts" to wells is defined as when instantaneous demand from a user is not met. A quantification of the number of wells that could be negatively impacted by low water levels was determined to be 1) 13% of wells located in areas with less than 100-ft of saturated aquifer thickness in the unconfined zone; and, 2) the total number of wells throughout the study area that partially-penetrate the aquifer resulting in less than 25-ft of saturated borehole, generally in the confined zone. These approaches and assumptions rely upon several key data sets and maps described in the sections below.

Attempts to eliminate duplication of wells that could be counted by both approaches does not appear possible as one is a broad, percentage-based approach, and the second is a well-by-well approach. However, the number of wells that may be included within each quantification approach is relatively small.

Contouring of all surfaces was done using the grid-based graphics program Surfer® in the UTM-ft coordinate system (NAD 83). Several methods of gridding data were evaluated, along with hand contouring, though all produced similar contour surfaces. Kriging was generally the method chosen because it produces the most realistic contour surface along data boundaries. Grid size of the cells was about 1200 ft by 1500 ft.

Saturated Thickness

Saturated aquifer thickness maps were created from three types of data: 1) structure contour of the bottom of the aquifer; 2) potentiometric maps representing drought-of-record conditions; and, 3) simulated drawdown for various annualized pumping rates. Saturated thickness maps in the unconfined zone were created using the following mathematical relationship at each grid node of a contour surface:

$$b_{wt} = (H_t - s) - A_b$$

where b_{wt} is the saturated thickness of the water-table aquifer (in ft), H_t is the total measured drought-of-record hydraulic head (in ft above mean sea level), s is the hydraulic head loss due to pumping (in ft), and A_b is the elevation of the bottom of the aquifer (in ft above msl).

For the purposes of this evaluation, 100-ft of saturated aquifer thickness was defined as the cut-off from which to derive adequate water-supplies for wells in the unconfined aquifer. This number is a reasonable thickness to assess impacts based upon discussions with the District's technical advisory groups, distribution of Edwards wells on the non-drought saturated thickness maps, and drawdown that occurs for in-yield wells along the western portion of the aquifer. Specific-capacity data were compiled (n=113) and mapped to determine the range and distribution of well yields in the unconfined aquifer. Thirteen percent (13%) of these wells have a specific capacity value of less than or equal to 0.17 gpm/ft. These wells would have greater than 100-ft of drawdown for a constant pumping rate of 15.90 gpm, the average rate (n=184) for domestic supply wells in the District. By this general approach, those wells will likely experience problems producing water since drawdown would exceed the saturated thickness of the aquifer under these conditions. For example, under a drought with minimal pumping (0.66 cfs), it is estimated that 230 wells may have less than 100-ft of saturated aquifer thickness, and it is estimated that 13%, or 30 wells, will therefore experience yield problems. It is assumed that all wells in this analysis penetrate the entire thickness of the aquifer as most of these wells are generally in the thinnest portion of the aquifer.

Quantification of the number of wells that would be impacted by the combined effects of lower head and partial-penetration of the aquifer required two types of data: 1) location and elevation of the bottom of the well borehole; and 2) a corresponding potentiometric surface elevation representing drought-of-record conditions and drawdown from pumping. .This generally applies to wells in the confined portion of the aquifer. The amount of saturated borehole for each well was created using the following mathematical relationship:

$$b_s = H_t - W_b$$

where b_s is saturated borehole thickness (in ft), H_t is the total hydraulic head (in ft above msl), and W_b is the elevation of the bottom of the borehole (in ft above msl). Hydraulic head for each well with sufficient depth and location information (n=614) was determined from residuals on the potentiometric surface maps in Surfer®.

Similar to the saturated thickness analysis, it is recognized that a negative impact to a well would likely occur before the saturated thickness of a well borehole reached zero. For this portion of the evaluation, 25-ft of saturated borehole was defined as sufficient for deriving adequate water supplies. This number recognizes that pumps are not generally set on the bottom of the borehole, and the confined portion of the aquifer generally has higher specific capacity values than the unconfined zone. For example, under a drought with minimal pumping (0.66 cfs), it is estimated that 46 of the total 971 wells may have less than 25-ft of saturated borehole thickness, and may therefore have problems with yield.

Structure Contours

The primary data set (n=245) for the structure contour surface of the bottom of the aquifer was derived from well logs composed of driller's descriptions, geophysical, and geotechnical borings, and core data (Fig. 3). Geologic contacts and geologic maps (Small et al., 1996) were also used for control. Faulting was not incorporated into the gridding process and does not appear to have a profound effect on the contour shapes owing to the relatively high density of data. The top of the basal nodular member of the Kainer Formation was used as the effective bottom of the aquifer. This member is about 50-ft thick in the study area, and despite the localized karst development in the recharge zone, has low permeability and storage compared to the rest of the Edwards Group (Small et al., 1996). In many areas the elevation of the bottom of the aquifer was derived by applying the known total aquifer thickness and unit thicknesses from well defined, stratigraphic control points.

In order to characterize the change in thickness of the aquifer as it relates to groundwater availability, a isopach map in the recharge zone and confined zones was created (Fig. 4).

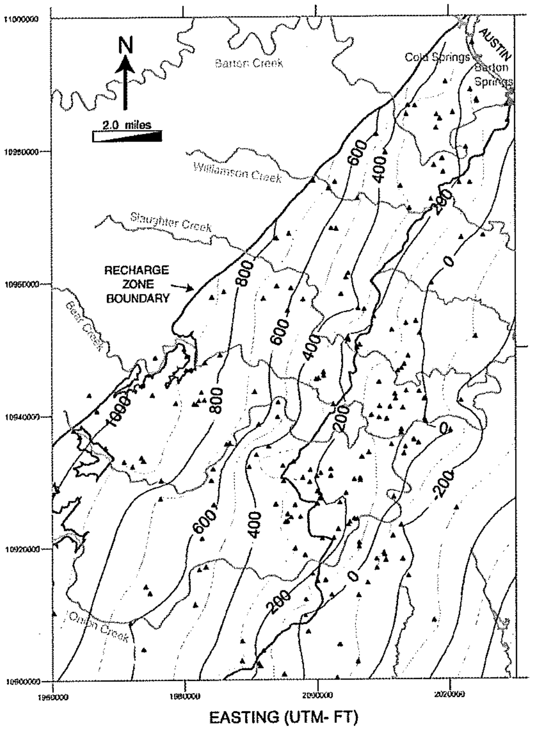

Figure 3. Structure contour of the elevation (msl-ft) bottom of the Edwards Aquifer with data control points shown as dots. Strike of the structure contours are NE, and dip to the SE. Variations in the strike and dip are common, and correspond to structural features including, grabens, half-grabens, and relay ramp features.

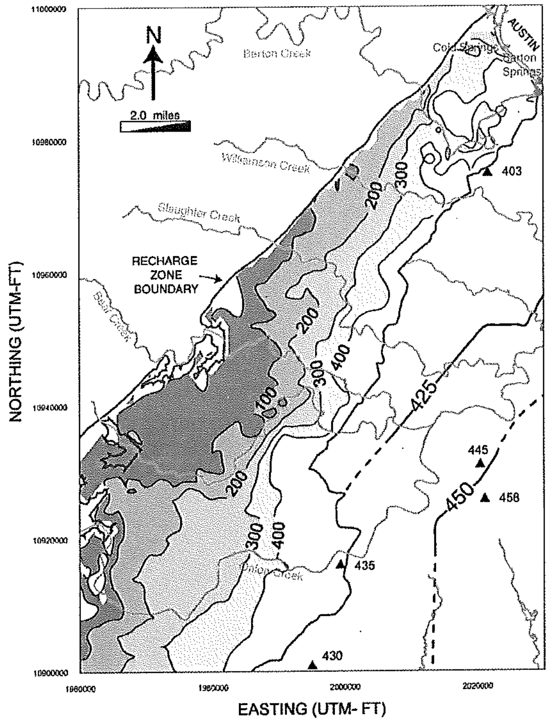

Figure 4. Isopach map of the Edward Aquifer. The recharge zone has a shaded contour interval of 100-ft and the confined portion of the aquifer is represented by the 25-ft contour lines. The Isopach map shows a general thickening to the SE, parallel to the structure contours. The isopach in the unconfined zone illustrate how quickly the aquifer thins to the west.

Potentiometric Maps

To construct the drought-of-record potentiometric map, water-level data since 1937 were collected from the Texas Water Development Board database and reports and the United States Geological Survey reports (Follet, 1956; DeCook, 1960; Slade et al., 1986). Limited water-level data from the 1950s drought period exists. A composite low water-level map was constructed with July and August 1956 water-level data as the base data set. Additional 1950s water-level data were adjusted to the July and August 1956 period when possible, and additional water-level data from low springflow periods were used (Fig. 5). The final data set used to construct the composite drought-of-record water-level map has about 50 control points within the District boundaries, with 20 values representing 1956 and other values adjusted to 1956 conditions.

The composite low water-level map shown in Figure 5 generally contains a steep west to east gradient along the western (unconfined) portion of the aquifer. The gradient decreases toward the confined portion of the aquifer and direction of flow changes from E-W to SW-NE, similar to other water-level maps that were constructed with many more data points. The composite low water-level map created by the above procedures is similar in shape, gradient, and elevation to the 1950's map in Slade et al. (1986). However, the most significant differences in the maps occur in the area of interest along the western Edwards Aquifer with some elevations having greater than 50 ft higher elevations in the Slade et al. (1986) map. The map constructed in this study contains more control data in this area, and may therefore account for these differences.

Simulated drawdown with annualized pumping rates of 5, 10, 15, and 19 cfs, were obtained from 41 wells from the revised Groundwater Availability Model (GAM) of the Barton Springs segment (Smith and Hunt, in press). Simulated drawdown was calculated as the difference in head between simulated drought (0.66 cfs pumping), and drought with each increment of pumping. The data were gridded and contoured to create drawdown surfaces (Fig. 6). Each of these surfaces was subtracted from the drought-of-record potentiometric map to create a combined drought and pumping potentiometric map (Fig. 7) to quantify the impacts to wells under drought and each pumping scenario as described above.

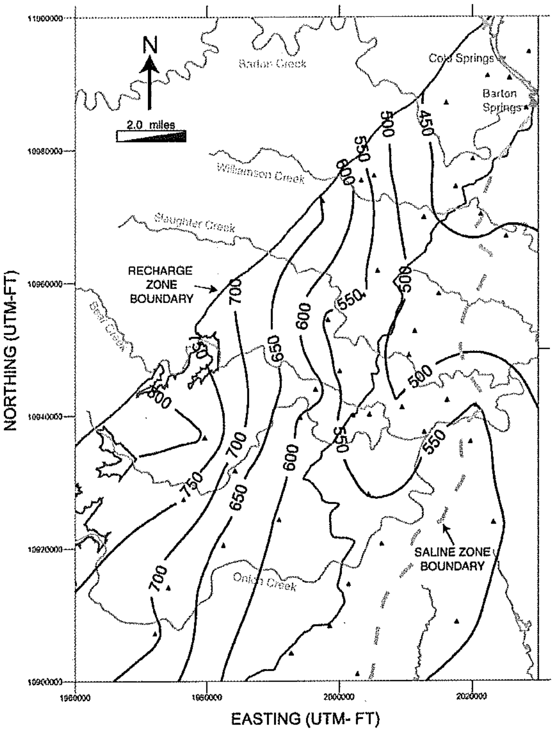

Figure 5. Drought-of-record potentiometric map of the Barton Springs segment of the Edward Aquifer.

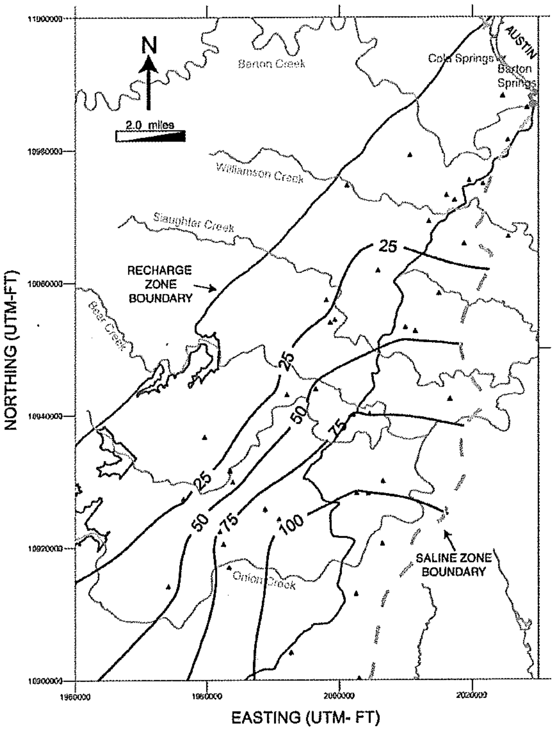

Figure 6. Simulated drawdown from pumping 10 cubic feet per second (cfs). Simulated drawdown maps show the greatest depression around the Buda area, the area of greatest current demand and pumping.

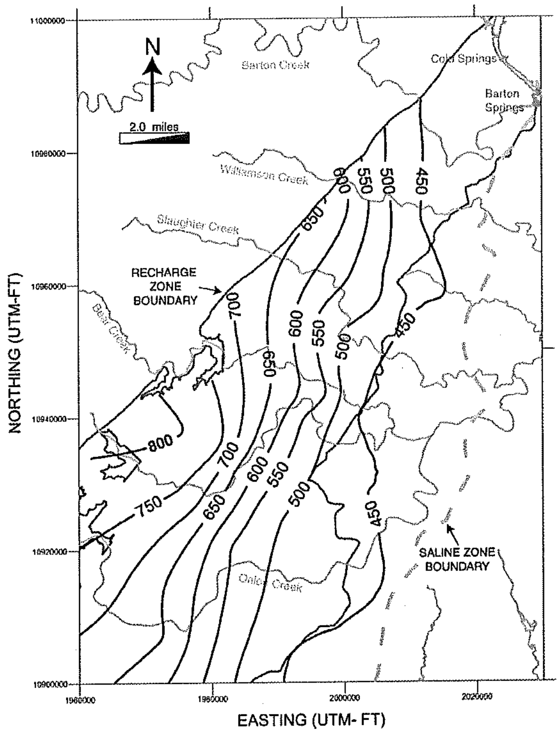

Figure 7. Potentiometric map under drought-of-record conditions and simulated drawdown from pumping 10 cfs. Well-defined potentiometric surface troughs that feed Barton Springs are no longer present indicating that most flow is no longer towards Barton Springs.

Well Data

Specific capacity is defined as a well production per unit decline in head, and is a function of the aquifer and well setting, and the pumping rate and duration (Mace, 2000). In this study, specific capacity was used to characterize drawdown of wells from pumping throughout the aquifer. Specific capacity data were assembled from well schedules and pumping test reports and reviewed to improve data quality. No attempts were made to normalize the specific capacity data to aquifer thickness. A total of 168 measurements, taken during various hydrologic conditions, were compiled and have a log-normal distribution of values. Twenty-nine of these values were taken from long-term aquifer pumping tests. The data show heterogeneity distributed throughout the aquifer; however, the lowest values are primarily located within the western unconfined area of the aquifer and along the bad-water zone on the eastern side of the aquifer.

Wells drilled to produce water in the Edwards aquifer range in depth from 40 to 800 ft, with an average well depth of about 400 ft. The distribution of the average depth is not systematic across the aquifer from unconfined to confined conditions. An investigation into wells reported to "go dry" or have yield problems during a drought revealed that cable-tool drilling, a drilling technology largely unused today, resulted in many shallow-penetrating wells.

Results

The saturated thickness of the aquifer, under drought conditions and minimal pumping (0.66 cfs), is shown in Figure 8. The cross sectional expression of this surface is shown in Figure 2. A significant portion of the unconfined aquifer in the recharge zone is likely to have little to no water available for supplies during a drought of record. A composite map of the 100-ft saturated thickness under drought conditions with various pumping scenarios (0.66, 5, 10, 15, 19 cfs) are shown in Figure 9. Figure 9 shows the effective "dewatering" of the aquifer with each scenario of increased pumping under drought-of-record conditions. The most significant decrease in saturated thickness occurs along the southwestern area of the unconfined aquifer, with the greatest shift in contours between high flow and drought water-level conditions. Dewatering of the aquifer becomes insignificant in the northern portion of the aquifer.

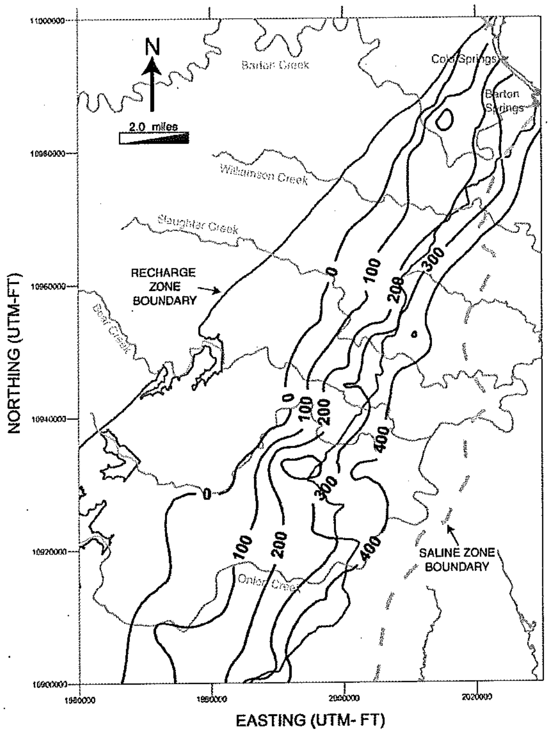

Figure 8. Saturated thickness contour map of the aquifer under drought conditions and minimal (0.66 cfs) pumping.

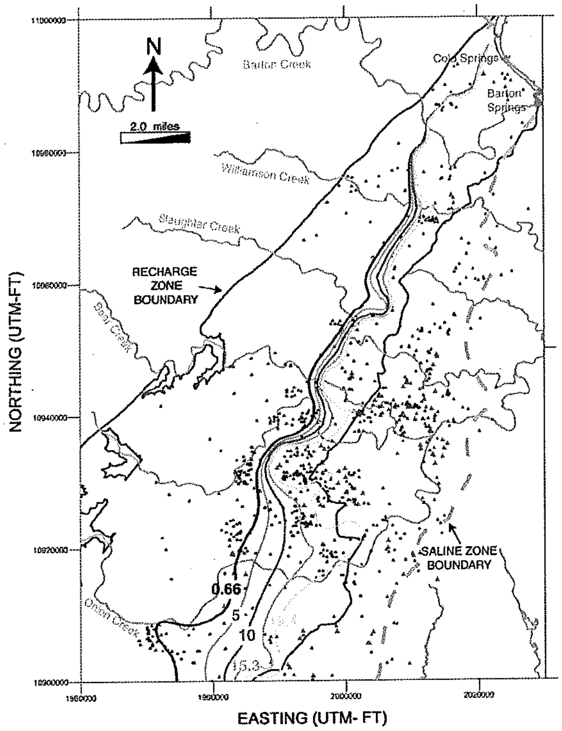

Figure 9. Saturated thickness map showing composite 100-ft contour line for drought and 5, 10, 15, and 19 cfs pumping.

The number of wells located west of the 100-ft saturated aquifer contour line, which indicates they have less than 100-ft of saturated aquifer thickness available, are presented in Table 1. For the given pumping rate (15.9 gpm) and well productivity (Sc= 0.17 gpm/ft), these wells will likely have insufficient yield due to the dewatering of the aquifer from drought and pumping.

Under drought conditions and increased demand, water levels (head) in the confined zone decrease. Though the saturated thickness of the aquifer does not appear to be severely impacted in the confined zone under these scenarios, decreases in head under drought and pumping does shift the boundary from unconfined to confined conditions to the east with increasing pumping (Fig. 2). Under drought conditions and 19 cfs of pumping, nearly the entire aquifer is hydraulically unconfined.

Head decreases will leave some wells with less than 25 ft of saturated borehole, and are presented in Table 2. These wells will likely have insufficient yield due to the dewatering of the well borehole primarily because of lower head values and partial-penetration of the aquifer.

Table 3 quantifies the impacts from dewatering of the aquifer and borehole. Figure 10 graphically summarizes these results.

All large public water-supply systems in the District were evaluated to determine if there was likely to be any impact under drought and pumping scenarios. Only two public water supply systems in the southwestern portion of the aquifer were found to have insufficient aquifer saturation under drought conditions alone. Those two systems are Oak Forest and the Ruby Ranch Subdivisions in Hays County. Most other public water supply systems are located in the highly transmissive, confined portion of the aquifer and penetrate most of the aquifer thickness. Some smaller public-supply systems rely primarily on the Trinity aquifer. The effects of drought and pumping on the Trinity Aquifer are beyond the scope of this investigation.

Table 1. Saturated Aquifer Thickness Analysis.

Drought and annualized pumping rate (cfs)	0.66*	5	10	15.3	19.4
Total number wells west of the 100-ft saturated thickness contour	230	267	291	330	408
Number of wells with high probability of insufficient yield**	30	35	38	43	53

*Pumping during 1950's drought
**based on 13% of wells with low specific capacity (Sc=0.17; Q=15.9 gpm)

Table 2. Saturated Borehole (Partial Penetration) Analysis.

Drought and annualized pumping rate (cfs)	0.66*	5	10	15.3	19.4
Number of wells with high probability of insufficient yield**	43	74	151	216	347

*Pumping during 1950's drought
**based on wells with <25 ft saturated thickness

Table 3. Total Impact to Wells from Drought and Pumping.

Drought and annualized pumping rate (cfs)	0.66	5	10	15.3	19.4
Total Number of Impacted Wells	72	109	189	259	400
Percentage of total wells (n=971)	7	11	19	27	41

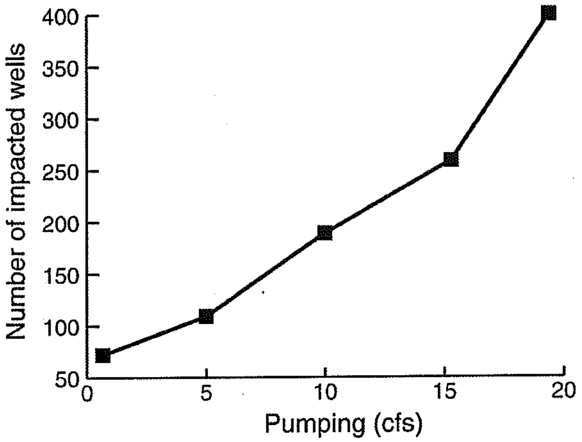

Figure 10. Chart summarizing the number of wells impacted due to drought and increased pumping. Negative impacts to wells appear to have a fairly linear relationship.

Discussion

Hydraulic properties of the aquifer are heterogeneous and anisotropic. Wells in the unconfined zone have lower and more variable specific capacity values than the confined zone, and are more susceptible to variations in saturated thickness (Fig. 9). In the unconfined zone we expect the transmissivity and therefore specific capacity values to be lower under lower hydraulic head conditions (drought). Therefore, the percentage of wells with greater than 100 ft of drawdown would likely increase. Accordingly, the results presented may represent a minimum estimate of negative impacts to wells from drought and pumping.

Wells in the confined zone are negatively impacted by the combination of decreases in hydraulic head and the partial penetration of wells into the aquifer (Figs. 2 and 7). A majority of the shallow-drilled wells were drilled with cable tool technology, and before current or projected demand.

A significant decrease in head in the fresh-water zone will increase the potential for flow from the bad-water zone, into the fresh-water zone (Fig. 2), resulting in water-quality implications for supply-wells and Barton Springs. However, more investigations are needed to fully characterize this potential.

The effects of drought and pumping have been characterized as "negative impacts," in this report. This description is deliberately vague due to the complexities of the problem and the potential remedies. Negative impacts do not necessarily mean that wells will "go dry." However, if water levels drop below the pump, borehole, or become quickly drawn down to the pump, air would enter the system causing it to cavetate and cease production. Potential remedies to negative impacts could include: deeping the well into the Edwards or Middle Trinity Aquifer, lowering the pump, setting a lower pumping rate, and obtaining more storage, to mention a few. Other solutions for municipalities or large public-supply coorporations include conservation, cross-connections to reliable, proven water sources such as surface-water lines, desalinization, or an aquifer storage and recovery facility.

Most public-supply wells are drilled to sufficient depth and are located in the confined portion of the aquifer and will not likely be negatively impacted. These systems are also more capable of mitigating impacts due to their ability to control pumping rates and store water, and some have the potential to inner-connect with other surface water-supply sources.

In the unconfined zone, it is common for wells to penetrate into the underlying Upper Trinity Aquifer. In general these wells penetrate less than 250 ft into the upper Glen Rose and likely derive their water from a mixed Edwards-Upper Trinity source. Based upon the literature, the Upper Trinity will have negligible contribution to supplies from these hybrid wells when compared to the Edwards. However, it is possible that the Upper Trinity may provide sufficient supplies to wells that penetrate through the thin Edwards under drought and pumping. Accordingly, our estimates would over estimate the impacts to such mixed wells. Further investigations are needed to fully understand the Trinity Aquifer system, and its potential as a source of water.

Although the District has the most complete and comprehensive database for this area, there are undocumented wells. In general, these wells likely pre-date the existence of the District (pre-1987), and could represent a higher number of wells that partially-penetrate the aquifer. Accordingly, our estimates would under estimate the impacts for these additional wells during drought and pumping.

The heterogeneity of the karst aquifer system requires some obvious assumptions in order to quantify an "impact" to wells. The primary assumptions that have a direct bearing on the number of well impacted include the specific definitions of impact- e.g., how much saturated aquifer and borehole is sufficient for supplies? For this system we chose 100 ft of saturated aquifer, and 25 ft of saturated borehole, generally corresponding to the recharge and confined zone, respectively. This approach gives a reasonably quantitative evaluation of potential impacts. Although all the measured data sets (structure, water-level, specific capacity) and contour surfaces have implicit assumptions, the results of this study rely heavily on measured data to assess the impacts of drought (alone). The effects of drawdown from pumping are the only data set that used model simulated results. We believe this greatly reduces the uncertainty of this assessment.

Other sources of water may not be accounted for in the drawdown simulations which might over-predict drawdown, such as influx from the badwater zone, San Antonio segment, or the Trinity aquifer. However, it is our understanding that these sources likely represent insignificant amounts of water, and is further discussed in Hauwert et al. (in press).

Previous studies have not attempted to quantify the impacts of drought and pumping in relation to the number and distribution of supply wells. This investigation will be used for policy decisions regarding aquifer management and protection for supply wells in the District.

Conclusions

1. Wells in the southwestern portion of the unconfined aquifer are the most susceptible to decreased saturated aquifer thickness, and lower transmissivities under drought-of-record conditions. Increased pumping further magnifies drawdown in this area.
2. Wells in the confined portion of the aquifer are most susceptible to decreases in head during a drought with high rates of pumping. Wells that partially penetrate the aquifer are most susceptible to yield problems.
3. As many as 7% of the wells, and two public water-supply systems may be negatively impacted with insufficient yield under drought-of-record conditions alone (with minimal pumping).
4. Under drought-of-record conditions and an annualized pumping rate of 10 cfs, as many as 19% of the wells in the District may be negatively impacted. The majority of those negative impacts are due to a combination of decreased head and partial penetration of wells into the aquifer.
5. During a severe drought and high rates of pumping, there will be in increased potential for saline water to flow from the bad-water zone into the fresh water aquifer.
6. These data are a critical component of the management of the Edwards Aquifer and will be used to set District sustainable yield policies for resource management.

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