REPORT ON THE EDWARDS AQUIFER SAN ANTONIO REGION, TEXAS

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1.0 General Description of the Edwards Aquifer (Balcones Fault Zone)

The entire Edwards Aquifer (Balcones Fault Zone) extends from Salado, Texas, in Bell County, through Austin (Travis County), San Marcos (Hays County), New Braunfels (Comal County), San Antonio (Bexar County), Hondo (Medina County), and Uvalde (Uvalde County) to Brackettville (Kinney County). The Edwards Aquifer is approximately 260 miles (mi.) long and varies in width from 5 to 40 mi. and crosses several streams in five major river basins, including the Nueces, San Antonio, Guadalupe, Colorado and Brazos River basins. The Aquifer is segmented into three parts. The Northern segment of the Edwards Aquifer extends from Salado to the Colorado River in Austin. The Barton Springs segment of the Edwards Aquifer extends from the Colorado River to a ground water "high" located between the cities of Buda (Hays County) and Kyle (Hays County). The San Antonio Region of the Edwards Aquifer extends from this ground water high to near Brackettville. Each segment of the Aquifer has major recharge sources and natural discharge points. For the most part, each segment acts independently of the other, although there is technical evidence that limited quantities of water may flow between adjacent segments under certain hydrogeologic conditions.

2.0 Formation of the San Antonio Region of the Edwards Aquifer

The Edwards Limestone, formed in the Early Cretaceous, is exposed throughout the Edwards Plateau. This limestone formation in the San Antonio Region consists of 400 to 600 ft of thin to massive-bedded carbonate rocks and is comprised of several stratigraphic[1] zones containing permeable beds with well developed vuggy porosity[2]. In some areas, these zones are vertically separated by beds of dense to chalky limestone having little to moderate permeability[3] and porosity. At some locations, the permeable[4] strata are hydraulically interconnected by open, inclined fractures. While at other locations, the lateral continuity of the permeable strata is made discontinuous by vertical/high angle faults that displace the entire thickness of the Edwards Limestone.

The Edwards Limestone was formed on the shores of ancient seas. Early Cretaceous barrier reefs, such as Stuart City Reef and Devils River Reef caused sediments comprising the Edwards Limestone to deposit, forming several limestone platforms (Figure 2.1). The Central Texas Platform and the San Marcos Platform developed to the north and west of the Stuart City Reef and the Maverick Basin (platform) developed due to the location of the Devils River Reef. These platforms were created by cyclic deposition of materials

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1 *Stratigraphic* - The arrangement of rocks in layers or strata.

2 *Porosity* - The ratio of the aggregate volume of interstices (openings) in a rock or soil to its total volume, usually stated as a percentage.

3 *Permeability* - The capacity of a rock, soil or sediment to transmit a fluid.

4 *Permeable* - Rock, soil or sediment having a texture that permits water to move through it perceptibly under the head differences ordinarily found in subsurface water. A permeable rock has communicating interstices (openings) of capillary or super-capillary size.

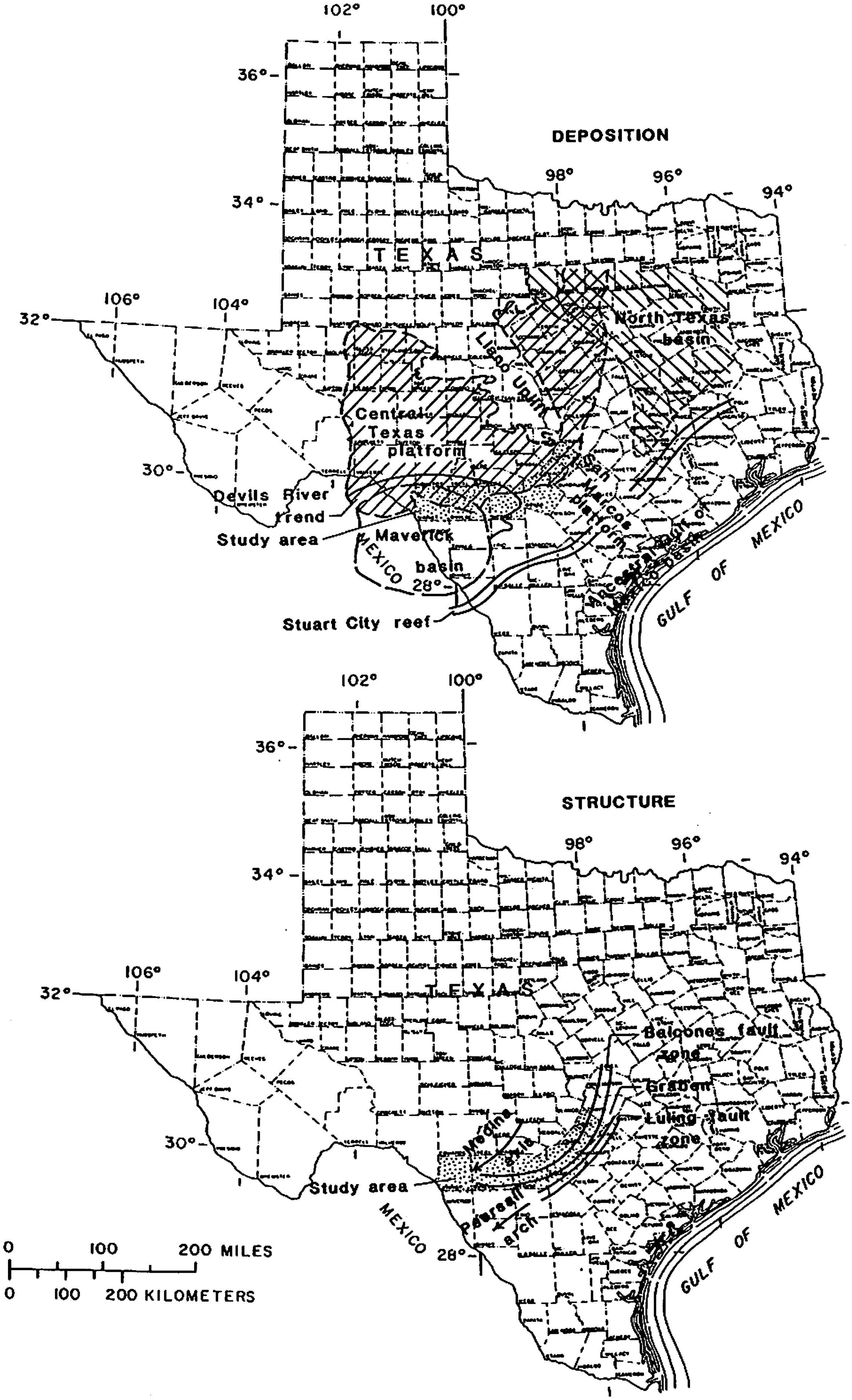

Figure 2.1 Depositional Provinces and Geologic Structure. (Source: USGS Report 86-532)

behind (north and west) the reefs. The sediments comprising the carbonate Edwards Limestone were formed by the transgressing and regressing seas. After the seas receded, the platforms were propagated by tidal and subtidal sediments originating from the north and west. Evaporites were deposited on these vast low lying platforms, further contributing to their formation. During the late Edwards time era, erosion removed more than 100 ft of the deposits from the San Marcos platform resulting in extensive karstification[5] of the limestones and dolomites. Porosity and karstification of the limestones was further developed by continual cycles of carbonate deposition and rainfall, which cemented and leached the sediments (USGS 1986).

Through the deposition and erosion process, the Cretaceous stratigraphic units of the Edwards Limestone in the San Antonio Region were formed (Rose 1972). These units, shown in Figure 2.1, include the Maverick Basin, Devils River Trend, and San Marcos Platform. The geologic unit located below the Edwards Limestone (Aquifer) is the Glen Rose Formation. This formation consists of marl, shale, and dolomite in its higher elevation parts and massive bedded limestone and dolomite in its lower elevation sections. The upper sections of Glen Rose Formation, which has low to very low permeability, is the lower confining unit of the Edwards Aquifer. The top of the Edwards Aquifer is confined by the Del Rio Clay. This clay strata is relatively impermeable and prevents the vertical movement of water to and from the Edwards Aquifer within the artesian zone.

The Edwards Limestone of the San Antonio Region is extensively faulted as shown in the cross-sections presented in Figures 2.2A

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[5] *Karstification* - Action by water, mainly chemical but also mechanical, that produces features of a karst topography including caves, sink holes, and solution channels.

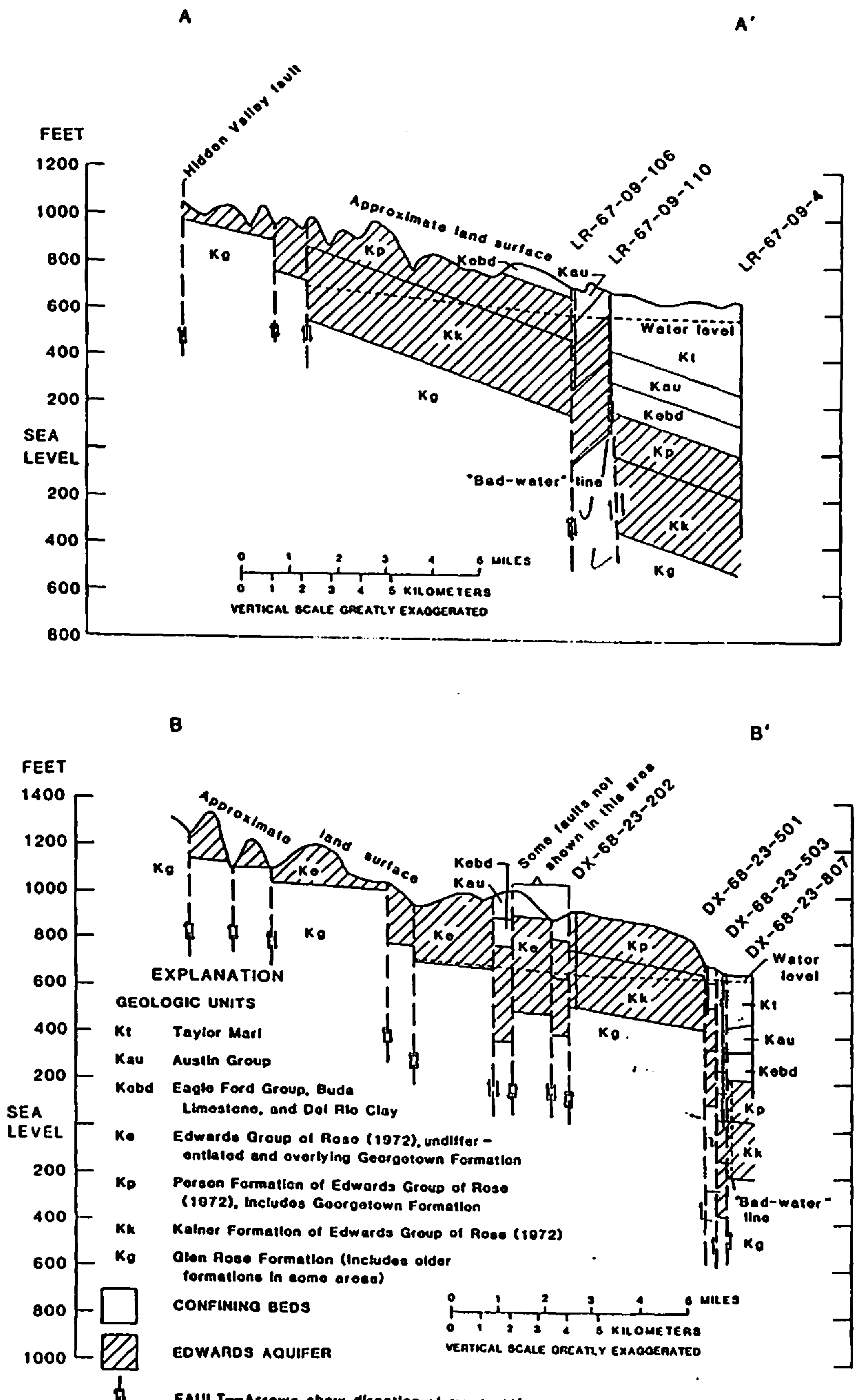

Figure 2.2A Hydrogeologic Cross-Sections for Sections A-A' and B-B'
(Source: USGS 1985)

through 2.2C[6] (USGS 1985). These faults, generally downthrown to the south and southeast, and trending east-northeast (USGS 1986), form a complex system of fault blocks that are differentially rotated and rise toward the San Marcos Platform. Along the strike[7] of some major faults, the displacement across the fault plane is sufficient to disrupt the continuity of the Aquifer. Maximum fault displacement is reported to be 600 ft. at the Comal Springs Fault, with fault displacement averaging 200 ft. to the west in Medina and Uvalde Counties (Klemt et al 1979). Typical geologic cross-sections of the Edwards Aquifer illustrating discontinuity of the Aquifer are shown in Figures 2.3 and 2.4 (TDWR 1979). Some cross faults intersect at acute angles. This complex system of faults include barrier faults. These faults function as controls in the Aquifer which locally divert the direction of ground water flow in the block updip from the barrier fault to a direction parallel to the strike of the fault (Patterson 1990). Where faults faces are contiguous, ground water can flow normal to the fault plane if permeable conditions exist.

The San Antonio Region of the Edwards Aquifer is shown in Figure 2.5. Within this Region (referred to herein as the "Edwards Aquifer" or the "San Antonio Region"), the lower confining bed of the Edwards Aquifer is the upper member of the Glen Rose formation, and the upper confining bed is the Del Rio Clay. As stated above, these confining units typically have very low permeabilities, which effectively impede vertical leakage to or from overlying or underlying water sources. However, vertical fractures and faults are widespread and provide pathways for the movement of water between strata. The San Antonio Region of the Edwards Aquifer is bounded on the north by the up-dip limits of its surface outcrop;

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6 A map showing the cross-section locations presented in Figures 2.2A through 2.2C is contained in Appendix A.

7 *Strike of a fault* - The direction in which a fault line is orientated with respect to true north.

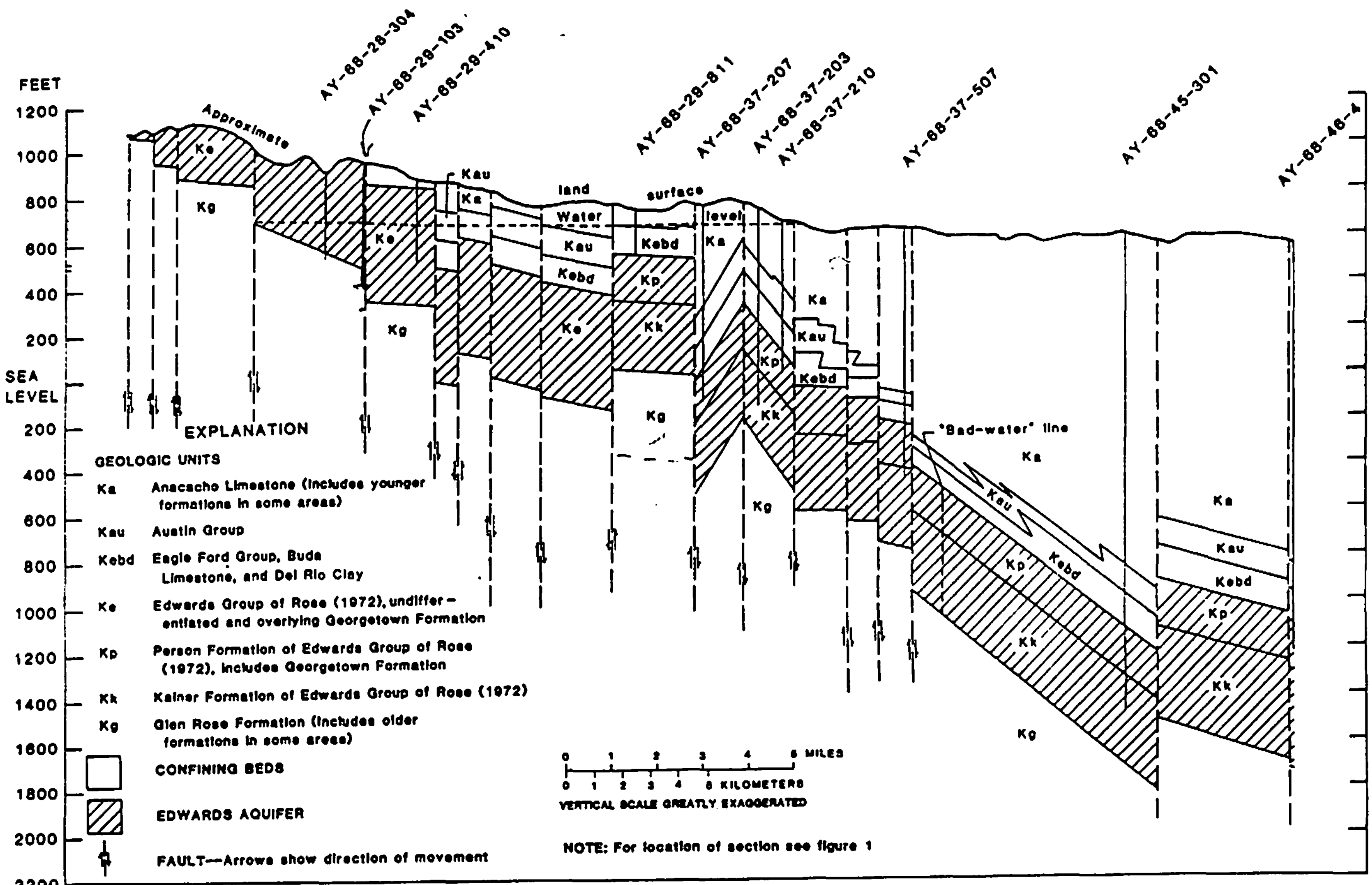

Figure 2.2B Hydrogeologic Cross-Section for Section G-G′
(Source: USGS 1985)

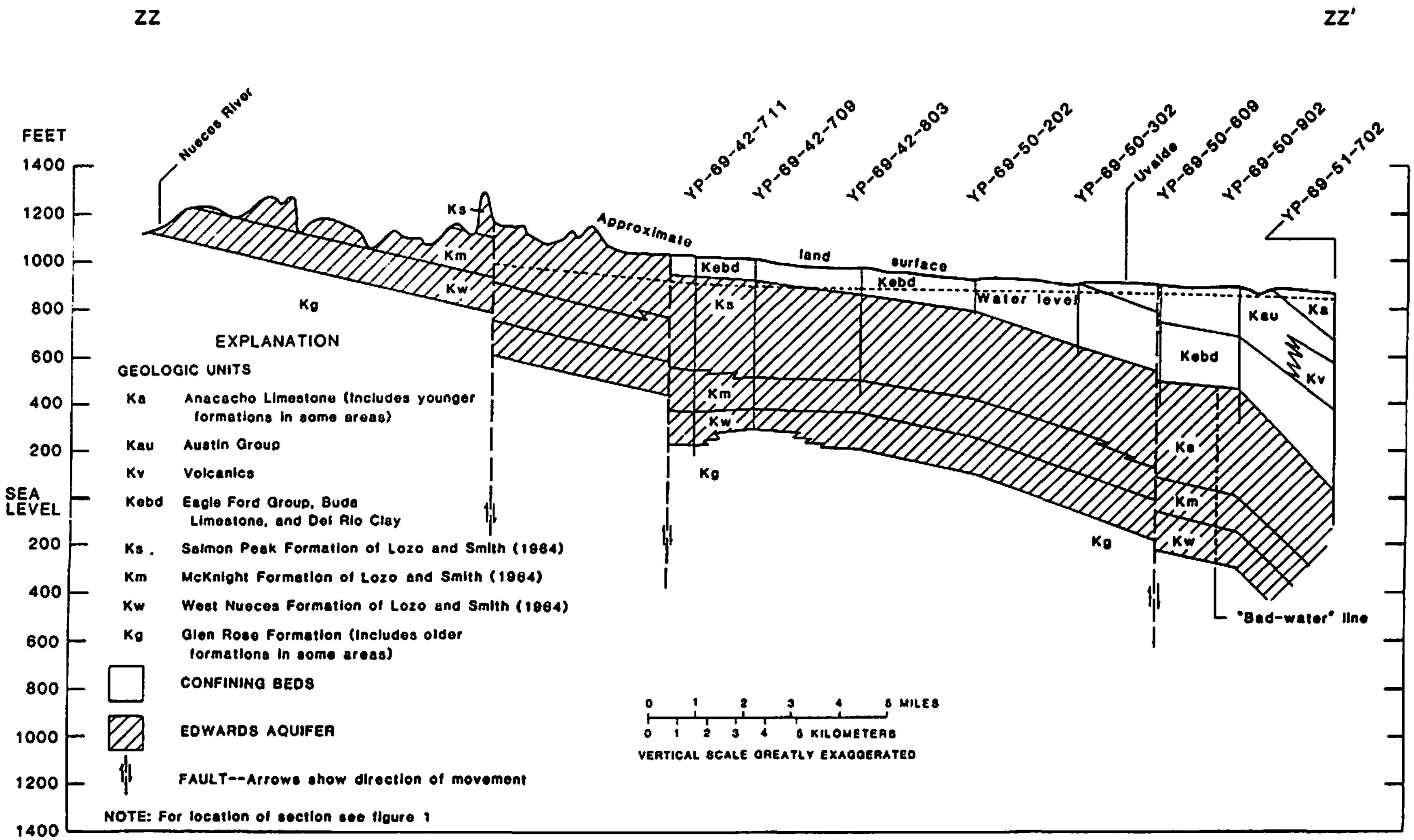

Figure 2.2C Hydrogeologic Cross-Section for Section ZZ-ZZ' (Source: USGS 1988)

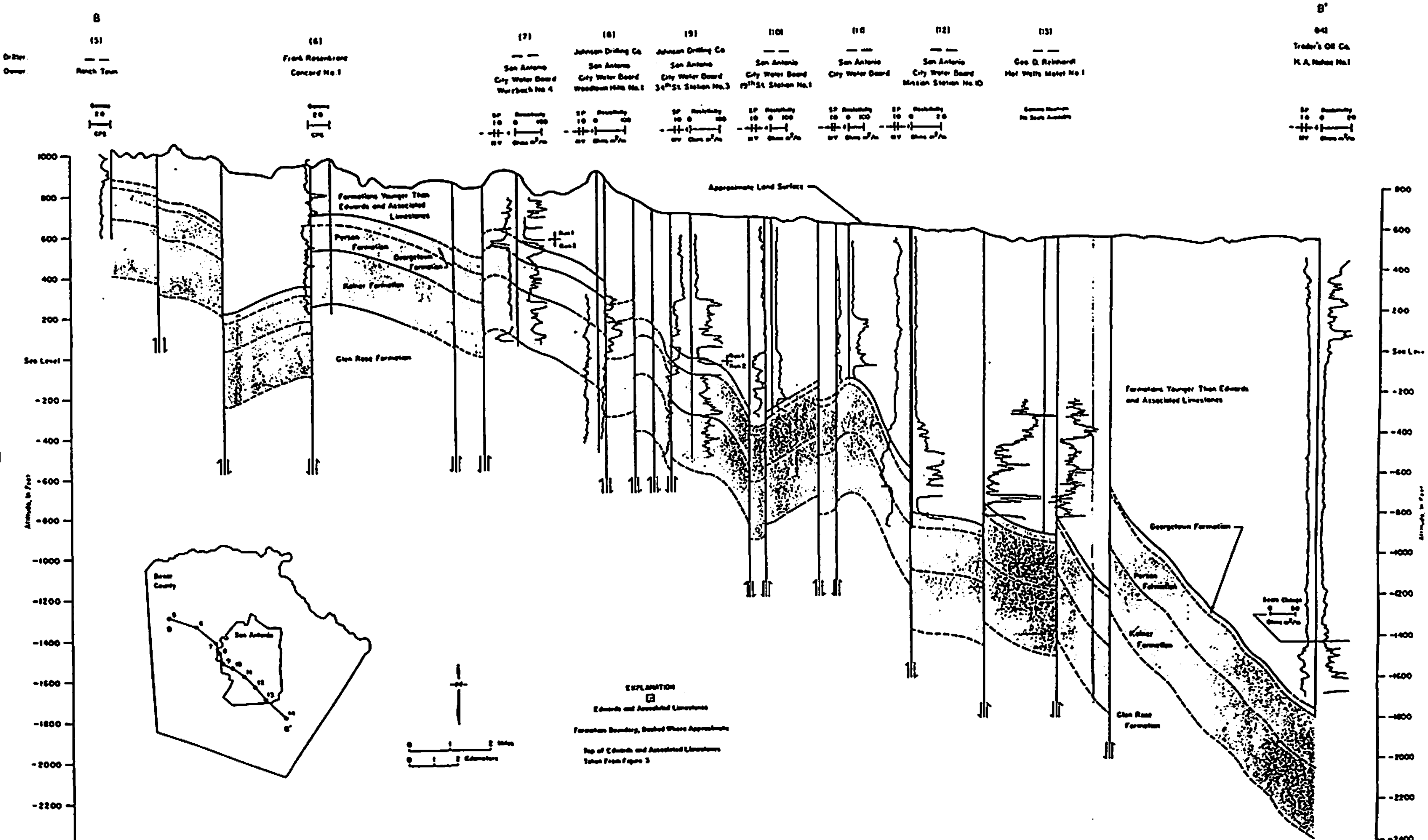

Figure 2.3 Geohydrologic Section B-B'
(Source: TDWR 1979)

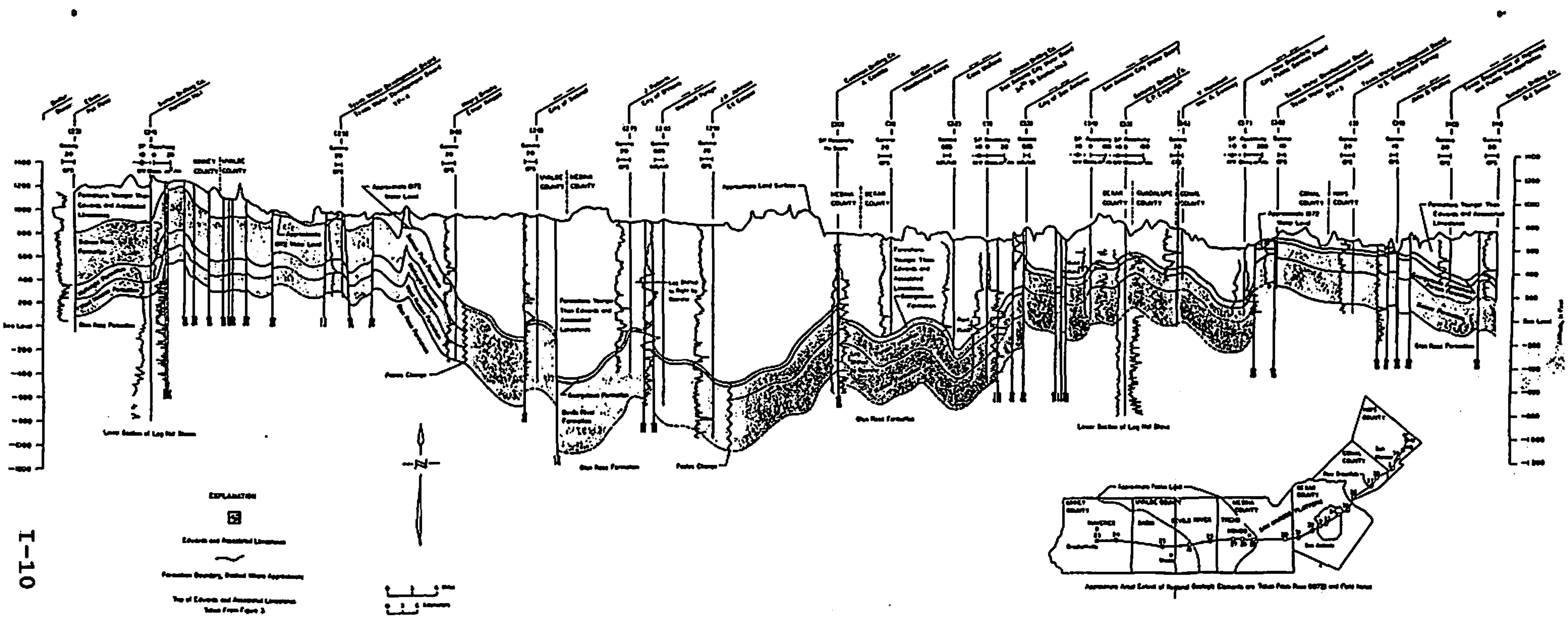

Figure 2.4 Geohydrologic Section D-D′
(Source: TDWR 1979)

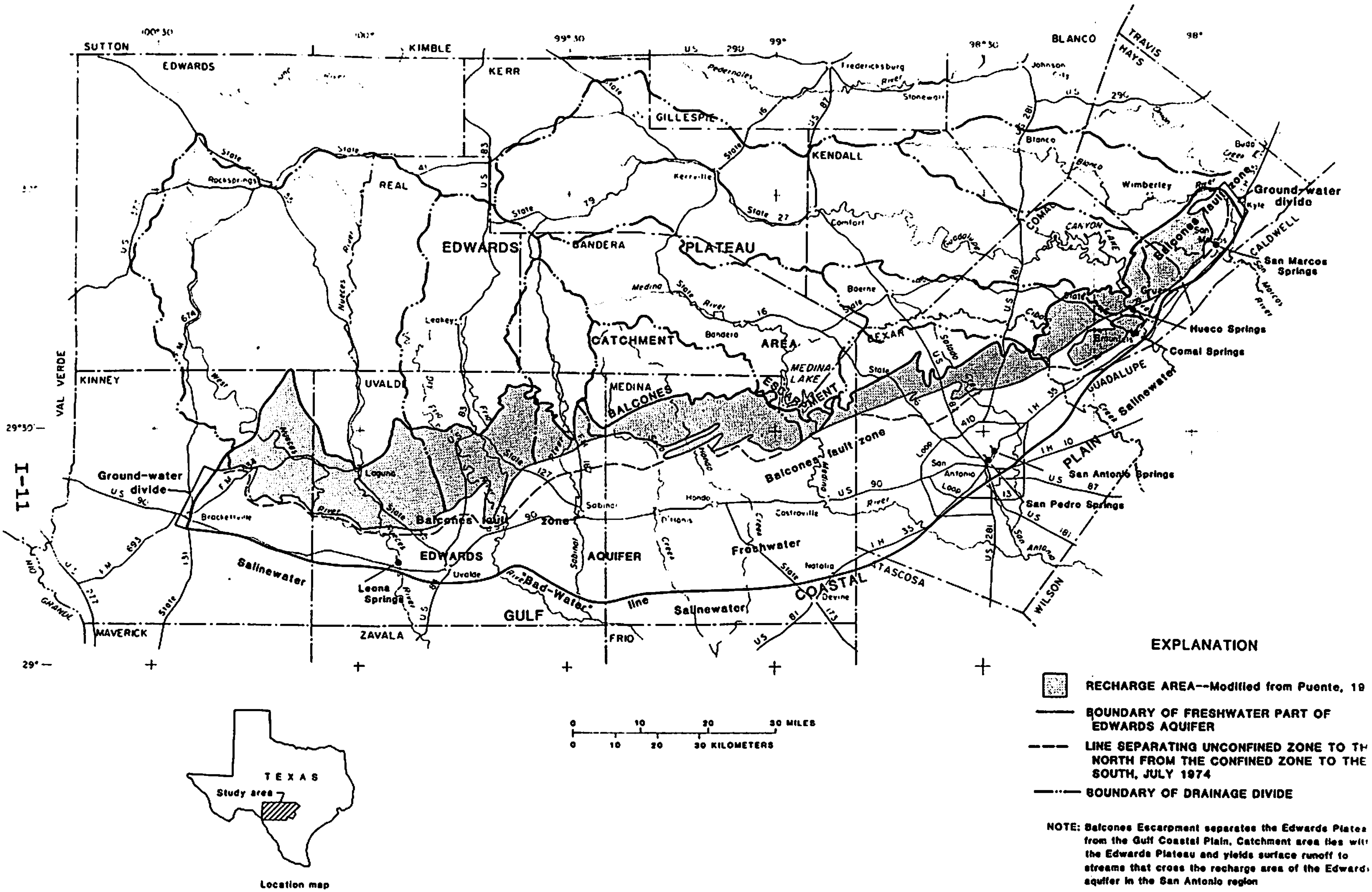

Figure 2.5 Location of the San Antonio, Edwards Aquifer, physiographic regions, and drainage basins that contribute to recharge.
(Source: USGS 1986)

on the west in Kinney County and in the east in Hays County by ground water "highs"; and on the south by the "bad-water" line.

Both unconfined[8] and confined[9] aquifer conditions exist within the Edwards Aquifer. The unconfined portion is located in the northern area of the Aquifer, where the Edwards and Associated Limestones outcrop at the surface in the Recharge Zone (see Figure 2.5). Within this portion, ground water is under water table or free surface conditions. The confined portion of the Aquifer occurs downdip of the recharge zone and extends southward to the bad-water line (see Figure 2.5). Within this area, groundwater is under artesian[10] or "pressure" conditions, since it is confined underneath the Del Rio Clay.

The Edwards Aquifer can be characterized as an underground storage reservoir, similar in nature to other regional subsurface formations such as the Carrizo-Wilcox Aquifer, Trinity Aquifer, Ogallala Aquifer, and Gulf Coast Aquifer. Like other major groundwater formations, the Edwards Aquifer receives surface water recharge and flow within the formation is diffused and highly influenced by barrier faults and geologic features. Also like other major groundwater formations, The Edwards Aquifer is used for beneficial purposes, via well pumpage, and has natural discharge points (springs).

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8 *Unconfined aquifer* - An aquifer in which the water table forms the upper boundary.

9 *Confined aquifer* - An aquifer contained between two rock or other restrictive strata that retard but do not prevent the flow of water to or from an adjacent aquifer.

10 *Artesian aquifer* - An aquifer which is overlain (confined) by an impermeable layer so that the water is under hydrostatic pressure. The water level in an artesian well will rise above the top of the aquifer to the level of the piezometric surface; however, the well may or may not flow at the land surface.

3.0 Recharge Zone: San Antonio Region of the Edwards Aquifer

Recharge to the Edwards Aquifer occurs within the outcrop area (recharge zone) of the Edwards and Associated Limestones (see Figure 2.5), where water quickly seeps from overland flow, streams, creeks, and rivers. All major watercourses in the region, with the possible exception of the Guadalupe River where the potentiometric head in the Edwards Aquifer is higher than the elevation of the river, lose water to the Edwards Aquifer as they traverse recharge zone.

The recharge to the Edwards Aquifer is derived mainly from seepage and infiltration from streams that cross the outcrop of the Aquifer and from direct infiltration of precipitation on the outcrop. Approximately 85% of the recharge (USGS 1986) is from the infiltration of streamflow where streams cross the outcrop area. Most of the remainder of the recharge is by precipitation on the outcrop. Additional recharge occurs to the Edwards Aquifer as cross-formational flow from the Glen Rose Formation particularly where this formation is placed together against the Edwards by faulting (USGS 1986).

The western part of the recharge zone is comprised of the Frio-Sabinal, the Nueces, and the Seco-Hondo-Medina River Basins that collectively have about 60 percent of the total catchment area but supplies about 70 percent of the total recharge to the Aquifer (about 2,950 sq. mi.). The remaining 30 percent of the recharge is derived from the eastern portion of the recharge zone which includes the San Antonio and Guadalupe River basins (EUWD 1988), excluding the Guadalupe River.

Recharge water, originating from surface sources, enters the unconfined zone of the Aquifer. Ground water then flows (by gravity) downndip toward the confined portion of the Aquifer where the water moves to the east and northeast through the artesian zone (confined zone) towards the areas of natural discharge. Major springs that discharge water from the San Antonio Region of the Edwards Aquifer include Leona Springs near Uvalde, San Antonio and San Pedro Springs in San Antonio, Comal Springs at New Braunfels, and San Marcos Springs at San Marcos. In addition, water is pumped from the Aquifer by thousands of wells located in Kinney, Uvalde, Medina, Bexar, Comal, and Hays Counties.

4.0 Artesian Zone: San Antonio Region of the Edwards Aquifer

The confined or artesian portion of the Aquifer occurs downdip of the recharge zone and extends to the bad-water line. Ground water moving from the unconfined recharge zone moves down-gradient into the deeper or confined (artesian) zone of the Aquifer. The flow of ground water (USGS 1986) within the Aquifer (unconfined and confined zones) is profoundly influenced by the presence of faults (Figure 4.1). Faults create extremely anisotropic[11] conditions, acting both as barriers to flow and as conduits for lateral and vertical flow. Displacement of highly permeable beds opposite impermeable beds causes flow to be diverted laterally, parallel to the strike of the faults. Disruption of flow paths in the Aquifer by faulting results in fault blocks with flow systems which are separate from the main flow systems of the Aquifer.

The structural complexity of the San Antonio Region effects water movement in both the confined and unconfined portions of the Aquifer. Researchers (Maclay and Small 1986) have found that in the artesian zone the hydraulic gradients are relatively flat and

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[11] *Anisotropic* - An aquifer is anisotropic if the hydraulic conductivity varies with the direction of measurement at a point within the aquifer.

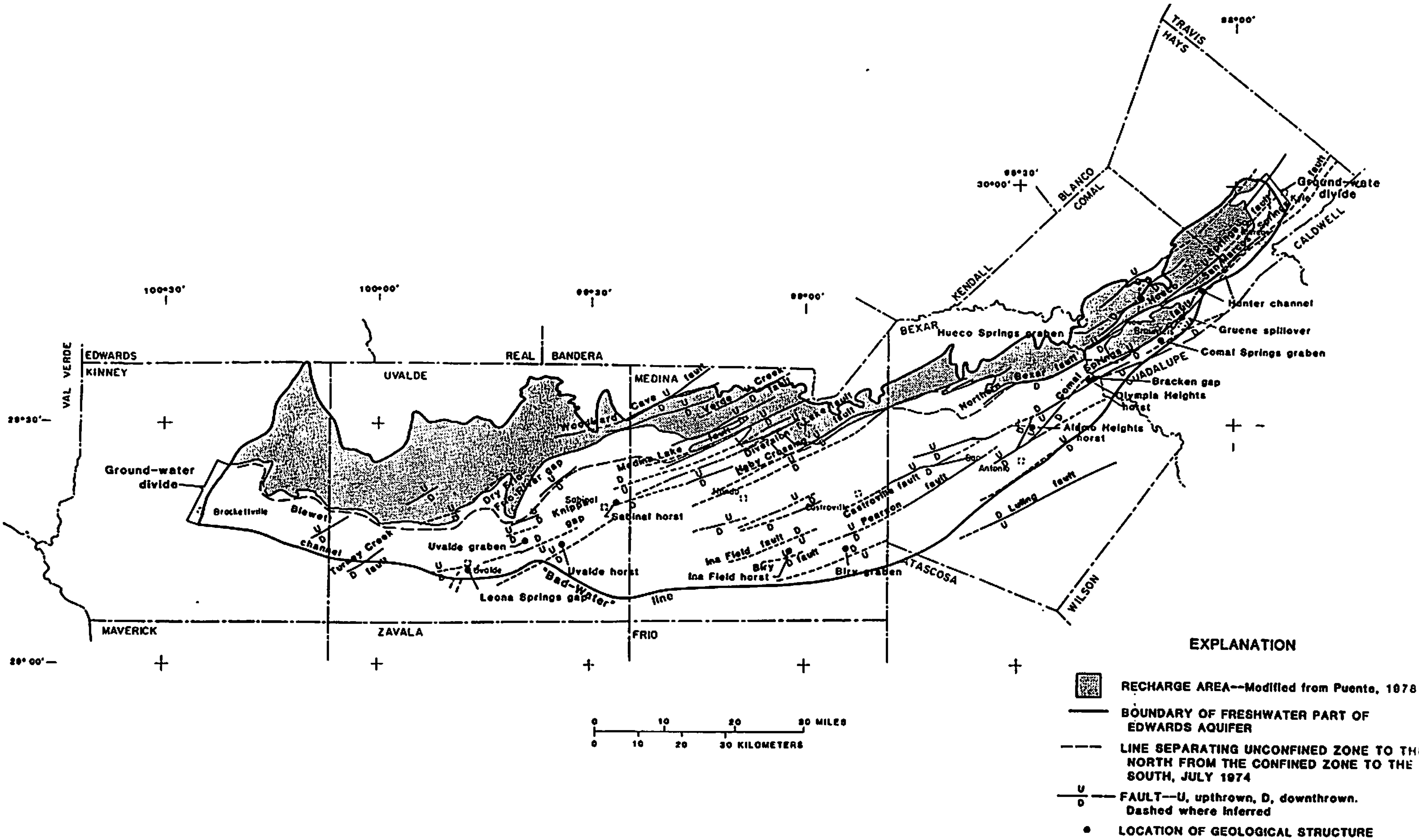

Figure 4.1 Major Faults
(Source: TDWR 1979)

transmissivities[12] are very large when compared to the unconfined (recharge) zone. Aquifer transmissivity values are difficult to quantify, due to the nature and regional characteristics (porosity and permeability) of the Aquifer. An estimate of transmissivities was calculated by Maclay and Small (1986) to be extremely high, ranging from 200,000 sq ft per day to 2 million sq ft per day. Specific yields[13] and storage coefficients[14] have also been estimated from previous work on the Edwards Aquifer. Maclay and Small (1986) estimated the storage coefficient to range from about 0.001 to 0.00001 within a specified yield of 3 percent. Klemt and others (1979) determined storage coefficients ranging from 0.0004 to 0.0008, with estimated specific yields of 6 percent.

The extremely high transmissivity of the artesian zone of the Edwards Aquifer is indicated by (1) very low hydraulic gradients, (2) excellent correlation of water levels among widely spaced wells, (3) large sustained springflows, and (4) uniform quality and temperature of water within the Aquifer (USGS 1986). This capacity to transmit large quantities of water is indicated by the presence of hundreds of wells, some of which produce thousands of gallons of water per minute with the resulting drawdown in water levels of only a few feet.

Researchers (Maclay 1990, Knowles 1990) have projected a wide

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12 *Transmissivity* - The rate at which water is transmitted through a unit width of an aquifer under a unit hydraulic gradient.

13 *Specific yield* - The quantity of water that an aquifer will yield by gravity if it is first saturated and then allowed to drain; the ratio expressed in percentage of the volume of water drained to volume of the aquifer that is drained.

14 *Storage coefficient or coefficient of storage* - A measure of the volume of water available for withdrawal and is defined as the volume of water released from or taken into storage per unit surface area of the aquifer per unit change in the component of head normal to that surface.

variance in the estimated water storage capacity of the Aquifer. Estimates range from 25 million af to 55 million af of water. Of this quantity, it is estimated that 1.5 million af of water can be stored in the Aquifer above the invert elevation (666 ft msl) of Comal Springs. Also, it is estimated that each one foot of the Aquifer represents an average of about 25,000 to 50,000 af of water storage (Maclay 1990).

5.0 Groundwater Storage

Storage in a saturated confined aquifer is defined as the volume of water that the Aquifer releases from storage per unit surface area of the Aquifer per unit decline in the hydraulic head. As the pressure in the Aquifer is reduced such as by pumping water from a well and yielding water, changes in pressure in a confined aquifer produce only very small changes in the volume available for the storage of water. In the unconfined parts of the Aquifer, the level of saturation changes as the water table moves up and down. The amount of water that the unconfined aquifer yields is the amount of water that will drain from the pore spaces. There is no compression of the Aquifer framework involved and the volume of water yielded from a given volume of aquifer rock, under unconfined conditions, is as much as five orders of magnitude greater than for an equivalent volume of rock under confined conditions (Patterson 1991).

Water stored between the historical range in water levels in the Edwards Aquifer is contained primarily within the unconfined zone (USGS 1986). Changes in water levels in the unconfined zone represent significant changes in the volume of water stored in the Aquifer, as compared to changes in water levels within the confined zone represent only very small changes in volume of water stored within the Aquifer. Because the area of the unconfined zone represents a significant part of the Aquifer, a very large percentage of the water released from storage for the historical range in water levels comes from this zone.

The quantity of water temporarily stored with the unconfined zone between recharge events is affected strongly by geologic structure (USGS 1986). A system of parallel faults are oriented in a manner to obstruct the flow of ground water from the unconfined zone to the confined zone (Figure 5.1). This results in very slow water movement from the unconfined zone to the confined zone, thus causing the quantity of water in storage in the unconfined zone to remain for longer periods.

As the water table drops in the unconfined part of the Aquifer, sections of the Aquifer in the recharge zone may be dewatered. Further declines in the water table could cause confined parts of the Aquifer to come under unconfined conditions, with a resulting change in storage capacity. The volume of the artesian or confined zone represents 30-40 percent of the total volume of the Aquifer. Therefore, a very large amount of water released from the Aquifer comes from storage (i.e. 60-70 percent) in the unconfined zone. The quantity of water retained in the artesian (confined) zone after a recharge event is affected strongly by the geologic structure of the Aquifer. Faults can act as barriers to reduce the flow of water moving from the unconfined zone to the artesian zone, thereby allowing a greater volume of water to remain in the unconfined zone for a longer period of time and with a slow lowering of water levels. Based on an analyses of the faulting system, water levels and modeling of generalized groundwater movement in the Aquifer, the USGS (1986) segmented or divided the unconfined zone of the San Antonio Region into the following four distinct areas or pools (Figure 5.2):

Western Storage Unit: This unit lies in Kinney and Uvalde County and includes the unconfined zone west of the Woodward Cave Fault

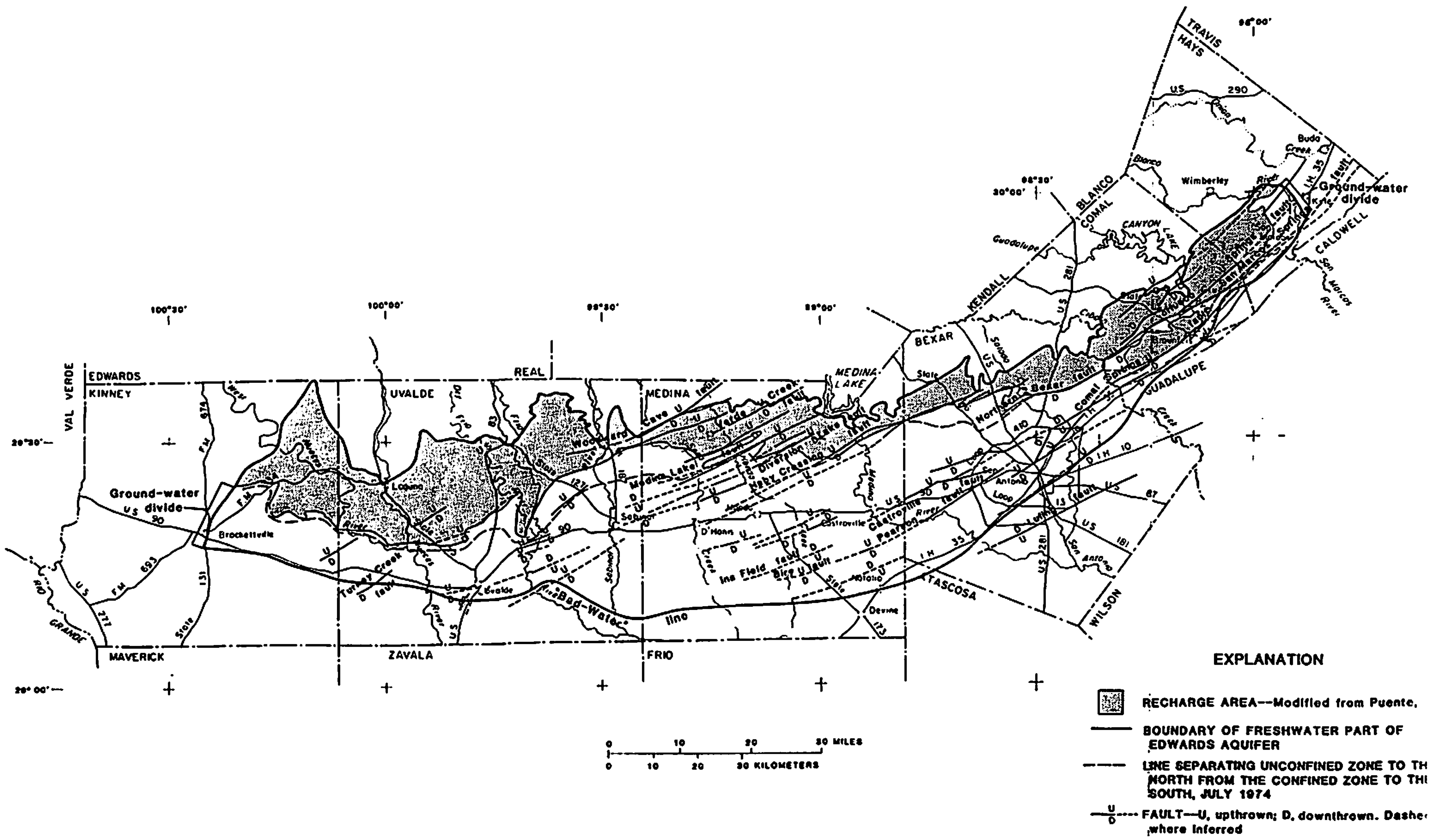

Figure 5.1 Locations of selected geologic structures restricting and conveying ground water. (Source: TDWR 1979)

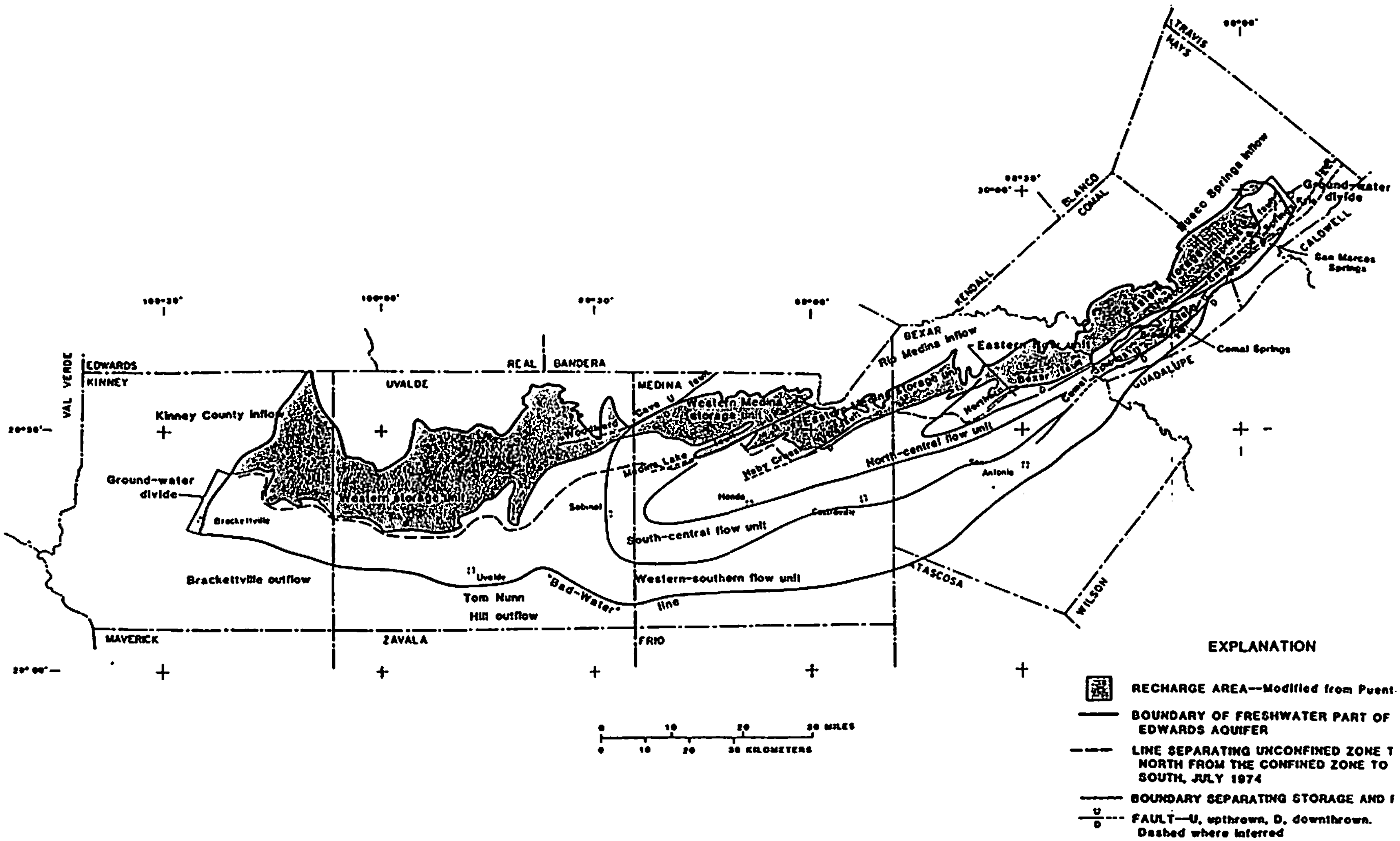

Figure 5.2 Storage and flow units and areas of flow across external boundaries.
(Source: TDWR 1979)

and the complex of faults in the Uvalde area that is an extension of the Medina Lake Fault. The Eastern limit is the topographic divide between Sabinal River and Seco Creek, located in eastern Uvalde County and western Medina County. Most of the recharge comes from losses of flow in the Nueces, West Nueces, Frio, Dry Frio, and Sabinal Rivers. This unit has the largest storage capacity of the four unconfined units and is the most remote from the major discharge points.

Western Medina Storage Unit: This unit includes the unconfined zone between the western storage unit and the Medina Lake Fault. Most of the recharge comes from Hondo and Seco Creeks and from Medina Lake.

Eastern Medina Storage Unit: This unit includes the unconfined zone between the western-Medina storage unit and generally along the Haby Crossing Fault. The unit receives most of its recharge from the Medina River, Medina Lake and several-small area creeks.

Eastern Storage Unit: This unit includes the unconfined zone east of the eastern-Medina storage unit. Its storage is strongly influenced by the northern Bexar County Fault and the Hueco Springs Fault. The recharge is primarily from several small-area streams, especially Cibolo Creek.

6.0 Groundwater Movement

The USGS (1986) performed extensive studies to evaluate and determine groundwater movement within the Edwards Aquifer. In the 1986 study, the USGS defined flow units as an area of the Aquifer that includes a storage unit and a zone that transmits water from the storage unit to major points of discharge (i.e., wells and springs). Based on the USGS study, four flow units were defined (see Figure 5.2):

Western-Southern Flow Unit: The source of water for this flow unit is the Western Storage Unit. Due to Aquifer geometry, water moves through this flow unit taking the southernmost route from the area of recharge to points of discharge that extend to Comal Springs. For the most part, water moves through the western part of an opening (Knippa Gap) in the Medina Lake Fault-Uvalde Horst[15] complex near Sabinal and a graben[16] in the Uvalde area. Most or all of this flow is withdrawal by irrigation wells in Medina County and by the City of San Antonio.

South-Central Flow Unit: The source of water for this unit is the Western Medina Storage Unit. Within this flow unit, the Medina Lake Fault functions as a major barrier of groundwater flow and diverts the water to the southwest and moves through the eastern part of the Knippa Gap near Sabinal that is described above. After the water moves past the opening it turns sharply to the east. The major discharge points are irrigation wells in Medina County and municipal wells in San Antonio and Comal Springs.

North-Central Flow Unit: The Eastern Medina Storage Unit provides the source of water to the North-Central Flow Unit. Much of the flow is diverted to the southwest by the Haby Crossing Fault before turning eastward. Major discharge points are municipal wells in San Antonio and Comal and San Marcos Springs. This flow unit merges with the two southern (i.e. Western-Southern and South Central) flow units at Comal Springs.

Eastern Flow Unit: The source of water for this unit is the

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15 *Horst* - A raised rock mass located between two faults.

16 *Graben* - A lowered rock mass located between two faults.

eastern storage unit. Water in the western part of the unit is diverted to the southwest by barrier faults, but in a short distance turns to the northeast. During normal Aquifer water levels, most of the flow from this unit discharges at San Marcos Springs.

Ground water velocities in the Edwards Aquifer have been estimated or measured by several different methods (TWDB 1986). A gross estimate can be made for the confined freshwater zone on the basis of the estimated total volume of water stored in the confined zone of the aquifer. The TWDB (1986) estimates that the total volume of water in the confined zone of the Edwards Aquifer is 19.5 million acre-feet (TWDB 1986), and that the approximate average annual recharge is 550,000 acre-feet. Using these TWDB estimates, the residence time for water in the confined zone is about 35-years (19,500,000 af / 550,000 af). The TWDB also estimates that the average distance an increment of water from the confined aquifer west of Comal Springs would travel through the confined aquifer to Comal Springs during the 35 years is about 65 miles (TWDB 1986). Based on these values the estimated ground-water velocity is about 27 ft/day (65 mi x 5,280 ft/mi / 35 yrs / 365 d/yr). However, a more recent study performed by the Bureau of Economic Geology (BEG 1993), UT at Austin, in 1993, estimates that the confined zone contains approximately 156.5 million acre-feet of water. Using this higher confined storage volume estimate yields a residence time for water of about 284.5 years (156,500,000 af / 550,000 af), and a ground-water velocity of about 3.3 ft/day (65 mi x 5,280 ft/mi / 284.5 yrs / 365 d/yr). Both calculations strongly indicates that the Edwards Aquifer is truly characteristic of a ground water formation with flow through restrictive porous media.

As described above, the southern boundary of the confined portion of the Edwards Aquifer is the "bad-water" line. This line is set where the concentration of 1,000 mg/l (milligrams per liter) of dissolved solids occurs in the Aquifer. The concentrations of dissolved solids at given sampling points vary slightly with time, but the lateral position of the "bad-water" line has not significantly shifted over time (TWDB 1986). In addition, there is no indication that the "bad-water" line shifted significantly, even during the 1950's drought when Comal Springs went dry. The difference with water quality between the bad water zone and the fresh water zone of the Edwards Aquifer occurs because there is little or no circulation of water in the bad water zone. Water has resided in the bad water zone for such a length of time that minerals have dissolved from the rocks in large enough quantities to produce high levels of dissolved solids. Given the extremely slow movement of water within the bad water zone, reduction in head of the in the fresh water zone should normally result in only minor and localized inflow of saline water.

In general, the aquifer in the saline-water zone (i.e. bad water zone) has considerable less capacity to transmit water than the aquifer in the freshwater zone because an integrated network of cavernous zones has not be developed by circulation of freshwater. As a comparison, the transmissivity of the saline water zone (668 ft^2/d) is 200 times less than the transmissivity of the freshwater zone (134,000 ft^2/d) for the freshwater zone (USGS 1986). In addition, faults significantly disrupt the lateral continuity of the geologic formations at places in Bexar County, impeding or preventing flow in faulted areas. These factors serve to restrict lateral ground water flow across the "bad-water" line. This is further confirmed by an examination of Aquifer cross-sections which transect the confined and "bad-water" zones. Approximately 30 such cross-sections were prepared by T. A. Small (USGS 1986). The USGS (1986) found that some undetermined amount (but relatively small due to low hydraulic gradients and low saline-water zone transmissivities) flow probably moves from the freshwater to the saline water part of the aquifer in Kinney, Uvalde and western Medina Counties and from the saline-water to freshwater part of the aquifer in Hays and Travis Counties. It should be noted that for purposes of mathematical modeling, the TWDB treats the "bad-water" line as an impermeable aquifer boundary, with the exception of a small area in southeast Uvalde County.

Based on a review of the literature and various mathematical modeling studies, regional Edwards Aquifer water quality degradation will not occur as a result of updip movement of the "bad-water" line. This line has limited opportunity for updip movement and if it does move up-dip due to extreme conditions in the fresh water zone, its movement will be very limited, not causing a threat to regional water quality.

The Edwards Aquifer also has some limited hydrologic communication with the underlying and "poorer" water quality Glen Rose Aquifer (EUWD 1995). Because of faulting, the Edwards Aquifer in many areas over the 180-mile length between the two ground-water divides is juxtaposed[17] to the Glen Rose Aquifer. Both at the surface and a depth, and therefore, the Glen Rose may discharge directly into the Edwards Aquifer. Regionally, underflow from the Glen Rose Formation to the Edwards Aquifer along the Balcones fault zone can occur by ground water moving laterally in a down-gradient direction within the Glen Rose and entering the Edwards aquifer through fault planes. The amount of ground water in transit is dependent on the length of the line of entry (fault plane) through which water enters the Edwards Aquifer, the water level gradient across the fault plane from the Glen Rose to the Edwards Aquifer, and the effective transmissivity for the Glen Rose Aquifer upgradient and along this line. The EUWD (1995) estimates that the approximate range of total Glen Rose underflow to the Edwards Aquifer would be about 2,700 to about 11,400 af/yr in the San Antonio Region. As compared to the total Edwards Aquifer water balance, these

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17 *Juxtaposed* - Formations or strata that lie next to or abut each other.

estimates indicate that the Glen Rose contributes less than 2 percent of the total water budget during average recharge conditions. The EUWD (1995) also estimated that, based on geochemical models, the chemical content of water representative of the Edwards Aquifer in the San Antonio Region include a small amount, less than 1 percent Glen Rose water (EUWD 1995). Thus, local communication between the formations occurs, but without significant impact on overall water quality of the Edwards Aquifer, due to the low transmissivity of the Glen Rose.

7.0 Historical Recharge

Table 7.1 lists the estimated historical annual recharge (USGS 1995) to the Edwards Aquifer from 1934 to 1991 and is presented in Figure 7.1. Estimated annual historical recharge for the Aquifer varied from 43,350 af in 1956 to 2,063,986 af in 1987. The average annual historical recharge for this period was 676,666 af.

Annual recharge by Edwards Aquifer Storage Unit, as identified above, is presented in Table 7.2 and shown in Figure 7.2. For the 1934 through 1994 period of record, recharge for the Western Storage Unit, which receives inflow from the Nueces, Frio and Sabinal River Basins, averaged 304,490 af/yr. Recharge to the Western Medina Storage Unit averaged 162,267 af/yr for the same period. This storage unit receives inflow from the Seco and Hondo Creek Basins and from Medina Lake (USGS 1986). The Eastern Medina Storage Unit received an average recharge from the Medina-Cibolo Creek Area of 67,466 af/yr for the 1934 through 1991 period. Recharge to the Eastern Storage Unit, which receives recharge from Cibolo and Comal Creek Basins, averaged 103,604 af/yr for the same period. The Blanco River, which provides recharge directly to the San Marcos Springs area, had an average annual recharge of 38,839 af/yr. Overall the Western Storage Unit received 45 percent of the

TABLE 7.1

TOTAL ANNUAL RECHARGE BY CONTRIBUTING WATERSHED TO THE EDWARDS AQUIFER - SAN ANTONIO REGION (ACRE-FEET/YEAR)

(SOURCE: U.S. GEOLOGICAL SURVEY, 1995)

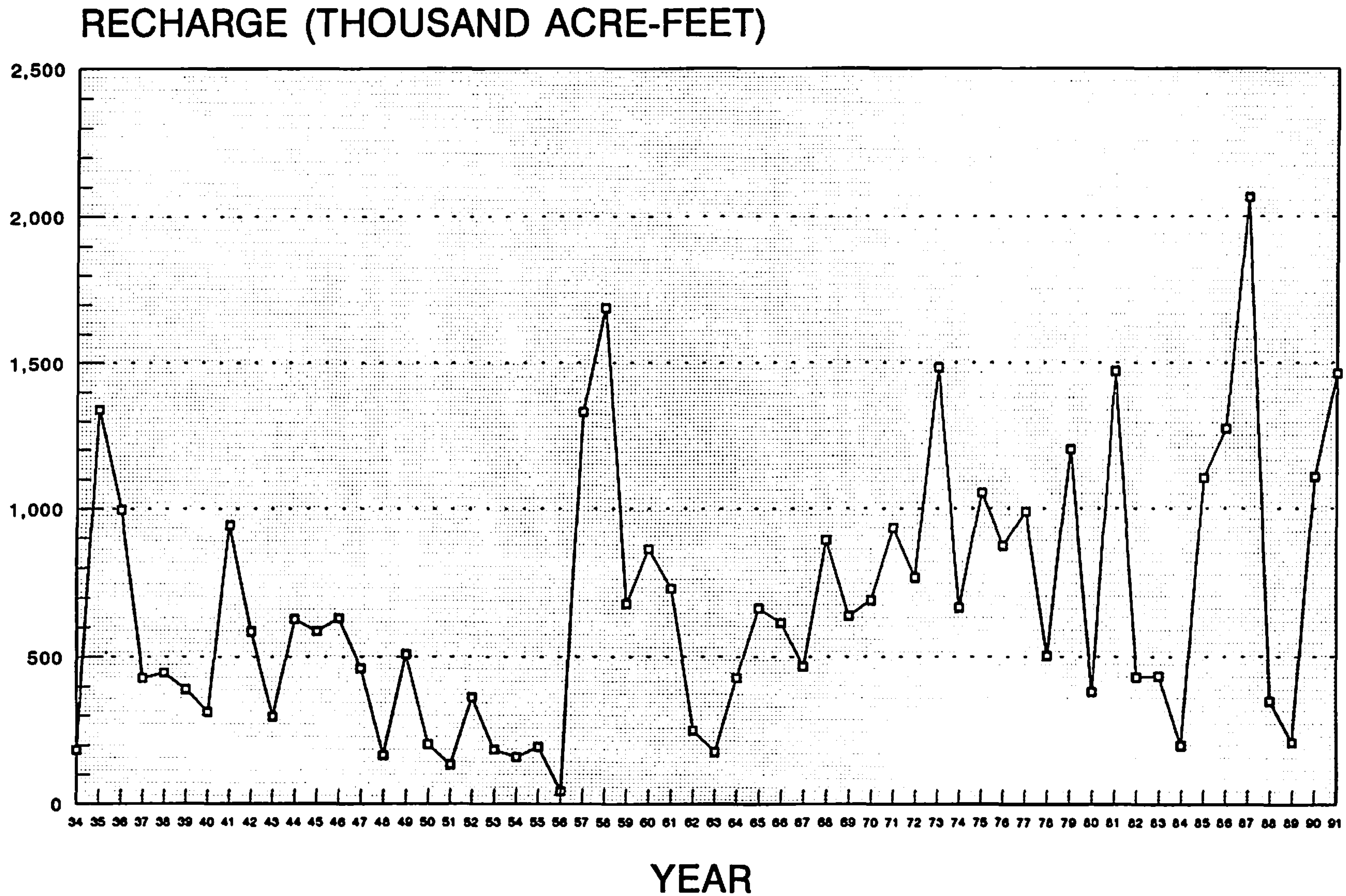
YEAR	NUECES RIVER BASIN	FRIO RIVER BASIN	SABINAL CREEK BASIN	SECO-HOND CREEK BASINS	MEDINA RIVER BASIN	MEDINA-CIBOLO CR. AREA	CIBOLO CREEK BASIN	COMAL CREEK BASIN	BLANCO RIVER BASIN	TOTAL ANNUAL RECHARGE
1934	8,600	27,901	11,844	19,902	46,500	21,000	11,844	16,555	19,798	183,944
1935	411,310	192,223	136,861	166,201	71,100	138,201	136,861	45,841	39,800	1,338,398
1936	176,490	157,390	129,773	142,899	91,600	108,899	129,773	16,325	42,702	995,851
1937	28,800	75,690	49,396	61,299	80,400	47,800	49,396	14,503	21,200	428,484
1938	63,520	69,278	34,704	54,100	65,500	46,200	34,704	42,102	36,400	446,508
1939	227,000	49,505	7,546	33,100	42,400	9,303	7,546	2,059	11,100	389,559
1940	50,400	60,313	27,418	56,600	38,800	29,299	27,418	3,383	18,801	312,432
1941	89,900	151,857	142,692	138,999	54,100	116,300	142,692	48,509	57,798	942,847
1942	103,500	95,091	61,360	84,400	51,700	66,900	61,360	32,240	28,600	585,151
1943	36,500	42,310	35,096	33,800	41,500	29,500	35,096	23,210	20,099	297,111
1944	64,109	75,967	90,983	74,303	50,500	72,500	90,983	61,515	46,201	627,061
1945	47,300	71,086	89,355	78,602	54,800	79,599	89,355	40,546	35,701	586,344
1946	80,900	54,215	90,179	51,999	51,400	105,100	90,179	65,122	40,699	629,793
1947	72,400	77,670	55,543	45,200	44,000	55,498	55,543	23,961	31,600	461,415
1948	41,100	25,606	13,846	20,200	14,800	17,501	13,846	6,057	13,200	166,156
1949	166,000	86,134	32,090	70,300	33,000	41,800	32,090	23,809	23,500	508,723
1950	41,500	35,496	16,444	27,000	23,600	17,298	16,444	8,161	17,400	203,343
1951	18,300	28,412	1,924	26,400	21,100	15,300	1,924	10,579	10,600	134,539
1952	27,900	15,695	91,284	30,200	25,400	50,100	91,284	11,017	20,700	363,580
1953	21,400	15,108	20,837	4,400	36,200	20,101	20,837	21,467	24,900	185,250
1954	61,324	31,600	5,400	11,900	25,300	4,190	5,400	4,600	10,700	160,414
1955	127,972	22,100	3,000	7,700	16,500	4,290	3,000	300	9,500	194,362
1956	15,600	4,200	1,200	3,600	6,350	2,000	1,200	1,000	8,200	43,350
1957	108,600	133,600	252,900	129,520	55,600	175,649	252,900	145,000	76,500	1,330,269
1958	266,700	300,000	201,000	294,900	95,500	190,910	201,000	67,700	70,702	1,688,412
1959	109,600	158,900	49,800	96,700	94,700	57,354	49,800	28,100	33,600	678,554
1960	88,700	128,100	101,600	126,980	104,000	89,741	101,600	58,500	62,400	861,621
1961	85,200	151,300	69,600	105,400	88,300	69,300	69,600	41,200	49,400	729,300
1962	47,400	46,600	15,700	23,499	57,300	16,700	15,700	9,000	18,900	250,799
1963	39,700	27,000	11,500	10,300	41,900	9,300	11,500	9,800	16,200	177,200
1964	126,100	57,100	32,400	61,300	43,300	35,800	32,400	18,700	22,200	429,300
1965	97,899	83,000	63,200	104,000	54,600	78,800	63,200	52,100	66,700	663,499

TABLE 7.1 - CONTINUED

TOTAL ANNUAL RECHARGE BY CONTRIBUTING WATERSHED TO THE EDWARDS AQUIFER - SAN ANTONIO REGION (ACRE-FEET/YEAR)
(SOURCE: U.S. GEOLOGICAL SURVEY, 1995)

YEAR	NUECES RIVER BASIN	FRIO RIVER BASIN	SABINAL CREEK BASIN	SECO-HOND CREEK BASINS	MEDINA RIVER BASIN	MEDINA-CIBOLO CR. AREA	CIBOLO CREEK BASIN	COMAL CREEK BASIN	BLANCO RIVER BASIN	TOTAL ANNUAL RECHARGE
1966	169,200	134,000	35,900	78,200	50,500	44,500	35,900	30,616	34,600	613,416
1967	82,235	137,900	30,480	64,800	44,650	30,200	30,480	26,800	19,000	466,545
1968	130,738	176,000	73,200	198,670	59,900	83,100	73,200	47,400	49,300	891,508
1969	119,739	113,800	57,700	84,230	55,400	60,200	57,700	42,200	46,600	637,569
1970	112,612	141,900	64,866	81,610	68,000	68,800	64,866	48,933	39,500	691,087
1971	263,400	212,400	46,968	155,570	68,700	81,400	46,968	35,432	22,200	933,038
1972	108,400	144,600	59,394	154,590	87,900	74,310	59,394	44,806	33,400	766,794
1973	190,600	256,900	120,669	286,380	97,600	237,195	120,669	91,031	82,200	1,483,244
1974	91,120	135,640	43,846	115,258	96,200	68,116	43,846	33,078	39,090	666,194
1975	71,815	143,627	127,446	195,943	93,450	138,816	127,446	68,284	85,866	1,052,693
1976	150,708	238,551	46,637	181,980	94,500	47,932	46,637	7,622	57,890	872,457
1977	102,892	192,964	99,008	159,494	77,735	97,922	99,008	92,568	66,718	988,309
1978	69,863	73,144	30,637	103,660	76,700	49,547	30,637	41,835	26,272	502,295
1979	128,431	201,391	152,596	203,095	89,400	85,370	152,596	113,696	75,202	1,201,777
1980	58,640	85,616	17,392	25,319	88,300	18,771	17,392	37,784	31,814	381,028
1981	205,046	365,180	128,095	252,109	91,300	164,979	128,095	68,728	67,303	1,470,835
1982	19,347	123,367	29,463	90,919	76,800	22,589	29,463	15,395	23,461	430,804
1983	79,194	85,980	34,279	42,894	74,350	31,885	34,279	28,258	23,155	434,274
1984	32,421	40,425	9,754	18,120	43,900	11,316	9,754	7,112	25,970	198,772
1985	105,855	186,936	150,956	148,538	64,700	136,737	150,956	108,236	50,691	1,103,605
1986	188,415	192,769	161,289	173,583	74,705	170,221	161,289	106,065	44,472	1,272,808
1987	308,507	473,328	171,022	405,527	90,425	229,339	171,022	99,924	114,874	2,063,968
1988	59,233	117,934	11,313	24,878	69,909	12,586	11,313	17,084	25,473	349,723
1989	52,577	52,645	3,523	13,497	46,867	4,562	3,523	8,795	23,565	209,554
1990	479,293	255,038	39,136	131,222	53,989	35,934	39,136	32,662	41,283	1,107,693
1991	325,155	421,009	57,743	315,250	52,800	84,477	57,743	51,967	96,939	1,463,083
ANNUAL AVERAGE	114,779	125,060	64,652	101,742	60,525	67,466	64,652	38,953	38,839	676,666

FIGURE 7.1
GRAPH OF ANNUAL RECHARGE TO THE EDWARDS AQUIFER - SAN ANTONIO REGION FOR 1934 THROUGH 1991



INCLUDES THE NUECES, FRIO, SABINAL, SECO, HONDO, MEDINA, CIBOLO, COMAL, AND BLANCO WATERSHEDS
SOURCE: U.S. GEOLOGICAL SURVEY, 1995

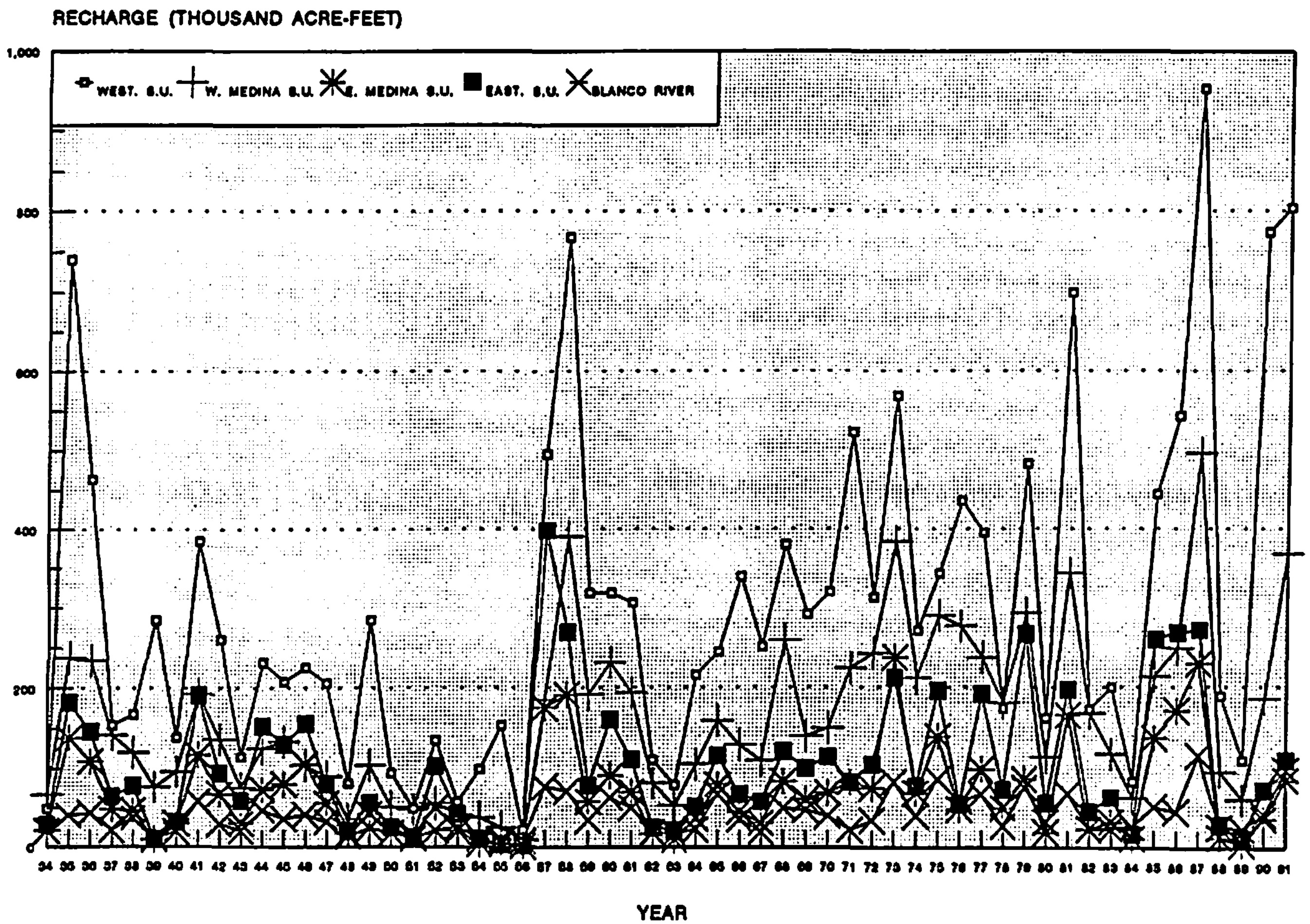
TABLE 7.2
TOTAL ANNUAL RECHARGE BY CONTRIBUTING FLOW UNIT TO THE EDWARDS AQUIFER - SAN ANTONIO REGION (ACRE-FEET/YEAR)
(SOURCE: U.S. GEOLOGICAL SURVEY, 1995)

YEAR	WESTERN STORAGE UNIT	WESTERN MEDINA ST. UNIT	EASTERN MEDINA ST. UNIT	EASTERN STORAGE UNIT	BLANCO RIVER BASIN	TOTAL ANNUAL RECHARGE
1934	48,345	66,402	21,000	28,399	19,798	183,944
1935	740,394	237,301	138,201	182,702	39,800	1,338,398
1936	463,653	234,499	108,899	146,098	42,702	995,851
1937	153,886	141,699	47,800	63,899	21,200	428,484
1938	167,502	119,600	46,200	76,806	36,400	446,508
1939	284,051	75,500	9,303	9,605	11,100	389,559
1940	138,131	95,400	29,299	30,801	18,801	312,432
1941	384,449	193,099	116,300	191,201	57,798	942,847
1942	259,951	136,100	66,900	93,600	28,600	585,151
1943	113,906	75,300	29,500	58,306	20,099	297,111
1944	231,059	124,803	72,500	152,498	46,201	627,061
1945	207,741	133,402	79,599	129,901	35,701	586,344
1946	225,294	103,399	105,100	155,301	40,699	629,793
1947	205,613	89,200	55,498	79,504	31,600	461,415
1948	80,552	35,000	17,501	19,903	13,200	166,156
1949	284,224	103,300	41,800	55,899	23,500	508,723
1950	93,440	50,600	17,298	24,605	17,400	203,343
1951	48,636	47,500	15,300	12,503	10,600	134,539
1952	134,879	55,600	50,100	102,301	20,700	363,580
1953	57,345	40,600	20,101	42,304	24,900	185,250
1954	98,324	37,200	4,190	10,000	10,700	160,414
1955	153,072	24,200	4,290	3,300	9,500	194,362
1956	21,000	9,950	2,000	2,200	8,200	43,350
1957	495,100	185,120	175,649	397,900	76,500	1,330,269
1958	767,700	390,400	190,910	268,700	70,702	1,688,412
1959	318,300	191,400	57,354	77,900	33,600	678,554
1960	318,400	230,980	89,741	160,100	62,400	861,621
1961	306,100	193,700	69,300	110,800	49,400	729,300
1962	109,700	80,799	16,700	24,700	18,900	250,799
1963	78,200	52,200	9,300	21,300	16,200	177,200
1964	215,600	104,600	35,800	51,100	22,200	429,300
1965	244,099	158,600	78,800	115,300	66,700	663,499

TABLE 7.2 - CONTINUED
TOTAL ANNUAL RECHARGE BY CONTRIBUTING FLOW UNIT TO THE EDWARDS AQUIFER - SAN ANTONIO REGION (ACRE-FEET/YEAR)
(SOURCE: U.S. GEOLOGICAL SURVEY, 1995)

YEAR	WESTERN STORAGE UNIT	WESTERN MEDINA ST. UNIT	EASTERN MEDINA ST. UNIT	EASTERN STORAGE UNIT	BLANCO RIVER BASIN	TOTAL ANNUAL RECHARGE
1966	339,100	128,700	44,500	66,516	34,600	613,416
1967	250,615	109,450	30,200	57,280	19,000	466,545
1968	379,938	258,570	83,100	120,600	49,300	891,508
1969	291,239	139,630	60,200	99,900	46,600	637,569
1970	319,378	149,610	68,800	113,799	39,500	691,087
1971	522,768	224,270	81,400	82,400	22,200	933,038
1972	312,394	242,490	74,310	104,200	33,400	766,794
1973	568,169	383,980	237,195	211,700	82,200	1,483,244
1974	270,606	211,458	68,116	76,924	39,090	666,194
1975	342,888	289,393	138,816	195,730	85,866	1,052,693
1976	435,896	276,480	47,932	54,259	57,890	872,457
1977	394,864	237,229	97,922	191,576	66,718	988,309
1978	173,644	180,360	49,547	72,472	26,272	502,295
1979	482,418	292,495	85,370	266,292	75,202	1,201,777
1980	161,648	113,619	18,771	55,176	31,814	381,028
1981	698,321	343,409	164,979	196,823	67,303	1,470,835
1982	172,177	167,719	22,589	44,858	23,461	430,804
1983	199,453	117,244	31,885	62,537	23,155	434,274
1984	82,600	62,020	11,316	16,866	25,970	198,772
1985	443,747	213,238	136,737	259,192	50,691	1,103,605
1986	542,473	248,288	170,221	267,354	44,472	1,272,808
1987	952,857	495,952	229,339	270,946	114,874	2,063,968
1988	188,480	94,787	12,586	28,397	25,473	349,723
1989	108,745	60,364	4,562	12,318	23,565	209,554
1990	773,467	185,211	35,934	71,798	41,283	1,107,693
1991	803,907	368,050	84,477	109,710	96,939	1,463,083
ANNUAL AVERAGE	304,490	162,267	67,466	103,604	38,839	676,666

FIGURE 7.2
GRAPH OF ANNUAL RECHARGE BY STORAGE UNIT TO THE EDWARDS AQUIFER - SAN ANTONIO REGION FOR 1934 THROUGH 1991



WESTERN STORAGE UNIT INCLUDES NUECES, FRIO AND SABINAL RIVER BASINS: WESTERN MEDINA STORAGE UNIT INCLUDES SECO, HONDO AND MEDINA LAKE: EASTERN MEDINA STORAGE UNIT INCLUDES MEDINA-CIBOLO CR. AREA: AND EASTERN STORAGE UNIT INCLUDES CIBOLO AND COMAL CREEK BASINS. BLANCO R. RECHARGES SAN MARCOS SP.

historical annual recharge to the Edwards Aquifer for the 1934 through 1991 period of record. However, most of the flow to and from this storage unit is used for irrigation and municipal purposes.

8.0 Historical Pumpage Spring Flows

The estimated total historical discharge (pumpage) from wells and springs in the Edwards Aquifer for 1934 through 1991 is shown in Table 8.1. The annual historical pumpage (EUWD 1992) from the Edwards Aquifer varied from 101,900 af in 1934 to 542,400 af in 1989. The average annual historical pumpage for this period was 284,810 af. The pumpage data shown in Table 8.1 is for irrigation, municipal and industrial withdrawals from the Edwards Aquifer within Kinney, Uvalde, Medina, Bexar, Comal, and Hays Counties.

In 1983, there were about 800 major wells producing water for the Edwards Aquifer for public water supply (municipal), industrial and irrigation purposes (SWTSU 1988). In 1991, there was an estimated 1,354 major wells located in the five counties overlying the Edwards Aquifer, as shown in Table 8.2. These major wells are generally distributed over the Edwards Aquifer as shown in Figure 8.1. Major well clusters are located in Uvalde County and eastern Medina County. However, the largest concentration of wells is located in Bexar, Comal and Hays Counties. Most of the wells used for irrigation purposes are located in Uvalde County and to a lesser extent in Medina County. However, most of the major wells located in Bexar, Comal and Hays Counties are used for municipal (public water supply) and industrial purposes. Besides these major wells, there was an estimated 3,500 additional wells that have been located or generally located by the TWDB (Stein 1993) within the five county region that are used for domestic and livestock purposes. However, there are numerous additional

TABLE 8.1
TOTAL ANNUAL PUMPAGE AND SPRING FLOW DISCHARGE
FROM THE EDWARDS AQUIFER - SAN ANTONIO REGION
(ACRE-FEET/YEAR)

YEAR	PUMPAGE	TOTAL SPRING DISCHARGE	COMAL SPRINGS	SAN MARCOS SPRINGS	TOTAL ANNUAL RECHARGE	MASS BALANCE (RECHARGE - PUMPAGE-TOTAL SPRING DISCHARGE
1934	101,900	336,000	230,155	MISSING	183,944	(253,956)
1935	103,700	415,900	244,561	MISSING	1,338,398	818,798
1936	112,700	485,500	265,171	MISSING	995,851	397,651
1937	120,200	451,000	259,108	MISSING	428,484	(142,716)
1938	120,100	437,700	255,332	MISSING	446,508	(111,292)
1939	118,900	313,900	217,804	MISSING	389,559	(43,241)
1940	120,100	296,500	208,371	MISSING	312,432	(104,168)
1941	136,800	464,400	260,632	MISSING	942,847	341,647
1942	144,600	450,100	265,084	MISSING	585,151	(9,549)
1943	149,100	390,200	246,597	MISSING	297,111	(242,189)
1944	147,300	420,100	253,159	MISSING	627,061	59,661
1945	153,300	461,500	270,747	MISSING	586,344	(28,456)
1946	155,000	428,900	276,230	MISSING	629,793	45,893
1947	167,000	426,500	257,827	MISSING	461,415	(132,085)
1948	168,700	281,900	201,011	MISSING	166,156	(284,444)
1949	179,400	300,400	211,958	MISSING	508,723	28,923
1950	193,800	272,900	189,631	MISSING	203,343	(263,357)
1951	209,700	215,900	148,819	MISSING	134,539	(291,061)
1952	215,400	209,500	162,366	MISSING	363,580	(61,320)
1953	229,800	238,500	142,644	MISSING	185,250	(283,050)
1954	246,200	178,100	98,314	MISSING	160,414	(263,886)
1955	261,000	127,800	66,796	MISSING	194,362	(194,438)
1956	321,100	69,800	27,991	MISSING	43,350	(347,550)
1957	237,300	219,200	138,696	110,241	1,330,269	873,769
1958	219,300	398,200	234,016	153,391	1,688,412	1,070,912
1959	234,500	384,500	229,178	116,012	678,554	59,554
1960	227,100	428,300	241,612	141,361	861,621	206,221
1961	228,200	455,300	247,878	138,226	729,300	45,800
1962	267,900	321,100	193,333	95,832	250,799	(338,201)
1963	276,400	239,600	150,770	78,683	177,200	(338,800)
1964	260,200	213,800	138,515	70,153	429,300	(44,700)
1965	256,100	322,800	209,172	122,983	663,499	84,599

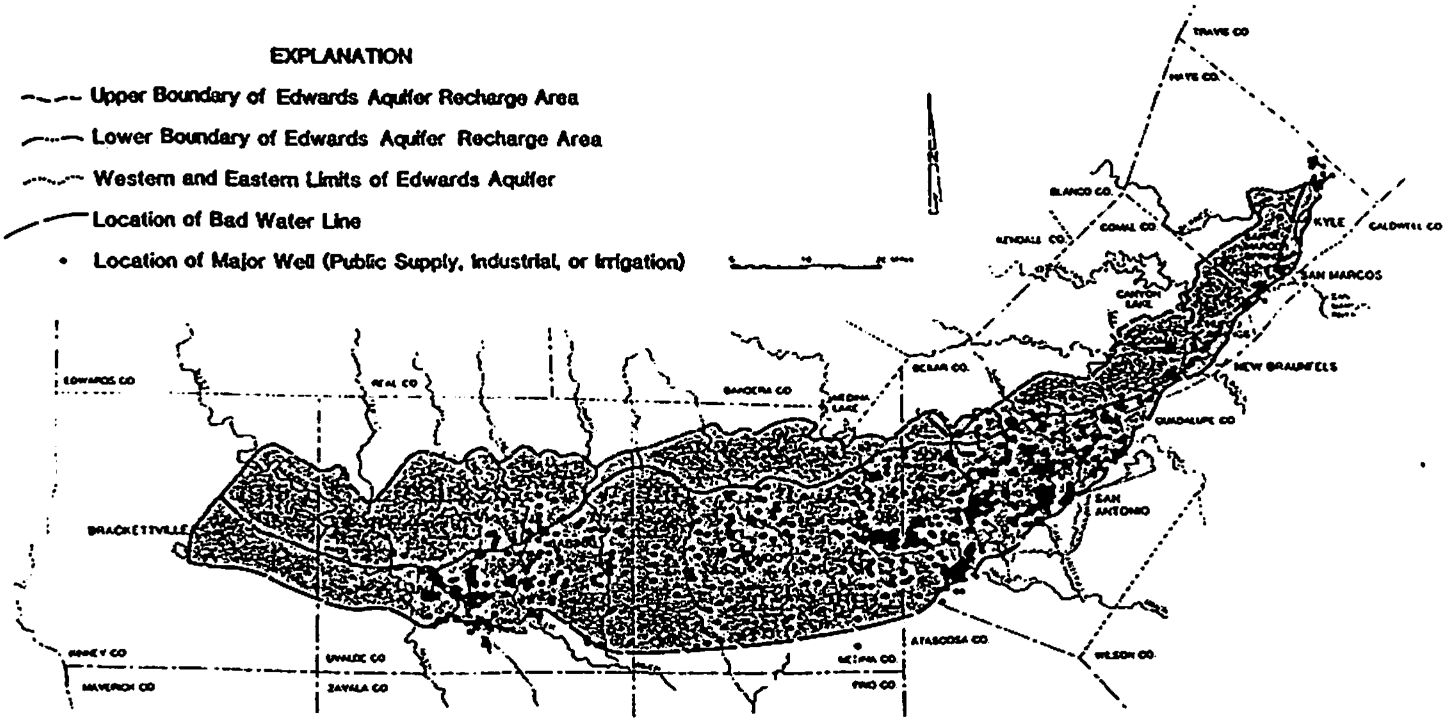
TABLE 8.1 - CONTINUED
TOTAL ANNUAL PUMPAGE AND SPRING FLOW DISCHARGE
FROM THE EDWARDS AQUIFER - SAN ANTONIO REGION
(ACRE-FEET/YEAR)

YEAR	PUMPAGE	TOTAL SPRING DISCHARGE	COMAL SPRINGS	SAN MARCOS SPRINGS	TOTAL ANNUAL RECHARGE	MASS BALANCE (RECHARGE - PUMPAGE-TOTAL SPRING DISCHARGE
1966	255,900	315,300	193,380	111,322	613,416	42,216
1967	341,300	216,100	136,406	77,625	466,545	(90,855)
1968	251,700	408,300	246,689	143,013	891,508	231,508
1969	307,500	351,200	212,325	117,792	637,569	(21,131)
1970	329,400	397,700	226,580	144,528	691,087	(36,013)
1971	406,800	272,700	159,752	91,800	933,038	253,538
1972	371,300	375,800	264,475	116,628	766,794	19,694
1973	310,400	527,600	293,919	158,158	1,483,244	645,244
1974	377,400	483,800	283,725	133,731	666,194	(195,006)
1975	327,800	540,400	295,345	170,030	1,052,693	184,493
1976	349,500	503,900	280,033	153,106	872,457	19,057
1977	380,600	580,300	289,610	161,682	988,309	27,409
1978	431,800	375,500	239,808	87,394	502,295	(305,005)
1979	391,500	523,000	292,654	144,889	1,201,777	287,277
1980	491,100	328,300	207,161	95,933	381,028	(438,372)
1981	387,100	407,300	234,395	130,955	1,470,835	676,435
1982	453,100	333,300	201,147	93,446	430,804	(355,596)
1983	418,500	301,600	171,989	106,230	434,274	(285,826)
1984	529,800	172,500	91,445	72,318	198,772	(503,528)
1985	522,500	334,000	192,508	131,986	1,103,605	247,105
1986	429,300	388,100	219,709	145,436	1,272,808	455,408
1987	364,100	558,000	271,477	183,480	2,063,968	1,141,868
1988	540,000	369,800	200,965	101,998	349,723	(560,077)
1989	542,400	224,100	118,278	72,509	209,554	(556,946)
1990	489,400	240,600	129,604	82,540	1,107,693	377,693
1991	436,000	354,300	MISSING	MISSING	1,463,083	672,783
1992	327400	802800	MISSING	MISSING		
1993	407300	589400	MISSING	MISSING		
ANNUAL AVERAGE 1934-1991	284,810	354,126			676,666	37,730
ANNUAL AVERAGE COMAL SPRINGS			210,471			
ANNUAL AVERAGE SAN MARCOS SPRINGS				119,277		

TABLE 8.2
NUMBER OF WELLS IN THE EDWARDS AQUIFER, SAN ANTONIO REGION, FOR WHICH RECORDS WERE OBTAINED FROM TEXAS WATER COMMISSION CENTRAL RECORDS FILE (11/91)

(SOURCE: STEIN, 1993)

COUNTY	TYPE OF RECORD	DOMESTIC	PUBLIC SUPPLY AND INDUSTRIAL	IRRIGATION	TOTAL
Bexar	Located	112	346	186	644
	Plotted	627	114	30	771
	Unplotted	107	13	2	122
	Total	846	473	218	1,537
Comal	Located	61	27	8	96
	Plotted	854	23	1	878
	Unplotted	108	5	1	114
	Total	1,023	55	10	1,088
Hays	Located	37	15	4	56
	Plotted	616	36	3	655
	Unplotted	89	3	0	92
	Total	742	54	7	803
Medina	Located	52	12	170	234
	Plotted	217	10	56	283
	Unplotted	36	1	2	39
	Total	305	23	228	556
Uvalde	Located	50	11	178	239
	Plotted	388	9	74	471
	Unplotted	39	2	8	49
	Total	477	22	260	759
TOTAL		3,393	627	723	4,743



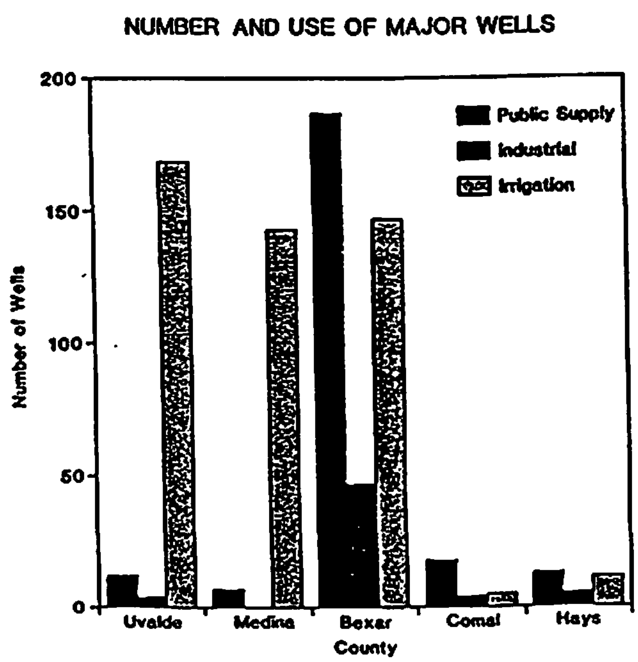


Figure 8.1 - Locations of Major Wells

domestic/livestock wells located over the Edwards Aquifer. Stein (1993) found that the most dense concentration of wells are located in the vicinity of Comal and San Marcos Springs. The wells in the vicinity of the springs are mostly domestic wells. The proximity of the large number of domestic wells to the springs creates an instantaneous effect on the local artesian head, and therefore, these domestic wells have an immediate impact on diminished springflow (Stein 1993). Stein estimated that there are between 10,000 to 20,000 wells that withdraw water from the Edwards Aquifer, which supplies water to over 1.3 million people in the San Antonio Region. Of these wells, Stein estimates that about 5,000 are actually recorded in the TWDB files. In examining short term measures that might be taken to influence springflow, the impact of use from the large number of domestic wells in the immediate vicinity of the springs should not be ignored. Pumping from these wells has a more direct and immediate effect on the springs, than almost any other wells in the aquifer.

The annual historical spring discharge for major springs[18] varied from 69,800 af in 1956 to 580,300 af in 1977, with an average annual spring discharge for the period 1934 through 1991 of 354,126 af. Of this annual average Comal Springs averaged approximately 210,470 af/yr or approximately 60 percent. According to EUWD records, Comal and San Marcos Springs average approximately 86 percent of the total spring discharge from the Edwards Aquifer on an annual basis (EUWD 1989).

A flow-duration curve for Comal Springs is shown in Figure 8.2 (USGS 1995). This curve indicates that Comal Springs, during the period 1930 through 1994, had a discharge rate of less than 150 cubic feet per second (cfs) approximately 10 percent of the time,

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18 Major springs include San Marcos Springs in Hays County, Comal and Hueco Springs in Comal County, San Antonio and San Pedro Springs in Bexar County, and Leona River Springs in Uvalde County (EUWD 1991).

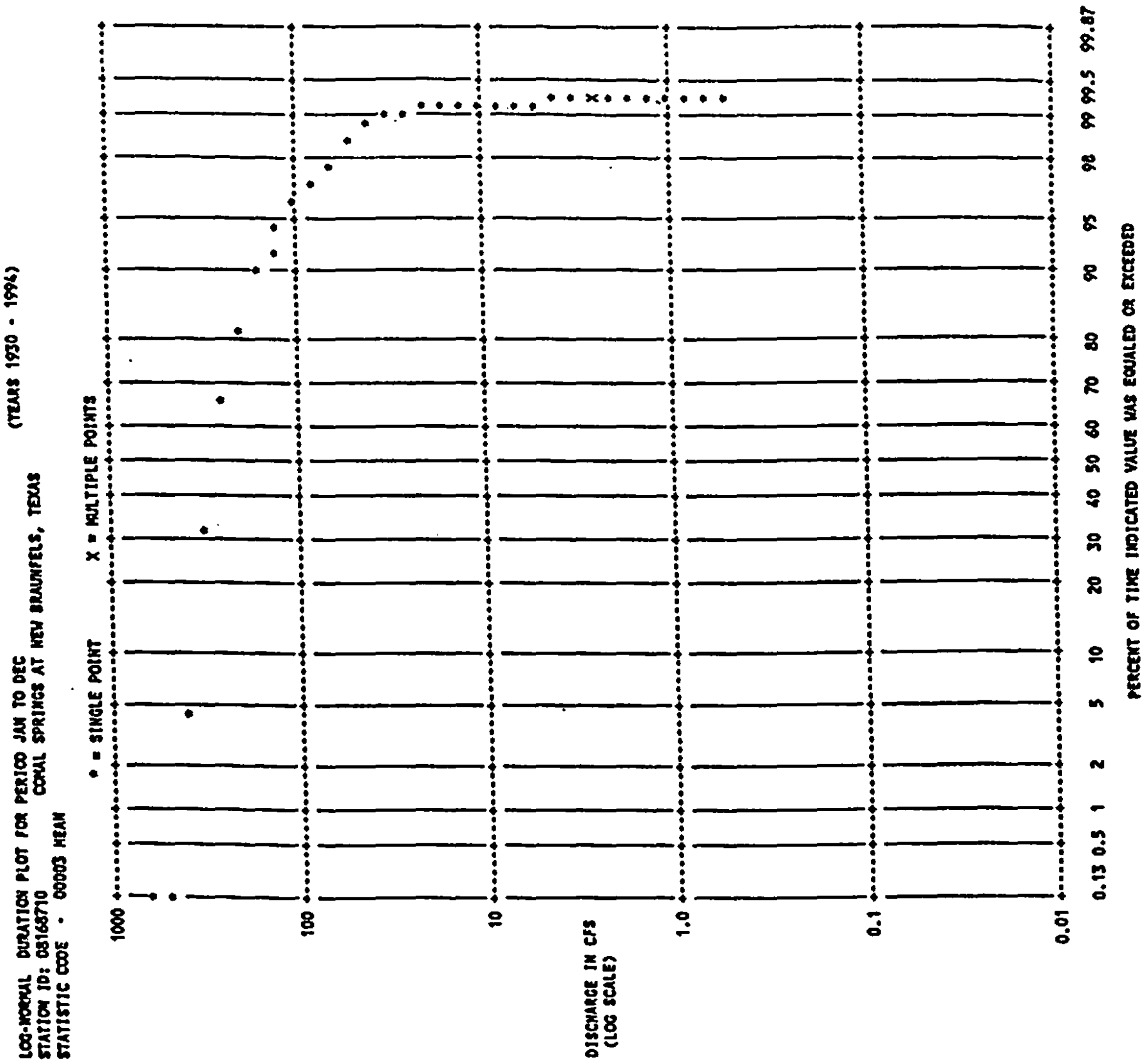

Figure 8.2 - Flow Duration Curve For Comal Springs

and a discharge rate of less than 60 cfs approximately 2.2 percent of the time. Flow-duration curve analyses for Comal Springs daily discharge for each individual calendar month with respect to the REWRP is shown below:

MONTH	DAILY DISCHARGE LESS THAN OR EQUAL TO 150 CFS	DAILY DISCHARGE LESS THAN OR EQUAL TO 60 CFS
JAN	4.6	1.5
FEB	3.4	1.4
MAR	4.7	.7
APR	5.6	1.5
MAY	6.9	1.6
JUN	13.0	2.1
JUL	14.1	3.7
AUG	16.7	4.7
SEP	12.5	4.3
OCT	7.8	2.4
NOV	6.9	1.9
DEC	4.7	1.6

SECTION II EDWARDS AQUIFER -- AN UNDERGROUND RIVER?

Wells A. Hutchins (The Texas Law on Water Rights) states:

> "A definite underground stream has the same characteristics as those of a watercourse on the surface. Even though buried in the ground, it has been treated historically on the same principles as surface streams, both under the law of appropriation and at common law. As recently as 1931, the Arizona Supreme Court held that to establish judicially the existence of an alleged subterranean stream, there must be afforded "clear and convincing proof to the satisfaction of a reasonable man, not only that there are subterranean waters, but that such waters have a definite bed, banks, current with the ordinary meaning of the terms as above set forth, and the evidence must establish with reasonable certainty the location of such bed and banks."

Using this standard, as well as, my experience as a hydrologist, it is my opinion that a surface water course possesses the following characteristics, none of which are satisfied by the Edwards Aquifer:

- **A FLOW WITHIN A DEFINED WATER COURSE, WITH READILY DEFINABLE BEDS AND BANKS**

  A river has a definable and readily identifiable bed and banks. The Edwards Aquifer has generalized flow paths, but flow channels within the Aquifer cannot be defined, located or identified with specific bed and banks. Nor are there land surface indications which allow one to discern the path of an underground river.

- **DISCERNABLE FLOW**

  A river has observable water flow, i.e. movement at a discernible velocity in a particular direction. The Edwards

Aquifer, as a whole, is without observable flow velocity and has flow paths conveying water in many directions.

- **FREE WATER SURFACE AND UNDERFLOW**
  A surface water river has a free water surface, that is a surface that is in contact with the atmosphere. A surface water river can have underflow in the sediments and deposits that make up its bed and banks. But such underflow is in continual contact with the surface river. Water in the Edwards Aquifer, however, is not underflow. It separates from its surface water source and moves independently in a different direction, by a different route, at a different speed, and to a different destination. Although the Edwards Aquifer does has a free water surface within its water table zone, most of its water is stored under artisan (pressure), without a free water surface.

- **FLOW THAT IS SUBJECT TO OPEN CHANNEL CONDITIONS**
  A river is subject to the physics and hydraulics of open channel flow. The Edwards Aquifer is not, and is subject to flow in confined and unconfined porous media.

The geographical limits of the Edwards Aquifer can be defined with reasonable certainty, but the Aquifer as a whole unit is not an underground river. The Edwards is an underground fresh and saline water storage unit, whose storage characteristics and flow conveyance systems are subject to the physics and dynamics of flow in and through porous media. In other words, the Edwards is an underground formation and aquifer, and does not possess the hydraulic characteristics of a surface water river.

If analogous to any surface water unit, the Edwards Aquifer is analogous to a watershed or river basin, as are other ground water aquifers. The Aquifer has geographic limits, as does a river basin. The Aquifer has collection channels and flow routes, as does a river basin. The Aquifer has natural discharge points, as does a river basin. The Aquifer is a geographic water collection unit, as is a river basin. However, the analogy breaks down. Within a river basin there are clearly identifiable tributaries, creeks and rivers that collect water originating from rainfall and channels it to a common discharge point. Within a river basin collection paths are clearly identifiable and can be precisely located and quantified. While the Edwards Aquifer collects water via recharge, which also originates from rainfall, its channels are specifically un-identifiable flow paths to underground storage areas and to numerous discharge points. Within the Edwards Aquifer, there are flow routes analogous to the tributaries and rivers characteristic of watersheds, but with at least four major exceptions: (1) the Edwards flow routes cannot be clearly identified and located; (2) flow routes are small or minute, compared to flow paths of a river basin; (3) do not demonstrate the consistent consolidation or down-gradient convergence that is characteristics of surface watercourses; and (4) the Edwards Aquifer, as a whole, does not exhibit a discernable velocity.

The Edwards Aquifer is like all other major and minor aquifer systems. Any aquifer's boundaries, generalized direction of flow and rate, recharge sources, discharge points, and general composition can be identified and generally quantified. Possibly the only thing that sets the Edwards Aquifer apart from other aquifers is that it has a higher transmissivity. But, having a higher transmissivity, does not make the Edwards Aquifer an underground river.

Plaintiffs in this case, as well as, other individuals have suggested that the Edwards Aquifer is an underground river. It is my professional opinion, that the Edwards Aquifer is not an underground river due to the above reasons.

SECTION III EDWARDS AQUIFER - WATER QUALITY ISSUES

- **ISSUE NO. 1: OVERPUMPING OF THE AQUIFER WILL NOT CAUSE REGIONAL WATER QUALITY PROBLEMS**

The freshwater potion of the Edwards Aquifer may experience water quality problems from the following three sources:

1. Movement of the "bad-water" line;
2. Communication from the Glen Rose Aquifer; and
3. Deterioration of surface water quality over in the recharge zone.

As discussed in Section I, within the fresh water portion of the Edwards Aquifer, there is very little opportunity for the movement of the "bad-water" line and limited communication from the Glen Rose Aquifer. Given these two facts, it is my professional opinion that, except on a very localized basis, Aquifer water quality deterioration will not occur due to overpumping. A significantly greater immediate and genuine threat to the Aquifer's water quality is attributable to development and urbanization over and upstream of the Aquifer's recharge zone.

- **ISSUE NO. 2: A COMAL SPRINGFLOW RATE OF LESS THAN 200 CFS IS UNRELATED TO WATER QUALITY IN THE AQUIFER**

Historical experience clearly demonstrates that neither the "bad-water" line or communication with the Glen Rose aquifer caused regional water quality problems during the severe 1950's drought, when Comal Springs went dry. Therefore, reduction of springflow below an arbitrary streamflow discharge rate of either 200 or 150 cfs at Comal Springs is anticipated to have no relation to Aquifer water quality and should not result in water quality problems to the Edwards Aquifer.

DISCUSSION:

A. Movement of the "bad-water" line

As described in Section I of this report, the southern boundary of the confined portion of the Edwards Aquifer is the "bad-water" line. This line is set where the concentration of 1,000 mg/l (milligrams per liter) of dissolved solids occurs in the Aquifer. The concentrations of dissolved solids at given sampling points vary slightly with time, but the lateral position of the "bad-water" line has not significantly shifted over time (TWDB 1986). In addition, there is no indication that the "bad-water" line shifted significantly, even during the 1950's drought when Comal Springs went dry. The difference with water quality between the bad water zone and the fresh water zone of the Edwards Aquifer occurs because there is little or no circulation of water in the bad water zone. Water has resided in the bad water zone for such a length of time that minerals have dissolved from the rocks in large enough quantities to produce high levels of dissolved solids. Given the extremely slow movement of water within the bad water zone, reduction in head of the in the fresh water zone, if it has any effect at all, should result in only minor and localized inflow of saline water.

In general, the aquifer in the saline-water zone (i.e. bad water zone) has considerable less capacity to transmit water than the aquifer in the freshwater zone because an integrated network of cavernous zones has not be developed by circulation of freshwater. As a comparison, the transmissivity of the saline water zone (668 ft^2/d) is 200 times less than the transmissivity of the freshwater zone (134,000 ft^2/d) for the freshwater zone (USGS 1986). In addition, faults significantly disrupt the lateral continuity of the geologic formations at places in Bexar County, impeding or preventing flow in faulted areas. These factors serve to restrict lateral ground water flow across the "bad-water" line. This is further confirmed by an examination of Aquifer cross-sections which transect the confined and "bad-water" zones. Approximately 30 such cross-sections were prepared by T. A. Small (USGS 1986). The USGS (1986) found that some undetermined amount (but relatively small due to low hydraulic gradients and low saline-water zone transmissivities) flow probably moves from the freshwater to the saline water part of the aquifer in Kinney, Uvalde and western Medina Counties and from the saline-water to freshwater part of the aquifer in Hays and Travis Counties. It should be noted that for purposes of mathematical modeling, the TWDB treats the "bad-water" line as an impermeable aquifer boundary, with the exception of a small area in southeast Uvalde County.

Based on a review of the literature and various mathematical modeling studies, regional Edwards Aquifer water quality degradation will not occur as a result of updip movement of the "bad-water" line. This line has limited opportunity for updip movement, and if it does move up-dip due to extreme conditions in the fresh water zone, its movement will be very limited, not causing a treat to regional water quality.

B. Communication from the Glen Rose Aquifer

The Edwards Aquifer also has some limited hydrologic communication with the underlying and "poorer" water quality Glen Rose Aquifer (EUWD 1995). Because of faulting, the Edwards Aquifer in many areas over the 180-mile length between the two ground-water divides is juxtaposed to the Glen Rose Aquifer. Both at the surface and a depth, and therefore, the Glen Rose may discharge directly into the Edwards Aquifer. Regionally, underflow from the Glen Rose Formation to the Edwards Aquifer along the Balcones fault zone can occur by ground water moving laterally in a down-gradient direction within the Glen Rose and entering the Edwards aquifer through fault planes. The amount of ground water in transit is dependent on the length of the line of entry (fault plane) through which water enters the Edwards Aquifer, the water level gradient across the fault plane from the Glen Rose to the Edwards Aquifer, and the effective transmissivity for the Glen Rose Aquifer upgradent and along this line. The EUWD (1995) estimates that the approximate range of total Glen Rose underflow to the Edwards Aquifer would be about 2,700 to about 11,400 af/yr in the San Antonio Region. As compared to the total Edwards Aquifer water balance, these estimates indicate that the Glen Rose contributes less than 2 percent of the total water budget during average recharge conditions. The EUWD (1995) also estimated that, based on geochemical models, the chemical content of water representative of the Edwards Aquifer in the San Antonio Region include a small amount, less than 1 percent Glen Rose water (EUWD 1995). Thus, local communication between the formations occurs, but without significant impact on overall water quality of the Edwards Aquifer, due to the low transmissivity of the Glen Rose.

SECTION IV. Effects of Selected Pumpage on Springflow

1. Effects of Client Pumpage

DGRA, Inc., represents 3 farmers[1] in Uvalde County who irrigate crops from Edwards Aquifer wells. In 1995, these farmers have a total of twelve wells, which irrigate approximately 2,460 acres of land located, within an approximate 10-mile radius of Knippa, Texas. Irrigated crops include corn, cotton, sesame, milo, and sunflower.

DGRA, Inc. simulated the effect on Comal Springs and San Marcos Springs flow assuming the farmers had to totally curtail their pumpage for the period May 20, 1995, through December 31, 1995. To achieve this simulation, DGRA, Inc. used the current version of the TWDB's Edwards Aquifer model (GW-SIM IV). The following four model simulations were made:

Simulation No. 1 - Base Run for the Period January 1978 through December 1989, Using 1983 Pumpage Levels, Historical Recharge and 1978 Starting Heads

Simulation No. 2 - Farmers Curtailment Run (i.e. curtailment of irrigation water for the May 15 through December 31 period) Applied in the Year 1984 to Simulate a Low Recharge Year

Simulation No. 3 - Farmers Curtailment Run (i.e. curtailment of irrigation water for the May 15 through December 31 period) Applied in the Year 1978 to Simulate an Average Recharge Year

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1 Mr. Danny McFadin, Knippa, Texas; Mr. Tommy Walker, Uvalde, Texas; and Mr. Carl Muecke, Knippa, Texas.

Simulation No. 4 - Farmers Curtailment Run (i.e. curtailment of irrigation water for the May 15 through December 31 period) Applied in the Year 1985 to Simulate a High Recharge Year

Simulation Nos. 2, 3 and 4 were compared to Simulation No. 1 (Base Run) to determine the impact of total irrigation curtailment for the farmers for the period May 20, 1995 through December 31, 1995, such curtailments occurred in a low, average and high recharge year. The farmers reported irrigation use for the period January 1, 1995 through May 19, 1995, were used in Simulation Runs Nos 2, 3, and 4. The results of the effects of the farmer's total curtailment of pumpage for the period May 20, 1995, through December 31, 1995 are shown below:

FOR LOW RECHARGE YEAR 1978

YEAR	MONTH	DIFFERENCE IS SPRING FLOW (ACRE-FEET) COMAL SPRINGS	SAN MARCOS SPRINGS
1984	1	0	0
1984	2	0	0
1984	3	0	0
1984	4	0	0
1984	5	4.0	0
1984	6	9.0	0
1984	7	9.2	0
1984	8	11.9	0
1984	9	15.4	.1
1984	10	12.8	.1
1984	11	12.9	.1
1984	12	13.2	.1
TOTAL		88.4	.4

FOR AVERAGE RECHARGE YEAR 1978

YEAR	MONTH	DIFFERENCE IS SPRING FLOW (ACRE-FEET) COMAL SPRINGS	SAN MARCOS SPRINGS
1978	1	0	0
1978	2	0	0
1978	3	0	0
1978	4	0	0
1978	5	1.6	0
1978	6	8.4	0
1978	7	10.7	0
1978	8	10.2	0
1978	9	10.6	0
1978	10	10.1	0
1978	11	9.8	.1
1978	12	5.2	.1
TOTAL		66.6	.2

FOR HIGH RECHARGE YEAR 1985

YEAR	MONTH	DIFFERENCE IS SPRING FLOW (ACRE-FEET) COMAL SPRINGS	SAN MARCOS SPRINGS
1985	1	0	0
1985	2	0	0
1985	3	0	0
1985	4	0	0
1985	5	0.2	0
1985	6	5.3	0
1985	7	8.1	.1
1985	8	6.9	0
1985	9	8.8	.1
1985	10	9.7	.1
1985	11	10.2	.1
1985	12	10.7	.1
TOTAL		59.9	.5

As shown above, total curtailment of farmer's pumpage for the period May 20, 1995, through December 31, 1995, as applied to the low (1984), average (1978) and high recharge (1985) years only resulted in a total Comal Springs flow reductions of 88.4 af, 66.6 af and 59.9 af, respectively. Similarly, San Marcos Springs exhibited reductions for the low (1984), average (1978) and high recharge (1985) years of 0.4 af, 0.2 af, and 0.4 af, respectively.

Taking the maximum Comal Springs flow reduction of 88.4 af for the low recharge year of 1984, only results in an average decrease in springflow discharge rate of 0.2 cfs. This streamflow reduction is negligible and well within modeling error, and as such the farmers' curtailment can be considered as having no impact on Comal Springs flow. Likewise, the farmer's pumpage curtailment will have no impact on San Marcos Springs flow.

I conclude from this analysis that curtailment of the three farmers' irrigation usage for the remainder of 1995 would have no impact of Comal Springs and San Marcos Springs flows whether 1995 is a low, an average, or a high recharge year.

2. Effects of Agricultural and Municipal Pumpage

In order to determine the relative effects of agricultural and municipal pumpage on Comal Springs and San Marcos Springs discharge, DGRA, Inc. performed the following analyses, using the current version of the TWDB's Edwards Aquifer model (GW-SIM IV):

Simulation No. 1 - Base Run for the Period January 1978 through December 1989, Using Historical Pumpage Levels, Historical Recharge and 1978 Starting Heads

Simulation No. 2 - Reduce Agricultural Pumpage in All Counties Withdrawing Water From the Edwards Aquifer by the factors of 10%, 25% and 50%, beginning the Year 1983 for the Simulation Period January 1978 through December 1989, While Maintaining Other Pumpage Uses at Historical Levels

Simulation No. 3 - Reduce Municipal Pumpage in All Counties Withdrawing Water From the Edwards Aquifer by the Same Amount (volumetric quantity not percentage) as Represented by 10%, 25% and 50% Agricultural Reductions, Beginning in the Year 1983 for the Simulation Period January 1978 through December 1989, While Maintaining Other Pumpage Uses at Historical Levels

Simulation No. 4 - Reduce Municipal Pumpage in All Counties Withdrawing Water From the Edwards Aquifer by the factors of 10%, 25% and 50%, beginning the Year 1983 for the Simulation Period January 1978 through December 1989, While Maintaining Other Pumpage Uses at Historical Levels

The results of these simulations are shown below:

ACTION	1983 - 1989 REDUCTION IN COMAL SPRINGS FLOW (AF)		1983 - 1989 REDUCTION IN SAN MARCOS SPRINGS FLOW (AF)	
	TOTAL FLOW	**AVG. FLOW**	**TOTAL FLOW**	**AVG. FLOW**
10% AGRICULTURAL REDUCTION	29,631	353	1,297	15
25% AGRICULTURAL REDUCTION	73,062	870	3,177	38
50% AGRICULTURAL REDUCTION	139,972	1,666	6,137	73

MUNICIPAL REDUCTION EQUAL TO 10% AGRICULTURAL CUT	70,856	844	6,832	81
MUNICIPAL REDUCTION EQUAL TO 25% AGRICULTURAL CUT	173,013	2,060	16,907	201
MUNICIPAL REDUCTION EQUAL TO 50% AGRICULTURAL CUT	335,077	3,989	33,439	398
10% MUNICIPAL REDUCTION	114,105	1,358	11,008	131
25% MUNICIPAL REDUCTION	273,471	3,256	27,078	322
50% MUNICIPAL REDUCTION	519,044	6,179	53,276	634

Examination of the above data dramatically shows that for corresponding reductions (i.e. 10%, 25% and 50%) in agricultural versus municipal pumpage that agricultural pumpage that municipal pumpage has an average of 3.7 times greater effect on Comal Springs flow and 8.5 times greater effect on San Marcos Springs flows than does agricultural pumpage. When comparing equal volumetric reductions between agricultural and municipal pumpage, municipal pumpage has an average 2.4 times greater effect on Comal Springs flow and an average 5.3 times greater effect on San Marcos Springs flow. The greater impact of municipal pumpage over agricultural pumpage is largely due to the fact that most agricultural pumpage occurs in Uvalde County and most municipal pumpage occurs in Bexar County, i.e. agricultural pumpage is centered further from the springs than municipal. Also, this may exhibit that Uvalde Pool area of the Edwards Aquifer may not directly feed flow to Comal and San Marcos Springs, as does the Edwards' pool that supplies municipal water to Bexar County.

I conclude from these analyses that the REWRP may be biased against agricultural users, since their water usage has a much lesser impact on Comal Springs and San Marcos Springs flow than does pumpage by municipal users.

V. REVISED EMERGENCY WITHDRAWAL REDUCTION PLAN

The Revised Emergency Withdrawal Reduction Plan (REWRP), March 331, 1995, has the following major deficiencies:

- **REWRP PROPOSES PUMPAGE LIMITATIONS ON MAJOR USERS WITHOUT REGARDS TO WELL LOCATIONS**
  The plan needlessly restricts pumping from wells too distant to have a impact upon Comal Springs and San Marcos Springs flow during the year in which the emergency reduction is required. While such restrictions may serve a purpose in a long-term aquifer management plan, they are pointless and punitive as a short-term, emergency management measure.

- **REWRP NEGLECTS REGULATION OF THE HUNDREDS AND POSSIBLY THOUSANDS OF DOMESTIC AND LIVESTOCK WELLS LOCATED NEAR THE SPRINGS**
  Domestic and livestock wells located near the springs have a direct and immediate effect on springflows. For a short-term REWRP to be effective, wells in the immediate vicinity of the springs cannot be ignored.

- **REWRP DOES NOT FUNCTION ON AN EMERGENCY BASIS AS INTENDED**
  The REWRP's rationale and intended purpose is as a short-term, emergency measure to preserve springflow. By its own terms however, it would implement "emergency" controls on irrigation almost 80% of the time. A plan implemented with this frequency should focus upon and utilize long-term management strategies.

- **THE REWRP IS BIASED AND UNFAIR TO IRRIGATION WATER USERS**
  The REWRP ignores the fact that irrigation pumpage effects on Comal Spring flows 2 to 3 times less than municipal pumpage on a short-term emergency basis. An analysis presented in Section IV and an independent Texas A&M University study clearly demonstrates that during the same year irrigation pumpage decreases Comal Spring by a factor of 2.4 to 3.0 times less than equivalent amount of municipal pumpage and about 5 times less for San Marcos Springs.

- **REWRP PROVIDES FOR UNFAIR COMPENSATION**
  The REWRP provides for financial compensation to public water purveyors, via doubling of water rates, for enforcing discretionary water use, but does not provide compensation to irrigation and industrial water users that are required to reduce non-discretionary uses.

- **REWRP REQUIREMENT OF SURCHARGING BY MUNICIPAL WATER PURVEYORS TO ITS CUSTOMERS FOR DISCRETIONARY WATER USE MAY BE IN VIOLATIONS OF PURVEYOR'S WATER TARIFFS**
  The REWRP requirement for surcharging customers of public water purveyors may be in violation of water tariffs. Amendments to purveyor's water tariffs to allow for such surcharging cannot be made by within the 1995 period of the REWRP.

- **PLAN IGNORES ECONOMICS IMPACT**
  The REWRP ignores the possible tremendous economic impact to agricultural, municipal and industrial water users.

- **PLAN IS RESTRICTED TO USERS OF CONFINED USERS**
  The REWRP apparently requires limitations on water users who withdraw water from only the confined (i.e. artesian) portion of the Edwards Aquifer, as inferred in the REWRP definition of the word "Aquifer".

- **PLAN PROHIBITS WITHDRAWALS OF WATER FROM THE AQUIFER FOR WELLS DRILLED AFTER JUNE 1, 1993**

  The prohibition on withdrawal from wells drilled after June 1, 1993 is unreasonable and discriminatory. Many Edwards Aquifer water users have drilled wells after June 1, 1993, for additional supply to meet expanding demands and/or for replacement wells. Imposing this requirement will be extremely burdensome and prejudicial.

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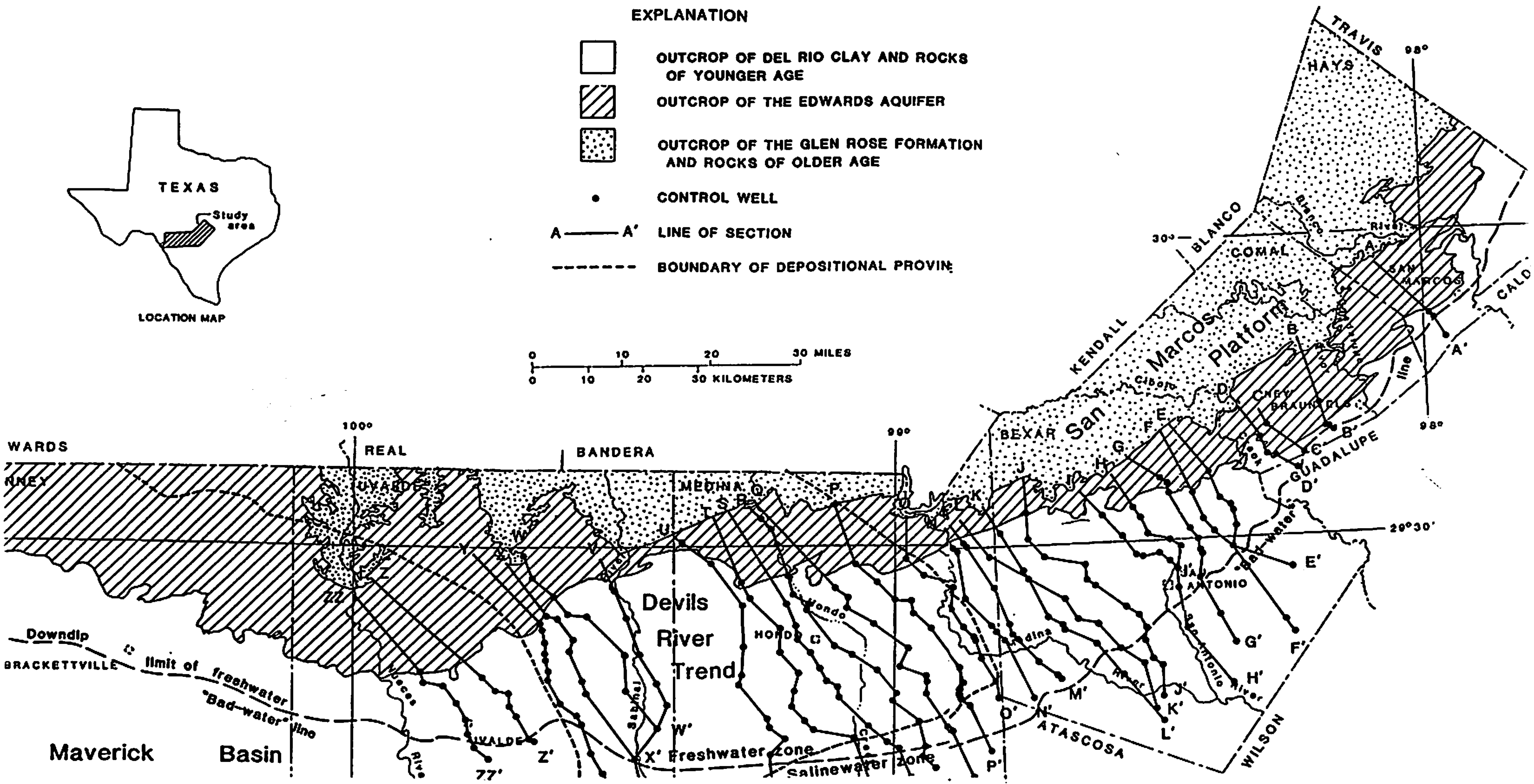
APPENDIX A



Appendix A

Map Showing Locations of Cross-Sections Presented in Figure 2.2A Through 2.2C