Technical Report

CRWR 247

Springflow Augmentation of Comal Springs and San Marcos Springs, Texas: Phase I-Feasibility Study

(DRAFT)

by

Daene C. McKinney
Assistant Professor

and

John M. Sharp, Jr.
Professor

March 1, 1994

CENTER FOR RESEARCH IN WATER RESOURCES

Bureau of Engineering Research • The University of Texas at Austin
Balcones Research Center • Austin, TX 78712

March 8, 1993

Mr. William K. Berg
W.K. Berg & Associates, Inc.
14760 Memorial Drive, Suite 304
Houston, Texas 77079

Dear Mr. Berg:

Re: Texas Water Development Board (Board) Request for Proposals to Conduct Research Relating to Augmentation of Spring Flows at Comal and San Marcos Springs, Texas

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Sincerely,

Tommy Knowles
Director of Planning

1-800-RELAYTX (for the hearing impaired)

P.O. Box 13231 • 1700 N. Congress Avenue • Austin, Texas 78711-3231
Telephone (512) 463-7847 • Telefax (512) 475-2053

March 8, 1993

Mr. T. David Chinn, P.E.
James Montgomery, Consulting Engineers, Inc.
9311 San Pedro Ave., Suite 700
San Antonio, Texas 78216

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TEXAS WATER DEVELOPMENT BOARD

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Ms. Peggy W. Glass
Alan Plummer & Associates, Inc.
106 East Sixth Street, Suite 250
Austin, Texas 78701

Dear ~~Ms. Glass~~: Peggy

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Jones and Neuse, Inc.
912 Capital of Texas Highway South
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Turner Collie & Braden Inc.
5757 Woodway
Houston, Texas 77057

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San Antonio, Texas 78216

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ACKNOWLEDGEMENTS

This research was co-directed by Dr. Daene C. McKinney, Assistant Professor of Civil Engineering, and Dr. John M. Sharp, Jr., Gulf Oil Foundation Centennial Professor of Geological Science. Co-investigators involved in the project were Dr. Dean Djokic of the University of Texas Center for Research in Water Resources, Mr. Marshall E. Jennings, P.E., and Mr. Ernest T. Baker, Jr., of the U.S. Geological Survey, Austin office; Dr. Doyle Stephens of the USGS, Salt Lake City, Utah office; and Mr. Fred R. Ore of the U.S. Bureau of Reclamation, Austin and OK City offices. The University of Texas at Austin graduate students who contributed greatly to the study were Zichuan Ye, and Gregory B. Gates of the Department of Covil Engineering and Maria Lebron, Mathew Ulliana, and Joanna Crowe of the Department of Geological Sciences. The University of Texas at Austin undergraduate students who contributed greatly to the study were Karl McArthur and Fedrous Mahmood.

Conversations with Drs. Glenn Longley and Thomas Arsuffi of the Edwards Aquifer Research and Data Center at Southwest Texas State University provided much insight into the complexity and interrelation of organisms in the San Marcos and Comal Springs systems. Patrick Connor, Robert Simpson, and Steve Cullinan of the U.S. Fish and Wildlife Service, and Kenneth Saunders of Texas Parks and Wildlife provided assistance, advice, and equipment during the habitat surveys as well as an appreciation for the uniqueness of the ecosystems. Dr. Thomas Hardy of Utah State University provided multi-spectral aerial photographs for the habitat maps of both spring systems. The facilities and collections of The Library at Southwest Texas State University were of great help during this study.

1.0 INTRODUCTION

1.1 THE EDWARDS AQUIFER-BALCONES FAULT ZONE

The Balcones Fault Zone segment of the Edwards aquifer, which constitutes a "major" aquifer on a statewide basis, is a tremendous natural resource for Central Texas. The Edwards aquifer underlies all or part Kinney, Uvalde, Medina, Atascosa, Bexar, Guadalupe, Comal, and Hays Counties in South Central Texas. The aquifer is the sole source of water for approximately 1.5 million people including the City of San Antonio, supplies spring flows which support a number of endangered species as well as a large recreation industry, and provides water to smaller municipalities, many farmers, ranchers, industrial and domestic users. Despite the aquifer's vast storage capacity and transmissive capabilities, average annual discharge is now approaching the average annual recharge (Tables 2.12 and 2.15), and the next drought could result in great economic and environmental hardship for the region.

Extensive pumping from the confined portion of the Edwards Aquifer by the City of San Antonio, which currently relies on the aquifer as its sole source of water, and numerous other municipalities and individuals has affected springflow from Comal and San Marcos Springs in Central Texas. Projections are that, if present pumping rates continue to increase unabated, both Comal Springs and San Marcos Springs will cease to flow by the year 2020. Because these springs are important as a recreation resource, as a source of water for downstream reservoirs, and as a habitat for several endangered species, it is important that we investigate the possibility of augmenting spring discharge before over pumping of ground water causes the problem to become too great to deal with.

Comal and San Marcos Springs make up about 25% of the baseflow of the Guadalupe River under average weather conditions, and up to 75% during drought conditions [Thornhill, 1988]. Hence, spring flow is crucial to provide the water demand for municipal, industrial, and recreational use, and to sustain wildlife in and around these river basins. Furthermore, a minimum river flow has to be maintained to prevent increasing pollution (by lack of dilution), and to prevent intrusion of salt water into the bays and estuaries. Another reason for emphasizing spring flow is that the amount of spring flow reflects the water level in the aquifer, and thus indicates the available water storage in the aquifer.

The study area for this research is located along the Balcones fault escarpment in Hays and Comal Counties, Texas, between the karstic Edwards Plateau and the Blackland Prairie of the Gulf Coastal Plain. Comal and San Marcos Springs, which issue from the Edwards aquifer in this area, are the largest and second largest springs in Texas with mean historic flows of 284 and 170 cubic feet per second (cfs), respectively (Tables 2.1 and 2.7).

The Edwards aquifer is a complex karstified aquifer that supplies large quantities of water to wells and to large springs such as Comal and San Marcos Springs. The Edwards aquifer, as it is here used, applies to the Balcones Fault Zone segment, which constitutes a "major" aquifer on a statewide basis. The boundaries of the Edwards-Balcones Fault Zone aquifer are a ground-water divide near Brackettville in Kinney County on the west, a subtle ground-water divide near Kyle in Hays County on the east, and a southern boundary--a so-called "bad-water" line that represents the downdip extent of water having less than 1,000 milligrams per Liter (mg/L) concentration of dissolved solids. The Edwards aquifer occupies an area of about 2,500 mi^2 along the Balcones Escarpment, which separates the Edwards Plateau from the Gulf Coastal Plain. This area is approximately 175 miles (mi) long and 5 to 30 mi wide. Comal Springs and San Marcos Springs are near the eastern end of the area. Groundwater in the Edwards aquifer east of the groundwater divide near Kyle does not move westward and does not discharge into Comal or San Marcos Springs. Similarly, groundwater in the Edwards aquifer west of Brackettville does not move eastward and does not move toward either Comal or San Marcos Springs. The direction of flow is from west to east--from Kinney County where the altitude of the exposed part of the aquifer reaches up to nearly 2,000 ft, past San Antonio at an altitude of around 700 ft, to Comal Springs at an altitude of 623 ft, and continuing eastward to San Marcos Springs at an altitude of 574 ft .

Numerous springs flow from Edwards aquifer at places where the water table intersects the land surface. Big springs such as Comal and San Marcos (the State's two largest springs, average flow of about 440 ft^3/sec or about 200,000 gal/min) are the general rule in karst regions, and big springs often emerge from underground streams or caves [Lamoreaux and others, 1989, p. 85-86]. Six of the largest such springs discharged an average of about 480 feet per cubic second (ft^3/sec) from 1936-86. Comal Springs at New Braunfels (averaging 288 ft^3/sec from 1940-85) flow from the Edwards aquifer at the base of the Balcones Escarpment. The Comal Springs Fault is the most conspicuous fault in the Balcones Fault Zone in the area, forming the escarpment separating the Gulf Coastal Plain from the Edwards Plateau. San Marcos Springs at San Marcos (averaging 154 ft^3/sec from 1940-85), like Comal Springs, flow from the Edwards aquifer at the base of the Balcones Escarpment. The conduit along which most of the flow moves to the springs is the San Marcos Springs Fault.

Wells pumping from the aquifer are among the world's largest [Baker and Wall, 1976, p. F-7]. For example, wells operated by the city of San Antonio have large capacities; one well drilled in 1941 had a natural flow of 16,800 gallons per minute (gpm) [Livingston, 1942, p. 3], and in 1991 a well drilled near San Antonio had a natural flow of about 25,000 gal/min. This well is reportedly the world's largest flowing well [Oral commun., P.L. Rettman, 1991; Swanson, 1991].

The Edwards aquifer and its associated springs are known to have a diverse number of highly adapted aquatic species. The Edwards aquifer is considered one of the most diverse subterranean aquatic ecosystems in the world [Harden, 1988; Longley, 1981]. A decreased water level in the aquifer jeopardizes this unique fauna because of reduced spring flow and possibly increased concentrations of pollutants. Organisms that live in the relatively constant environment of springs do so to reduce competition with other species for food and habitat. An organism that has developed the ability to live within a narrow physiologic range of environmental conditions becomes more efficient and expends much less energy living in that range than does one capable of survival within a broad range of environmental conditions.

There is a rich diversity of organisms in the San Marcos Springs ecosystem and slightly less diversity in the Comal Springs system as shown by not only the threatened and endangered organisms, but by the large numbers of uncommon species (Table 4.1). The high species diversity reflects the stability of the environment. Long periods of stable temperature, flow, and chemical constituents have enabled species to coexist even within similar niches. However, these organisms are now tolerant of only a narrow range of environmental conditions, and under changing conditions the community would not persist. The threatened and endangered species are so because they are the species least able to survive environmental changes. The narrow ecological tolerance of these species also means they are not available to recolonize from nearby sources should they be extirpated. In order to preserve the integrity of the spring ecosystems, environmental conditions must stay relatively constant.

Declining water levels in the Edwards Aquifer would be accompanied by loss of species habitat as areas dried up. Decrease in the number and volume of spring flows may cause a decline in reproduction of such organisms as the San Marcos salamander. Decreases in current velocity and changes in substrate will change the distribution of aquatic vegetation and redistribute microhabitat. Some species would gain habitat at the expense of loss to other species. Declining water quality would stress or eliminate may species dependent on low concentrations of dissolved salts, trace elements, and pesticides. As water temperatures increased and fluctuated over a wider range, many of the spring organisms that can tolerate limited temperature variation would disappear. Organisms inhabiting the springs are often more affected by the variation in water temperature than by the absolute value of the temperature. Organisms capable of a wide range of environmental conditions would be favored and species diversity would likely decline in the spring and river systems.

1.2 OUTLINE OF THE REPORT

The objective of this research was to evaluate the general feasibility of augmenting water flows from Comal and San Marcos Springs for the purpose of protecting endemic plant and animal species which now depend upon artesian spring flows from the Edwards aquifer for their existence. The study has compiled and examined information needed to consider springflow augmentation as a viable means of protecting rare and endangered species associated with these large spring systems.

Specific research objectives of Phase I of the study have included an assessment of potential supplementary water sources; characterization of the geological properties of the Edwards aquifer in the study area; identification of potential locations and alternative methods for augmenting spring flows; and analyses of the engineering, environmental, economic and institutional aspects (costs, benefits, and uncertainties). The study has relied on existing data and published studies of hydrology, biology, geology, and other disciplines. The engineering, environmental, and economic analyses in this phase have been undertaken on the basis of the existing information, with a minimum of primary data collection. The following chapters of this report include:

Chapter 2: Historical hydrology—Historical information about the volume of daily flow from the springs, the elevation of water in the aquifer and the quality of water emanating from the springs, and in the Comal and San Marcos Rivers in the vicinity of endemic and endangered species.

Chapter 3: Geological characterization of study area—A description of the basic geological information necessary to be able to select sites for springflow augmentation, especially those alternatives that include injection into or recharge of the aquifer formation leading to the springs.

Chapter 4: General biological habitat characteristics of Comal and San Marcos Springs—A general description and detailed maps of the springs and the federally-designated critical habitats of threatened and endangered species occurring there, including the elevations of the springs, normal elevations and areas of spring lakes and related impoundments, and the channel morphology of springruns and downstream segments of Comal and San Marcos Rivers to their confluences with the Guadalupe and Blanco Rivers, respectively.

Chapter 5: Sources of water for augmentation—Using the historical hydrology and habitat characteristics from Chapters 2 and 4, an estimate of the quantity and quality of waters that must be supplied for augmentation is made. Sources that may serve as water for springflow augmentation are evaluated and identified.

Chapter 6: Alternative augmentation sites and methods—Using information derived from the Chapters 2-5, specific augmentation alternatives and effective and efficient locations sites are defined and discussed.

Chapter 7: Feasibility analysis of augmentation alternatives—Information on the location of water sources, augmentation techniques, and sites for augmentation is combined and an evaluation is made of the engineering feasibility, environmental impacts, economic costs, and the institutional framework for financing, constructing, and operating the augmentation facilities.

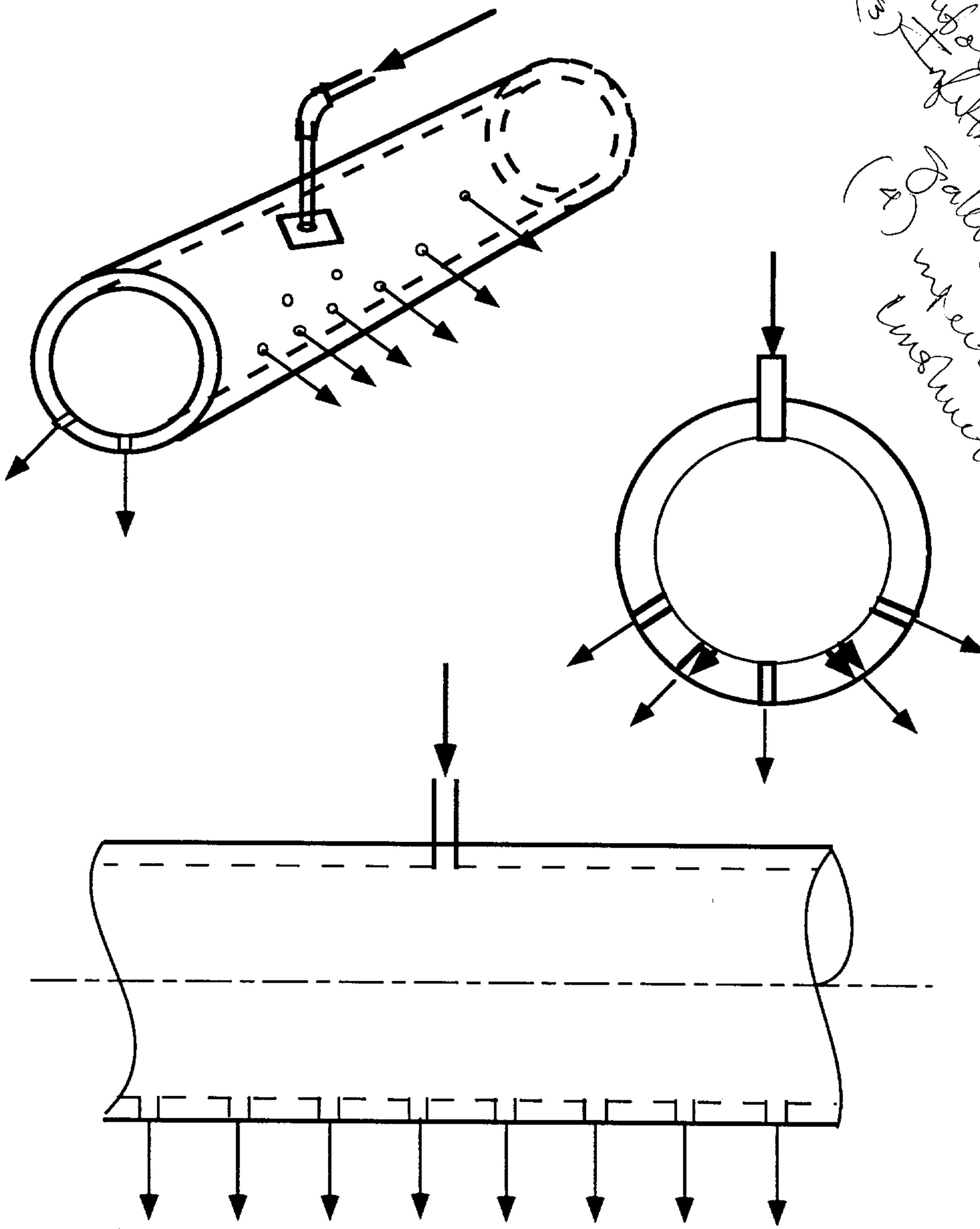


Figure 6.8. Typical infiltration gallery construction details.

(1) Subsurface dam
(2) Manifold
(3) Infiltration
(4) gallery & injection well construction details to be provided in final

2.0 HISTORICAL HYDROLOGY

2.1 WATER QUANTITY DATA

Historical information about the volume of flow from the springs and the elevation of water in the aquifer was compiled from a variety of sources and analyzed. Much of the work required to accomplish this task was nearly complete when the study began, thanks to previous work done by the Austin office of the USGS [Jennings and Buckner, 1993] and information available from the literature. Additional information was collected and analyzed. Daily records were used whenever possible and flow analyzed to relate water elevation to springflow, as well as the relationship between water levels and recharge in the Blanco River Basin.

The historical flows at Comal Springs and San Marcos Springs are characterized in this section in preparation for estimating the volume of water needed for spring flow augmentation in order to keep the Comal and San Marcos Springs flow rates above certain threshold levels. The analysis consists of two parts: (1) general descriptions of the historic daily flows at Comal and San Marcos Springs. The statistical parameters of the spring flow are computed and analyzed, and (2) a drought analysis. All of the analyses are based on the following data sets: (1) Comal Springs daily flow data collected by the USGS from 1929 to 1992, (2) San Marcos Springs daily flow data collected by the USGS from 1956 to 1993 [USGS, 1993].

Discharge of the Comal River, as measured at the San Antonio Street bridge, has varied slightly and has ceased in response to drought (Figure 2.1). Discharge of the San Marcos River, as measured at the USGS gage near the San Marcos City sewage treatment plant from 1957 to 1988 and thereafter as a water level/discharge relation at an index well 6 km south San Marcos City, has varied slightly and then only in response to drought (Figure 2.2). Although flows declined severely during the drought of the mid 1950's, the river has never ceased flowing during the period it has been monitored.

The San Marcos River upstream of the confluence with the Blanco River may be divided into three reaches based on current velocity and substrate [Espey, Huston and Associates, 1975]. From Spring Lake dam to Rogers Dam (Rio Vista Dam), it is typically broad, slow flowing, with mud substrate (except near the dam) and has dense beds of aquatic vegetation. Downstream of Rogers Dam to a point just below Thompsons Island, the current velocities are higher, the substrate is rocky, and the vegetation is less dense. Downstream of Thompsons Island velocities are very slow, there are deep pools, greater turbidity, and fewer aquatic macrophytes. The lower reach is very different from the upper reaches due to extensive canopy of trees, backwater from the impoundment at Alvord Dam (about 0.5 km downstream of the confluence with the Blanco River), and discharge of turbid and nutrient-rich water from the San Marcos City wastewater treatment plant. The differences in velocity and substrate greatly influence the types of organisms living in each reach and changes in the velocity result in alteration of the substrate with consequent changes in the biota.

2.1.1 Hydrologic Analysis of Historic Daily Spring Flow at Comal Springs

This section presents the summary statistics and a drought analysis of the historic daily spring flows at Comal Springs from 1929 to 1992.

2.1.1.1 Statistics of Comal Springs Daily Flow

Monthly statistics of the daily flow at Comal Springs were computed and are listed in Table 2.1. These results show that the mean flow rate for December through June are above the annual average flow of 284 cfs, and the mean flow rate for July through May are below the average. The monthly spring flows for all 12 months are slightly negatively skewed with skew coefficients ranging between -0.63 and -0.87. The annual flow histogram exhibits a skewness of -0.81. The histograms of the daily flow at Comal Springs grouped by month are plotted in Appendix D.

The histogram and empirical cumulative frequency distributions of the daily flows at Comal Springs are shown in Figures 2.3 and 2.4. Figure 2.3 illustrates the negative skewness of the spring flow. Figure 2.4 illustrates the definite periods of relatively high and low spring flow. According to Beran et al. [1985], river flow or precipitation can be divided into five classes: very wet, wet, normal, dry, and very dry, based on their cumulative frequency distribution. The criteria for these five classes are listed in Table 2.2.

In searching for possible long term trends of spring flow, the daily spring flow records were cut into 10-year intervals and summary statistics computed for these intervals. The results of the analysis are listed in Table 2.3. It can be seen from the statistics that 1949-1959 was a very dry period. The average flow rate in this 10 year interval was 186 cfs, substantially below the long term average flow rate of 284 cfs. Other dry periods were 1959-1969, and 1979-1992. The histograms of daily spring flows in 10 year intervals were also computed to show the distribution of the spring flow.

30-day, 60-day, 90-day, and 120-day moving averages and flow frequency analysis were performed on the daily spring flow data for Comal Springs to see the flow rate variations between 1929 and 1992. The purpose of doing a n-day moving average is to check (1) if there is any cyclic trend imbedded in the daily flow pattern, and (2) to find abnormal records that might result from sample or computation mistake. The daily flow and 30, 60, 90, 120-day moving averages were computed and no cyclic trends were evident.

2.1.1.2 Drought Analysis for Comal Springs

Using the historical records, the severity and duration of spring flow above (wet) or below (dry) a given threshold were computed. The duration is the number of consecutive days for which the flow is either below (dry) or above (wet) a given flow rate threshold. The severity is the cumulative excess or deficit of the spring flow above or below a threshold for that duration. The duration and severity are related by the magnitude which is defined by [Dracup et al., 1990]: Magnitude = Severity/Duration. This analysis reveals the frequency of dry and wet periods for different threshold flow rates under historic pumping and recharge conditions. The results of the computations are listed in Table 2.4. It can be seen from Table 2.4 that the flow rate crosses the thresholds of 100 cfs, 200 cfs, and 284 cfs (long-term average flow), 24, 52 and 132 times, respectively. Based on these results, the frequency curves of the dry/wet duration under the flow thresholds of 283, 100, and 200 cfs were constructed (see Figure 2.5).

From the historic daily flow records, maximum one time deficits of Comal Springs flow from various thresholds flow levels were computed for the period of 1929 to 1992. The purpose of the computation is to show, under historic pumping and recharge conditions, how much augmentation water would need to be added if the spring flow were to be maintained at a specific threshold flow level. The deficit can be estimated using the following formula:

$$\text{Deficit} = (Q_{th} - \overline{Q}) * \Delta t * K$$

where Q_{th} = the spring flow rate to be maintained (cfs)

$\overline{Q}$ = the average spring flow rate for the duration that spring flow is less than Q_{th}

Δt = number of days that spring flow is less than Q_{th}

K = 1.98 (AF/cfs*day)

For example, if the threshold flow level is 100 cfs, the historic record shows that from June 1955 to April 1957, the flow at Comal Springs was below 100 cfs for 677 days with an average flow of 46.35 cfs. The total deficit during this period was (100-46.35)*677*1.98 = 71910.6 AF (see Figure 2.6 and Table 2.5).

Figure 2.7 shows plots of the 7, 30, 60, and 90 day minimum flow frequency curves. These curves were prepared using the following procedures:

(1) For each year of the 63 year daily flow records, one minimum *s*-day average value was found,

(2) The 63 annual *s*-day minimum values were ranked in ascending order,

(3) The recurrence interval for each value was computed by the formula m/(n+1)= m/64, (m is the rank of the value in the sequence prepared in step 2),

(4) Graphs of *s*-day minimum flow rate vs. recurrence interval were plotted.

The recurrence intervals for the events that the 7, 30, 60, and 90 day minimum flows are less than or equal to 100 cfs were estimated from the graphs toe between three and five years.

2.1.1.3 Auto Regression Analysis for Comal Springs

Auto regression coefficients were computed for the historic Comal Springs daily flow lags of 1, 2, 10, 30, 60, 90, and 150 days. The results of these computations are presented in Table 2.6. The results show that the Comal Springs daily historic flow has a very strong auto correlation. Because of the strong auto correlation of the spring flow, it is possible to predict the future spring flow rate based on the current spring flow records. A strong auto correlation also implies that variation in the spring flow is slow and gradual, therefore, by closely observing the spring flow and carefully managing the pumping and artificial recharge, it should be possible to prevent the spring flow from dropping below a specified threshold level.

2.1.2 Hydrologic Analysis of Historic Daily Spring Flow at San Marcos Springs

This section presents the summary statistics and a drought analysis of the historic daily spring flows at San Marcos Springs from 1956 to 1993.

2.1.2.1 Statistics of San Marcos Springs Daily Flow

Monthly statistics of the daily flow at Comal Springs were computed and are listed in Table 2.7. These results show that the mean flow rates for February through July are above the annual average flow of 170 cfs, and the mean flow rate for August through January are below the average. The monthly spring flows for all 12 months are positively skewed with skew coefficients ranging between 0.47 and 1.81. The annual flow histogram exhibits a skewness of 1.21.

The histogram and empirical cumulative frequency distributions of the daily flows at San Marcos Springs are shown in Figures 2.8 and 2.9. Figure 2.8 illustrates the positive skewness of the spring flow. Figure 2.9 is used to classify the daily flow at San Marcos springs and illustrates the definite periods of relatively high and low spring flow. The criteria and the threshold flow level for these classes are listed in Table 2.8.

2.1.2.2 Drought Analysis for San Marcos Springs

Using the historical records, the severity and duration of San Marcos spring flow above (wet) or below (dry) a given threshold were computed. This analysis reveals the frequency of dry and wet periods for different threshold flow rates under historic pumping and recharge conditions. The results of the computations are listed in Table 2.9. It can be seen from Table 2.9 that the flow rate crosses the thresholds of 100 cfs and 170 cfs (long-term average flow), 38 and 74 times, respectively.

From the historic daily flow records, maximum one time deficits of San Marcos Springs flow from various thresholds flow levels were computed for the period of 1956 to 1992. The purpose of the computation is to show, under historic pumping and recharge conditions, how much augmentation water would need to be added if the spring flow were to be maintained at a specific threshold flow level. The results of these computation are plotted in Figure 2.10 and Table 2.10. Figure 2.11 shows plots of the 7, 30, 60, and 90 day minimum flow frequency curves. The recurrence intervals for the events that the 7, 30, 60, and 90 day minimum flows are less than or equal to 100 cfs were estimated from the graphs to be between three and five years.

2.1.2.3 Auto Regression Analysis for San Marcos Springs

Auto regression coefficients were computed for the historic San Marcos Spring's daily flow lags of 1, 2, 10, 30, 60, 90, and 150 days. The results of these computations are presented in Table 2.11. The results show that the San Marcos Springs daily historic flow has a strong auto correlation for only the one to ten day lag periods. Because of the weak auto correlation of the spring flow beyond lag 10, it is probably not possible to predict the future spring flow rate based on the current spring flow records.

2.1.3 Recharge and Pumpage in the Edwards Aquifer-Balcones Fault Zone Region

The recharge of the Edwards Aquifer comes from nine gaged recharge basins: Nueces-West Nueces River, Frio-Dry Frio River, Sabinal River, Area between Sabinal and Medina Rivers, Medina River, Area between Medina River and Cibolo Creek, Cibolo Creek and Dry Comal Creek, Guadalupe River, and Blanco River, and eight ungaged recharge basins [EUWD, 1991]. The nine gaged recharge basins belong to three river basins: Nueces (containing the first four recharge basins), San Antonio (containing the next three), and Guadalupe (containing the last two). The estimated historic annual recharge to the Edwards aquifer from 1934 to 1992 is shown in Table 2.12 [EUWD, 1993]. The historic pumpage from the Edwards aquifer from 1934 to 1992 is shown in Table 2.13 [EUWD, 1993].

HDR Engineering, Inc., has developed a recharge calculation method for the Edwards aquifer [HDR, 1993]. Table 2.13 lists the mean annual recharge for the period 1934-1989 for nine basins estimated by the USGS and HDR methods, respectively. It can be seen from the table that USGS estimates are higher than the HDR estimates for the Nueces River basin, while HDR estimates are higher for the San Antonio and Guadalupe River basins. The difference in recharge estimates of USGS and HDR results from the different methods employed by USGS and HDR. These differences are summarized below [HDR, 1993; EUWD, 1993]:

(1) The HDR method shows generally lower recharge in the western counties of the recharge zone and higher values for the northeastern counties.

(2) In estimating runoff directly over the recharge zone, the USGS method assumes that runoff is equal to the runoff from the area upstream of the recharge zone, adjusted for drainage area size and precipitation differences. The USGS method assumes that runoff varies linearly with precipitation when adjusting for precipitation differences and assumes that the runoff potential of the soil-cover complex is about the same in both the area upstream of and the area directly over the recharge zone. The HDR method is based on Soil Conservation Service (SCS) procedures which take into account differences in soil-cover complexes as well as differences in rainfall.

(3) The HDR method accounts for water rights diversions and return flows.

(4) The HDR and USGS methods use different stage-recharge relationships for Medina Lake.

(5) The HDR method calculates recharge in the Guadalupe River Basin in the intervening area below Canyon Lake and above New Braunfels, including that occurring in the river channel when Edwards aquifer levels are low. The USGS method does not calculate recharge in the Guadalupe river basin.

Table 2.13 shows that Nueces River Basin contribute about 57% of the surface water recharge to the Edwards Aquifer, San Antonio River Basin Contributes 37%, and Guadalupe River Basin, 6%. The net difference in the USGS and HDR estimated recharge values for the San Antonio region of the aquifer is only about two to three percent [EUWD, 1993].

From the data in Table 2.12, an empirical cumulative frequency curve of the recharge to the Edwards aquifer over the period of record was prepared (Figure 2.12). This figure was used to estimate the classification of dry, normal, and wet natural recharge periods. The thresholds of very dry, dry, normal, wet, and very wet were estimated and are listed in Table 2.14. Over the period of record, the USGS recharge estimates range form 43,700 AF in 1956 to 2,486,000 AF in 1992. The estimated average annual recharge to the aquifer over this period was 682,800 AF. The average annual recharge in the drought period of 1947 to 1956 was 229,000 AF, which correspond to the 16th and 57th percentiles, respectively, in Figure 2.12.

The estimated annual distribution of discharge form the Edwards aquifer for the period 1934 to 1992 is shown in Table 2.15 [EUWD, 1993]. These data include both well pumping and spring flow discharge. Springflow discharge is calculated by measuring downstream flow from spring orifices [EUWD, 1993]. The discharge from the aquifer varies from a low of 388,1000 AF in 1956 to 1,100,000 AF in 1992. Springflow over this period varied from 69,800 AF in 1956 to 802,800 AF in 1992. The average annual springflow over the period of record is 362,900 AF. Pumping in the aquifer over the period of record has steadily increased. The lowest pumpage was 101,900 AF in 1934, and the highest was 542,400 AF in 1989. Since the 1970's, annual groundwater pumping has exceeded springflow in periods of lower than normal recharge. Figure 2.13 is a plot of the annual pumping and recharge from the aquifer.

A simple regression of monthly pumpage vs. time shows that there is an increasing trend of pumping over years in the Edwards Aquifer. Various regression models have been developed to predict the spring discharge from the aquifer as a function of different factors, such as previous year spring discharge, aquifer water levels, recharge, and pumping [Puente, 1976; Jennings *et al.*, 1992; Asquith and Jennings, 1993]. perhaps the most successful of these regression expressions is that reported by Asquith and Jennings (1993)

$$Q_y = 76.04 + 0.6555 Q_{y\text{-}1} + 0.1726 R_y - 0.2341 P_y$$

where Q_y and $Q_{y\text{-}1}$ [1000 AF] are the estimated and previous year's annual spring discharge, R_y and P_y are the current year's estimated annual recharge and pumpage. The standard error of estimate is 51 (1000 AF) or 14% of the estimated value, and the multiple correlation coefficient is 0.90.

2.2 WATER QUALITY DATA

The Edwards aquifer in the San Antonio is a vast source of relatively high quality water for the region. Carbonate aquifers such as the Edwards are extremely susceptible to groundwater contamination due to the rapid rates of groundwater flow and the volumes of water moving through the aquifer [USGS, 1987]. Water quality in the Edwards aquifer has been monitored since the 1930's. Data for trace elements and pesticides have been reported since 1968 and for volatile organic compounds since 1982 [EUWD, 1985]. The water quality of groundwater in the freshwater parts of the aquifer (north of the "bad-water" line) has been found suitable for all uses including human consumption [USGS, 1987].

There is a large water quality data base available for the Edwards aquifer because water quality has been monitored on a regular and frequent basis [USGS, 1987; Ogden et al., 1986]. Data have been collected on the quality of water emanating from Comal and San Marcos Springs and in the Comal and San Marcos Rivers in the vicinity of endemic and endangered species, along with water quality data from area monitoring wells. Parameters of interest include turbidity; temperature; conductivity; and chemical concentrations of nitrate, nitrite, ammonia, nitrogen, phosphate, silicate, organic carbon, alkalinity, pH, oxygen, sulfate, sulfide, methane, calcium, magnesium, chloride, sodium, potassium, and contaminants such as herbicides, pesticides, and heavy metals.

Because most of the water in the Edwards aquifer originates as precipitation on the Edwards Plateau, which is mainly undeveloped range land, low contamination levels can be expected. This indeed has been found by most studies. Contamination events that have been limited to the unconfined area [USGS, 1987] and to uncased wells or to wells with defective casings [Clement, 1989]. Volatile organic compound (VOC) concentrations ranging from 1 to 5 μg/L have been detected in a few wells [EUWD, 1983, 1990, 1991]. Trihalomethanes have been found in concentrations ranging from 0.60 μg/L to 6.4 μg/L, and chlorinated hydrocarbons concentrations have ranged from 0.2 to 7.4 μg/L. Again, in most of the samples none of the above were detected [EUWD, 1990; USGS, 1987; TDWR, 1979]. The presence of nitrate has been studied intensely [Browning, 1977; USGS, 1985; USGS; 1987]. It seems that nitrate concentrations are highly dependent on the recharge rate [Browning, 1977]. Nitrate concentrations range from 0 to 15 μg/L, with a lower concentration in the lower part of the aquifer. The potential for contamination of the Edwards aquifer from existing human activity is limited [USGS, 1987]. Urbanization of the area north of San Antonio, in the recharge zone, poses the risk of recharging the aquifer with contaminated runoff water. In addition, many landfills and storage tanks are present near the recharge zone. Leakage has been minimal thus far, but this is likely to change over time [USGS, 1987]. Over-pumping the aquifer may cause intrusion of saline water from the bad-water zone, thus threatening the water quality in many public wells located near the transition zone [Clement, 1989]. Historical files of water quality data from USGS and other sources were available for use in this investigation.

2.2.1 Analysis of the USGS Water Quality Database for Ground and Surface Water in Comal and Hays Counties, Texas

An analysis of the water quality databases for Hays and Comal Counties has been performed. The purpose of this analysis is to assess the ground and surface water quality of Comal and Hays counties in terms of concentration levels of selected chemicals. The results of the analysis can be used to (1) identify highly polluted areas that might exist, (2) present measures of the time and spatial variation of the water quality in the Edwards Aquifer, and (3) serve as a water quality standard when searching for possible sources of augmentation waters for Comal and San Macros Springs. All of the analyses are based on the water quality data collected by the USGS between 1968 and 1992, from 112 locations.

The USGS water quality data for Comal and Hays Counties are stored in 5 database files. These data consist of (1) ground water quality in Comal County, (2) surface water quality in Comal County, (3) ground water quality in Hays County, (4) surface water quality in Hays County, and (5) water quality in Canyon Lake. There are two data items associated with each sample collected (1) the concentration level of the chemical and (2) a flag indicating the existence of subsidiary information. The Comal County ground water quality database contains data samples collected from 70 locations in Comal County (Figure 2.14). The Comal County surface water quality database contains the water quality data collected from 4 sites on the Guadalupe River and 1 site at Canyon Lake near New Braunfels. The Hays County ground water quality database contains the data collected from 32 locations in Hays County (Figure 2.14). The Hays County surface water quality database contains the water quality data collected from 2 sites located on Onion Creek, 3 sites located on Bear Creek, Blanco River, and Little Bear Creek. The data in the Canyon Lake water quality database were collected from 5 sites located on the lake. Table 2.16 is a brief description of the databases.

A regional analysis was performed to provide summary statistics on a regional basis for the chemical constituents in the water quality databases. This analysis quantifies the ground and surface water quality in terms of the chemical concentration levels and their variation. The maximum, mean, minimum and standard deviation are computed for each chemical constituent in the Comal County ground water, surface water, Hays County ground water, surface water and Canyon Lake databases. The items listed in the tables are, Chemical Code and Name, Maximum (first date/location where the maximum value occurred), Mean, Minimum, Number of Observations, Number of non-zero flags, Maximum Contaminant Levels (MCLs) under National Primary Drinking Water Regulations, time and locations showing when and where each of the Maximum and Minimum values are recorded.

The only constituents whose average concentration levels were above MCLs in surface water samples in Comal County were Turbidity (46.12 vs. 1 NTU) and Beryllium (0.505 vs. 0 μG/L). Summary statistics of chemical constituents in the Canyon Lake database show that the concentration levels of all constituents are below MCLs wherever MCLs are available. Summary statistics of chemical constituents in the Hays County surface water database show that Turbidity, Beryllium , and Cadmium have been reported above MCLs. Tables 2.17 and 2.18 list the times and locations when and where MCL violations occurred in surface water. The times and locations where MCLs violations occurred in ground water are listed in Tables 2.19 and 2.20 for Hays and Comal Counties, respectively.

Because samples from wells located near the bad water line were included in the ground water databases, some of the chemical concentrations are high compared to the level that would normally found in fresh water portion of the Edwards aquifer. In this report, freshwater is defined to be that with a total dissolved solids concentration of less than 1000 mg/L. To give a more reasonable representation of the ground water quality of the Edwards Aquifer near Comal and San Marcos Springs, the wells located near the bad water line were excluded. Table 2.21 lists the identification numbers of wells located near the bad water line in Hays and Comal Counties.

After excluding the wells near the bad water line, the water quality statistics were recomputed for ground water in Comal and Hays Counties. These results show that wherever drinking water standards are available, the average chemical concentrations are below the MCLs except for Beryllium, which has an average concentration value of 1 μg/l which exceeds the MCL value of 0 μg/l. Comparing the maximum concentration values with the MCLs, it can be seen that for Comal County ground water, the maximum concentration of Lead and Vinyl Chloride are above MCLs, and for Hays County ground water, Fluoride, Beryllium, and Vinyl Chloride are above the MCLs values. Table 2.19 lists all the locations and dates showing where and when the concentration levels exceeding MCLs were sampled in Hays County and the flag values of these samples. Table 2.20 lists all the locations and dates showing where and when the concentration levels exceeding MCLs were sampled in Comal County and the flag values of these samples. For all the chemicals whose maximum values are greater than MCLs, a "<" signs appears in its associated flag field.

This is also the case for the chemicals whose maximum concentrations exceed the MCLs in Hays County ground water. The "<" sign indicates that the actual concentration is lower than the value recorded in the field MAX. Further investigation of the lead MCL violation data shows that the concentration of 100 μg/l occurred only once in Comal County. The next largest figure recorded is 22 μg/l (once) and several other measurements of 10 μg/L are also recorded. The lead concentration of 100 μg/l seems to be an unusually high value that persisted for only a short time.

To further characterize the water quality of Comal and San Macros Springs, the USGS water quality data collected at wells near the spring locations were selected to create a new database so that the water that affects the spring water quality most can be examined separately. From well location maps, the wells located near Comal and San Marcos Springs were identified and marked in the databases. Table 2.22 lists and Figure 2.14 illustrates the well locations and names of those sites. Subsets of the Comal and Hays County ground water quality databases were created containing only the samples collected at these sites. Using these two subsets, the maximum, minimum, mean, and standard deviation of chemical concentrations in the areas near these two springs were computed.

2.2.2 Analysis of Water Quality Studies in the Vicinity of Comal and San Macros Springs

2.2.2.1 San Marcos River

Espey, Huston and Associates [1975, p. 4-11] measured dissolved oxygen and water temperatures in the San Marcos River at monthly intervals over diel (24 hour) periods from July 29 to November 27, 1974. They found little variation in diel temperatures between upstream (immediately downstream of Spring Lake) and a station immediately downsteam of the confluence with the Blanco River. At any given time, temperatures did not vary more than ±1°C. Temperatures within this reach were similar to those in the springs (22.6 ±2°C). This is likely due to the short travel time from the springs to the confluence with the Blanco River. Travel time from Spring Lake dam to a point about 1.6 km downstream of the confluence with the Blanco River was 11.25 hours on August 26 and 27, 1974 at a discharge of about 243 cfs (6.9 m^3/s) [Espey, Huston, and Associates, 1975, p. 4-29]. Concentrations of dissolved oxygen varied widely over the reach due to differences in densities of aquatic vegetation. From July through September, stations 2 and 3 (upstream of Rogers Dam), had wide fluctuations in dissolved oxygen, often exceeding 150 percent of saturation. Other investigators have shown the water temperature to be remarkably constant at about 22°C and dissolved oxygen concentrations to be variable with location and time-of-day (Table 2.25).

2.2.2.2 San Marcos Springs System

The general water quality of Spring Lake was reported by Devall [1940, p. 34]. Concentrations of dissolved oxygen in 2 surface samples were 8.8 and 10 mg/L; pH of 7.2 and 7.3; water temperature 22.9 and 23.2 ^oC. Near-bottom (7 m) concentrations of dissolved oxygen were 4.8 and 6.4 mg/L; pH was 7.1 at both sites; and water temperature 22.2 and 23.8 ^oC. Other than dissolved oxygen, conditions showed little variation between sites or with depth. Water-quality data reported in earlier studies are summarized in Tables 2.25 and 2.27. Except for dissolved oxygen, there is typically little variation in most constituents throughout the river. Diel studies that measured changes in pH as well as dissolved oxygen show relatively small changes in pH compared to large diel variations in dissolved oxygen [Hannan and Dorris, 1970, p. 445]. In most river systems, algae and macrophytes produce oxygen as a byproduct of photosynthesis during the daytime as they remove carbon dioxide for fixation into sugars. This often creates oxygen supersaturation in the daytime and generally low concentrations of oxygen at night. The removal of carbon dioxide during the daytime causes pH to rise considerably during daytime and decline at night. In both San Marcos and Comal Spring systems, the high alkalinity serves as a buffer to pH changes, maintaining a relatively narrow range of pH and providing more constant conditions. Data reported by Espey, Huston and Associates [1975] and presented in Table 2.27 show water from the San Marcos River is a calcium bicarbonate type with low concentrations of dissolved solids and is very hard. It contains moderate amounts of nitrate but concentrations of phosphate, another plant nutrient, are generally small. Concentrations of ammonium ion (an indicator of unionized ammonia which is toxic to fish), are less than 0.1 mg/L.

2.2.2.3 Comal Springs System

Total alkalinity for water from the Comal Springs system is generally high and shows little variation around 230 mg/L (Table 2.23). The water is a calcium bicarbonate type and is hard (Table 2.27). Discharge and general water quality were measured for the four primary orifices at Comal Springs at weekly intervals from August 1982 to September 1983 for the Edwards Aquifer Research and Data Center by Rothermel and Ogden [1987]. Table 2.28 shows the minimum and maximum values for the four springs. There were wide variations in discharge among the four springs and considerable variation within any one spring. Water temperatures and pH varied little among springs and at any one spring. Concentrations of major ions affecting hardness and alkalinity varied by factors of 2 or 3 among the 4 springs.

Near-continuous monitoring by the U.S. Geological Survey at five sites on the Comal River in the summer of 1993 showed generally stable values for several constituents. There was little variation in pH; maximum values never exceeded 7.8 and minimum values were no lower than 7.2. There were only small variations in specific conductance within and between sites and the maximum value recorded was 632 μS/cm. Water samples from the five sites on the Comal River did not contain concentrations of any common or trace elements known to be hazardous to aquatic life (Table 2.29). Concentrations of organochlorine and organophosphate insecticides and common herbicides in water were less than the reporting limits shown in Table 2.30 at all sites except at Torrey Mill Dam where diazinone was present at a concentration of 0.02 μg/L on August 20 and at the site above Hinman Island Drive where the diazinone concentration was 0.01 μg/L. The concentration of diazinone in a second sample from the site at Torrey Mill Dam taken on September 20 was less than the reporting limit.

Table 2.23 shows ranges for water temperature and dissolved oxygen recorded in previous studies of the Comal Springs system. Water temperatures of the source springs typically vary less than 2 °C from 23 °C. Downstream temperatures are usually slightly warmer but seldom exceed 25 °C. Concentrations of dissolved oxygen show large variations with location and time of day. Near-continuous monitoring of water temperature, dissolved oxygen, pH, and specific conductance was done by the U.S. Geological Survey on the Comal River in the summer of 1993. Water temperature varied a maximum of 2.7 °C at any one station during the entire recorded period and during any one day it varied only 2 °C (Table 2.26). Due to large numbers of aquatic macrophytes and algae, dissolved oxygen concentrations varied widely with time-of-day but were less variable between stations.

Table 2.1. Monthly Statistics of Historic Daily Flow at Comal Springs.

Month	Min. (cfs)	Max. (cfs)	Mean (cfs)	Median (cfs)	St. Dev. (cfs)	St. Error	Skew
January	34	478	296.9	308.0	75.51	1.71	-0.87
February	39	514	300.0	312.0	76.84	1.82	-0.69
March	55	500	298.2	312.0	77.17	1.75	-0.79
April	32	506	294.1	308.0	81.57	1.88	-0.67
May	19	506	294.4	311.0	86.38	1.95	-0.71
June	0	503	288.0	308.0	98.48	2.27	-0.77
July	0	495	271.3	297.0	101.36	2.29	-0.73
August	0	476	257.5	282.0	100.62	2.28	-0.63
September	0	468	262.8	282.0	94.24	2.17	-0.77
October	0	534	272.3	290.0	85.83	1.94	-0.76
November	0	462	282.2	291.0	80.15	1.84	-0.8
December	18	483	291.2	304.0	77.87	1.76	-0.85
63 years	0	534	284.0	304.0	88	0.58	-0.81

Table 2.2. Classification of the historic daily flow at Comal Springs.

Class Name	Exceedance Frequency	Threshold for Comal Springs Flow
Very wet	0% to 15 %	above 360 cfs
Wet	15% to 35 %	327 to 360 cfs
Normal	35% to 65 %	267 to 327 cfs
Dry	65% to 85 %	196 to 267 cfs
Very dry	85% to 100 %	below 196 cfs

Table 2.3. Statistics of Historic Daily Flow at Comal Springs from 1929-92 in 10-year Intervals

	Min. (cfs)	Max. (cfs)	Mean (cfs)	Median (cfs)	St. Dev. (cfs)	St. Error	Skew
1929-1939	32	483	321.9	31.04	0.51	-0.28	4.78
1939-1949	238	425	329.5	42.62	0.71	0.17	2.32
1949-1959	0	360	186.0	93.33	1.54	-0.21	2.17
1959-1969	42	375	263.7	64.22	1.06	-0.7	3.07
1969-1979	92	534	346.0	68.16	1.13	-0.79	4.2
1979-1989	26	484	263.3	79.25	1.31	-0.85	3.77
1989-1992	46	514	262.5	120.06	3.63	0.74	2.28
1929-1992	0	534	284.0	88	0.58	-0.81	3.78

Table 2.4. Dry and Wet Duration Frequency Analysis of Comal Springs.

Threshold level (cfs)	284	200	100
Number of crossings of the threshold level	132	52	24
Mean Duration of Crossing (days)			
Dry	71	68	51
Wet	103	368	874
Maximum Duration of Crossing (days)			
Dry	2827	1186	677
Wet	2713	6213	7336

Table 2.5. Maximum One-time Deficit and Duration at Comal Springs for Given Threshold Flow Levels.

Threshold Flow (cfs)	Deficit (acre-ft)	Duration (months)
0	0	5
25	8,513	7
50	20,874	10
75	38,278	12
100	71,911	22
125	109,216	25
150	167,014	35
175	223,068	38
200	281,072	39
225	366,419	51
250	558,731	86
275	695,151	91
300	843,869	102

Table 2.6. Auto Correlation Coefficients for Comal Springs Daily Historic Flow

Lag Days	Auto Correlation Coefficient
1	0.9976
2	0.9958
10	0.9852
30	0.9518
60	0.8993
90	0.845
150	0.7442

Table 2.7. Monthly Statistics of Historic Daily Flow at San Marcos Springs.

Month	Min. (cfs)	Max. (cfs)	Mean (cfs)	Median (cfs)	St. Dev. (cfs)	St. Error	Skew
January	68	393	166.03	153.00	60.47	1.79	1.29
February	65	431	171.35	164.00	66.36	2.05	1.49
March	82	451	173.37	162.00	67.69	2.00	1.78
April	89	439	172.69	165.00	62.48	1.88	1.81
May	93	421	185.13	178.00	63.55	1.88	1.09
June	87	427	194.28	185.00	73.87	2.24	0.99
July	74	403	182.26	177.00	69.67	2.09	0.79
August	68	353	166.28	162.00	57.03	1.71	0.74
September	64	289	156.60	152.00	46.65	1.42	0.47
October	59	310	153.87	152.00	46.46	1.37	0.48
November	65	316	156.76	145.50	50.98	1.53	0.74
December	60	385	162.83	147.00	54.88	1.62	0.83
37 years	59	451	170.1	160.00	61.7	0.53	1.25

Table 2.8. Classification of the historic daily flow at San Marcos Springs.

Class Name	Exceedance Frequency	Threshold for Comal Springs Flow
Very wet	0% to 15 %	above 227 cfs
Wet	15% to 35 %	184 to 227 cfs
Normal	35% to 65 %	139 to 184 cfs
Dry	65% to 85 %	115 to 139 cfs
Very dry	85% to 100 %	below 115 cfs

Table 2.9. Dry and Wet Duration Frequency Analysis of San Marcos Springs.

Threshold level (cfs)	100	170.1
Number of crossings of the threshold level	38	74
Mean Duration of Crossing (days)		
Dry	31	101.9
Wet	298.7	70.6
Maximum Duration of Crossing (days)		
Dry	248	952
Wet	2553	520

Table 2.10. Maximum Duration and Deficit at San Marcos Springs Under a Given Threshold.

Threshold Flow (cfs)	Deficit (acre-ft)	Duration (months)
0	0	0
25	0	0
50	0	0
75	641	3
100	4,729	6
125	13,945	21
150	36,779	30
175	60,447	31
200	106,666	44
225	146,150	49
250	184,721	51
275	313,708	84
300	879,250	205
325	1,424,387	297
350	2,056,603	369
375	2,336,684	369
400	2,616,920	369

Table 2.11. Auto Correlation Coefficients for San Marcos Springs Daily Historic Flow

Lag Days	Auto Correlation Coefficient
1	0.9976
2	0.9941
10	0.9641
30	0.8853
60	0.7727
90	0.6677
150	0.4871

Table 2.12. USGS Estimated Historical Edwards Aquifer Recharge by Basin by year (1000's AF) 1934-1991 [EUWD, 1993].

Year	Nueces-West Nueces	Frio-Dry Frio	Sabinal	Sabinal to Medina	Medina	Medina to Cibolo	Cibolo - Dry Comal	Blanco	Total
1934	8.6	27.9	7.5	19.9	46.5	21	28.4	19.8	179.6
1935	411.3	192.3	56.6	166.2	71.1	138.2	182.7	39.8	1258.2
1936	176.5	157.6	43.5	142.9	91.6	108.9	146.1	42.7	909.8
1937	28.8	75.7	21.5	61.3	80.5	47.8	63.9	21.2	400.7
1938	63.5	69.3	20.9	54.1	65.5	46.2	76.8	36.4	432.7
1939	227	49.5	17	33.1	42.4	9.3	9.6	11.1	399
1940	50.4	60.3	23.8	56.6	38.8	29.3	30.8	18.8	308.8
1941	89.9	151.8	50.6	139	54.1	116.3	191.2	57.8	850.7
1942	103.5	95.1	34	84.4	51.7	66.9	93.6	28.6	557.8
1943	36.5	42.3	11.1	33.8	41.5	29.5	58.3	20.1	273.1
1944	64.1	76	24.8	74.3	50.5	72.5	152.5	46.2	560.9
1945	47.3	71.1	30.8	78.6	54.8	79.6	129.9	35.7	527.8
1946	80.9	54.2	16.5	52	51.4	105.1	155.3	40.7	556.1
1947	72.4	77.7	16.7	45.2	44	55.5	79.5	31.6	422.6
1948	41.1	25.6	26	20.2	14.8	17.5	19.9	13.2	178.3
1949	166	86.1	31.5	70.3	33	41.8	55.9	23.5	508.1
1950	41.5	35.5	13.3	27	23.6	17.3	24.6	17.4	200.2
1951	18.3	28.4	7.3	26.4	21.1	15.3	12.5	10.6	139.9
1952	27.9	15.7	3.2	30.2	25.4	50.1	102.3	20.7	275.5
1953	21.4	15.1	3.2	4.4	36.2	20.1	42.3	24.9	167.6
1954	61.3	31.6	7.1	11.9	25.3	4.2	10	10.7	162.1
1955	128	22.1	0.6	7.7	16.5	4.3	3.3	9.5	192
1956	15.6	4.2	1.6	3.6	6.3	2	2.2	8.2	43.7
1957	108.6	133.6	65.4	129.5	55.6	175.6	397.9	76.4	1142.6
1958	266.7	300	223.8	294.9	95.5	190.9	268.7	70.7	1711.2
1959	109.6	158.9	61.6	96.7	94.7	57.4	77.9	33.6	690.4
1960	88.7	128.1	64.9	127	104	89.7	160	62.4	824.8
1961	85.2	151.3	57.4	105.4	88.3	69.3	110.8	49.4	717.1
1962	47.4	46.6	4.3	23.5	57.3	16.7	24.7	18.9	239.4
1963	39.7	27	5	10.3	41.9	9.3	21.3	16.2	170.7
1964	126.1	57.1	16.3	61.3	43.3	35.8	51.1	22.2	413.2
1965	97.9	83	23.2	104	54.6	78.8	115.3	66.7	623.5
1966	169.2	134	37.7	78.2	50.5	44.5	66.5	34.6	615.2
1967	82.2	137.9	30.4	64.8	44.7	30.2	57.3	19	466.5
1968	130.8	176	66.4	198.7	59.9	83.1	120.5	49.3	884.7
1969	119.7	113.8	30.7	84.2	55.4	60.2	99.9	46.6	610.5
1970	112.6	141.9	35.4	81.6	68	68.8	113.8	39.5	661.6
1971	263.4	212.4	39.2	155.6	68.7	81.4	82.4	22.2	925.3
1972	109.4	144.6	49	154.6	87.9	74.3	104.2	33.4	757.4
1973	190.6	256.9	123.9	286.4	97.6	237.2	211.7	82.2	1486.5
1974	91.1	135.7	36.1	115.3	96.2	68.1	76.9	39.1	658.5
1975	71.8	143.6	47.9	195.9	93.4	138.8	195.7	85.9	973
1976	150.7	238.6	68.2	182	94.5	47.9	54.3	57.9	894.1
1977	102.9	193.6	62.7	159.5	77.7	97.9	191.6	66.7	952.6
1978	69.8	73.1	30.9	103.7	76.7	49.6	72.4	26.3	502.5
1979	128.4	201.4	68.6	203.1	89.4	85.4	266.3	75.2	1117.8
1980	58.6	85.6	42.6	25.3	88.3	18.8	55.4	31.8	406.4

Table 2.12 (continued). USGS Estimated Historical Edwards Aquifer Recharge by Basin by year (1000's AF) 1934-1991 [EUWD, 1991].

Year	Nueces-West Nueces	Frio-Dry Frio	Sabinal	Sabinal to Medina	Medina	Medina to Cibolo	Cibolo - Dry Comal	Blanco	Total
1981	205	365.2	105.6	252.1	91.3	165	196.8	67.3	1448.3
1982	19.4	123.4	21	90.9	76.8	22.6	44.8	23.5	422.4
1983	79.2	85.9	20.1	42.9	74.4	31.9	62.5	23.2	420.1
1984	32.4	40.4	8.8	18.1	43.9	11.3	16.9	25.9	197.7
1985	105.9	186.9	50.7	148.5	64.7	136.7	259.2	50.7	1003.3
1986	188.4	192.8	42.2	173.6	74.7	170.2	267.4	44.5	1153.8
1987	308.5	473.3	110.7	405.5	90.4	229.3	270.9	114.9	2003.5
1988	59.2	117.9	17	24.9	69.9	12.6	28.5	25.5	355.5
1989	52.6	52.6	8.4	13.5	46.9	4.6	12.3	23.6	214.5
1990	479.3	255	54.6	131.2	54	35.9	71.8	41.3	1123.1
1991	325.2	421	103.1	315.2	52.8	84.5	109.7	96.9	1508.4
1992	234.1	586.9	201.1	566.1	91.4	290.6	286.6	226.9	2486.0
Ave.	116.8	132.9	42.4	109.6	61.0	71.2	106.7	42.0	682.8
10 yr ave	186.5	241.3	61.7	184.0	66.3	100.8	138.6	67.3	1046.6
30 yr ave	140.1	181.9	51.9	148.2	70.7	83.5	119.5	52.6	848.5

Table 2.13. Comparison of USGS and HDR Edwards Aquifer Recharge Estimates [HDR, 1993]

River Basin	Recharge Basin	HDR Estimate (AF/yr)	USGS Estimate (AF/yr)	HDR Estimate (%)	USGS Estimate (%)
Nueces	1 Nuesec-W.Nueces	88,744	104,509	13.82	16.64
	2 Frio-Dry Frio	111,739	117,454	17.40	18.70
	3 Sabinal	32,581	38,307	5.07	6.10
	4 Between Sabinal & Medina	92,998	97,404	14.48	15.51
	Subtotal	326,062	357,674	50.78	56.96
San Antonio	5 Medina	41,833	60,780	6.52	9.68
	6 Between Medina & Cibolo	88,274	67,705	13.75	10.78
	7 Sibolo-DryComal	110,139	104,045	17.15	16.57
	Subtotal	240,246	232,530	37.42	37.03
Guadalupe	8 Guadalupe	11,255	0	1.75	0.00
	9 Blanco	64,523	37,758	10.05	6.01
	Subtotal	75,778	37,758	11.80	6.01
	Total :	642,086	627,962	100	100

Table 2.14. Classification of the Edwards Aquifer Annual Recharge.

Class Name	Exceedance Frequency (%)	Threshold for Edwards Aquifer Recharge (1000 AF/yr.)
Very dry	0 - 15	< 220
Dry	15 - 35	220 - 420
Normal	35 - 65	420 - 720
Wet	65 - 85	720 - 1140
Very wet	85 - 100	> 1140

Table 2.15. Estimated annual discharge from the Edwards Aquifer (1000 Acre-feet) [EUWD, 1993].

Year	Kinney-Uvalde	Medina	Bexar	Comal	Hays	Total	Wells	Springs
1934	12.6	1.3	109.3	229.1	85.6	437.9	101.9	336.0
1935	12.2	1.5	171.8	237.2	96.9	519.6	103.7	415.9
1936	26.6	1.5	215.2	261.7	93.2	598.2	112.7	485.5
1937	28.3	1.5	201.8	252.5	87.1	571.2	120.2	451.0
1938	25.2	1.6	187.6	250.0	93.4	557.8	120.1	437.7
1939	18.2	1.6	122.5	219.4	71.1	432.8	118.9	313.9
1940	16.1	1.6	116.7	203.8	78.4	416.6	120.1	296.5
1941	17.9	1.6	197.4	250.0	134.3	601.2	136.8	464.4
1942	22.5	1.7	203.2	255.1	112.2	594.7	144.6	450.1
1943	19.2	1.7	172.0	249.2	97.2	539.3	149.1	390.2
1944	11.6	1.7	166.3	252.5	135.3	567.4	147.3	420.1
1945	12.4	1.7	199.8	263.1	137.8	614.8	153.3	461.5
1946	6.2	1.7	180.1	261.9	134.0	583.9	155.0	428.9
1947	13.8	2.0	193.3	256.8	127.6	593.5	167.0	426.5
1948	9.2	1.9	159.2	203.0	77.3	450.6	168.7	281.9
1949	13.2	2.0	165.3	209.5	89.8	479.8	179.4	300.4
1950	17.8	2.2	177.3	191.1	78.3	466.7	193.8	272.9
1951	16.9	2.2	186.9	150.5	69.1	425.6	209.7	215.9
1952	22.7	3.1	187.1	133.2	78.8	424.9	215.4	209.5
1953	27.5	4.0	193.7	141.7	101.4	468.3	229.8	238.5
1954	26.6	6.3	208.9	101.0	81.5	424.3	246.2	178.1
1955	28.3	11.1	215.2	70.1	64.1	388.8	261.0	127.8
1956	59.6	17.7	229.6	33.6	50.4	390.9	321.1	69.8
1957	29.0	11.9	189.4	113.2	113.0	456.5	237.3	219.2
1958	23.7	6.6	199.5	231.8	155.9	617.5	219.3	398.2
1959	43.0	8.3	217.5	231.7	118.5	619.0	234.5	384.5
1960	53.7	7.6	215.4	235.2	143.5	655.4	227.1	428.3
1961	56.5	6.4	230.3	249.5	140.8	683.5	228.2	455.3
1962	64.6	8.1	220.0	197.5	98.8	589.0	267.9	321.1
1963	51.4	9.7	217.3	155.7	81.9	516.0	276.4	239.6
1964	49.3	8.6	201.0	141.8	73.3	474.0	260.2	213.8
1965	46.8	10.0	201.1	194.7	126.3	578.9	256.1	322.8
1966	48.5	10.4	198.0	198.9	115.4	571.2	255.9	315.3
1967	81.1	15.2	239.7	139.1	82.3	557.4	341.3	216.1
1968	58.0	9.9	207.1	238.2	146.8	660.0	251.7	408.3
1969	88.5	13.6	216.3	218.2	122.1	658.7	307.5	351.2
1970	100.9	16.5	230.6	229.2	149.9	727.1	329.4	397.7
1971	117.0	32.4	262.8	168.2	99.1	679.5	406.8	272.7
1972	112.6	28.8	147.7	234.3	123.7	647.1	371.3	275.8
1973	96.5	14.9	273.0	289.3	164.3	838.0	310.4	527.6
1974	133.3	28.6	272.1	286.1	141.1	861.2	377.4	483.8
1975	112.0	22.6	259.0	296.0	178.6	868.2	327.8	540.4
1976	136.4	19.4	253.2	279.7	164.7	853.4	349.5	503.9
1977	156.5	19.9	317.5	295.0	172.0	960.9	380.6	580.3
1978	154.3	38.7	269.5	245.7	99.1	807.3	431.8	375.5
1979	130.1	32.9	294.5	300.0	157.0	914.5	391.5	523.0
1980	151.0	39.9	300.3	220.3	107.9	819.4	491.1	328.3
1981	104.2	26.1	280.7	241.8	141.6	794.4	387.1	407.3

Table 2.15 (continued). Estimated annual discharge from the Edwards Aquifer (1000 Acre-feet) [EUWD, 1993].

Year	Kinney-Uvalde	Medina	Bexar	Comal	Hays	Total	Wells	Springs
1982	129.2	33.4	305.1	213.2	105.5	786.4	453.1	333.3
1983	107.7	29.7	277.6	186.6	118.5	720.1	418.5	301.6
1984	156.9	46.9	309.7	108.9	85.7	708.1	529.8	178.3
1985	156.9	59.2	295.5	200.0	144.9	856.5	522.5	334.0
1986	91.7	41.9	294.0	229.3	160.4	817.3	429.3	388.0
1987	94.9	15.9	326.6	286.2	198.4	922.0	364.1	557.9
1988	156.7	82.2	317.4	236.5	116.9	909.7	540.0	369.7
1989	156.9	70.5	305.6	147.9	85.6	766.5	542.4	224.1
1990	118.1	69.7	276.8	171.3	94.1	730.0	489.4	240.6
1991	76.6	25.6	315.5	221.9	181.0	820.6	436.0	384.6
1992	76.5	9.3	370.5	412.4	261.3	1130.0	327.2	802.8
Average	67.6	17.0	230.0	215.6	117.2	647.3	285.5	362.0
10 yr ave	119.6	45.1	308.9	220.1	141.7	835.1	459.6	375.2
30 yr ave	108.4	29.4	271.2	226.2	132.3	767.5	385.1	382.3

Table 2.16. Description of the Hays and Comal Counties Water Quality Databases.

Database Name	No. of Constituents	Begin Date - End Date	No. of locations
Comal County Ground Water	148	3/5/68-4/27/93	70
Comal County Surface Water	95	1/30/68-4/15/93	5
Canyon Lake	39	4/2/70-4/15/93	12
Hays County Ground Water	147	3/15/68-1/25/93	32
Hays County Surface Water	98	3/24/70-3/16/93	5

Table 2.17. Time and Locations of the MCL Violations in Comal County Surface Water.

Constituent	Max.	Mean	MCL	Location	Date
TURBIDITY (NTU)	880	42.16	10	GUADALUPE RIVER NEAR SPRING BRANCH	19811014
BERYLLIUM (µg/L)	0.6	0.505	1E-04	GUADALUPE RIVER AT SATTLER, TX	19910812

Table 2.18. Time and Locations of the MCL Violations in Hays County Surface Water.

Constituent	Max.	Mean	MCL	Location	Date
TURBIDITY (NTU)	1200	39.32	10	ONION CREEK AT BUDA, TX	19811006
BERYLLIUM (µg/L)	0.8	0.514	1E-04	BEAR CREEK BELOW FM RD	19930316
CADMIUM (µg/L)	14	1.116	5	ONION CREEK NR DRIFTWOOD	19761012

Table 2.19. Times and Locations of MCL Violations in Hays County Ground Water Samples.

Constituent	Max.	Flag	MCL	Location	Date
BERYLLIUM (µg/L)	1	<	0	LR-67-09-105	19840830
	1	<	0	LR-67-01-802	19840830
	2		0	LR-67-01-801	19840904
	0.5	<	0	LR-67-01-801	19890713
	1	<	0	LR-67-01-302	19840831
	0.5	<	0	LR-67-01-302	19890711
FLUORIDE (µg/L)	6		4	LR-67-01-302	19890120
VINYL CHLORIDE (µg/L)	3	<	2	LR-67-09-105	19840830
	3	<	2	LR-67-01-802	19840221
	3	<	2	LR-67-01-802	19840830
	3	<	2	LR-67-01-806	19840221
	3	<	2	LR-67-01-806	19840830
	3	<	2	LR-67-01-801	19840904
	3	<	2	LR-67-01-302	19840831
	3	<	2	LR-58-58-403	19850809
	3	<	2	LR-58-58-403	19860503
	3	<	2	LR-58-58-403	19870520
	3	<	2	LR-58-58-403	19870819
	3	<	2	LR-58-58-403	19880229
	3	<	2	LR-58-58-403	19880817

Table 2.20. Times and Locations of MCL Violations in Comal County Ground Water Samples.

Constituent	Max.	Flag	MCL	Location	Date
LEAD (µg/L)	100	<	50	DX-68-23-301	19820614
VINYL CHLORIDE (µg/L)	3	<	2	DX-68-22-901	19840817
	3	<	2	DX-68-23-303	19840820
	3	<	2	DX-68-23-305	19840820

Table 2.21. Identification Numbers of Wells Located Near the Bad Water Line in Hays and Comal Counties.

Comal County	Hays County
DX-68-23-318	LR-67-01-812
DX-68-23-616A	LR-67-01-813A
DX-68-23-616B	LR-67-01-813B
DX-68-23-617	LR-67-01-814A
DX-68-23-619A	LR-67-01-814B
DX-68-23-707	LR-68-16-601
DX-68-23-708	LR-58-58-701
DX-68-23-807	LR-58-58-707
NEW BRAUNFELS EUWD TEST	

Table 2.22. Identification Numbers of Wells Located Near Comal and San Marcos Springs.

Locations near Comal Springs	Locations near San Marcos Springs
DX-68-23-301	LR-67-01-802
DX-68-23-303	LR-67-01-805
DX-68-23-304	LR-67-01-402
DX-68-23-305	LR-67-01-502
DX-68-23-601	LR-67-01-701
DX-68-23-602	LR-67-01-703
DX-68-23-618	LR-67-01-806
DX-68-23-619B	

Table 2.23. Chemical Concentrations in Ground Water Near Comal Springs.

Constituent	Max.	Mean	Min.	St Dev.	MCL	No. of Samples
SPECIFIC CONDUCTIVITY (µs/cm)	752	555.97	479	40.529		154
PH (STANDARD UNITS)	7.8	7.177	6.5	0.223		146
TEMPERATURE (°C)	27	24.579	21	1.253		151
OXYGEN (mg/L)	4.5	4.5	4.5	0		1
COD LOW LEVEL (mg/L)	0	0	0	0		1
BOD 5-DAY (mg/L)	0.7	0.7	0.7	0		1
CALCIUM (mg/L)	86	68.371	0.02	13.134		143
MAGNESIUM (mg/L)	37	21.632	0.01	7.062		144
SODIUM (mg/L)	41	13.382	0.2	6.991		137
POTASSIUM (mg/L)	3.5	1.73	0.9	0.602		137
ALKALINITY (mg/L)	250	215.39	180	14.114		78
SULFATE (mg/L)	85	37.819	15	16.206	400	149
CHLORIDE (mg/L)	67	21.573	7.4	11.329		149
SILICA (mg/L)	14	12.423	9.4	0.697		138
DISSOLVED SOLIDS (mg/L)	433	315.02	272	25.557		135
PHOSPHATE (mg/L)	0.15	0.105	0.06	0.045		2
CARBON ORGANIC (mg/L)	19	1.623	0	3.195		56
ARSENIC (mg/L)	4	1.015	0	0.503	50	67
BARIUM (µg/L)	130	56.797	32	23.04	2000	64
BERYLLIUM (µg/L)	1	0.75	0.5	0.25	0.0001	4
CADMIUM (µg/L)	2	0.971	0	0.568	5	68
CHROMIUM (µg/L)	20	3.926	0	4.83	100	68
COPPER (µg/L)	24	3.71	0	4.093	1300	69
LEAD (µg/L)	100	3.71	0	12.036	50	69
MANGANESE (µg/L)	20	2.93	0	3.948		71
MERCURY (µg/L)	0.5	0.197	0	0.165	2	60
NICKEL (µg/L)	10	3.111	0	3.784	100	9
SELENIUM (µg/L)	2	0.9	0	0.351	50	60
SILVER (µg/L)	1	0.609	0	0.488	5	64

Table 2.24. Chemical Concentrations in Ground Water near San Marcos Springs.

Constituent	Max.	Mean	Min.	St Dev.	MCL	No. of Samples
SPECIFIC CONDUCT (µs/cm)	638.00	591.000	512.000	28.28		31
PH (STANDARD UNITS)	7.40	7.010	6.600	0.17		29
TEMPERATUR (°C)	24.00	22.603	22.000	0.38		29
OXYGEN (mg/L)	5.50	5.500	5.500	0.00		1
BOD 5-DAY (mg/L)	0.30	0.300	0.300	0.00		1
CALCIUM (mg/L)	110.00	93.607	87.000	5.56		28
MAGNESIUM (mg/L)	18.00	15.300	7.600	2.85		28
SODIUM (mg/L)	13.00	10.492	4.500	2.86		25
POTASSIUM (mg/L)	1.60	1.232	0.700	0.27		25
ALKALINITY (mg/L)	270.00	265.000	260.000	5.00		4
SULFATE (mg/L)	33.00	21.196	5.900	8.11	400	28
CHLORIDE (mg/L)	27.00	16.825	7.500	5.18		28
DISSOLVED SOLIDS (mg/L)	352.00	329.385	284.000	17.38		26
PHOSPHATE (mg/L)	0.03	0.030	0.030	0.00		1
CARBON ORGANIC (mg/L)	7.80	1.127	0.000	1.59		22
ARSENIC (µg/L)	1.00	1.000	1.000	0.00	50	19
BARIUM (µg/L)	100.00	49.789	34.000	22.17	2000	19
BERYLLIUM (µg/L)	1.00	1.000	1.000	0.00	1E-04	1
CADMIUM (µg/L)	2.00	1.000	0.000	0.46	5	19
CHROMIUM (µg/L)	20.00	8.158	0.000	6.65	100	19
COPPER (µg/L)	20.00	6.750	0.000	6.51	1300	20
LEAD (µg/L)	10.00	2.300	0.000	3.10	50	20
MANGANESE (µg/L)	20.00	3.000	1.000	4.75		20
MERCURY (µg/L)	0.50	0.172	0.000	0.15	2	18
NICKEL (µg/L)	0.00	0.000	0.000	0.00	100	2
SELENIUM (µg/L)	1.00	0.944	0.000	0.23	50	18
SILVER (µg/L)	1.00	0.684	0.000	0.47	5	19

Table 2.25. Summary of discharge and general water-quality data for San Marcos and Comal Springs, and San Marcos and Comal Rivers where threatened or endangered species have been observed

[Min, minimum reported value; Max, maximum reported value; $CaCO_3$, calcium carbonate; cms, cubic meters per second; °C, degrees Celsius; μS/cm, microsiemens per centimeter; mg/L, milligrams per liter; USGS, United States Geological Survey; R., river; E. fonticola, Etheostoma fonticola (fountain darter); E. nana, Eurycea nana (San Marcos salamander); Z. texana, Zizania texana (Texas wildrice); G. georgei, Gambusia georgei (San Marcos gambusia)]

Discharge: In cubic meters per second.

Temperature: In decrees Celsius.

Specific conductance: In microsiemens per centimeter.

Dissolved oxygen: In milligrams per liter.

Total alkalinity: In milligrams per liter.

Location	Species observed	Discharge			Temperature			pH	Specific conductance	Dissolved oxygen		Total alkalinity, as $CaCO_3$	Reference [1]
		Mean	Min	Max	Mean	Min	Max			Min	Max		
					San Marcos Ecosystem								
San Marcos Springs	E. fonticola and E. nana												
(six major orifices) [2]		3.75			21.9	21.5	22.3	7.1	500	3.8	5.4	249	6
(Big Spring and Deep Hole) [3]						22.2	23.8	7.1-7.3		4.8	10		3
(exact location unknown) [4]					21.8	21	22						9
(exact location unknown)							7.2		4			12	
(do.)									510-540			[5]220-232	11
(do.)					[6]21			7.1		3.1			11
(do.)								6.9-7.8					10
(do.)					[6]22.6								2
Spring Lake Dam [7]	E. nana								550	7.0		257	4
Thompson Island area [8]	G. georgei				23.8	20.0	25.2		510	5.5	13.0	229	4
USGS gaging station [9]	E. fonticola and Z. texana	4.73	1.65	12.63									1
San Marcos R. from Spring Lake Dam to sewage treatment plant [8]	E. fonticola and Z. texana				23.6	20.0	25.4		520	5.5	17.5	241	4

Table 2.25 (continued). Summary of discharge and general water-quality data for San Marcos and Comal Springs, and San Marcos and Comal Rivers where threatened or endangered species have been observed.

Location	Species observed	Discharge Mean	Discharge Min	Discharge Max	Temperature Mean	Temperature Min	Temperature Max	pH	Specific conductance	Dissolved oxygen Min	Dissolved oxygen Max	Total alkalinity, as $CaCO_3$	Reference[1]
San Marcos R. from Spring Lake Dam to Interstate 35 bridge[10]	E. fonticola and Z. texana	3.36			22.4	21.5	23.5.	7.4	510				6
San Marcos R. near confluence with Blanco R.[4]	E. fonticola				22.9	20.4	25.0						9
Comal Ecosystem													
Comal Springs	none known												
(3 western orifices)[11]		0.52	0.02	2.39									8
(3 western orifices)[12]		0.19	<0.01	0.53	23.8			7.0	550	4.7	5.7	231	7
(4 western orifices)[11]					23.2	21.3	24.6	7.2	500	3.7	5.9		8
(location unknown)[13]					23.4								5
(location unknown)[4]					24.0	23.3	24.5						9
(most eastern orifice-Espey's station 1)[14]						24.5	25.0		490	1.0	1.1	225	4
(most eastern orifice)[15]				24.8			7	560	5.9 (mean)	229	7		
Landa Lake (Espey's station 2)[14]	E. fonticola and E. nana					24.6	25.0		495	1.9	4.6	230	4
Landa Lake Dam[15]	E. fonticola				24.3			7.1	560	7.2 (mean)	232	7	
USGS gaging station[16]	E. fonticola	7.95	0	14.95									1
USGS gaging station[15]	do.				24.6			7.2	560	8.1 (mean)	230	7	
Comal R. near confluence with Guadalupe R.	E. fonticola												
(unknown location)[4]					23.7	21	26						9
(Espey's station 4)[14]									490	6.2	6.4	225	4
(near Espey's station 4)[15]				24.7			7.2	560	8 (mean)		233	7	

[1]References:

1. Buckner and others (1992)
2. DeCook (1957), as cited in Espey, Huston, and Associates (1975, p. 4-11).
3. Devall (1940)
4. Espey, Huston, and Associates (1975)
5. George and others (1952), as cited in U.S. Fish and Wildlife Service (1984, p. 21).
6. Ogden and others (1985)
7. Ottmers (1987)
8. Rothermel and Ogden (1987)
9. Schenck and Whiteside (1976)
10. Texas Water Development Board (1968), as cited in U.S. Fish and Wildlife Service (1984, p.2).
11. Tupa and Davis (1976)
12. U.S. Fish and Wildlife Service (1984)

[2]Period of record: October 1981 to September 1983. Samples were collected from six sites; all values reported are means, including minimum and maximum values; and the mean values reported are means of means.

[3]Unknown period of record; reported in 1940.

[4]Period of record: March 1973 - April 1974.

[5]It is uncertain if the reported alkalinity is as calcium carbonate or bicarbonate.

[6]It is uncertain if this is a mean.

[7]Values are from single measurements made on June 6, 1974.

[8]The minimum and maximum values for temperature and dissolved oxygen are from five diurnal studies conducted from July through November 1974; mean temperature, specific conductance, and alkalinity values were determined from values reported for seven sites that were sampled four times from June 1974 through November 1974.

[9]Period of record: 1957-1992; the mean is a mean of annual means for those water years; the maximum discharge is an instantaneous peak flow, which was measured on March 12, 1992; the minimum discharge is the lowest daily mean on record and was recorded on October 3, 1956.

[10]Period of record: October 1981 to September 1983. Samples were collected from four sites; all values reported are means, including minimum and maximum values; and the mean values reported are means of means.

[11]Period of record: September 1982 - August 1983 (dissolved oxygen measurements: January 1983 - August 1983 only); 3-13 discharge measurements per month; 1-5 dissolved-oxygen measurements per month; pH and specific conductance values are means; means are means of means.

[12]Uncertain if orifices are the same as Espey described. Unknown, one-year period of record. Samples were collected from each orifice four times; all values reported are means, including minimum and maximum values; and the mean values reported are means of means.

[13]Unknown period of record; reported in 1952.

[14]Values are from single measurements made on June 6, 1974; temperature and dissolved-oxygen maximum and minimum reflect difference in top and bottom layers, respectively.

[15]Unknown, one-year period of record; reported in 1987; each site was sampled four times per year; all values reported are means.

[16]Period of record: 1930-1992; the mean is a mean of annual means for those water years; the maximum discharge is an instantaneous peak flow, which was measured on October 16, 1973; the minimum discharge of zero flow occurred from June 13 to November 3, 1956.

Table 2.26. Maximum and minimum daily values for water temperature and dissolved oxygen in Landa Lake and the Comal River for various time periods in 1993.

[nd, not determined]

Water Temperature: In degrees Celsius
Dissolved oxygen: In milligrams per liter.

Location	Measurement period	Water temp. Max.	Water temp. Min.	Water temp. Diff.	Dissolved oxygen Max.	Dissolved oxygen Min.
Landa Lake	8/20 - 9/20	24.6	23.0	1.6	9.8	4.4
Comal River, old channel above West Torrey Street	7/27 - 8/18	26.2	23.6	2.6	9.0	4.8
Comal River, old channel below West Torrey Street	6/29 - 7/20	26.1	23.6	2.5	nd	nd
Comal River, old channel above Hinman Island Drive	6/30 - 8/19	27.3	24.6	2.7	nd	nd
Comal River, new channel above confluence of old and new channels	8/20 - 9/20	25.0	22.7	2.3	10.4	7.5
Comal River at Torrey Mill Dam	6/25 - 9/20	25.3	22.7	2.6	11.0	6.7

Table 2.27. Summary of water-quality data for the San Marcos and Comal Rivers (Adapted from Espey, Huston, and Associates, 1975).

[oC, degrees Celsius; mS/cm, microsiemens per centimeter; na, not analyzed; <, less than; values in milligrams per liter, unless indicated next to property or constituent]

	San Marcos River[1]		Comal River[2]	
Property or constituent	Min.	Max.[3]	Min.	Max
Temperature (oC)	20.0	25.4	24.5	25
Dissolved oxygen	5.5	17.5	1.0	6.2
Specific conductance (mS/cm)	508	550	490	495
Total dissolved solids	263	339	295	300
Total hardness (as CaCO3)	223	307	260	260
Total alkalinity (as CaCO3)	196	277	225	230
Bicarbonate	239	338	276	282
Calcium	65	95	76	79
Chloride	10	21	15	15
Fluoride	0.2	0.5	na	na
Magnesium	11	17	15	17
Silica	9	13	na	na
Sodium	10	11	na	na
Sulfate	17	24	23	27
Total organic carbon	<1	14	na	na
Chlorophyll	0.004	0.004	na	na
Ammonium	<0.1	<0.1 (0.1)	na	na
Organic nitrogen	0.2	0.2 (0.3)	0.09	0.20
Nitrate	1.2	2.1	1.5	1.6
Nitrite	0.005	0.008 (0.014)	0.004	0.005
Orthophosphate	<0.01	<0.01 (0.12)	na	na
Total phosphorous	<0.01	<0.01 (0.12)	na	na

[1] The values for temperature and dissolved oxygen for the San Marcos River are approximate and were extrapolated from figures 4.1 - 4.10. These figures show variation in temperature and dissolved oxygen for 5, 21-hour periods from July through November 1974, at 5 locations (stations 2-6) on the San Marcos River, from about 0.8-1.2 km to about 2.25 km downstream of Spring Lake Dam. Values for top and bottom, left and right, or channel and rice layers were sometimes indicated and were included in range of values reported.

The values for specific conductance and chlorophyll for the San Marcos River are approximate and were extrapolated from figures 2.41 and 2.45. These figures show variation in specific conductance and chlorophyll at nine locations along the San Marcos River on June 6, 1974. Only the specific-conductance values reported for the seven locations (stations 1-7) upstream of the San Marcos city wastewater treatment plant were included. Only the chlorophyll values reported for the eight locations (stations 1-8) above the confluence with the Blanco River, which did include one station below the wastewater treatment plant, were included.

The values for the rest of the properties and constituents listed were determined from values reported for samples collected from June through November 1974 on tables 4.1 - 4.8. Values for locations downstream of the confluence with the Blanco River were not used.

[2] The values of properties and constituents listed for the Comal River are approximate and were extrapolated from figures 2.8 - 2.19. The values reported above were determined from values reported for samples collected from four locations on the Comal River, from Comal Springs (Landa Lake) to about 0.16 km upstream of the confluence with the Guadalupe River, on June 6, 1974.

[3] If there was a significant difference in the numeric value of a property or constituent for samples collected upstream and downstream of the San Marcos city wastewater treatment plant, the value representative of the area upstream of the plant was reported and the value representative of the area downstream of the plant was reported in parentheses.

Table 2.28. Discharge and selected water-quality data for the four major springs at Comal Springs, August 1982 to September 1983.

[m3/s, cubic meters per second; oC, degrees Celsius; mS/cm, microsiemens per centimeter; na, not analyzed; <, less than]

Property or constituent	Comal Springs[1]	
	Minimum value (mg/L, unless indicated otherwise with parameter)	Maximum value (mg/L, unless indicated otherwise with parameter)
Discharge (m3/s)	0.02	2.39
Temperature (oC)	21.3	24.6
Dissolved oxygen	3.66	5.90
pH (unitless)	6.9	7.6
Specific conductance (mS/cm)	370	595
Total hardness (as CaCO3)	198	340
Calcium hardness (as CaCO3)	70	224
Magnesium hardness (as CaCO3)	38	144
Bicarbonate alkalinity	188	264
Chloride	10.5	24.6
Sulfate	10.2	22.1
Nitrate	0.61	2.84
Orthophosphate	0.08	0.60

[1] The values of properties or constituents include measurments at four of the major spring orifices of Comal Springs and were reported in tables 1a - 1e in Rothermel and Ogden (1987). Water from the four spring orifices emerges at land surface and flows into Landa Lake.

Table 2.29. Water-quality data for Landa Lake and the Comal River, August and September 1993.

[µS/cm, microsiemens per centimeter; <, less than reporting limit specified]

	Landa Lake	Comal River			
		Old channel above West Torrey Street	Old channel above Hinman Island Drive	New channel, above confluence of old and new channels	Torrey Mill Dam
(Dates samples were collected) Parameter (units)	(9/20/93)	(8/20/93)	(8/20/93)	(9/20/93)	(9/20/93)
Field Measurements					
Barometric pressure (mm of Hg)	745	745	745	745	745
Water temperature (°C)	24.0	24.0	25.5	24.0	24.5
Specific conductance (µS/cm)	550	550	560	550	540
pH	7.6	7.7	7.5	7.8	7.8
Dissolved oxygen (mg/L)	7.2	8.1	4.4	9.0	9.0
Alkalinity (mg/L as CaCO3)	230	230	240	230	240
Laboratory Measurements					
Ammonia (mg/L as N)	0.030	0.030	0.060	0.030	0.030
Ammonia plus organic nitrogen (mg/L as N)	<0.20	<0.20	<0.20	<0.20	<0.20
Nitrite (mg/L as N)	<0.010	<0.010	0.010	<0.010	<0.010
Nitrite plus nitrate (mg/L as N)	1.80	1.70	1.39	1.80	1.80
Phosphorous (mg/L)	<0.010	<0.010	<0.010	<0.010	<0.010
Orthophosphate (mg/L as P)	<0.010	0.010	0.020	<0.010	0.010
Calcium (mg/L)	83	83	85	81	80
Magnesium (mg/L)	16	16	16	16	16
Potassium (mg/L)	0.70	1.9	1.6	0.70	0.70
Sodium (mg/L)	9.9	9.6	10	11	10
Chloride (mg/L)	15	16	16	15	15
Fluoride (mg/L)	0.20	0.30	0.20	0.20	0.20
Silica (mg/L as silicon dioxide)	12	12	11	12	12
Sulfate (mg/L)	23	25	26	24	23
Arsenic (mg/L)	<1	<1	<1	<1	<1
Barium (mg/L)	51	51	53	52	52
Beryllium (mg/L)	<0.5	<0.5	<0.5	<0.5	<0.5
Cadmium (mg/L)	<1.0	<1.0	<1.0	<1.0	<1.0
Chromium (mg/L)	<5	<5	<5	<5	<5
Cobalt (mg/L)	<3	<3	<3	<3	<3
Copper (mg/L)	<10	<10	<10	<10	<10
Iron (mg/L)	<3	3	4	<3	3
Lead (mg/L)	<10	<10	<10	10	<10
Lithium (mg/L)	7	12	13	8	7
Manganese (mg/L)	<1	2	5	<1	<1
Mercury (mg/L)	<0.1	<0.1	<0.1	<0.1	<0.1
Molybdenum (mg/L)	<10	<10	<10	<10	<10
Nickel (mg/L)	<10	<10	<10	<10	<10
Silver (mg/L)	<1.0	<1.0	<1.0	<1.0	<1.0
Selenium (mg/L)	1	<1	<1	1	1
Strontium (mg/L)	610	620	650	620	610
Vanadium (mg/L)	<6	<6	<6	<6	<6
Zinc (mg/L)	3	6	4	<3	<3

Table 2.30. Minimum reporting limits for polychlorinated biphenyls, polychlorinated napthalenes, and pesticides in water.

Parameter	Minimum reporting limit (µg/L)
Gross Polychlorinated biphenyls	0.1
Gross Polychlorinated napthaleness	0.1
2,4,5-T	0.01
2,4-D	0.01
2,4-DP	0.01
Aldrin	0.01
Chlordane	0.1
Chlorpyrifos	0.01
DDD	0.01
DDT	0.01
DEF (butifos)	0.01
Di-Syston (disulfoton)	0.01
Diazinon	0.01
Dieldrin	0.01
Endrin	0.01
Ethion	0.01
Fonofos	0.01
Heptachlor	0.01
Heptochlor epoxide	0.01
Lindane	0.01
Malathion	0.01
Methoxychlor	0.01
Methyl parathion	0.01
Mirex	0.01
Parathion	0.01
Perthane	0.1
Phorate	0.01
Silvex	0.01
Toxaphene	1
Trithion	0.01

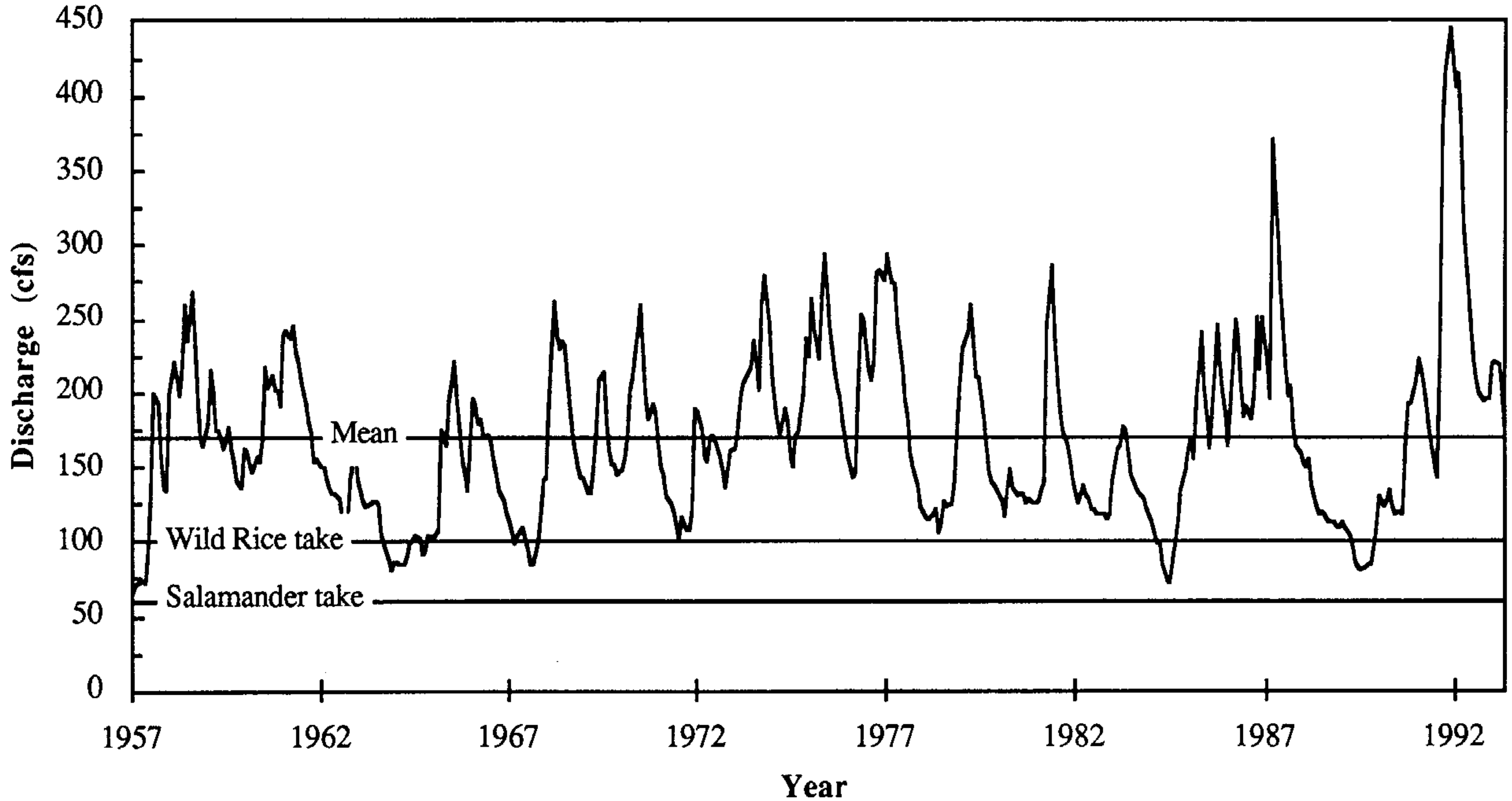


Figure 2.1. San Marcos Springs mean monthly discharges (period of record).

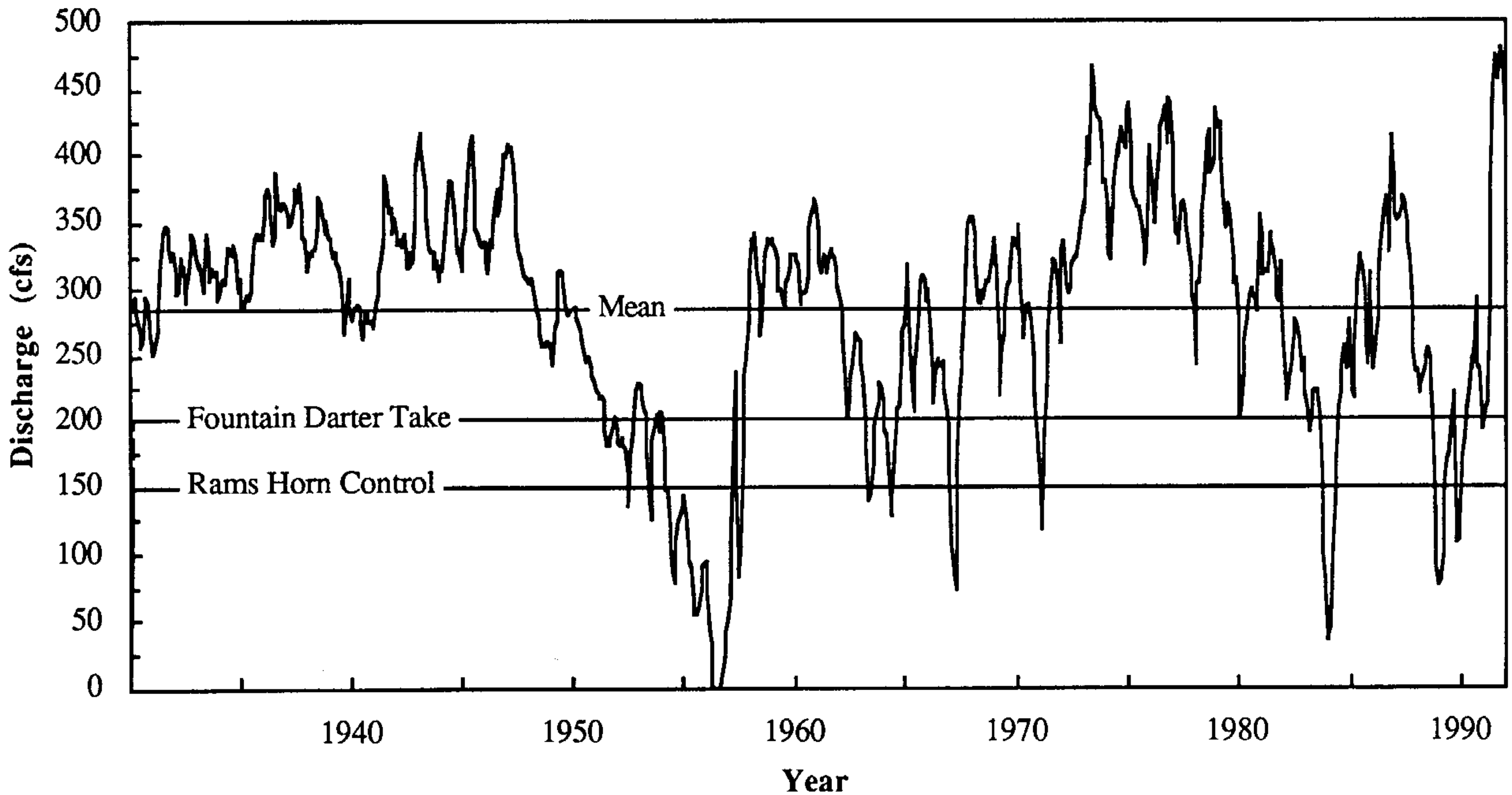


Figure 2.2. Comal Springs mean monthly discharge (period of record).

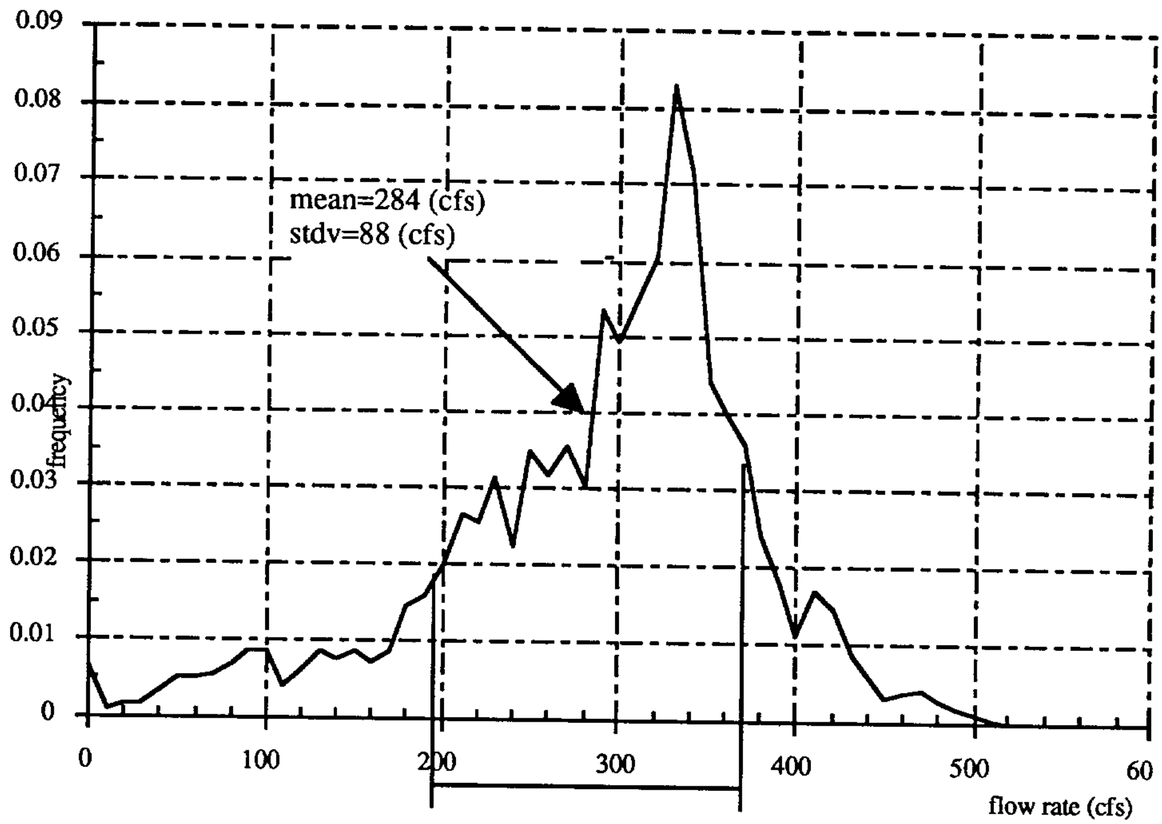


Figure 2.3. Histogram of the historic daily flow at Comal Springs.

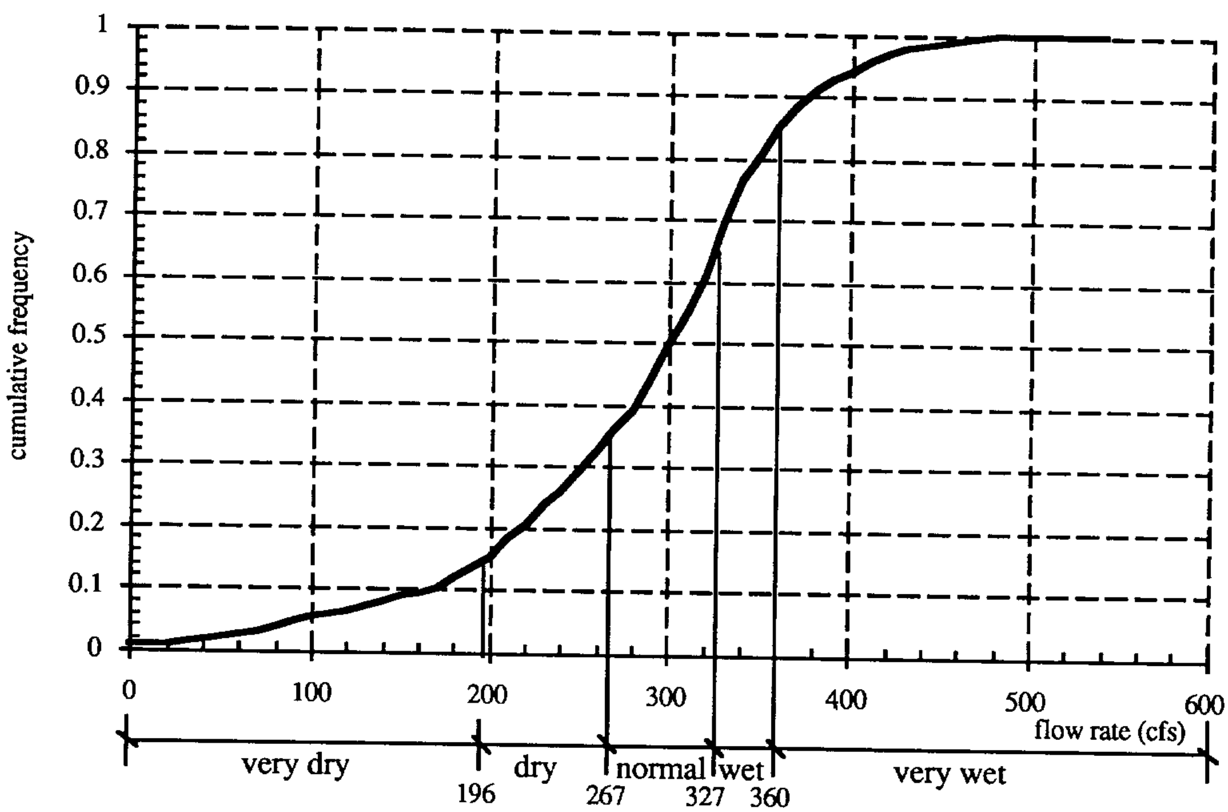


Figure 2.4. Cumulative frequency distribution of the historic daily flow at Comal Springs.

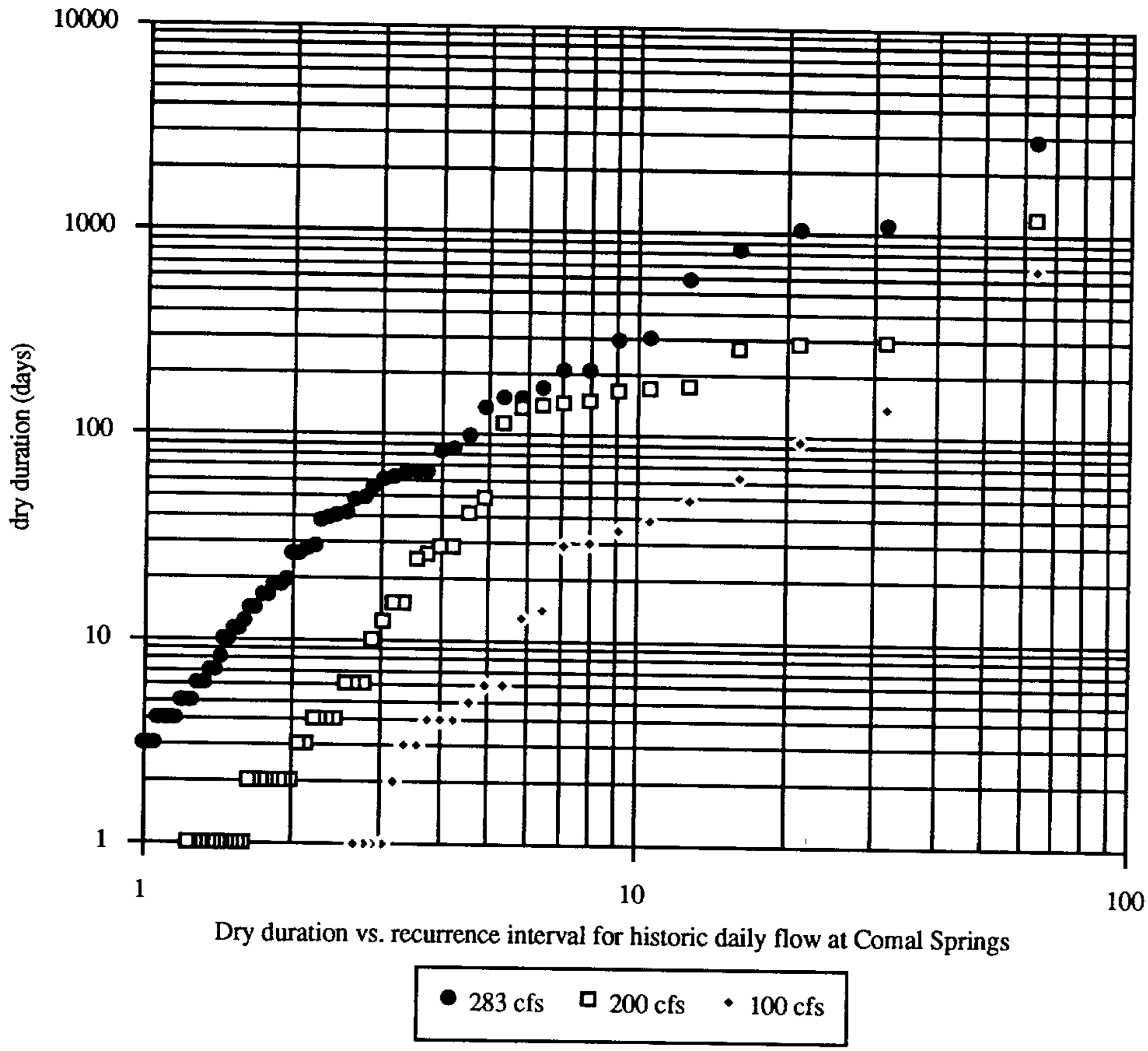


Figure 2.5. Dry duration vs. recurrence interval for historic daily flow at Comal Springs for thresholds of 284, 200, and 100 cfs.

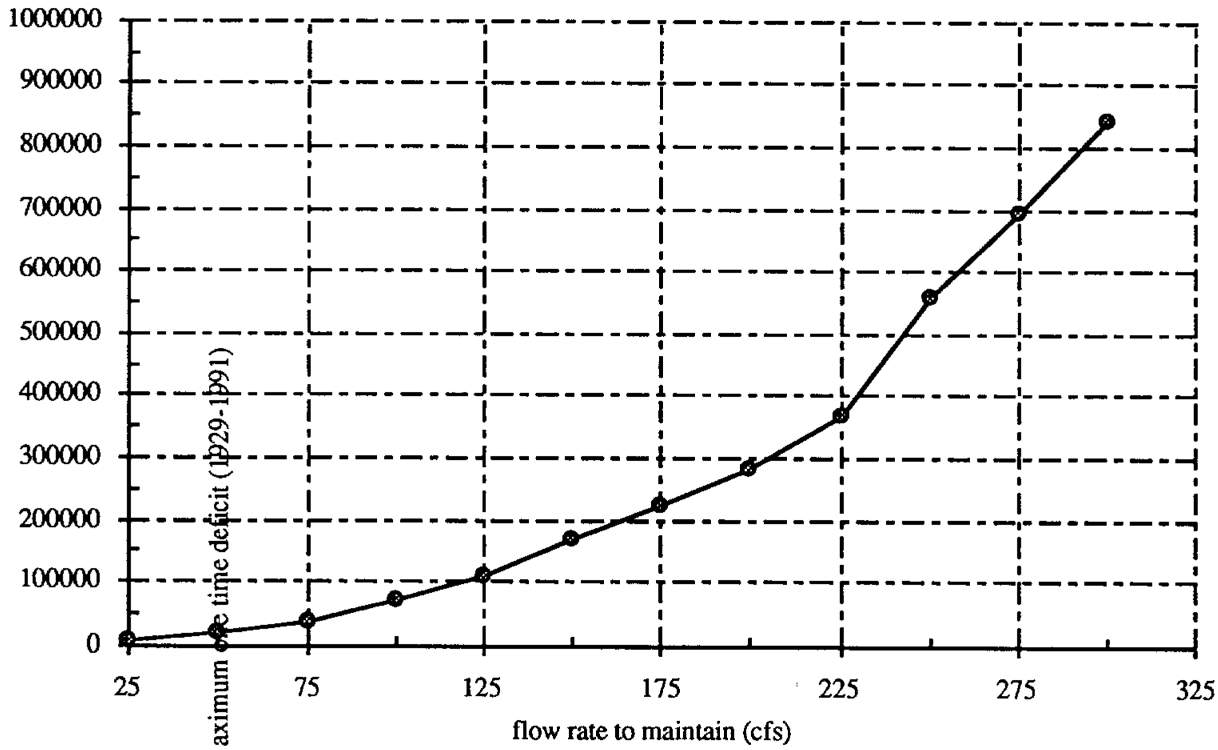


Figure 2.6. Comal Springs historic maximum one-time deficit of spring flow from various threshold flow levels.

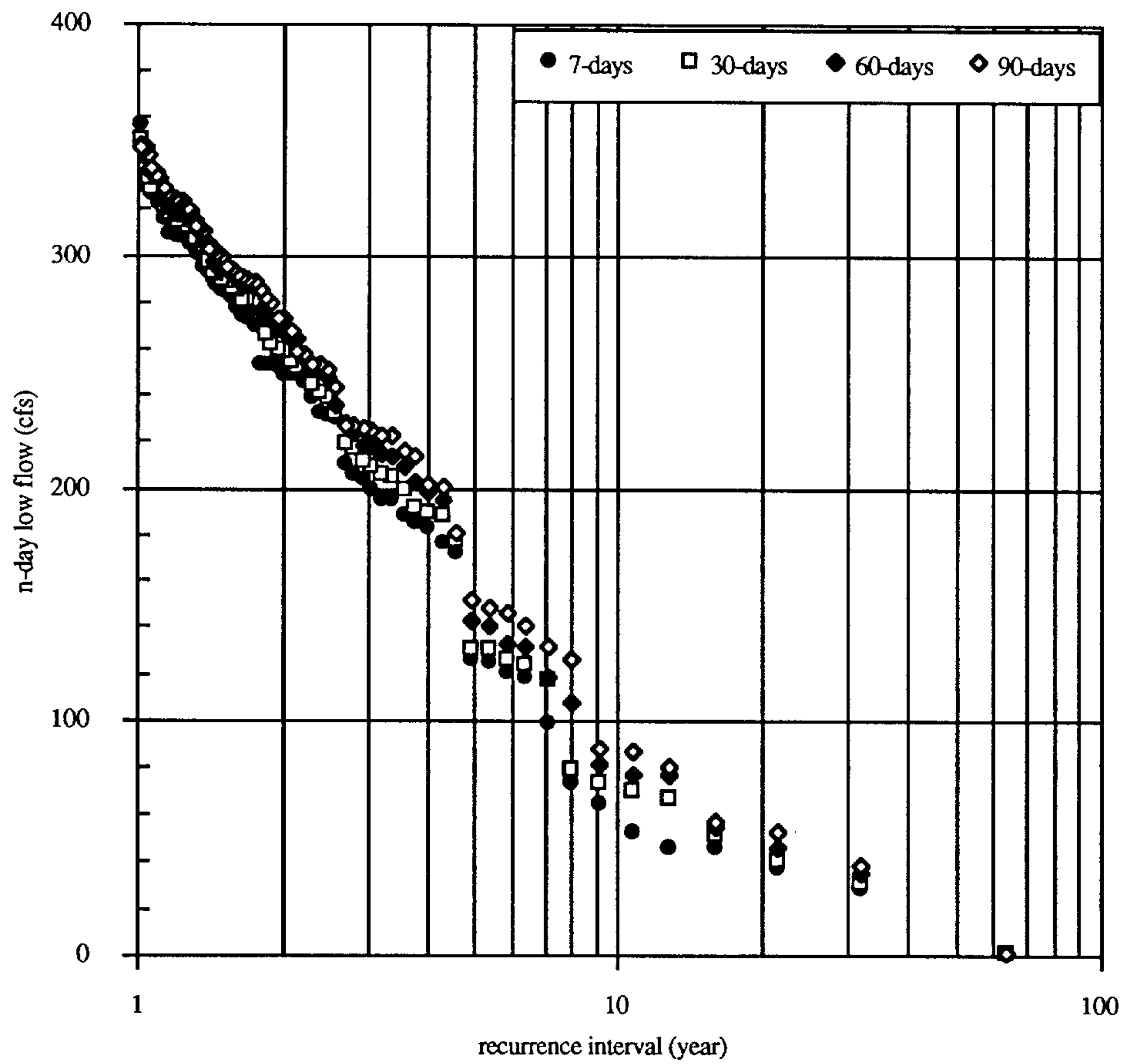


Figure 2.7. Comal Springs 7-day, 30-day, 60-day, and 90-day low flow frequency plot.

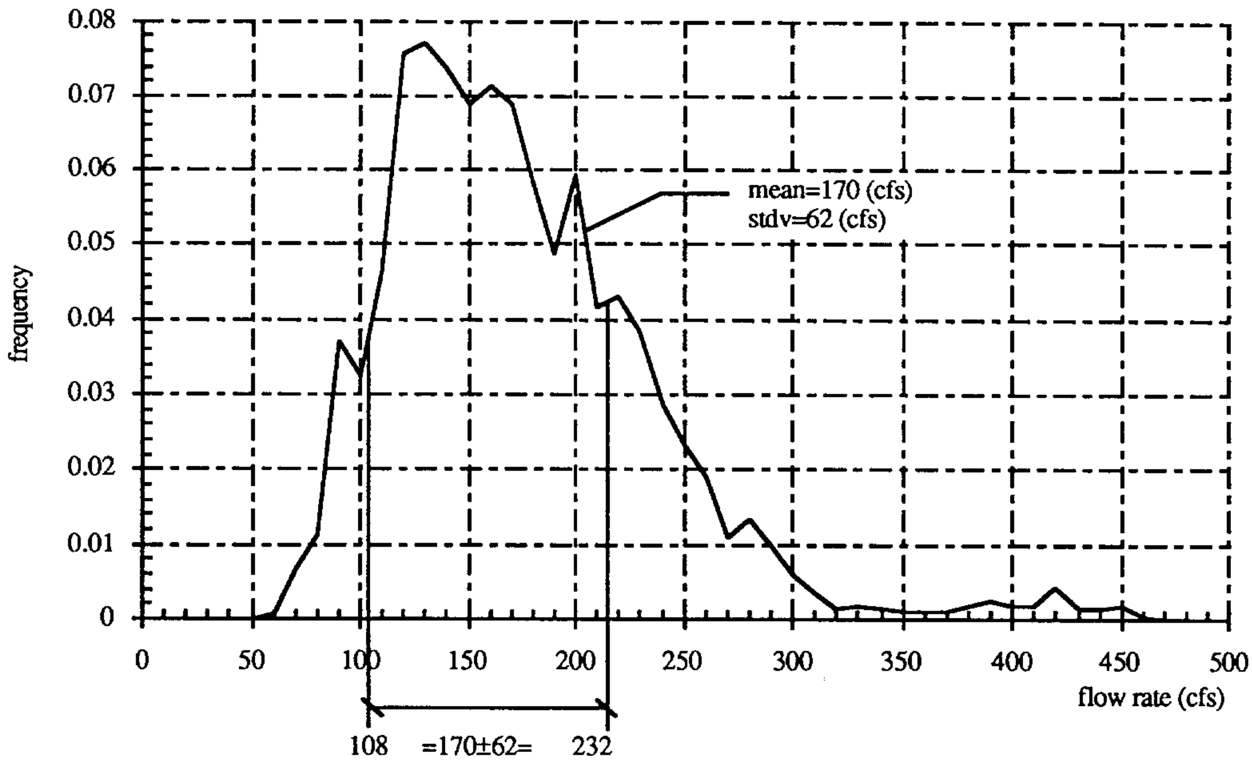


Figure 2.8. Histogram of the historic daily flow at San Marcos Springs

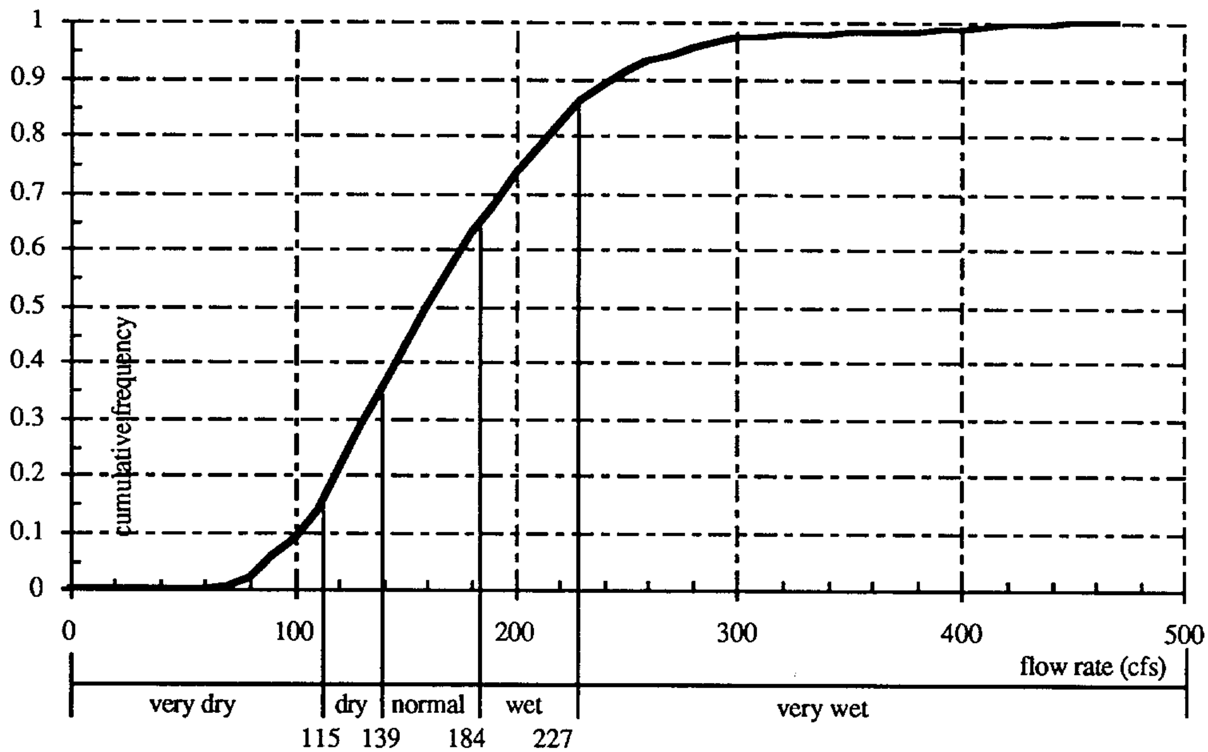


Figure 2.9. Cumulative frequency distribution of the historic daily flow at San Marcos Springs.

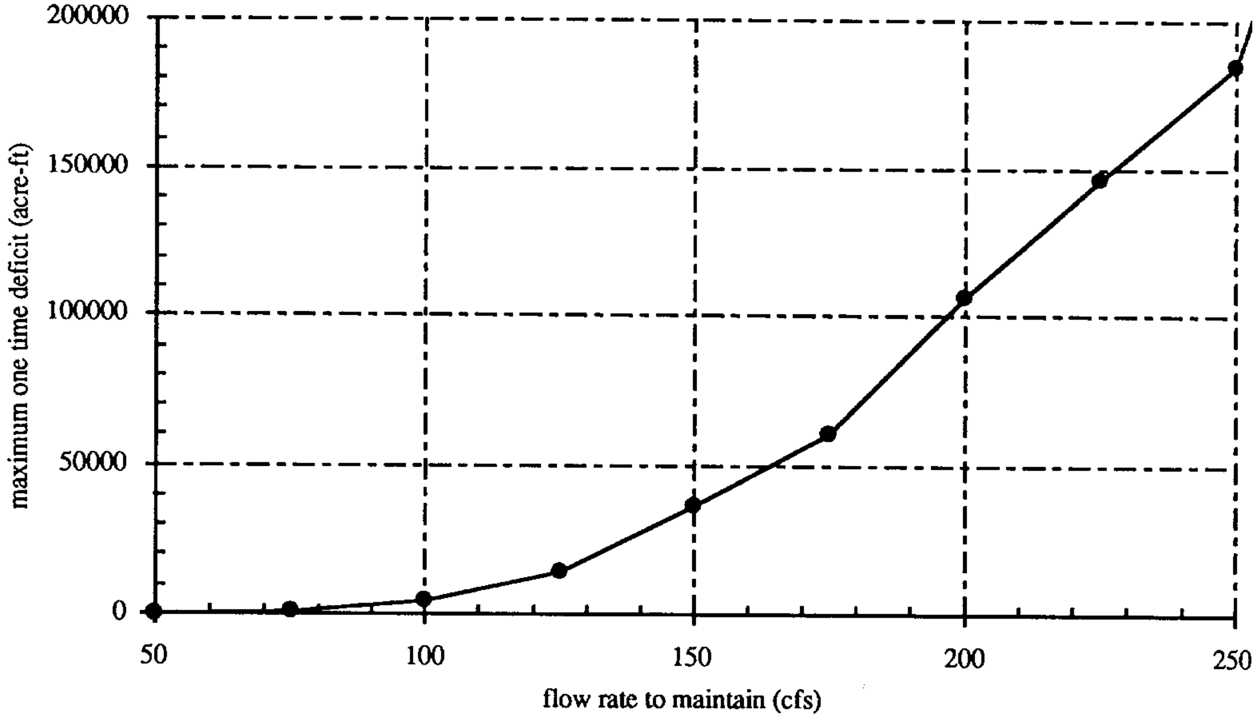


Figure 2.10. San Marcos Springs historic maximum one-time deficit of spring flow from various threshold flow levels.

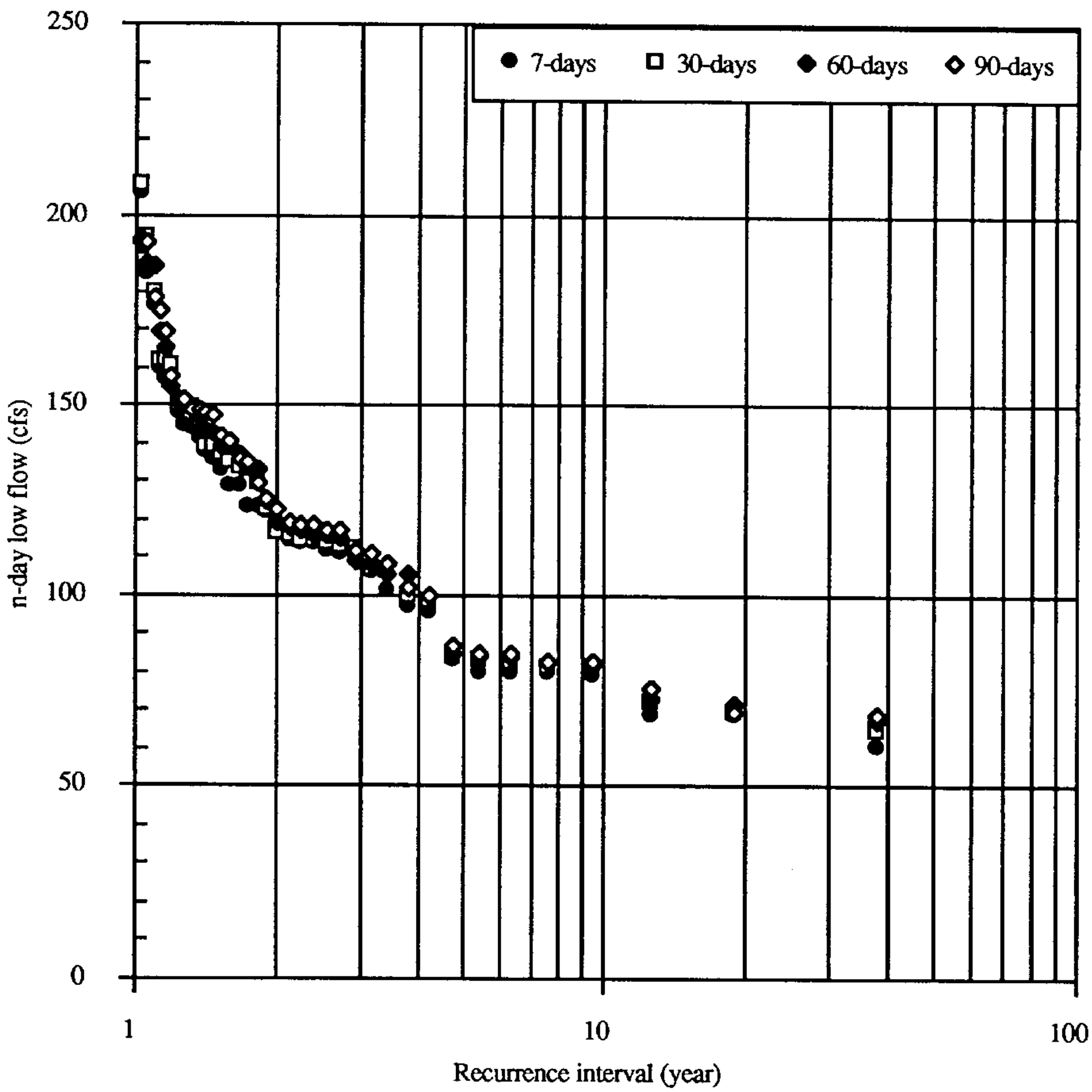


Figure 2.11. San Marcos Springs 7-day, 30-day, 60-day, 90-day low flow frequency plot.

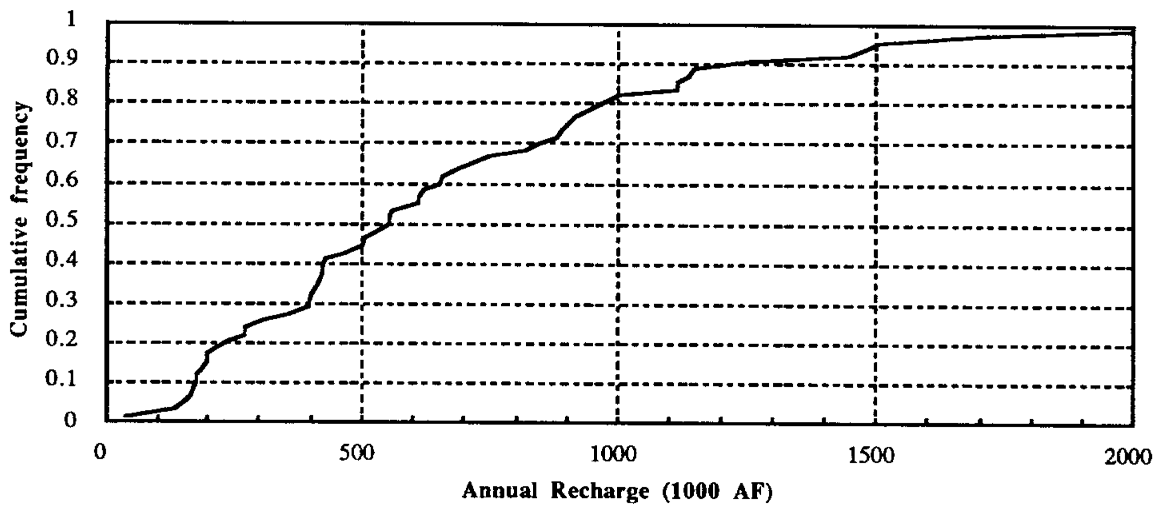


Figure 2.12. Cumulative frequency distribution of the annual Edwards aquifer recharge.

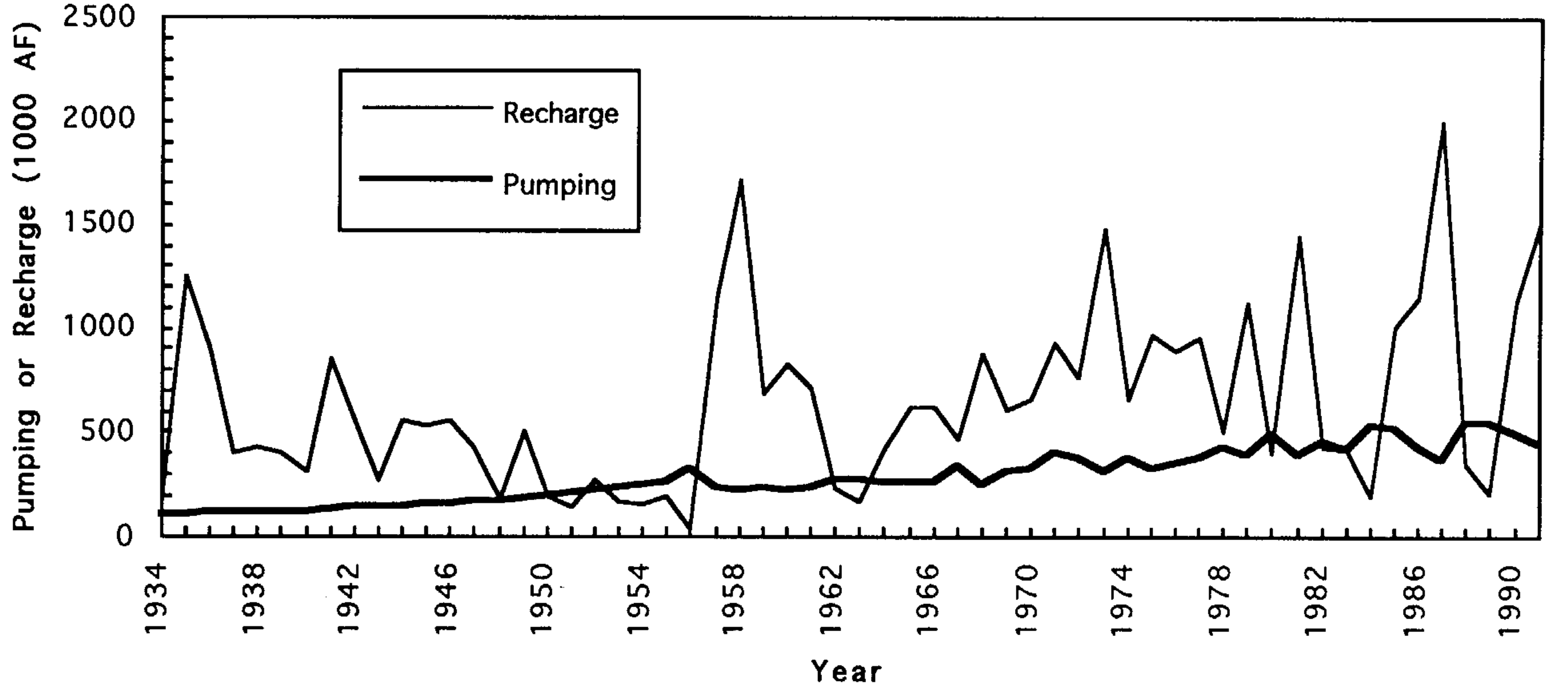


Figure 2.13. Monthly pumpage and recharge in the Edwards aquifer, 1934-1992.

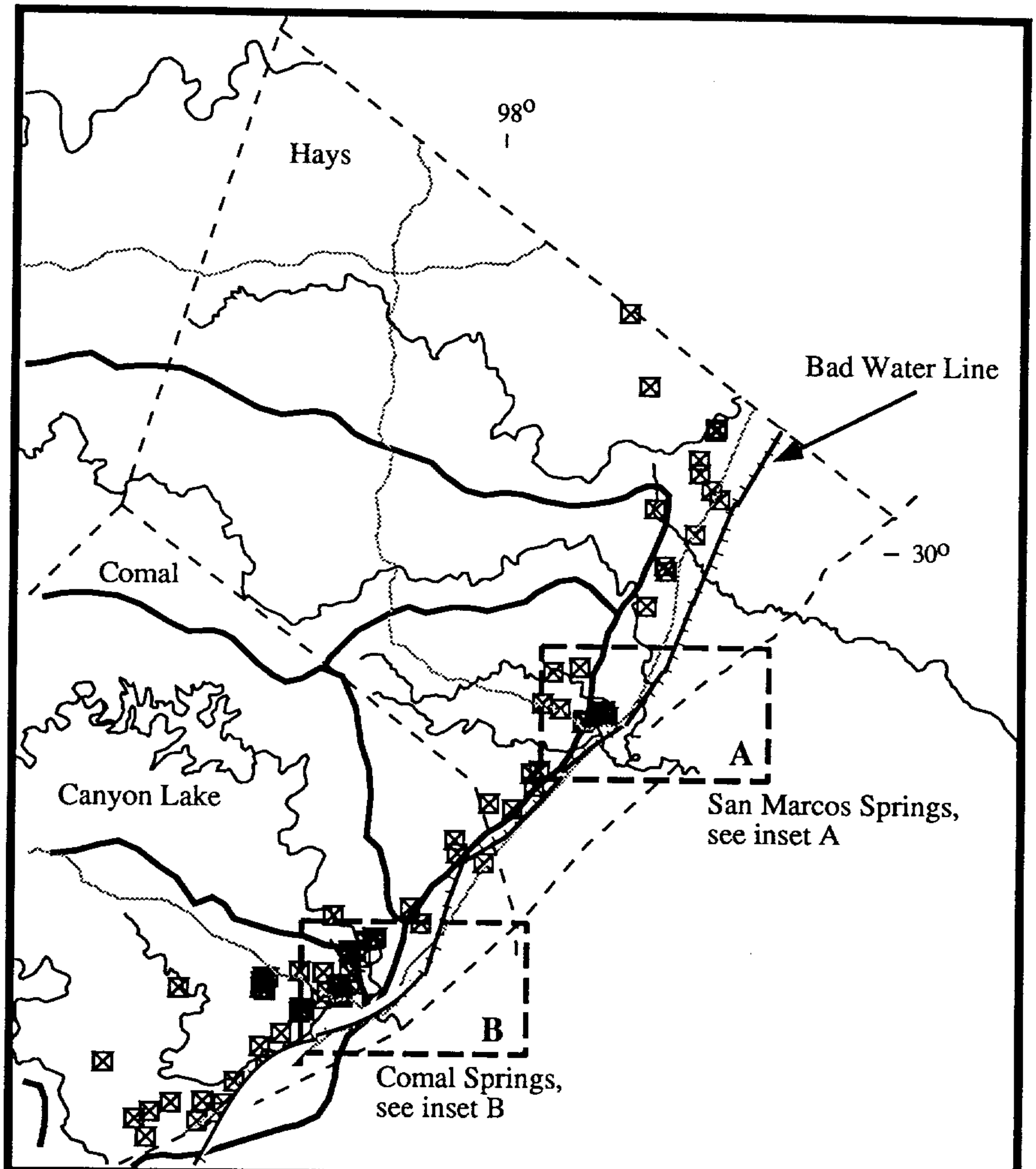
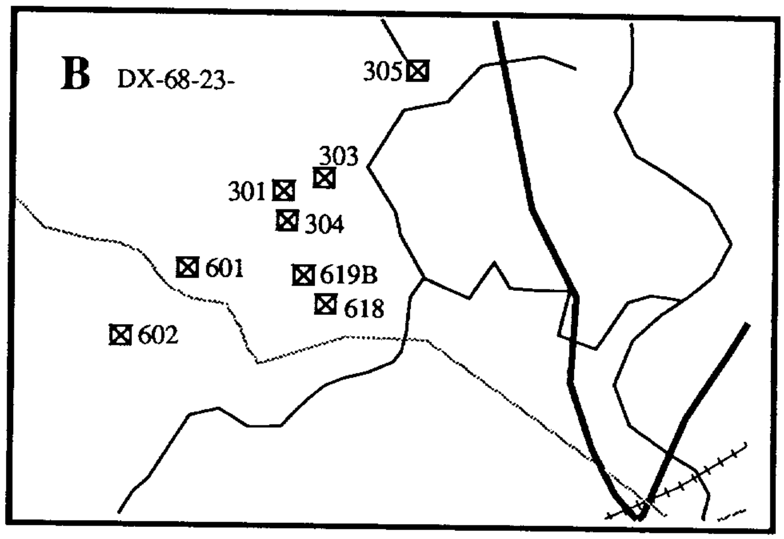


Figure 2.14 (a). Groundwater sampling wells in Comal and Hays Counties.



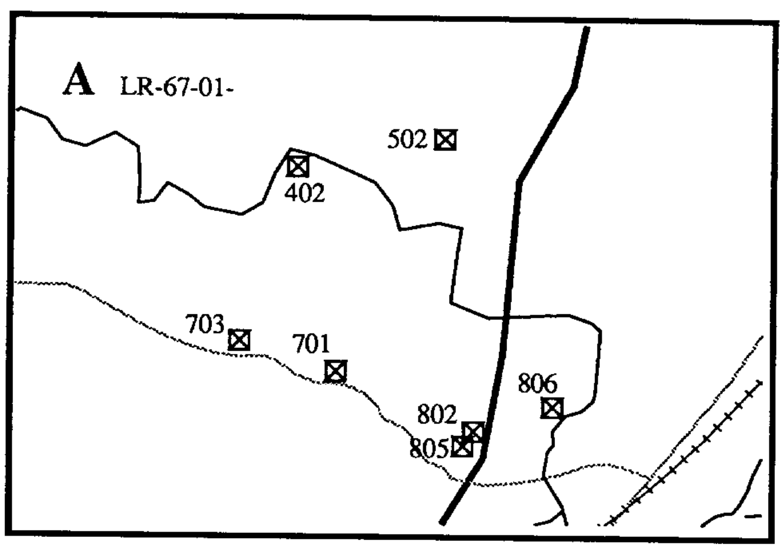


Figure 2.14 (b). Groundwater sampling wells near (A) San Marcos Springs and (B) Comal Springs. The numbers near the well locations are the last three digits of the well number.

3.0 GEOLOGY AND HYDROGEOLOGY OF THE EDWARDS AQUIFER

3.1 SPECIFIC REGION OF STUDY

3.1.1 Geology of the Edwards Aquifer

The Edwards aquifer of Texas is a regionally-extensive carbonate aquifer, and the sole source of water for nearly two million people, including the City of San Antonio (Figure 3.1). This aquifer is located along the Balcones Escarpment, a topographic feature in Central Texas that separates the Edwards Plateau from the Gulf Coastal Plain. Geologic mapping and hydrologic studies show that the Edwards is a complex karstified aquifer that supplies large quantities of water to wells and to large springs such as Comal and San Marcos Springs. The aquifer is intensively fractured, causing the limestone to be porous, permeable and receptive to recharge [Figure 3.2; Caran and others, 1981; Maclay and Small, 1984, 1986; Maclay and Land, 1988]. This breakup of the rocks has facilitated the development of karstic features, such as honeycombing, caves, caverns, and other solution channeling over wide areas.

3.1.1.1 Thickness and Areal Limits

The Cretaceous Edwards Group consists of 400 to 600 feet of thin to massive bedded limestone and dolomite. The lower confining unit of the Edwards aquifer is the upper shaley member of the Glen Rose Formation and, where present, the Walnut Clay. The upper confining unit of the aquifer is the Del Rio Clay .

The area of the Edwards aquifer is about 180 miles long and varies in width from about 5 to 40 miles. The Edwards aquifer in the San Antonio area is bounded by:

(1) Groundwater divides in Kinney County on the west (Brackettville divide) and Hays County to the east (Kyle divide);

(2) Up-dip limits of the surface outcrop of the Edwards Group in the Balcones fault zone to the north; and

(3) The "bad-water" line, to the south.

The bad water line separates ground water with less than 1000 mg/l of total dissolved solids (hereafter referred to as "fresh water") from ground water with greater than 1000 mg/l of total dissolved solids (hereafter referred to a "saline water"). The fresh water zone of the Edwards aquifer is underlain by saline water throughout the region. Comal Springs and San Marcos Springs are near the eastern end of the area and are about 25 mi and 8 mi, respectively, from the Town of Kyle.

The total area of the Edwards aquifer is about 3,200 square miles along the Balcones Escarpment, which separates the Edwards Plateau from the Gulf Coastal Plain, of which about 2,000 square miles is within the freshwater zone of the artesian aquifer [Maclay and Small, 1986].

3.1.1.2 Depositional history and lithofacies of the Edwards Formation

The rocks that make up the Edwards Group extend across the San Marcos platform, the Devils River reef, and the Maverick basin in a wedge which thickens to the south and southwest from about 200 to 900 ft [Rose, 1972; 1986]. During early Cretaceous time, a shallow marine carbonate shelf similar to the modern Bahama Banks covered most of Texas and deposited the Edwards aquifer formations. A broad rise formed by the Central Texas platform and its southern extension, the San Marcos platform, divided the carbonate shelf into shallower tidal flats and deeper basinal depositional provinces. While tidal flats and shallow lagoons alternated with open shelves on the platform, deeper water in the adjacent basins promoted the growth of rudistid and algal bioherms on platform margins, especially in the Devils River reef north of the Maverick basin and at the shelf edge. The current stratigraphic nomenclature of the aquifer also reflects these different sedimentary environments and resulting lithofacies [Figure 3.3; Klemt et al., 1979].

3.1.1.3 Structural Features

Balcones and Luling fault zones. The Balcones Escarpment is the surface expression of the Balcones fault zone, a series of sub-parallel, discontinuous, high-angle, normal faults which strike northeast and display a net down-to-the-coast displacement. Although most individual faults exhibit less than 200 ft of throw, some offset the aquifer by as much as 900 ft [Figure 3.2; Small, 1986]. The Edwards aquifer is vertically displaced for its entire thickness at several places along several major northeastward-striking normal faults.

The Luling fault zone extends from Caldwell to southeastern Medina County, where the Luling fault zone is approximately 10-20 miles southeast of the Balcones Escarpment. The Luling fault zone is a belt of nearly parallel faults similar to but more narrow than the Balcones fault zone. Like the Balcones, the Luling is normally faulted. However, the down thrown sides of the individual faults of the Luling fault zone are to the northwest rather than to the southeast as in the case of the Balcones. Fault displacement for individual strands within the Luling fault zone varies from a few feet to a combined displacement of more than 1,500 feet.

These features appear to follow persistent zones of weakness in Paleozoic basement rocks deformed during the Pennsylvanian Ouachita-Marathon orogeny. Faults provide important conduits for groundwater flow within the aquifer.

3.2.2 Hydrogeology of the Edwards Aquifer

The extensive fracturing and subsequent karstification of the Edwards Group has created an extremely porous and permeable aquifer that is capable of storing and moving large quantities of water. Because of this high porosity and permeability, the Edwards aquifer is one of the most productive aquifers in the world. Well yields in the Edwards are among the world's largest [Baker and Wall, 1976, p. F-7]. For example, one well drilled by the city of San Antonio in 1941 had a natural flow of 16,800 gallons per minute (gpm) [Livingston, 1942, p. 3], and in 1991 a well drilled near San Antonio had a natural flow of about 25,000 gal/min. This well is reportedly the world's largest flowing well [Oral commun., P.L. Rettman, 1991; Swanson, 1991].

Large, high-discharge springs, rather than small springs and diffuse seepage, are the general rule in karst regions. These high-discharge springs often emerge from underground streams or caves [Lamoreaux et al., 1989, p. 85-86]. Such cave passages may occur at more than one level in the Edwards aquifer. Most ground-water flow, however, occurs in large solution openings near the top of the saturated zone, which carries much of the ground water to the springs.

Six of the largest springs in the Edwards aquifer discharged an average daily flow of about 480 cubic feet per second (cfs) from 1936-86. Comal Springs at New Braunfels (averaging 284 cfs from 1929-92) and San Marcos Springs at San Marcos (averaging 170 cfs from 1956-93) are the State's two largest springs and accounted for a combined average of about 454 cfs or about 200,004 gpm. Flow from these two springs represents about 40 percent of the total average discharge from the aquifer's wells and springs.

3.2.2.1 Groundwater Velocity and Direction

Ground-water infiltration and ground-water flow in the recharge zone are controlled largely by the southerly and southeasterly stratigraphic dip of the aquifer, southerly to southeasterly-dipping normal faults, and by the easterly to northeasterly-trending fracture systems. The fracture systems are open and, in conjunction with the stratigraphic dip can readily transport ground water toward Comal and San Marcos Springs. Faults within the Balcones fault zone form the master conduits for flow within the Edwards aquifer and are responsible for its very high transmissivity [Clement, 1989; Woodruff and Abbott, 1979].

Movement in the recharge areas is vertically downward to the water table or top of the zone of saturation. From here the direction of flow is lateral and, in general, is (1) in the direction of inclination of the aquifer, (2) along the orientation of fractures, and (3) in the direction of decreasing hydraulic head. Regionally this movement is from west to east--from Kinney County where the altitude of the exposed part of the aquifer reaches up to nearly 2,000 ft, past San Antonio at an altitude of around 700 ft, to Comal Springs at an altitude of 623 ft, and continuing eastward to San Marcos Springs at an altitude of 574 ft (Figure 3.4).

The aquifer's potentiometric surface gives a false representation of the complexity of the flow paths in the Edwards. Because subsurface water is commonly channeled around or between faults that are parallel rather than perpendicular to the equipotential lines [Clement, 1989], the flow paths are generally not perpendicular to the equipotentials. At places where faults displace the aquifer for its entire thickness, ground water circulation is diverted either southwestward or northeastward.

Maclay and Small [1986] estimated an average velocity in the confined fresh water zone to be about 27 ft/d. Estimates of groundwater velocities made at well sites range from 2-31 ft/d.

3.2.2.2 Transmissivity

Transmissivity is a difficult property to quantify for a solutioned and heterogeneous carbonate aquifer like the Edwards which lacks uniform distribution of permeability. However, Maclay and Small (1986) have estimated transmissivities of the Edwards aquifer in the San Antonio area based on its geology, hydrology and hydrochemistry. Estimated values range from a negligible values in parts of the recharge area to about 2 million ft^2/d for the most permeable subarea in the confined zone (Figure 3.5). High transmissivity of the confined zone is indicated by very low hydraulic gradients, good correlation of water levels among widely spaced wells, large sustained springflows, and uniform temperature and water quality within the aquifer.

3.2.2.3 Storage Estimates

Maclay *et al.* [1973; 1980] have estimated the specific yield of the Edwards aquifer using regional water balance studies, geophysical tests, and laboratory examination of recovered core samples. Estimates are in the range of 1.7-14% with a representative value of 4%. The estimated volume of water in storage in the confined freshwater zone of the aquifer, given an area of 1,500 square miles, and a thickness of 500 ft, and an average specific yield of 4% would be 19.5 million acre-feet. Todd [1983] estimated a value of 2 million acre-feet using a cut-off depth of 400 feet for recoverable water in storage. Water below 400 feet, which may or may not be recoverable, was reported to be 13 million acre-feet. Total storage was estimated to be 15 million acre-feet by CH2M Hill [1986]. A current study (1994) sponsored by the Edwards Underground Water District and being performed by the Bureau of Economic Geology, The University of Texas, seeks to refine these estimates.

The storage coefficient in the confined zone varies with porosity and thickness of the aquifer. The order of magnitude of variation estimated by Maclay and Small [1986] ranges from $1x10^{-4}$ to $1x10^{-5}$. The volume of the unconfined zone represents 30 to 40% of the total volume of the aquifer. Therefore, a large amount of water released from the aquifer comes from storage in this zone. Maclay and Small [1986] also determined regional specific yield in the confined zone to be about 3%, and estimated a drainable porosity for the full thickness of the aquifer to be about 2%, based on geophysical and laboratory data. The quantity of water retained in the unconfined zone after a recharge event is affected strongly by the geologic structure of the aquifer. Faults can act as barriers, reducing the flow of water moving from the unconfined zone to the confined zone and allowing a greater volume of water to remain in the unconfined zone for longer period of time. Structural effects therefore complicate estimates of storage at any given water level or from any recharge event.

3.2.2.4 Recharge

Recharge occurs where the Edwards formation and equivalent rocks are exposed in the Balcones fault zone. Streams draining the Cretaceous limestone uplifted along the Balcones fault and forming the higher topographic elevations of the Edwards Plàteau lose all of their base flow and much of their storm runoff by infiltration from channels passing over porous and fractured Edwards limestone (Figure 3.1). Infiltration losses account for 60 to 80 % of the recharge to the Edwards aquifer in the San Antonio area; the remainder of the recharge is derived from direct infiltration in the interstream areas. Additional recharge occurs as cross formational flow from the Glen Rose Formation. Such flow occurs especially where the Glen Rose Formation is juxtaposed against the Edwards limestone along the Balcones fault zone. Locations of the major faults within the Balcones fault zone are shown in Figure 3.2.

The approximate balance of cumulative recharge and discharge over the past 50 years in the San Antonio area [cf., Reeves and Ozuma, 1986] suggests that the fault zone aquifer may be approximated by steady-state flow conditions over the long term, if the balance is not disturbed by excessive pumping. The average annual recharge of the Edwards aquifer for the period 1934-1992 is estimated by EUWD [1993] to be 682,800 acre-feet/year (AF/yr). The maximum annual estimated recharge of 2,486,000 acre-feet (AF) occurred in 1992, and a minimum estimated annual recharge of 43,700 acre-feet occurred in 1956 [EUWD, 1993]. Natural discharge occurs through springflow at Comal, Hueco, San Marcos, Leona, San Antonio, and San Pedro Springs. The Edwards Underground Water District reports estimated annual discharge from the Edwards aquifer by county from 1934-1992 (Table 2.15). The combined major discharge for 1991 in Comal and Hays Counties was 402,900 acre-ft, which is about 105% of the total spring discharge for 1991.

The Edwards aquifer often has seasonal or weather-related variations in ground-water levels of many feet, and the effects of recharge in the recharge area from isolated rains are nearly instantaneous. A controlling factor in the range of seasonal or weather-related ground-water levels is the great infiltration capacity of the karst terranes. Large volumes of water from intense storms infiltrate into the air-filled caverns of the karst terranes causing the water table to rise rapidly. From a single storm, the rise in the water table in relatively impermeable parts of the saturated aquifer can be many feet, whereas the rise of the water table in much more permeable zones can be only a few feet.

3.2.2.5 Comal Springs Area

Comal Springs (Figure 4.2) flow from the Edwards aquifer at the base of the Balcones Escarpment. Here the aquifer has been downdropped by the Comal Springs Fault and several antecedent faults. The Comal Springs Fault is the most conspicuous fault in the Balcones Fault Zone in the area, forming the escarpment separating the Gulf Coastal Plain from the Edwards Plateau. At some places along the fault, such as at Comal Springs, the Taylor Marl is faulted into contact with the Edwards aquifer indicating the possibility of a stratigraphic displacement of 400 to 600 ft. This juxtaposition of the aquifer with the Taylor Marl--a tight, thick (300 ft) confining bed is partially responsible for the existence of Comal Springs. Other factors include the exceptional karstic development, both vertically and laterally, of the Edwards aquifer and the topographic low at the spring site.

Good ground-water flow patterns undoubtedly follow the Comal Springs Fault throughout much of its more than 50-mile length from near San Antonio to east of San Marcos Springs. Transmissivities are exceptionally large (Figure 3.4). Maclay and Small [1986, fig. 20, p. 67] state, "Subarea R is the most transmissive zone in the San Antonio area. Water flows through the confined aquifer along the Comal Springs Fault on the down thrown side of the fault. Well yields are very large. Geophysical logs indicate that both the Person and Kainer Formations (of the Edwards aquifer) are very cavernous. Water is discharged to Comal Springs in New Braunfels by moving upward along the fault plane." Subarea R is a narrow 2-mile-wide corridor extending from the Bexar-Comal County line to New Braunfels--a distance of 17 mi.

At the surface, the Comal Springs area is relatively simple geologically. Within a 1-mile radius of Comal Springs, only two geologic formations appear at the land surface. The Edwards aquifer is north of the Comal Springs Fault and Quaternary alluvium is south of the fault (Figure 3.6). In the subsurface, however, the geology is relatively complex structurally. The Comal Springs fault, with two probable parallel faults of smaller displacement to the south, have caused a serious disruption of the homoclinal dip of the Edwards aquifer. Relatively impermeable clay and chalk beds--Taylor Group, Austin Group, Eagle Ford Group, Buda Formation, and Del Rio Formation--form a subsurface barrier to normal southeastward ground-water flow in the Edwards aquifer (Figure 3.7).

3.2.2.6 San Marcos Springs Area

San Marcos Springs (Figure 4.4), like Comal Springs, flow from the Edwards aquifer at the base of the Balcones Escarpment. The conduit along which most of the flow moves to the springs is the San Marcos Springs Fault. The points of issuance of the flow are where the fault intersects the land surface at topographic lows--namely Spring Lake, the pool receiving the spring's water.

San Marcos Springs Fault is the continuation of the Hueco Springs Fault in Comal County [George, 1952, p. 29] (Figure 3.2). The San Marcos Springs Fault, with its Hueco Springs Fault continuation, is about 35 mi long and extends from near Bexar County past San Marcos Springs and terminates in southeastern Hays County. The stratigraphic displacement caused by the San Marcos Springs Fault in the vicinity of San Marcos Springs is greater than 300 ft [DeCook, 1956, p. 43].

Exceptionally good ground-water flow is associated with the Edwards aquifer where it is cut by the San Marcos Springs Fault. Transmissivities are very large along the fault where intense fracturing occurs for considerable distance either side of the fault. This is the zone shown as subarea T in Figure 3.5). Maclay and Small [1986, p. 67] describe subarea T: "Subarea T probably is very transmissive. It is adjacent to the Hueco Springs and San Marcos faults and extends from Comal County into Hays County. Large-capacity wells have been drilled near these faults. Ground water in this subarea moves to San Marcos Springs, and the greatest transmissivity occurs in the vicinity of San Marcos Springs." Subarea T is a narrow zone about 3 mi wide and 13 mi long reaching from 10 mi west of San Marcos Springs to 3 mi east of the springs.

The San Marcos Springs area on the surface is more varied geologically and somewhat more complex structurally than the Comal Springs area. Within a 1-mile radius of the springs seven geologic formations have been mapped (Figure 3.8). Surface exposures of the Edwards aquifer (including Georgetown Limestone, which forms the top of the aquifer) are restricted to mostly arcuate outcrops along stream channels or along topographic breaks on hillsides. The San Marcos Springs Fault is seen cutting the area of San Marcos Springs and passing beneath the spring lake. Comal Springs Fault passes less than one-half of a mile south of the springs and parallels the San Marcos Springs Fault.

The position of the Edwards aquifer in the subsurface is clearly seen, however, in the geologic cross section through San Marcos Springs (Figure 3.9). The Georgetown, Person, and Kainer Formations composing the Edwards aquifer are a short distance below the surface in the area of the springs, and the top of the aquifer probably is at the bottom of the spring lake. Closely affecting the hydrology of the area and closely tied to the existence of San Marcos Springs is the San Marcos Springs Fault. Figure 3.9 shows more than 300 ft of displacement caused by the fault, which brings massive confining beds such as the Austin Chalk, Eagle Ford Shale, Buda Limestone, and Del Rio Clay opposite the Edwards aquifer. These tight, confining beds downdropped against the Edwards formed the subsurface barrier to normal ground-water flow southeastward and forced the ground water to exit vertically upward along the fault plane to the surface.

3.3 AREAS OF NATURAL RECHARGE TO COMAL AND SAN MARCOS SPRINGS

In order to identify the recharge areas for Comal and San Marcos Springs, one must first be familiar with the extent of the infiltration (recharge) areas of the Edwards aquifer throughout its entire reach from Kinney County 100 mi west of San Antonio to Hays County 50 mi northeast of San Antonio (Figure 3.1). Secondly, one must keep in mind that the flow of water in the recharge zone is basically southward with minor components of flow eastward, and, most importantly, that the flow of water in the deeper parts of the aquifer south of the recharge zone is strongly eastward. Simply put, a molecule of water as recharge in Kinney County moves eventually eastward and ultimately may be discharged at Comal and San Marcos Springs some 150 mi away if it escapes the other natural discharge sites and pumpage by the many wells along the way.

Yearly water balances in the Edwards have been made since 1934. From this, recharge to the Edwards can be calculated from the measured loss of flow of streams crossing the outcrop plus estimates of infiltration of rainfall directly on the outcrop. Discharge, of course, is determined from the flow of springs and from records of pumpage by wells. From this, the amount of water entering the aquifer in each stream basin and crossing east of the county lines can be calculated

[Garza, 1962]. Table 2.15 shows the average annual water balance for the Edwards aquifer for 1934-92.

Source areas of recharge also can be identified by analyzing for tritium concentration in ground water. Since 1963, the U.S. Geological Survey has been regularly analyzing the tritium content of samples from a number of wells, springs, and streams that are part of the Edwards aquifer system. Some conclusions can be drawn from such data in regards to source areas, flow rates, and mixing processes within the Edwards. In general, tritium distribution within the Edwards aquifer confirms the accepted pattern of water flow within the aquifer. According to Pearson, Rettman, and Wyerman [1975, p. 1], concentrations of greater than 20 tritium units (TU) occur in the recharge areas, while less than 1 tritium unit is present along the aquifer's southern and southeastern boundary.

The general pattern of tritium concentration agrees with present knowledge of the hydrology of the Edwards. The highest tritium values reported are in the Edwards aquifer outcrop, especially along the lower limit of the outcrop, and in the western part of the aquifer. These are recharge areas and would receive tritium resulting from thermonuclear explosions first. Very low tritium values occur deeper within the aquifer suggesting, according to Pearson, Rettman, and Wyerman [1975, p. 15], that no significant amount of tritium resulting from thermonuclear explosions has yet penetrated into these deeper parts of the aquifer. These authors also conclude that the tritium shows that significant recharge to the aquifer occurs along the northern (updip/outcrop) portion of the aquifer and in the western part of the aquifer in Uvalde County, and that ground-water flow is to the east and northeast parallel to the Balcones fault system.

3.3.1 Comal Springs

The source areas of water flowing from Comal Springs are largely regional (across possibly many counties) and, to a very minor extent, local. These two possible areas of recharge are discussed separately.

3.3.1.1 Regional Areas West of Comal Springs

Most of the water discharging at Comal Springs follows flow routes paralleling faults and fault zones extending westward from the springs across several counties. The flow reach extends westward as far as the Bracketville divide in Kinney County 140 mi west of Comal Springs. This significant portion of the total flow is within the downdip or artesian part of the Edwards aquifer, where karstic development and ease of flow (high transmissivity) has been enhanced by the breakup of the aquifer due to faulting, fracturing, and jointing. This ease of flow has led to the presence of the narrow subsurface corridor barely 2 mi wide that reaches from the Comal-Bexar County line just north of Interstate Highway 35 to Comal Springs at New Braunfels. Here in this underground chamber in the Edwards aquifer, the transmissivity is highest in the entire 150-mile reach of the Edwards.

Table 2.15 indicates that a significant amount of water as recharge moves eastward from the western end of the Edwards aquifer crossing several counties and generally picking up water as it moves eastward. The heavy pumpage at San Antonio, however, taps off a large part of the recharge. Nevertheless, a large amount of ground water continues to move past Bexar County into Comal County where discharge by mostly Comal Springs uses up most of the remaining water. The 106,700 AF recharged locally by Cibolo and Dry Comal Creeks (Table 2.12) was far exceeded by the 362,000 AF discharged mostly by Comal Springs (Table 2.15). Therefore, a significantly large part of the water discharged by Comal Springs is furnished by areas to the west of Comal County, possibly reaching back to Kinney county at the extreme western end of the Edwards aquifer.

Tritium studies by Pearson, Rettman, and Wyerman [1975, p. 21-22] show that Comal Springs had what was probably prebomb-era tritium only in 1963 and 1964, and from 1967 to 1971 has had a maximum of only 6.7 TU. Tritium concentrations reached a maximum of 7.0 TU in 1975 and 1977 as reported by Maclay, Rettman, and Small [1980, p. 29], and Nalley and Thomas [1990, p. 77] reported only 4.4. TU in 1989. This implies that Comal Springs is discharging water of considerable residence time and that most of the water originated probably far to the west of the springs, possibly in Kinney, Uvalde, Medina and Bexar Counties, whose distances from Comal Springs would provide longer travel paths and, consequently, more residence time in the aquifer. Additionally, the tritium studies showed that ground-water flow through the Edwards aquifer is not well mixed with recently recharged water from local areas. That is, water having passed through the entire Edwards system flows through that part of the aquifer adjacent to the Comal Springs Fault as it enters Comal County and most of it is discharged at Comal Springs [Pearson, Rettman, and Wyerman, 1975, p. 22-23].

Water chemistry and dye tracing studies were done in 1982 and 1983 [Rothermel and Ogden, 1986, p. 115-147] for Comal Springs. Samples were taken weekly over the 2-year period from four orifices of Comal Springs and were taken more frequently during storm events to determine if local recharge (if occurring) affected water chemistry and discharge volumes. A tritium value of 5.0 TU obtained from Comal Springs showed that the water had a considerable residence time. This reinforces the findings of Pearson, Rettman, and Wyerman [1975], who got a maximum of 6.7 TU in 1971, that recharge areas are distant from the springs. Other supporting evidence, determined by Rothermel and Ogden [1986, p. 115] that recharge areas for Comal Springs are not, for the most part, local are (1) lack of turbidity during and after storms, (2) inability to dye-trace local sink sites in the area of the springs, (3) low coefficients of variation for different chemical constituents, and (4) Comal Spring's warmer temperature than that approximating the mean annual air temperature.

3.3.1.2 Local Areas Near Comal Springs

Little or no reportable evidence exists to confirm that there is any substantial natural recharge locally to Comal Springs. The bulk of the evidence convincingly points to more distant regional areas to the west. Although Cibolo and Dry Comal Creeks, in the vicinity of Comal Springs, contributed 106,700 AF of recharge to the Edwards aquifer (Table 2.12) there is no knowledge of how much of this water discharges at Comal Springs. It is highly likely, however, that some of this recharge mixes with the eastward-flowing ground water coming out of the San Antonio area, both increments of which would be needed to sustain the flow of Comal Springs.

Tritium studies by Pearson, Rettman, and Wyerman [1975] also show no local recharge of substantial proportions, as the low concentration of tritium from Comal Springs implies a relatively long residence time. This conclusion also is substantiated by the water-chemistry studies, which showed constancy of water quality throughout storm events and constancy of relatively warm water temperature. These authors conclude that "faulting has hydrogeologically isolated Comal Springs from any large sources of local recharge."

3.3.2 San Marcos Springs

San Marcos Springs, unlike Comal Springs, has both regional and local components of ground-water flow supplying the springs. Both of those source (recharge) areas are discussed below.

3.3.2.1 Regional Areas West of San Marcos Springs

A part (percent not known) of the flow of San Marcos Springs probably follows the regional flow of ground water in the Edwards aquifer from the western part of the aquifer in Kinney County eastward through Uvalde, Medina, Bexar, and Comal Counties into Hays County. The hydraulic gradient is in this direction, so there is a natural tendency for flow to move eastward from distant recharge areas. Because San Marcos Springs are 49 ft lower in altitude than Comal Springs, Edwards water flowing past Comal Springs should move downgradient to the aquifer's second largest natural outlet--San Marcos Springs. According to William F. Guyton & Associates [1979, p. 71], this concept of underflow from Comal Springs to San Marcos Springs appears to be sound.

Highly transmissive subsurface corridors are present in the Edwards aquifer from west of San Antonio to San Marcos. Figure 3.5 shows 40 to 50 mi of various subareas having higher-than-average transmissivity that would easily convey Edwards water over these distances past Comal Springs to the springs at San Marcos.

The exact pathway of Edwards water flowing to San Marcos Springs from recharge areas to the west may diverge in places from the pathway conveying water to Comal Springs. This departure is believed to be due to the existence of discrete faulting in Comal and Hays Counties. Contrary to Comal Springs whose flow is channelized in the subsurface by the position of the Comal Springs Fault (Figures 3.2, 3.6, and 3.7), the flow toward San Marcos Springs is controlled largely by the San Marcos Springs Fault--a parallel fault less than one-half of a mile north of the Comal Springs Fault (Figures 3.2, 3.8, and 3.9). This shifting of pathways, even in a short distance, is believed to have a major influence in determining the source areas (recharge areas) for San Marcos Springs.

Source areas are believed to be closer to San Marcos Springs than source areas for Comal Springs. This supposition is based on the geographic location of the San Marcos Springs Fault, which is the eastward continuation of the Hueco Springs Fault (Figure 3.2). This 35-mile-long fault has its western extremity in a more northerly portion of the Edwards aquifer outcrop (recharge area) in Comal County and eastern Bexar County than the Comal Springs fault, which is more closely associated with the artesian portion of the Edwards aquifer. Consequently, a possibly significant portion of the total recharge to San Marcos Springs may originate from sites in Comal County and eastern Bexar County at distances of 10 to 30 mi west from San Marcos Springs. Substantiating this possibility were the tritium studies by Pearson, Rettman, and Wyerman [1975, p. 24] who conclude that water recharging in northern Bexar and Comal Counties does not mix with water from further west in the Edwards, but rather flows to the east in a subsystem of its own and discharges in part at Hueco Springs, but primarily at San Marcos Springs.

The water balance shown by Table 2.15 also reveals that about one-half of the flow of San Marcos Springs possibly could be supplied by the balance of Edwards water passing into Hays County from Comal County. Contributions to Edwards aquifer recharge by Hays County areas primarily north and west of the springs could augment the flow of San Marcos Springs.

3.3.2.2 Local Areas Near San Marcos Springs

It is possible that there is a component of natural recharge to San Marcos Springs that is "local" as opposed to the suspected component of recharge that is considered to be more "distant." Because the ground-water pathways leading to San Marcos Springs are believed to be well-developed along the San Marcos Springs Fault, it is reasonable to expect that multiple recharge areas exist on the Edwards outcrop along, and in close proximity to, this fault.

Creeks crossing the San Marcos Springs Fault (Hueco Springs Fault in Comal County) in Hays and Comal Counties west of San Marcos Springs are channelways for inflow (recharge) into that portion of the Edwards aquifer feeding the springs. In Hays County, one such creek is Purgatory Creek which has its headwaters in eastern Comal County but which flows across the San Marcos Springs Fault in western Hays County at a point 2.5 mi southwest of San Marcos Springs. Another such creek is York Creek, which is mostly in eastern Comal County, but which enters Hays County in its lower reaches. This creek crosses the San Marcos Springs Fault just north of Interstate Highway 10 near the easternmost tip of Comal County. This site is 10 mi southwest of San Marcos Springs. These sites in and near Hays County and San Marcos Springs probably augment the flow of the springs to a relatively small extent. Pearson, Rettman, and Wyerman [1975, p. 22] suggest that there is insufficient recharge in the immediate vicinity of San Marcos Springs to account for more than about 35 percent of the discharge, and conclude that the remainder must be from areas further south and west in the Edwards aquifer. Their tritium studies found that San Marcos Springs had tritium levels of 30 TU or more in 1964-71 compared to Comal Springs maximum tritium level of 6.7 TU in 1971. From this, they conclude that much of San Marcos Springs discharge is "locally" recharged. However, "locally" here is meant to imply mostly areas east of Bexar County.

A direct flow path to San Marcos Springs was revealed by Ogden (1986) from dye-tracing studies in the vicinity of San Marcos Springs. Sodiumfluorescein green dye was injected into a deep lake at the bottom of a cave about 2 mi west of San Marcos Springs. This injection site is along the San Marcos Springs Fault and is about 1 mile east of where Purgatory Creek crosses the fault. Two of the six orifices of the springs that were monitored (Deep Spring and Catfish Spring orifices) were positive. The velocity of the dye travel was approximately 1,500 feet per day. Water from none of the other four spring orifices monitored encountered any dye. The conclusion drawn by Ogden [1986, p. 159] is that water from San Marcos Springs is not from a single discrete pathway, but that the springs receive water from different flow paths.

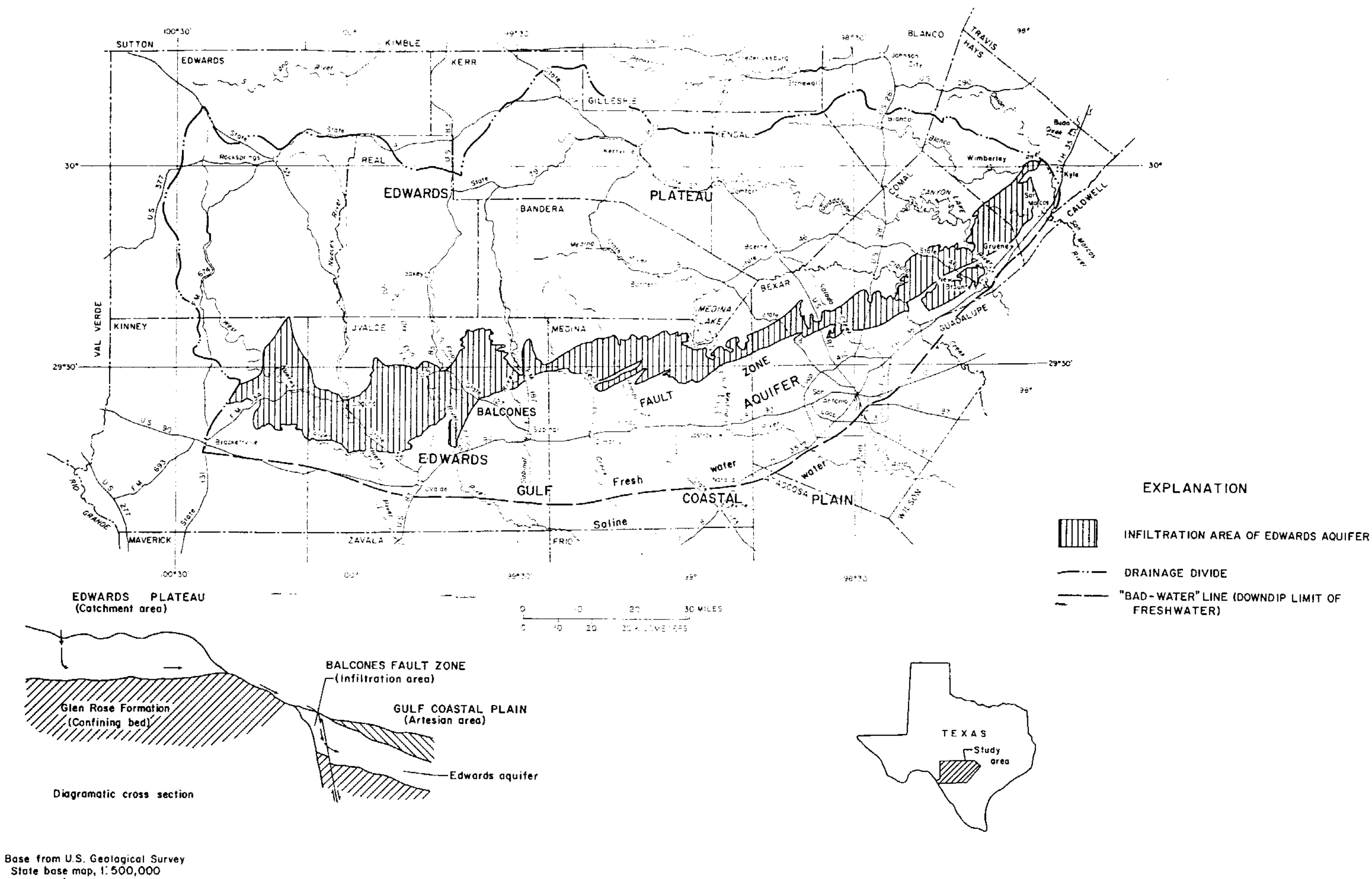


Figure 3.1. Regional extent of the Edwards aquifer [from Small, 1985]

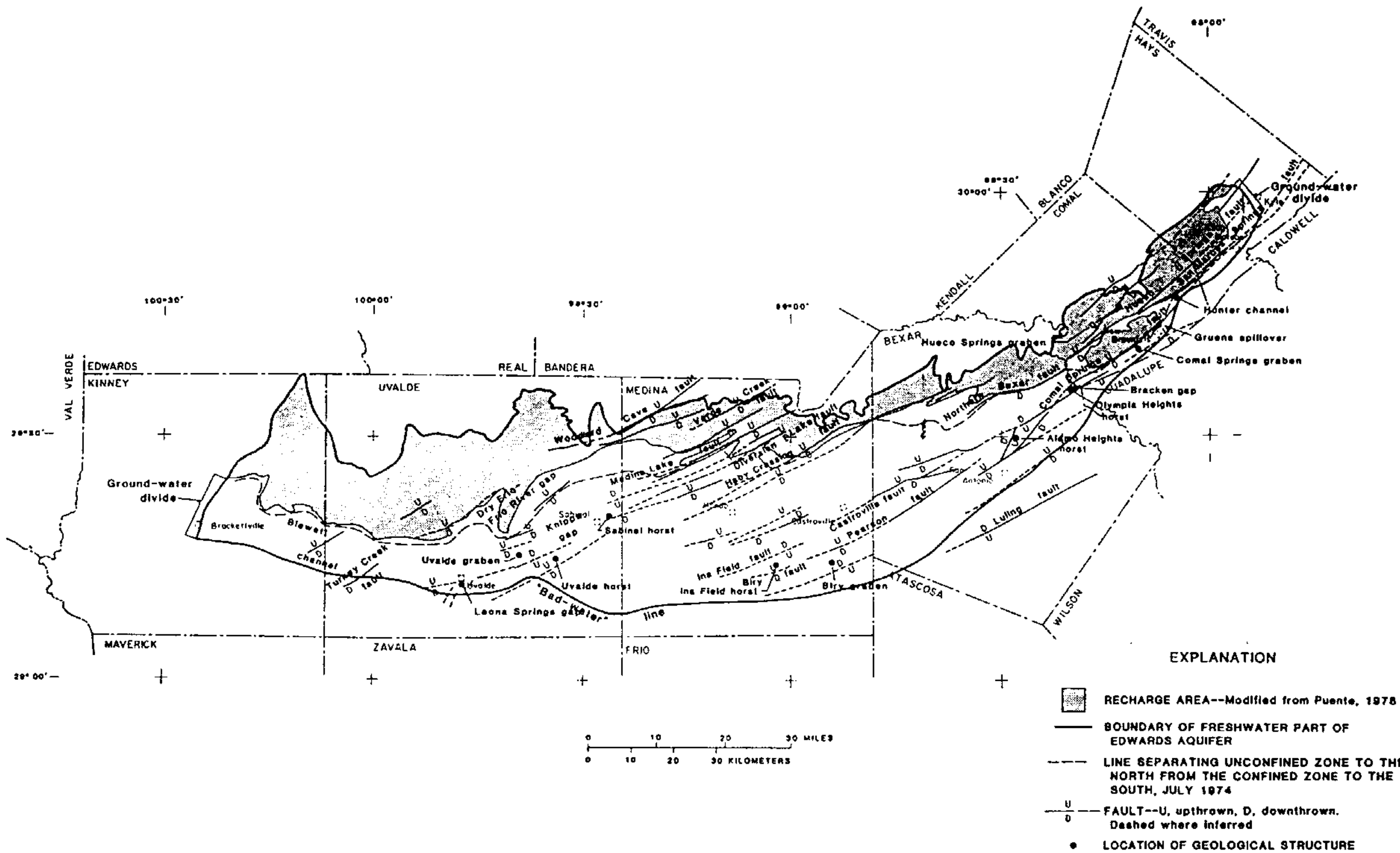


Figure 3.2. Surface geology of the Edwards aquifer area northeast of San Antonio including the Comal and San Marcos Springs localities [from Maclay and Land, 1988]

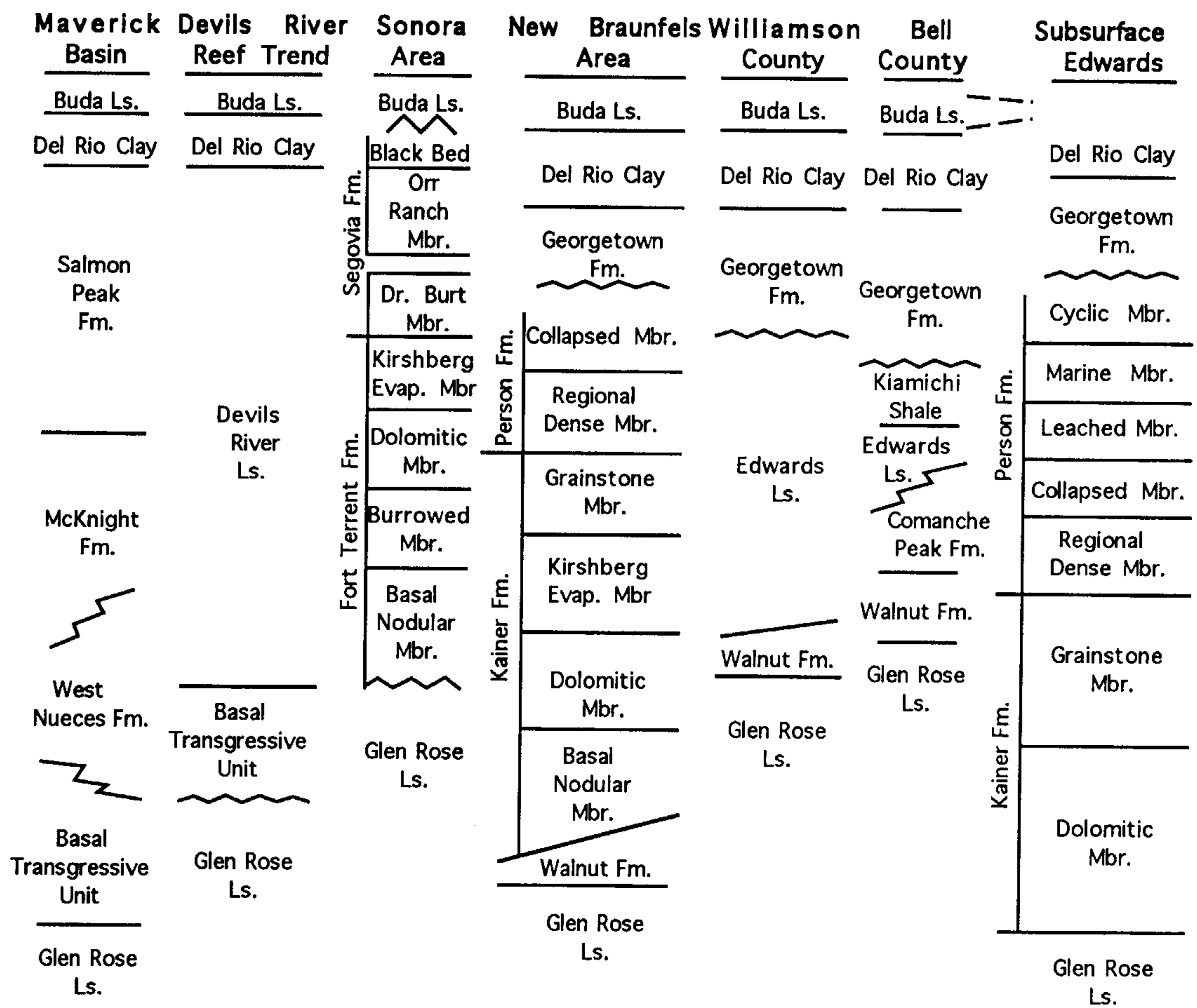


Figure 3.3. Stratigraphic columns of the Edwards aquifer

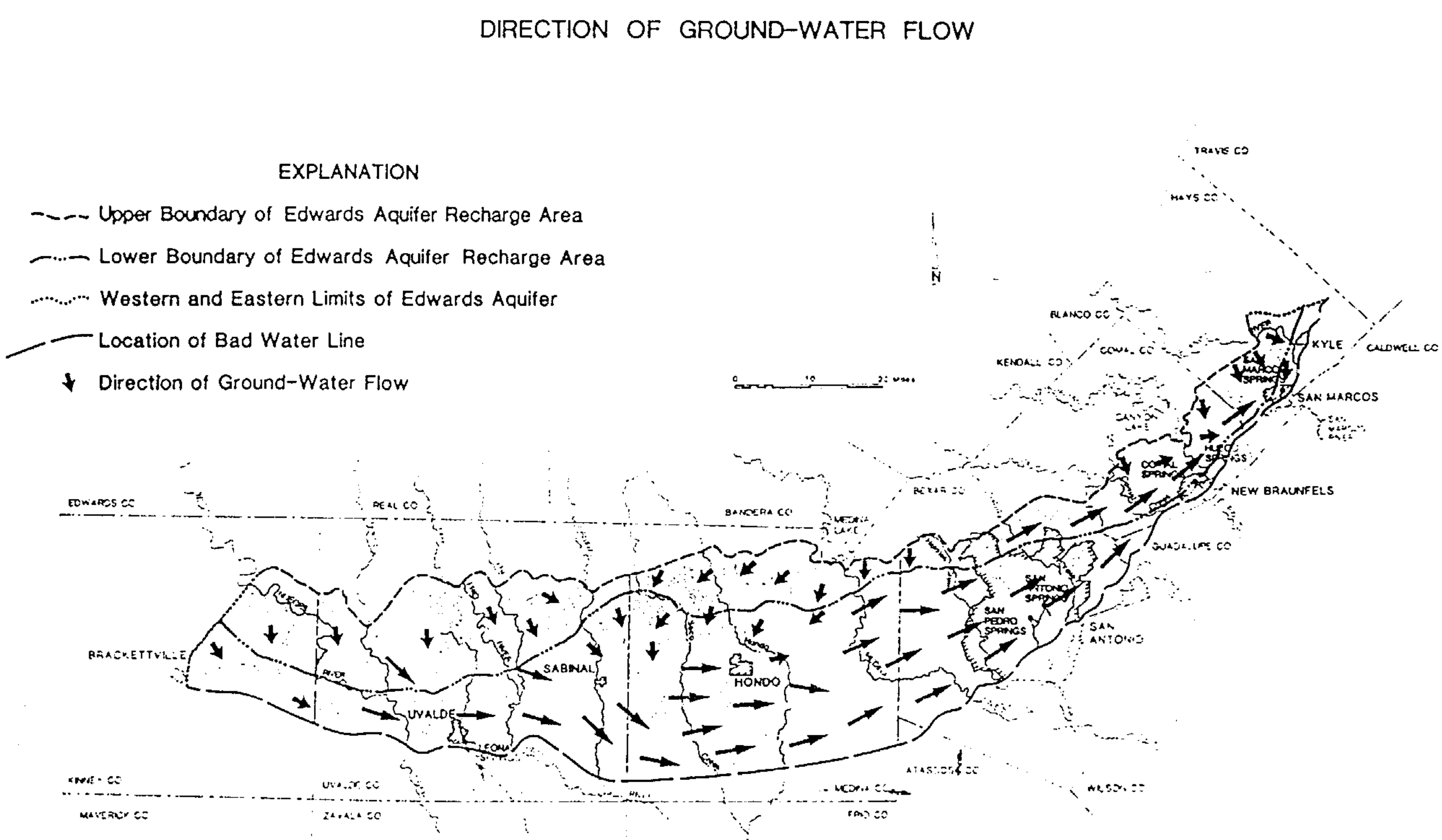


Figure 3.4. Direction of flow in the Edwards aquifer [from Hardin, 1988]

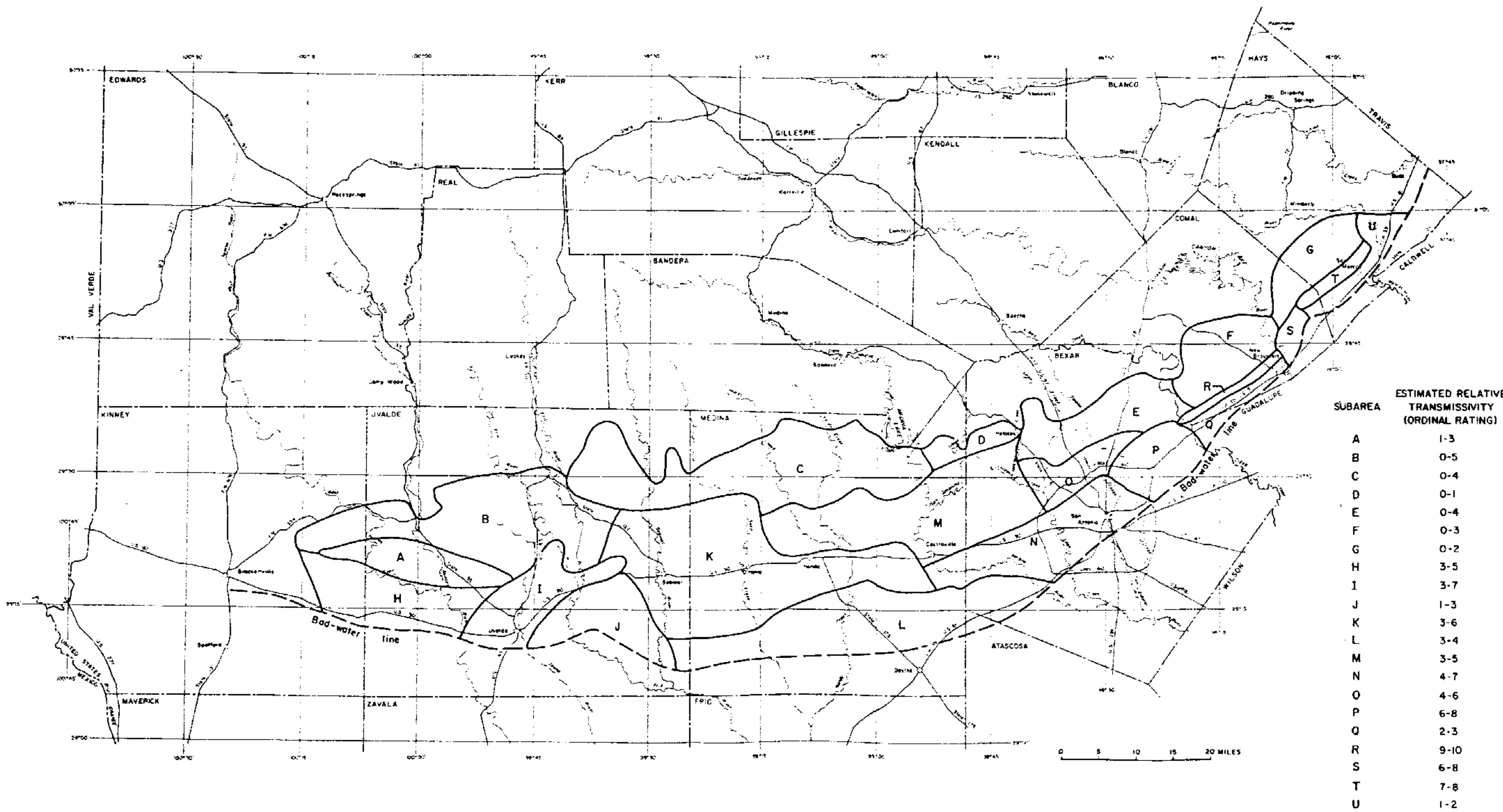


Figure 3.5. Estimated transmissivities by subareas of the Edwards aquifer [Maclay and Small, 1986]