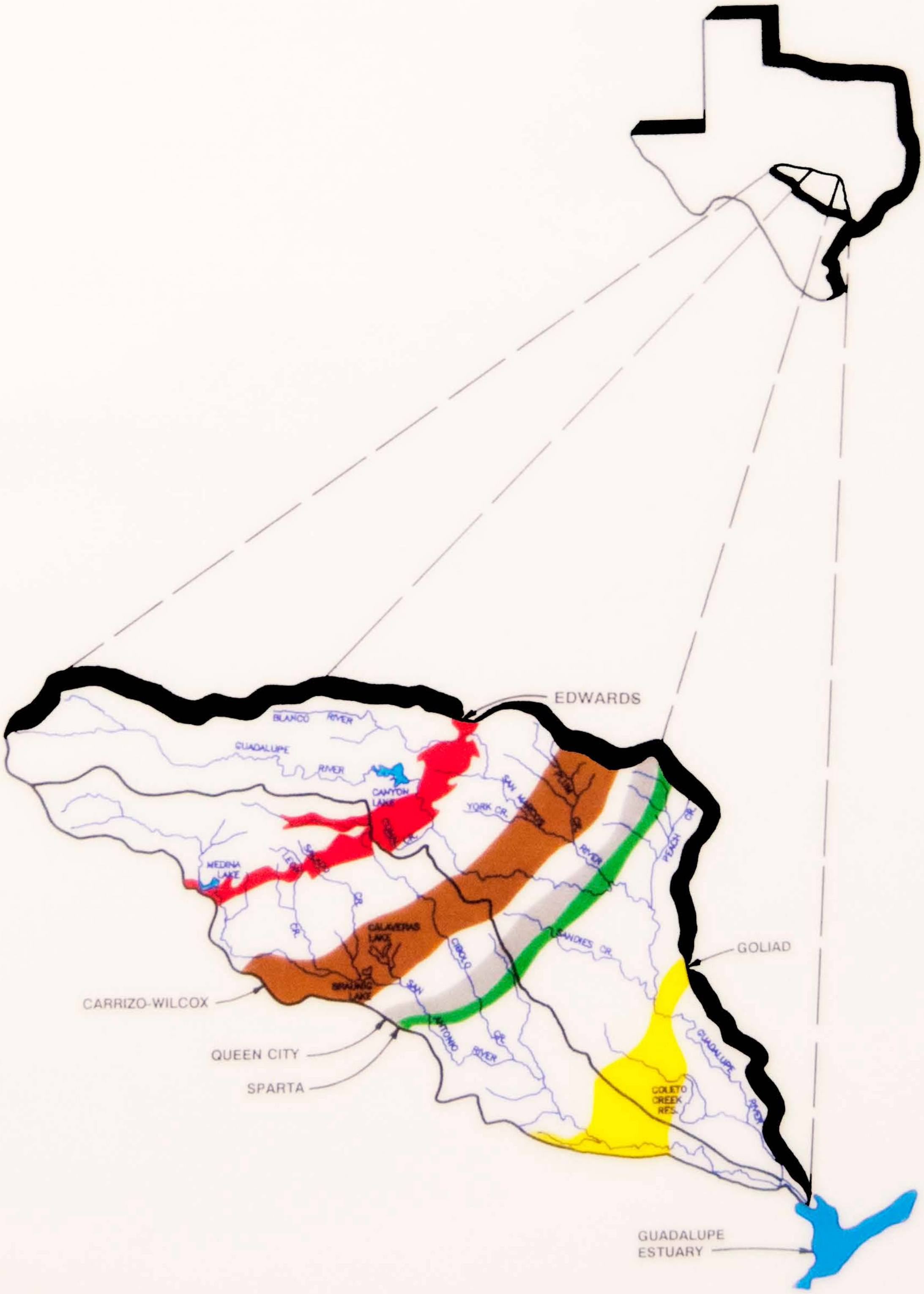
Recharge Enhancement Study

Guadalupe - San Antonio River Basin



Volume II - Technical Report

Edwards Underground Water District

HDR

HDR Engineering, Inc.
in association with
Espey, Huston & Assoc., Inc.

GUADALUPE - SAN ANTONIO RIVER BASIN

RECHARGE ENHANCEMENT STUDY

VOLUME II - TECHNICAL REPORT

Prepared for

Edwards Underground Water District

by

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September, 1993

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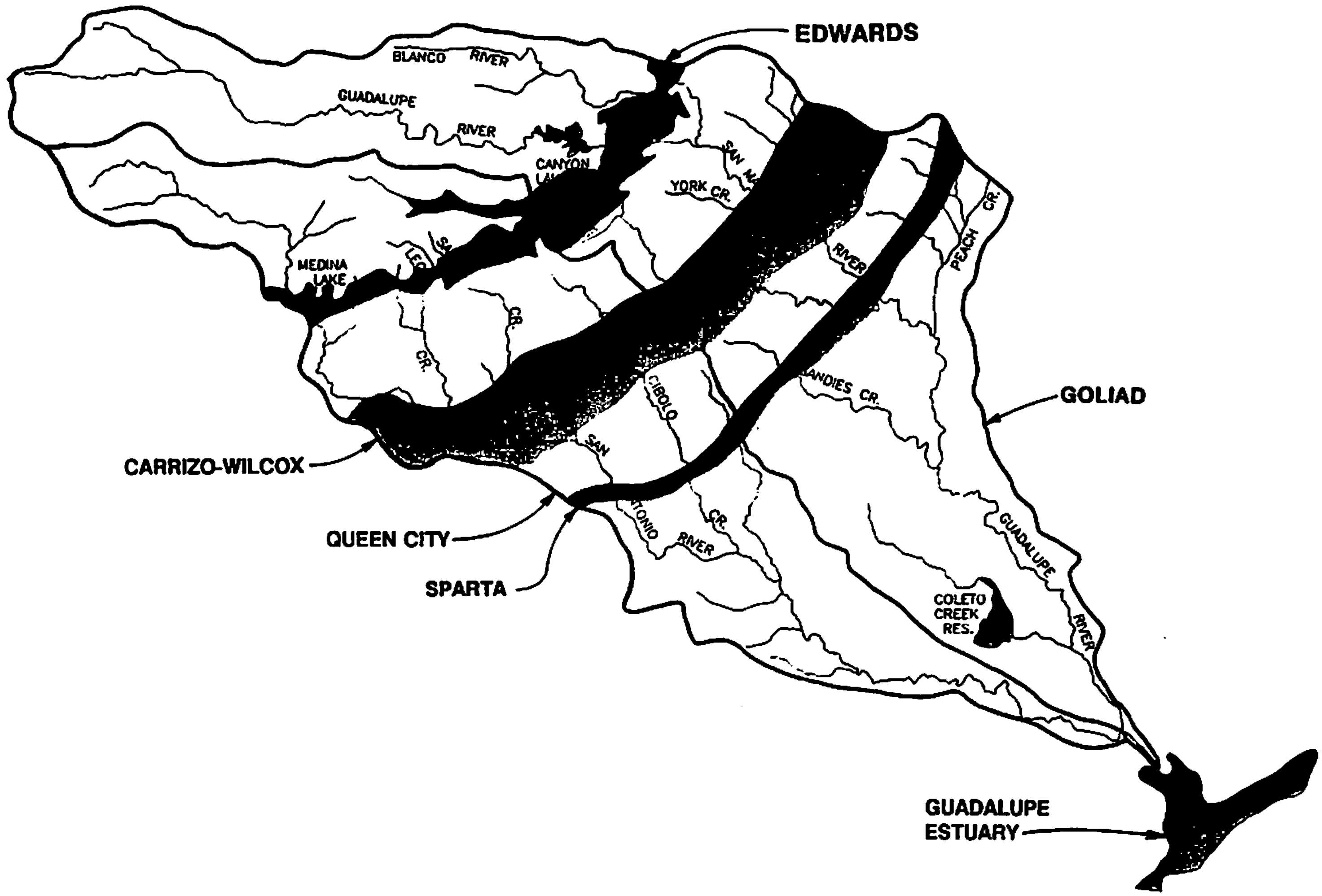
GUADALUPE - SAN ANTONIO RIVER BASIN RECHARGE ENHANCEMENT STUDY

1.0 INTRODUCTION

The Guadalupe - San Antonio River Basin encompasses over 10,100 square miles extending from the headwaters on the Edwards Plateau north and west of San Antonio through the Texas Blackland Prairie and Claypan Area, the Northern Rio Grande Plain, and the Gulf Coast Prairies to the Guadalupe Estuary south of Victoria. Land use in the basin is predominantly classified (Ref. 21) as range and pasture (79%) with the remainder classified as cropland (14%), urban (6%), or miscellaneous uses (1%). As is apparent in Figure 1-1, the Guadalupe - San Antonio River Basin is crossed by at least five aquifer outcrops or recharge zones, including the Edwards, Carrizo-Wilcox, Queen City, Sparta, and Gulf Coast (Goliad). The most transmissive of these recharge zones is associated with the Edwards limestone aquifer and is generally located along the Balcones Escarpment. The Edwards Aquifer is presently the water supply source for the City of San Antonio as well as numerous other cities and agricultural interests throughout Uvalde, Medina, Bexar, Comal, and Hays Counties. The aquifer also feeds Leona, San Pedro, San Antonio, Comal, and San Marcos Springs, creating unique environments and recreational opportunities while providing base flow to the Nueces, Leona, San Antonio, Comal, Guadalupe, and San Marcos Rivers.

The present and future economic dependence of entities currently served by the Edwards Aquifer and the flows emanating from its springs has prompted the Edwards Underground Water District (EUWD) to sponsor this Guadalupe - San Antonio River Basin



GUADALUPE-SAN ANTONIO RIVER BASIN
RECHARGE ENHANCEMENT STUDY

STUDY AREA MAP

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FIGURE 1-1

Recharge Enhancement Study. An Advisory Committee representative of the diverse interests potentially affected by enhancement of Edwards Aquifer recharge was assembled by the EUWD to provide guidance and technical review throughout the study effort.

The concept of recharge enhancement is not new. In 1964, the U. S. Army Corps of Engineers (USCE) published a report identifying a number of potential projects located near the Edwards Aquifer recharge zone intended to capture and recharge additional flood flows which would not have entered the aquifer naturally. Since that time, the EUWD and others have constructed projects on Seco, Parkers, Verde, San Geronimo, Salado, Dry Comal, Sink, and Purgatory Creeks which have served to enhance recharge. The EUWD has also sponsored detailed studies of 19 potential recharge enhancement projects in the Nueces River Basin. Significant results and products of studies of the Nueces River Basin include new estimates of historical Edwards Aquifer recharge and development of a new river basin model capable of calculating potential recharge enhancement while considering downstream water rights and estuarine inflows.

1.1 Study Objectives

The key objectives of the Guadalupe - San Antonio River Basin Recharge Enhancement Study are summarized as follows:

- Development of new monthly estimates of historical Edwards Aquifer recharge consistent with those for the Nueces River Basin, thereby completing recharge estimates for the entire aquifer for the 1934-89 historical period.

- Development of a river basin computer model capable of evaluating recharge enhancement projects and water availability subject to variable water rights constraints and springflows.

- Calculation of maximum enhanced recharge potential and estuarine inflow reductions associated with a program of recharge projects subject to a range of springflow and water rights utilization scenarios.

- Calculation of maximum water potentially available at selected locations subject to a range of springflow and water rights utilization scenarios.

The following sections of this Technical Report describe the basic data collected, previous studies referenced, methodologies applied, and results obtained in accomplishing these objectives.

2.0 WATER RIGHTS AND USE

2.1 Water Rights

The Texas Water Commission (TWC) maintains a master listing of all water rights and applications for water rights within the state. A current listing of all water rights and applications in the Guadalupe and San Antonio River Basins was extracted from the master listing, sorted by river order number (downstream to upstream), and included in Appendix A (Volume III). Water rights in terms of authorized diversion for consumptive use are summarized by river basin and type of use in Table 2-1. Table 2-1 shows that industrial water rights are the most dominant type of use in the Guadalupe River Basin and irrigation water rights are the most dominant type of use in the San Antonio River Basin. Municipal, industrial, and irrigation rights comprise virtually all of the rights for consumptive use in the Guadalupe - San Antonio River Basin. The Edwards Underground Water District (EUWD) currently holds the only authorized diversion right for recharge which accounts for 0.2 percent of total basin diversion rights.

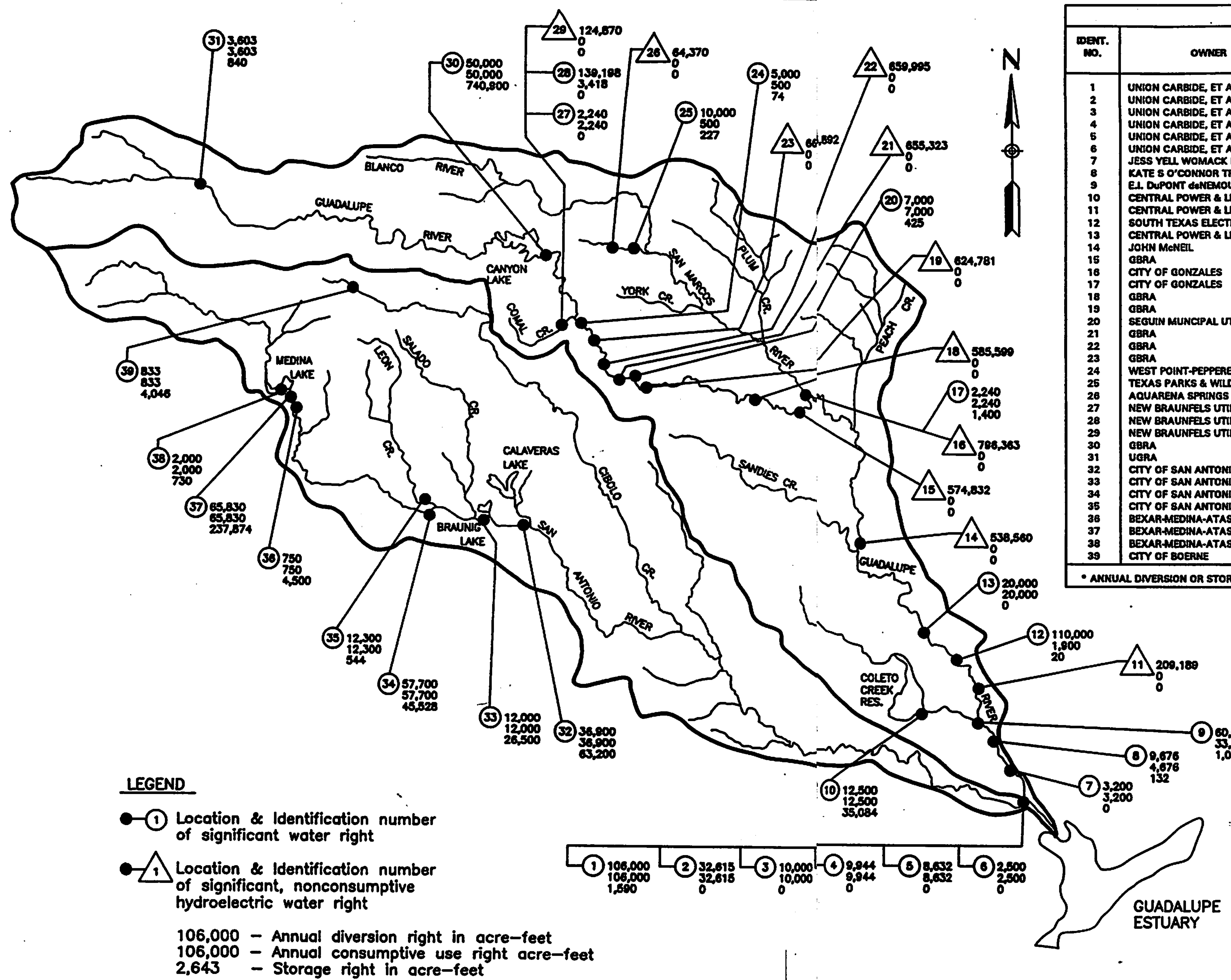
Several non-consumptive hydroelectric power generation rights exist in the Guadalupe River Basin. Most of these hydroelectric rights are located in series along the Guadalupe River, with the largest authorized right being 796,363 ac-ft/yr held by the City of Gonzales. The City of Gonzales hydroelectric rights, however, are subordinated to other rights to use the water of the Guadalupe River for municipal, industrial, irrigation, and/or mining purposes. The Guadalupe-Blanco River Authority (GBRA) holds six hydroelectric rights upstream of the City of Gonzales site ranging from 574,832 ac-ft/yr to 663,892 ac-ft/yr.

Table 2-1 Summary of Consumptive Use Water Rights[1]						
	Guadalupe River Basin		San Antonio River Basin		Total	
Type of Use	Authorized Diversion (Ac-Ft/Yr)	Percent of Total Diversion	Authorized Diversion (Ac-Ft/Yr)	Percent of Total Diversion	Authorized Diversion (Ac-Ft/Yr)	Percent of Total Diversion
Municipal	105,800	18.3%	71,862[2]	12.4%	177,662	30.7%
Industrial	149,912[3]	25.9%	48,925[4]	8.5%	198,837	34.4%
Irrigation	98,648	17.0%	102,180	17.7%	200,828	34.7%
Mining	153	0.0%	5	0.0%	158	0.0%
Recharge	0	0.0%	961	0.2%	961	0.2%
TOTAL	354,513	61.2%	223,933	38.8%	578,446	100.0%

Notes:

1) Summary excludes all non-consumptive water rights including non-consumptive hydroelectric, industrial, and recreation water rights. The non-consumptive hydroelectric and non-consumptive industrial water rights were included in the GSA River Basin Model. See Section 5 for a description of water rights assumptions used in the GSA River Basin Model.
2) Includes the Applewhite Reservoir diversion rights totalling 70,000 ac-ft/yr which are presently undeveloped.
3) Includes the 20,000 ac-ft/yr diversion right from the Guadalupe River upstream of Victoria for use as make-up water and the 12,500 ac-ft/yr diversion right from Coleto Creek for Central Power and Light at Coleto Creek Reservoir.
4) Includes the 12,000 ac-ft/yr and 36,900 ac-ft/yr diversion rights associated with Braunig Lake and Calaveras Lake, respectively.

A total of about 580 individual water rights currently exist in the Guadalupe - San Antonio River Basin, with the vast majority of these being individual irrigation water rights with authorized annual diversions of less than 100 ac-ft. There are 39 owners of storage or annual diversion rights which are in excess of 2,000 ac-ft. The geographic location of each of these significant water rights is shown in Figure 2-1 along with a listing of the authorized diversion, consumptive use, and storage amounts. These significant water rights represent



SIGNIFICANT WATER RIGHTS*					
IDENT. NO.	OWNER	DIVERSION RIGHT (AC-FT/YR)	CONSUMPTIVE RIGHT (AC-FT/YR)	STORAGE RIGHTS (AC-FT/YR)	NOTES
1	UNION CARBIDE, ET AL.	106,000	106,000	1,590	
2	UNION CARBIDE, ET AL.	32,615	32,615	0	
3	UNION CARBIDE, ET AL.	10,000	10,000	0	
4	UNION CARBIDE, ET AL.	9,944	9,944	0	
5	UNION CARBIDE, ET AL.	8,632	8,632	0	
6	UNION CARBIDE, ET AL.	2,500	2,500	0	
7	JESS YELL WOMACK II ET AL.	3,200	3,200	0	
8	KATE S O'CONNOR TRUST	9,676	4,676	132	
9	E.I. DuPONT deNEMOURS & CO.	60,000	33,000	1,056	
10	CENTRAL POWER & LIGHT CO.	12,500	12,500	35,084	COLETO CREEK RES.
11	CENTRAL POWER & LIGHT CO.	209,189	0	0	
12	SOUTH TEXAS ELECTRIP COOP	110,000	1,900	20	
13	CENTRAL POWER & LIGHT CO.	20,000	20,000	0	
14	JOHN McNEIL	538,560	0	0	HYDROELECTRIC
15	GBRA	574,832	0	0	HYDROELECTRIC, H-5
16	CITY OF GONZALES	798,363	0	0	HYDROELECTRIC
17	CITY OF GONZALES	2,240	2,240	1,400	
18	GBRA	585,599	0	0	HYDROELECTRIC, H-4
19	GBRA	624,781	0	0	HYDROELECTRIC, TP-5
20	SEGUIN MUNCIPAL UTILITIES	7,000	7,000	425	
21	GBRA	655,323	0	0	HYDROELECTRIC, TP-4
22	GBRA	659,995	0	0	HYDROELECTRIC, TP-3
23	GBRA	663,892	0	0	HYDROELECTRIC, TP-2
24	WEST POINT-PEPPERELL, INC.	5,000	500	74	
25	TEXAS PARKS & WILDLIFE	10,000	500	232	
26	AQUARENA SPRINGS CORP.	64,370	0	0	HYDROELECTRIC
27	NEW BRAUNFELS UTILITIES	2,240	2,240	0	
28	NEW BRAUNFELS UTILITIES	139,198	3,418	0	
29	NEW BRAUNFELS UTILITIES	124,870	0	0	HYDROELECTRIC
30	GBRA	50,000	50,000	740,900	CANYON LAKE
31	UGRA	3,603	3,603	840	
32	CITY OF SAN ANTONIO	36,900	36,900	63,200	CALAVERAS LAKE
33	CITY OF SAN ANTONIO	12,000	12,000	26,500	BRAUNIG LAKE
34	CITY OF SAN ANTONIO	57,700	57,700	45,528	APPLEWHITE RES.
35	CITY OF SAN ANTONIO	12,300	12,300	544	
36	BEXAR-MEDINA-ATASCOSA WCID	750	750	4,500	DIVERSION LAKE
37	BEXAR-MEDINA-ATASCOSA WCID	65,830	65,830	237,874	MEDINA LAKE
38	BEXAR-MEDINA-ATASCOSA WCID	2,000	2,000	730	
39	CITY OF BOERNE	833	833	4,048	

* ANNUAL DIVERSION OR STORAGE RIGHTS IN EXCESS OF 2,000 ACRE-FEET.

GUADALUPE-SAN ANTONIO RIVER BASIN RECHARGE ENHANCEMENT STUDY

SIGNIFICANT WATER RIGHTS LOCATION MAP

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FIGURE 2-1

87 percent of the total authorized consumptive use in the Guadalupe - San Antonio River Basin, including 96 percent of the municipal rights, 99 percent of the industrial rights, and 68 percent of the irrigation rights. Some of the major water rights in the basin have specific conditions associated with their authorized diversion amount. A more detailed description of how specific water rights were addressed in the GSA River Basin Model is presented in Section 5 of this report.

2.2 Historical Surface Water Use

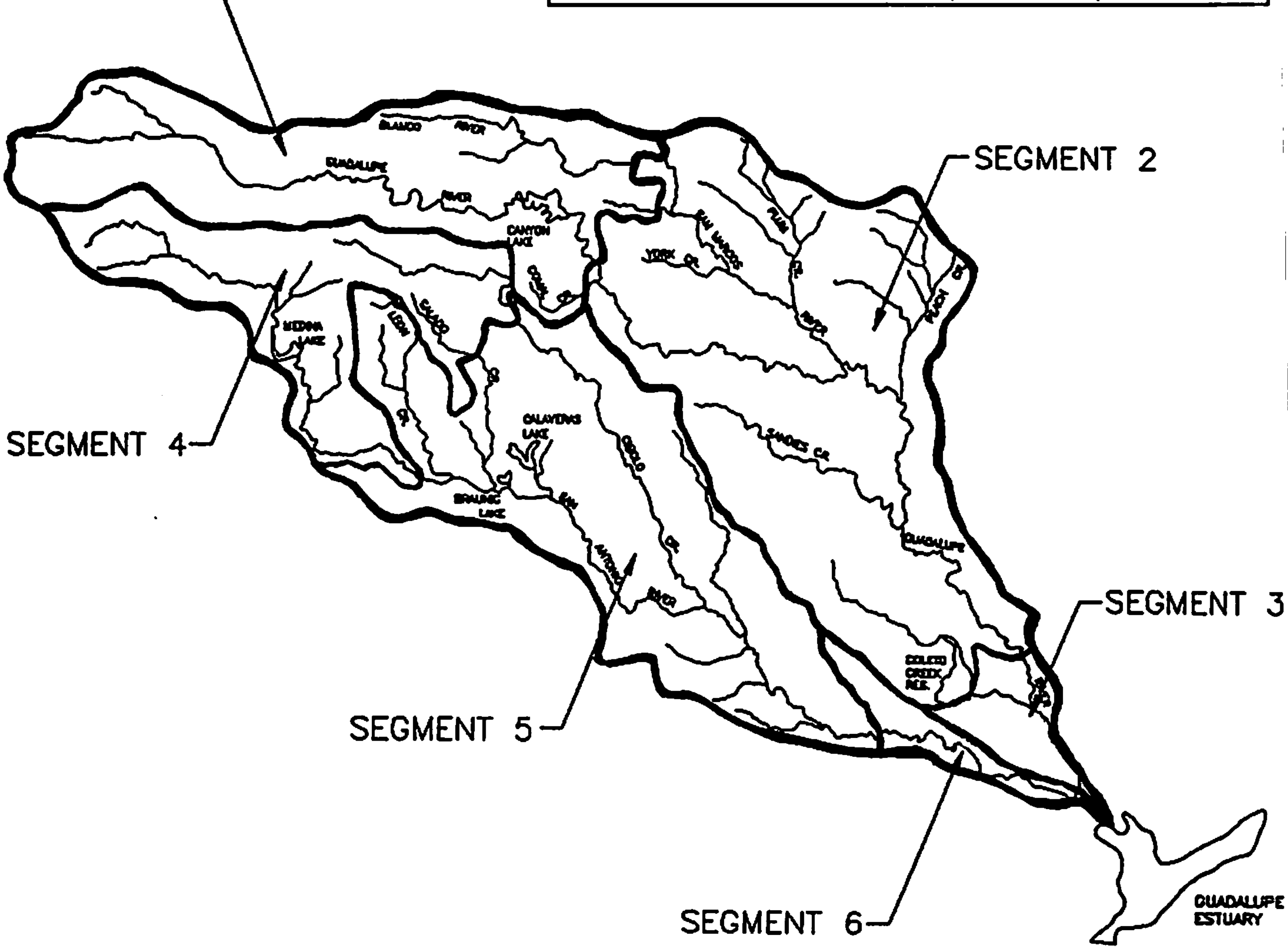
Detailed analyses of surface water use were performed as a part of this study in order to adjust gaged streamflow records for historical diversions to obtain natural streamflow. Natural streamflow is defined as that which would have occurred historically exclusive of human influences. In addition, monthly water use patterns for each type of use were needed to accurately model diversions for water rights.

For this study, the Guadalupe - San Antonio River Basin was subdivided into six major segments in order to develop regionally applicable monthly water use patterns. These segments and associated drainage areas are presented in Figure 2-2 and are described as follows:

Segment 1 - Extends from the headwaters of the Guadalupe River Basin to the downstream edge of the Edwards Aquifer recharge zone including areas upstream of the USGS streamflow gaging stations on the Guadalupe River at New Braunfels (ID# 1685), San Marcos River at San Marcos (ID# 1700), and Blanco River at Kyle (ID# 1713).

Segment 2 - Extends from the lower edge of Segment 1 to the USGS streamflow gaging stations on the Guadalupe River at Victoria (ID# 1675) and Coleto Creek near Victoria (ID# 1775).

DRAINAGE AREAS OF MODEL SEGMENTS			
SEGMENT		DRAINAGE AREA (SQ.MI.)	PERCENT OF TOTAL BASIN
GUADALUPE RIVER BASIN	1	2,153	21.3%
	2	3,539	34.9%
	3	256	2.5%
SAN ANTONIO RIVER BASIN	4	1,420	14.0%
	5	2,501	24.7%
	6	259	2.6%
TOTAL		10,128	100.0%



GUADALUPE-SAN ANTONIO RIVER BASIN
RECHARGE ENHANCEMENT STUDY

BASIN MODEL SEGMENTS

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FIGURE 2-2

Segment 3 - Extends from the lower edge of Segment 2 to the Gulf of Mexico.

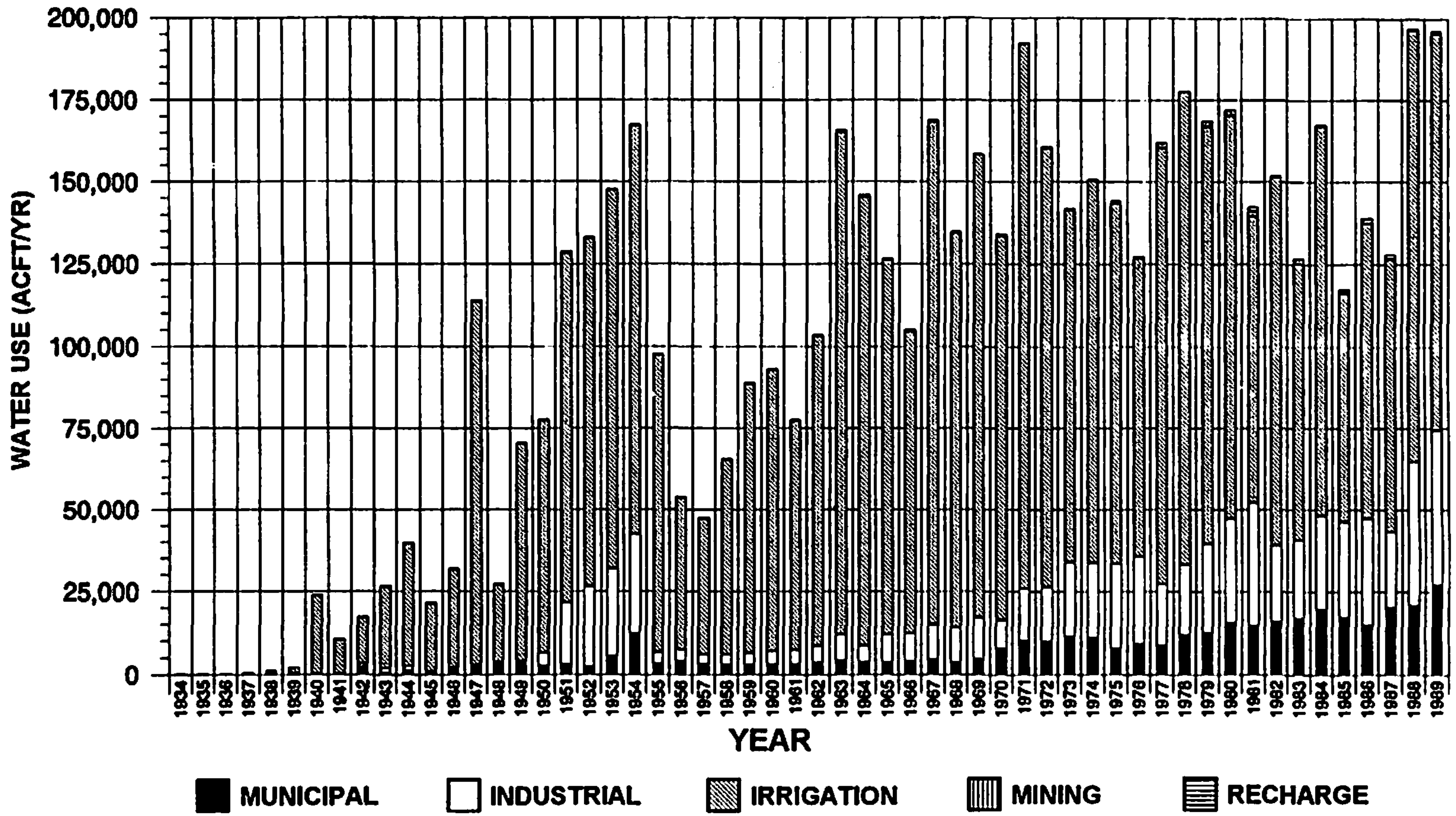
Segment 4 - Extends from the headwaters of the San Antonio River Basin to the downstream edge of the Edwards Aquifer recharge zone, including the areas upstream of the nearby USGS streamflow gaging stations on the Medina River at Somerset (ID# 1808), San Antonio River at San Antonio (ID# 1780), Salado Creek at San Antonio (ID# 1787), and Cibolo Creek at Selma (ID# 1850).

Segment 5 - Extends from the lower edge of Segment 4 to the USGS streamflow gaging station on the San Antonio River at Goliad (ID# 1885).

Segment 6 - Extends from the lower edge of Segment 5 to the confluence of the San Antonio and Guadalupe Rivers.

Records of historical surface water use as reported by individual water rights owners for the 1915-89 period were obtained from the TWC in digital format. These records are comprised of annual totals from 1915 to 1955 and available monthly totals from 1955 through 1989 and are categorized by designated type of use including municipal, industrial, irrigation, mining, and recharge. Figure 2-3 and Table 2-2 summarize historical surface water use by type of use for the entire Guadalupe - San Antonio River Basin. Table 2-3 summarizes historical surface water use according to the type of use for each segment within the basin. Comprehensive tables of reported annual surface water use, which are broken down by type of use for each reach and the entire basin, are included in Appendix B (Volume III).

As shown in Table 2-2 and Figure 2-3, the maximum historical use was 196,866 ac-ft/yr in 1988 which represents only 35 percent of the total consumptive water rights in the Guadalupe - San Antonio River Basin. A comparison of the total consumptive water rights by river basin and the corresponding 1988 water usage, is presented in Figure 2-4.



GUADALUPE-SAN ANTONIO RIVER BASIN
RECHARGE ENHANCEMENT STUDY

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GUADALUPE - SAN ANTONIO RIVER BASIN HISTORICAL SURFACE WATER USE

FIGURE 2-3

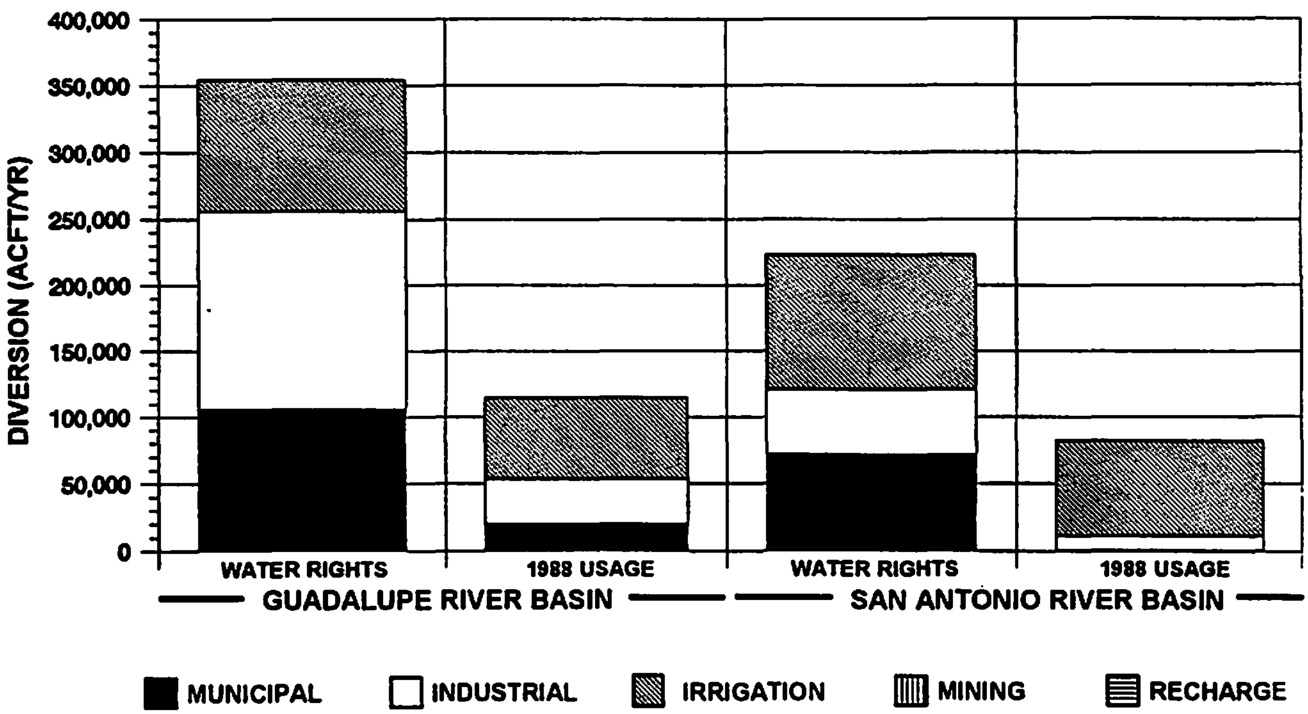
Table 2-2 Historical Consumptive Use of Surface Water Guadalupe - San Antonio River Basin				
Type of Use	Average Use[1] (Ac-Ft/Yr)	Percentage of Average Use	Maximum Use (Ac-Ft/Yr)	Year of Maximum Use
Municipal	18,371	12.0%	27,183	1989
Industrial	31,974	20.8%	47,357	1989
Irrigation	102,235	66.5%	166,218	1971
Mining	635	0.4%	1,535	1980
Recharge	474	0.3%	1,407	1981
Total	153,689	100.0%	196,866	1988

Notes:
1) Average use based on 1980-89 period.

Table 2-3 Historical Consumptive Use of Surface Water By Model Segment Guadalupe - San Antonio River Basin								
Type of Use	Percentage of Basin Average Use[1]							
	Guadalupe River Basin				San Antonio River Basin			
	Segment 1	Segment 2	Segment 3	Total	Segment 4	Segment 5	Segment 6	Total
Municipal	2.7%	5.0%	4.0%	11.7%	0.3%	0.0%	0.0%	0.3%
Industrial	0.4%	4.5%	10.0%	14.9%	0.0%	5.9%	0.0%	5.9%
Irrigation	1.7%	2.6%	27.8%	32.1%	29.5%	4.9%	0.0%	34.4%
Mining	0.0%	0.2%	0.0%	0.2%	0.1%	0.1%	0.0%	0.2%
Recharge	0.0%	0.0%	0.0%	0.0%	0.3%	0.0%	0.0%	0.3%
All Uses	4.8%	12.3%	41.8%	58.9%	30.2%	10.9%	0.0%	41.1%

Notes:
1) Based on average use for 1980-89 period.

Type of Usage	Guadalupe River Basin		San Antonio River Basin		Total	
	Full Water Rights (Ac-Ft/Yr)	1988 Usage (Ac-Ft/Yr)	Full Water Rights (Ac-Ft/Yr)	1988 Usage (Ac-Ft/Yr)	Full Water Rights (Ac-Ft/Yr)	1988 Usage (Ac-Ft/Yr)
Municipal	105,800	20,428	71,862	493	177,662	20,921
Industrial	149,912	33,072	48,925	10,874	198,837	43,946
Irrigation	98,648	61,286	102,180	70,444	200,828	131,730
Mining	153	0	5	269	158	269
Recharge	0	0	961	0	961	0
Total	354,513	114,786	223,933	82,080	578,446	196,866



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GUADALUPE-SAN ANTONIO RIVER BASIN
RECHARGE ENHANCEMENT STUDY

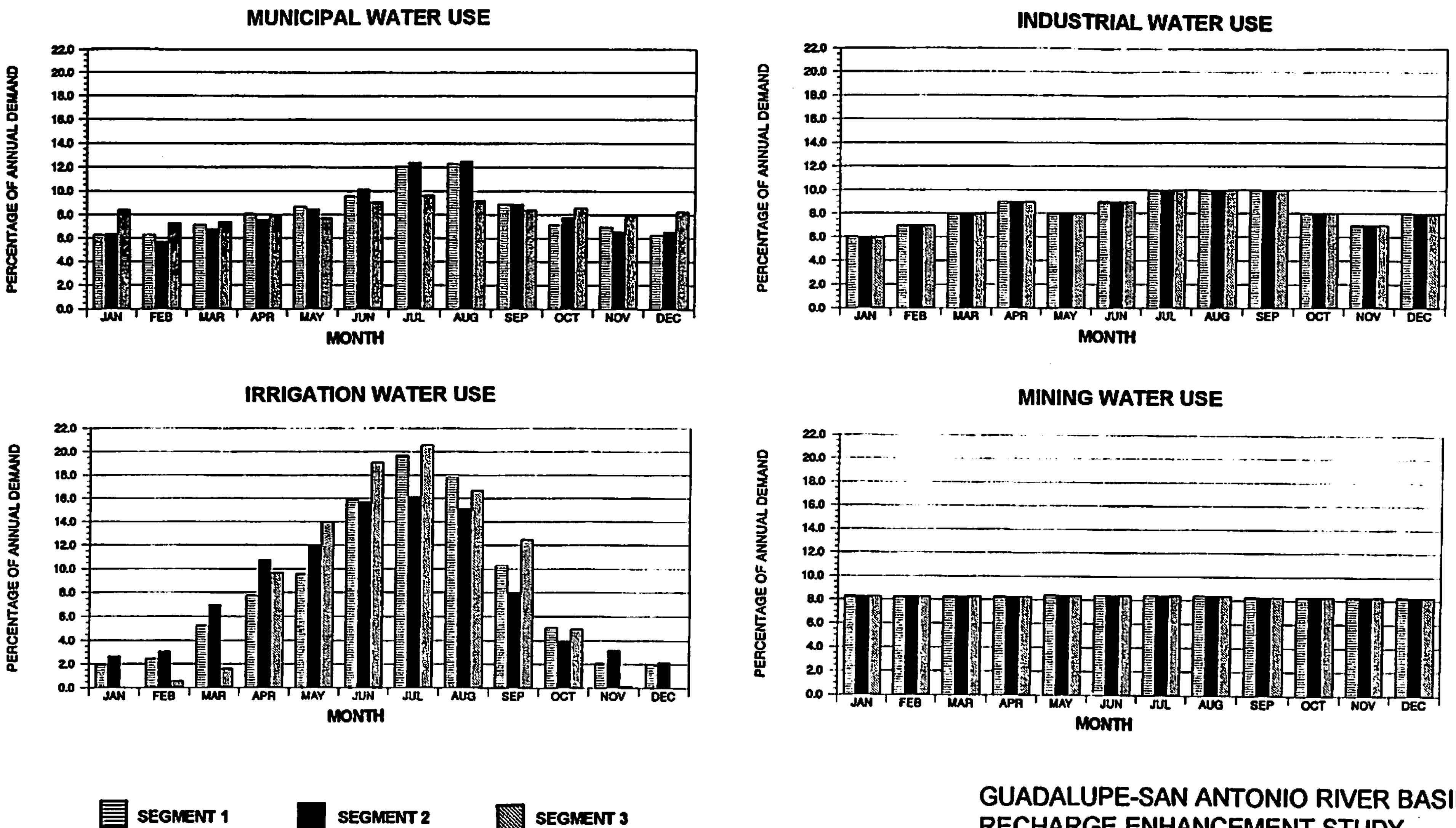
COMPARISON OF FULL WATER RIGHTS AND 1988 WATER USAGE

FIGURE 2-4

Irrigation accounted for 67 percent of total surface water use in 1988 representing about 62 percent and 69 percent of the total authorized irrigation rights in the Guadalupe and the San Antonio River Basins, respectively. Municipal use accounted for 11 percent of total surface water use in 1988, representing about 19 percent and less than 1 percent of the total authorized municipal rights in the Guadalupe and San Antonio River Basins, respectively. Municipal surface water rights in the San Antonio River Basin total 71,862 ac-ft/yr, of which 70,000 ac-ft/yr is associated with Applewhite Reservoir, which is currently incomplete. Industrial use accounted for 22 percent of total surface water use in 1988 representing about 22 percent of the total authorized industrial rights in both the Guadalupe and San Antonio River Basins.

Water demand can be highly variable from month to month depending on the type and geographic location of use. Typical monthly percentages of annual water demand were calculated for municipal, industrial, and irrigation use types for each of the six segments within the basin where significant use has occurred. Surface water use for mining was assumed to occur uniformly throughout the year. Reported monthly water use data for the 1955 to 1989 period was used for calculation of the monthly percentages presented in Figure 2-5 and Figure 2-6 for the Guadalupe and San Antonio River Basins, respectively.

Municipal water demand typically peaks during the summer months at between about 9 percent and 13 percent of annual demand, with summer demand percentages being higher in the upper segments of the basin. Significant industrial water use occurs primarily in the lower Guadalupe River Basin (Segment 3). Industrial demand has a more uniform monthly pattern than do municipal and irrigation demands and peaks during the summer months at



GUADALUPE-SAN ANTONIO RIVER BASIN
RECHARGE ENHANCEMENT STUDY

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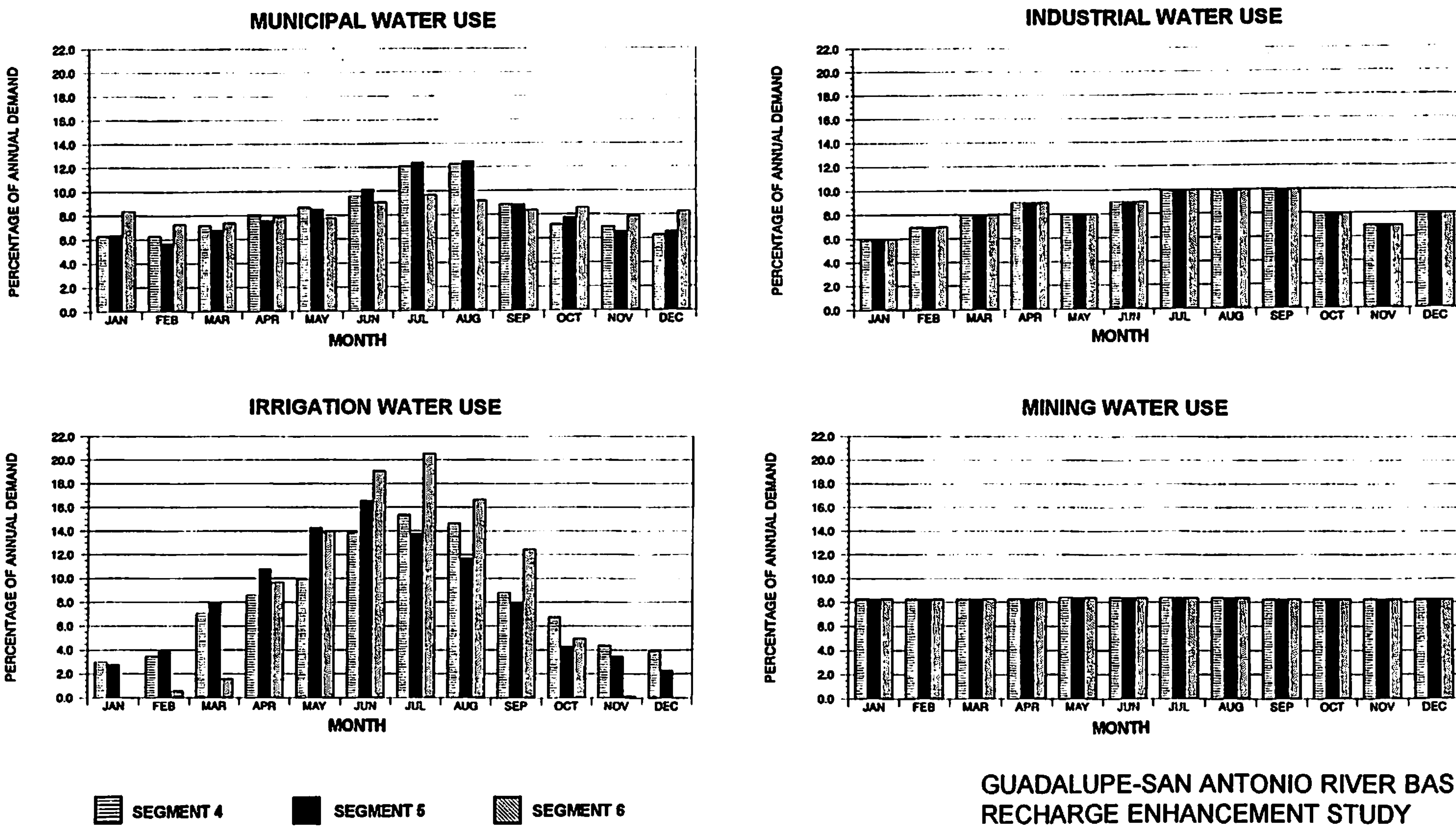
MONTHLY PERCENTAGES OF ANNUAL SURFACE WATER DEMAND FOR THE GUADALUPE RIVER BASIN

FIGURE 2-5



GUADALUPE-SAN ANTONIO RIVER BASIN
RECHARGE ENHANCEMENT STUDY

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MONTHLY PERCENTAGES OF ANNUAL SURFACE WATER DEMAND FOR THE SAN ANTONIO RIVER BASIN

FIGURE 2-6

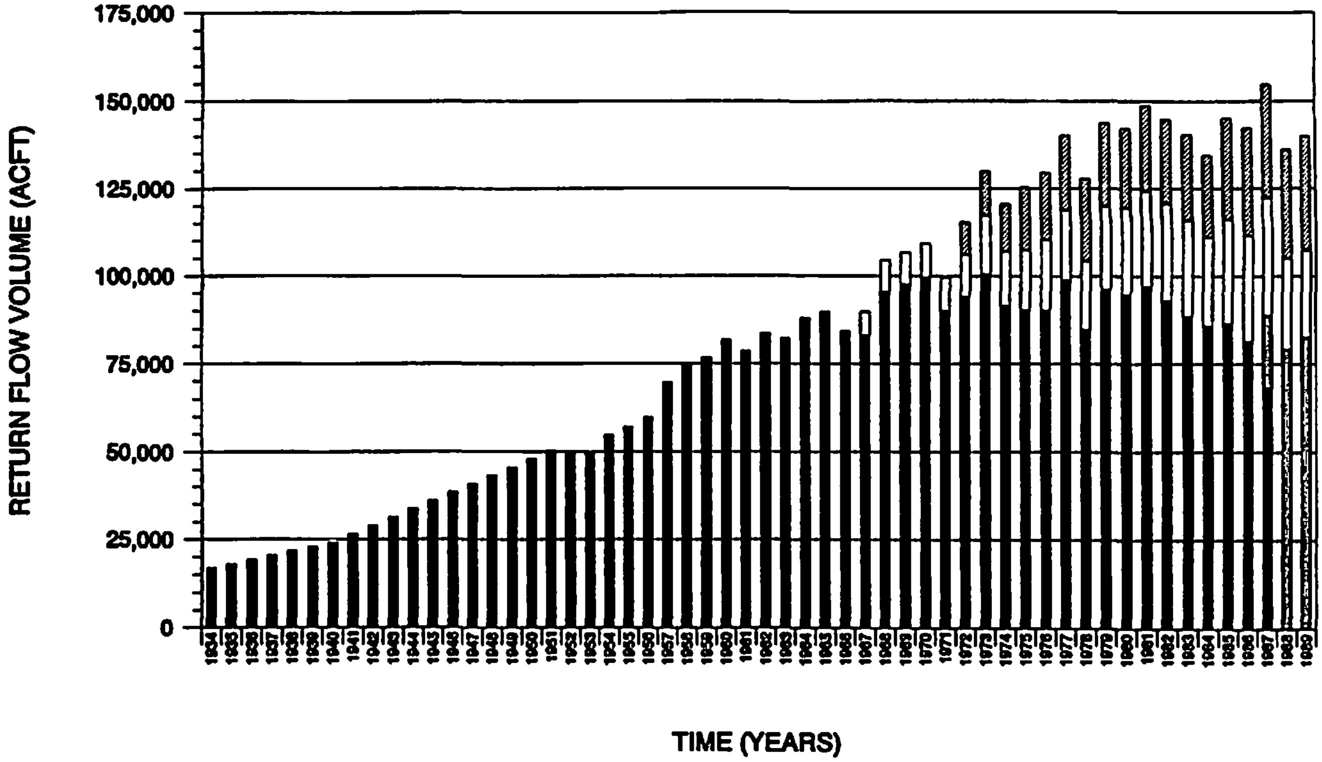
about 10 percent of the annual demand. Significant water use for irrigation purposes occurs in both the Guadalupe and San Antonio River Basins. In the Guadalupe River Basin, irrigation water use occurs primarily in the lower portion of the basin (Segment 3) and is associated with rice irrigation. Peak monthly irrigation demands are about 21 percent of the annual water demand in Segment 3 and range from 16 percent to 20 percent of the annual demand in the upper portions of the Guadalupe River Basin (Segments 1 and 2). In the San Antonio River Basin, irrigation water use predominantly occurs in the upper portion of the basin (Segment 4). The peak monthly demand in this region is about 15 percent of the annual demand. In the central portion of the San Antonio River Basin (Segment 5), irrigation water demand peaks during the summer months at about 16 percent of the annual demand. In the lower San Antonio River Basin (Segment 6), where no historical irrigation use has been reported, a monthly demand distribution identical to the lower Guadalupe River Basin (Segment 3) was assumed.

The typical monthly percentages of annual demand presented in Figure 2-5 and Figure 2-6 were used to disaggregate reported annual diversion totals prior to 1955 in order to approximate historical monthly diversions, adjust gaged streamflows, and develop a natural streamflow database for the Guadalupe - San Antonio River Basin. The same monthly demand percentages were included in the model in order to simulate typical monthly diversion patterns for water rights according to type of use and geographic location.

2.3 Return Flows

Historical return flows in the Guadalupe - San Antonio River Basin were analyzed in this study in order to adjust gaged streamflow records and obtain estimates of natural streamflow. The TWC maintains a database of self-reporting return flows since 1972 for all wastewater discharge permits. Portions of this return flow database were obtained from the TWC in digital format and manually adjusted for apparent discrepancies or omissions. For the 1934-71 period, return flows were estimated for communities discharging in excess of 0.5 million gallons per day (mgd) in 1972. These estimates were based on the product of average per capita return flow for the available period of record and historical population figures (Ref. 2).

Historical return flows from the City of San Antonio were obtained from C. Thomas Koch, Inc. (Ref. 16) and verified for the 1972-89 using the TWC self-reporting data. Annual return flows from the four major wastewater treatment plants (Leon Creek, Salado Creek, Rilling Road, and Dos Rios) operated by the City of San Antonio are presented in Figure 2-7. City of San Antonio return flow accounted for about 77 percent of all return flows in the Guadalupe - San Antonio River Basin in 1988. A summary of annual return flows used in the Guadalupe - San Antonio River Basin model is provided in Appendix C (Volume III).



NOTE:

INCLUDES CITY OF SAN ANTONIO RETURN FLOWS FROM THE FOLLOWING WASTEWATER TREATMENT PLANTS: RILLING ROAD, DOS RIOS, LEON CREEK AND SALADO CREEK.

LEGEND:
- RILLING ROAD
- DOS RIOS
- LEON CREEK
- SALADO CREEK

GUADALUPE-SAN ANTONIO RIVER BASIN
RECHARGE ENHANCEMENT STUDY

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HISTORICAL RETURN FLOWS FOR THE CITY OF SAN ANTONIO

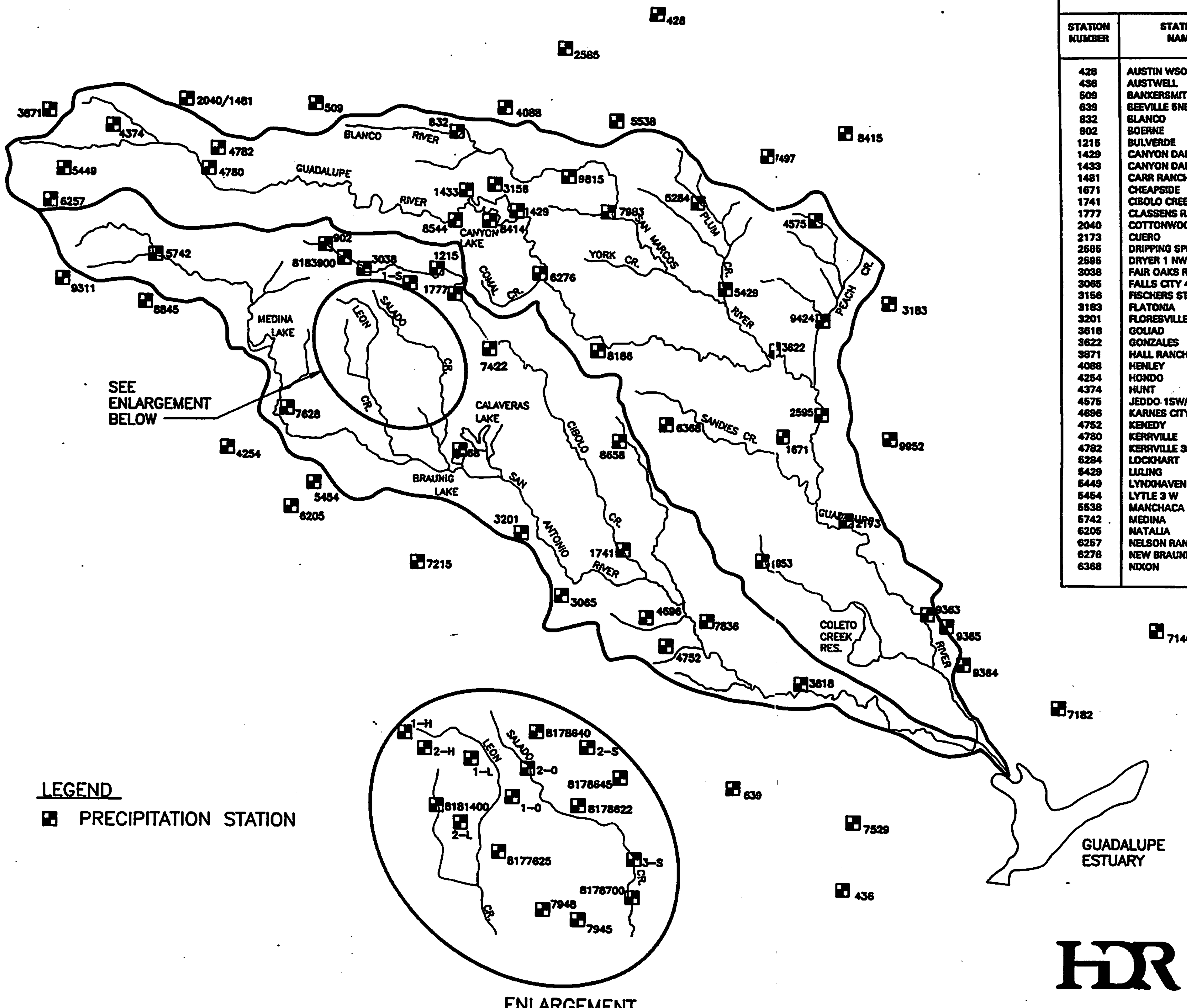
FIGURE 2-7

3.0 CLIMATOLOGICAL DATA

3.1 Precipitation

Annual precipitation in the Guadalupe - San Antonio River Basin generally increases from west to east with the westernmost portion receiving about 27 inches and the easternmost portion about 40 inches (Ref. 20). Precipitation data from approximately 90 stations was used in the development of areal precipitation for the 1923-89 historical period for each of 38 subwatersheds comprising the Guadalupe - San Antonio River Basin. The geographical location of each of these stations is presented in Figure 3-1. Inset in Figure 3-1 is a table summarizing the station name, identification number, and portion of the period of record used in this study for each precipitation station. The primary source of historical precipitation data was the National Weather Service (NWS); however, supplementary records were obtained from the U.S. Geological Survey (USGS) and the Texas Water Development Board (TWDB). Monthly areal precipitation for each of the 38 subwatersheds in the Guadalupe - San Antonio River Basin is summarized for reference in tables included in Appendix D (Volume III).

Areal precipitation for each subwatershed was developed by applying the Thiessen Polygon Method (Ref. 46) in which individual stations become the centers of polygonal areas constructed by drawing the perpendicular bisectors of lines connecting the stations. Subwatershed boundaries are superimposed on the polygons and Thiessen weights are calculated for each station and subwatershed, based on the percentage of the subwatershed area within the polygonal subarea. Monthly areal precipitation was then computed as the sum of the products of the measured station precipitation and the associated Thiessen weight.



GUADALUPE AND SAN ANTONIO RIVER BASINS PRECIPITATION STATIONS

STATION NUMBER	STATION NAME	PERIOD OF RECORD USED IN STUDY	STATION NUMBER	STATION NAME	PERIOD OF RECORD USED IN STUDY
428	AUSTIN WSO AP	1923-89	7140	POINT COMFORT	1957-89
436	AUSTWELL	1923-60	7182	PORT LAVACA #2	1940-88
509	BANKERSMITH	1940-89	7216	POTEET	1941-89
639	BEEVILLE 5NE	1923-89	7422	RANDOLPH FIELD	1941-89
832	BLANCO	1923-89	7497	RED ROCK	1966-89
902	BOERNE	1923-89	7529	REFUGIO	1948-85
1215	BULVERDE	1940-89	7628	RIOMEDINA 2N	1923-89
1429	CANYON DAM	1961-89	7706	ROCKSPRINGS	1932-86
1433	CANYON DAM 3	1961-89	7836	RUNGE	1923-89
1481	CARR RANCH	1923-61	7945	SAN ANTONIO WSFO	1947-89
1671	CHEAPSIDE	1940-89	7948	SAN ANTONIO NURSERY	1923-61
1741	CIBOLO CREEK	1948-82	7983	SAN MARCOS	1923-89
1777	CLASSENS RANCH	1947-72	8186	SEGUIN	1923-72
2040	COTTONWOOD	1962-89	8414	SMITHSONS VALLEY	1947-65
2173	CUERO	1923-89	8415	SMITHVILLE	1923-89
2585	DRIPPING SPRINGS 6E	1984-89	8544	SPRING BRANCH	1956-89
2595	DRYER 1 NW	1940-75	8658	STOCKDALE 4N	1978-89
3038	FAIR OAKS RANCH	1947-73	8845	TARPLEY	1938-89
3065	FALLS CITY 4WSW	1946-89	9311	VANDERPOOL	1979-89
3156	FISCHERS STORE	1941-89	9363	VICTORIA WSO AP	1946-61
3183	FLATONIA	1923-89	9364	VICTORIA WB AP	1961-89
3201	FLORESVILLE	1923-89	9365	VICTORIA HWY 77 BR	1923-48
3618	GOLIAD	1923-89	9424	WAELDER 7SSW	1947-89
3622	GONZALES	1940-89	9815	WIMBERLEY 2	1984-89
3871	HALL RANCH	1940-76	9952	YOAKUM	1923-89
4088	HENLEY	1948-65	9953	YORKTOWN	1947-89
4254	HONDO	1923-75	68	BRAUNIG LAKE	1977-82
4374	HUNT	1947-89	8183900	CIBOLO CREEK	1988-89
4575	JEDDO 1SW/2NNE	1947-89	8178700	SALADO CREEK	1986-89
4696	KARNES CITY	1923-89	8177625	OLMOS CREEK	1987-89
4752	KENEDY	1949-77	8181400	HELOTES CREEK	1987-89
4780	KERRVILLE	1923-74	8185000	CIBOLO CREEK	1988-89
4782	KERRVILLE 3NNE	1974-89	8178645	EAST ELM CREEK	1987-89
5284	LOCKHART	1947-89	8178622	LORENCE CREEK	1988-89
5429	LULING	1923-89	8178640	WEST ELM CREEK	1987-89
5449	LYNXHAVEN RANCH	1951-76	1-H	HELOTES CREEK	1971-81
5454	LYTLE 3 W	1977-89	2-H	HELOTES CREEK	1971-81
5538	MANCHACA	1948-65	1-L	LEON CREEK	1971-81
5742	MEDINA	1966-89	2-L	LEON CREEK	1971-81
6205	NATALIA	1923-77	1-O	OLMOS CREEK	1971-81
6257	NELSON RANCH	1962-83	2-O	OLMOS CREEK	1971-81
6276	NEW BRAUNFELS	1923-89	1-S	SALADO CREEK	1971-81
6368	NIXON	1923-89	2-S	SALADO CREEK	1971-77
			3-S	SALADO CREEK	1971-81

GUADALUPE-SAN ANTONIO RIVER BASIN RECHARGE ENHANCEMENT STUDY

PRECIPITATION STATION LOCATION MAP

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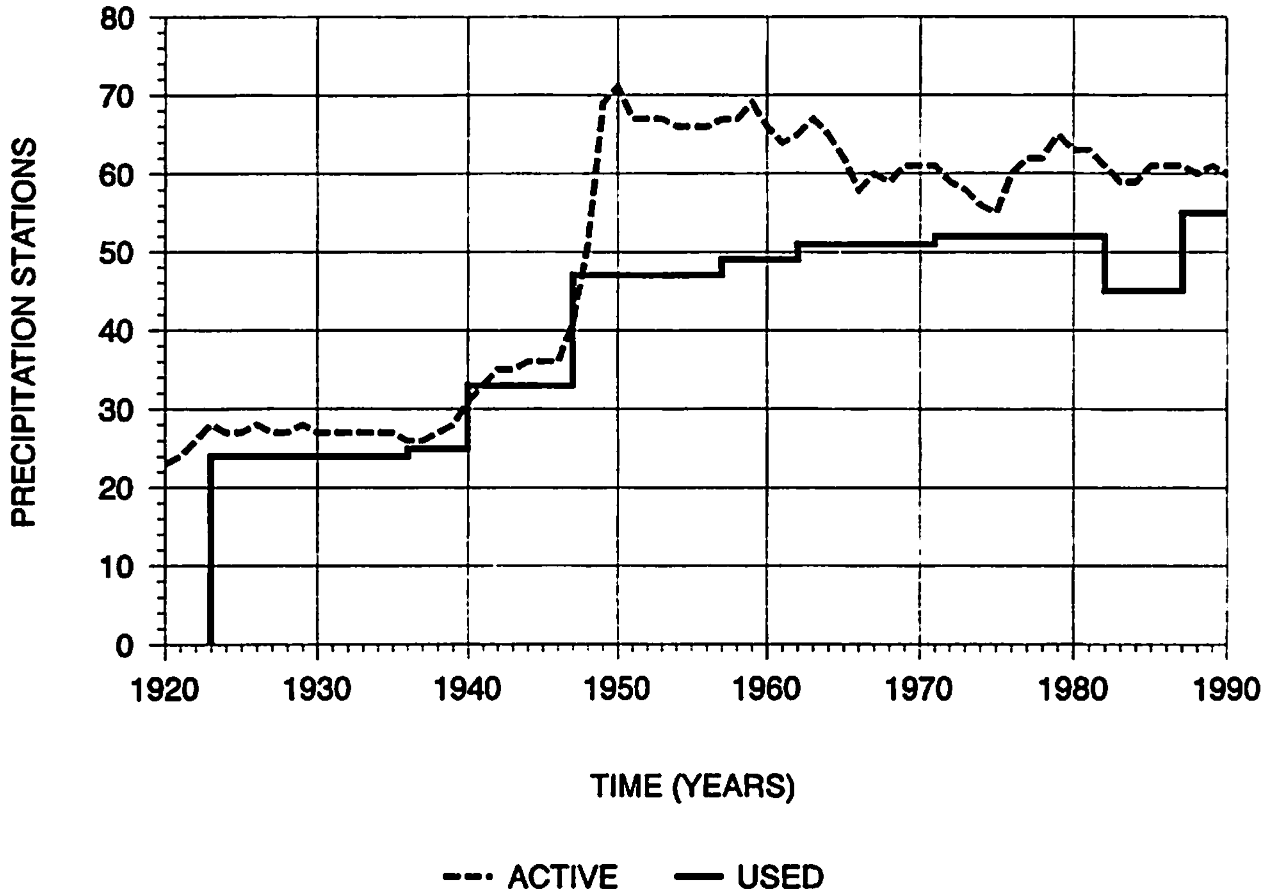
FIGURE 3-1

Missing monthly precipitation totals for some stations were estimated using available daily records. A computer program was developed for computation of missing daily precipitation values which operates in accordance with the following steps: 1) Establish a Cartesian (XY) coordinate system with the origin located at the station with a missing daily value; 2) Locate and calculate the distance to the nearest station in each quadrant with a record for that day; and 3) Apply a standard inverse distance ratio procedure to obtain a weighted average daily precipitation estimate based on the four surrounding stations. Once the missing daily values were estimated, they were summed along with the available daily records to obtain a reasonable estimate of monthly precipitation.

Because computed Thiessen weights for a given subwatershed can change significantly with the addition or deletion of precipitation stations, the 1923-89 historical period was divided into nine subperiods based on the availability of records at key stations. Figure 3-2 presents the number of stations used in each subperiod as well as the total number of precipitation stations which were active in each year of the 1920-89 period. As is apparent in Figure 3-2, records for several stations were extended during 1940 and 1947 based on geographically proximate stations using the computer program described in the previous paragraph. The actual number of stations used to compute areal precipitation during a particular subperiod ranged from a minimum of 24 during the 1923-35 period up to a maximum of 55 during the 1987-89 period.

3.2 Net Evaporation

Net evaporation is generally defined to be the difference between gross evaporation and direct precipitation at the free water surface of a reservoir and is typically expressed in



GUADALUPE-SAN ANTONIO RIVER BASIN
RECHARGE ENHANCEMENT STUDY

PRECIPITATION STATION UTILIZATION

HDR Engineering, Inc.

FIGURE 3-2

inches or feet. Because evaporation is a function of many factors, including wind speed, temperature, and relative humidity, it is a rather difficult quantity to measure. Evaporation rates have historically been estimated by recording changes in water level in evaporation pans and adjusting the readings using pan coefficients to reflect differences between evaporation from a pan and evaporation from the surface of a reservoir. Since the turn of the century, evaporation pans have been maintained at various locations throughout the state by numerous federal and state agencies, municipalities, and local interests. The TWDB has compiled much of the available historical pan evaporation data (Ref. 31) and has developed monthly reservoir evaporation rates for the entire state by one degree quadrangles of latitude and longitude (Ref. 32) for the 1940-90 period. Annual net evaporation in the Guadalupe - San Antonio River Basin generally decreases from west to east with the westernmost portion experiencing about 40 inches and the easternmost portion about 20 inches (Ref. 20).

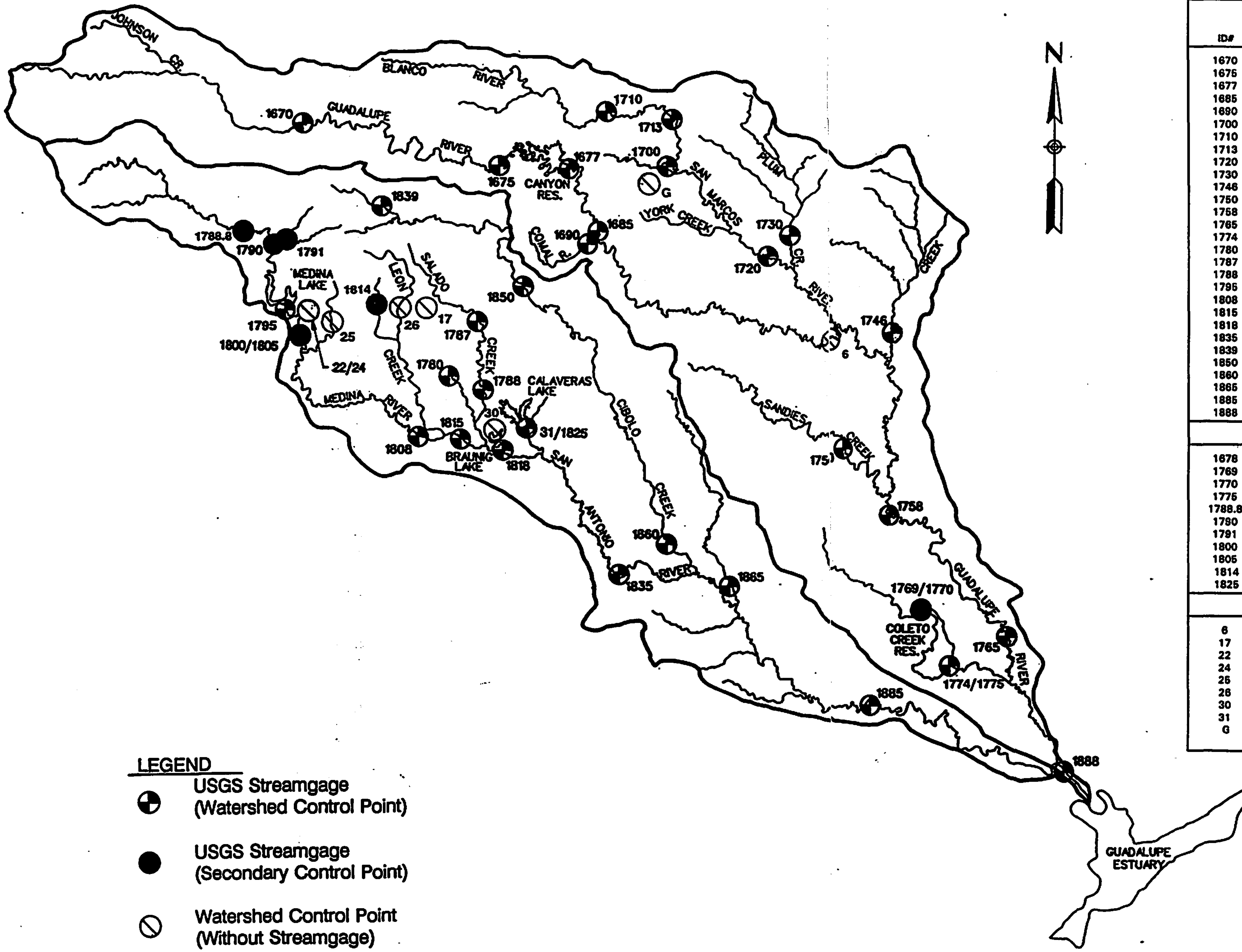
Monthly net evaporation rates for the 1934-89 period were needed in this study to calculate historical inflows to Canyon and Calaveras Lakes and to simulate lake level fluctuations in these reservoirs and other existing and/or potential reservoir projects including Medina, Diversion, and Braunig Lakes and Coleto Creek, Applewhite, Cloptins Crossing, and Lower Blanco Reservoirs. The evaporation rates used in this study for the 1940-89 period were calculated from the TWDB quadrangle data using a standard inverse distance ratio procedure to convert values typical of the centroids of adjacent quadrangles to values representative of a specific reservoir site. TWDB net evaporation data was used directly for Applewhite Reservoir, potential recharge enhancement projects, and existing reservoir sites prior to dam construction. Net evaporation rates for existing reservoirs after dam construction were calculated from TWDB gross evaporation data and locally measured precipitation. Net evaporation rates for the 1934-39 period were computed from available pan evaporation records adjusted by pan coefficients recommended by the TWDB (Ref. 32) and by coincident measured precipitation. Tables summarizing historical net evaporation rates used in this study are included in Appendix E (Volume III).

4.0 NATURAL STREAMFLOW DEVELOPMENT

The compilation of accurate estimates of historical natural streamflow is a key prerequisite to the development of a useful model of the Guadalupe - San Antonio River Basin. As previously defined in Section 2.2, natural streamflow is that which would have occurred historically exclusive of human influences. In this study, natural streamflow was computed by adjustment of monthly gaged streamflow for historical water supply diversions, municipal and industrial return flows, and reservoir operations. The effects of pumpage from the Edwards Aquifer on historical springflow, and hence, on streamflow were not addressed in the naturalization process, but were considered in the application of the GSA Model. Once an historical natural streamflow database is complete, the potential effects of future diversions and/or additional recharge reservoir construction can be accurately quantified. The steps involved in the development of natural streamflows for selected locations throughout the basin are discussed in this section. Natural streamflow summary tables for each control point in the model are included in Appendix F (Volume III).

4.1 Streamflow Data Collection

Records of streamflow in the Guadalupe - San Antonio River Basin have been collected at numerous streamflow gaging stations maintained by the U.S. Geological Survey (USGS). Figure 4-1 indicates the location, drainage area, and period of record of each streamflow gaging station used in this study, including those selected as watershed control points for the Guadalupe - San Antonio River Basin Model. Several streamflow gaging stations were considered secondary control points in this study and used to extend records



ID#	STREAM NAME, LOCATION	DRAINAGE AREA (SQ.MI.)	PERIOD OF RECORD
STREAMGAGES USED AS WATERSHED CONTROL POINTS			
1670	GUADALUPE R., COMFORT	839	6/39-12/89
1675	GUADALUPE R., SPRING BRANCH	1315	7/22-12/89
1677	CANYON LAKE	1432	7/62-12/89
1685	GUADALUPE R., ABOVE COMAL R.	1518	1/28-12/89
1690	COMAL R., NEW BRAUNFELS	130	1/28-12/89
1700	SAN MARCOS SPR., SAN MARCOS	N/A	6/56-12/89
1710	BLANCO R., WIMBERLEY	355	7/28-12/89
1713	BLANCO R., KYLE	412	6/56-12/89
1720	SAN MARCOS R., LULING	838	5/39-12/89
1730	PLUM C., LULING	309	4/30-12/89
1746	PEACH C., DILWORTH	460	8/59-9/79
1750	SANDIES C., WESTHOFF	549	8/59-12/89
1758	GUADALUPE R., CUERO	4934	9/20-11/35, 1/64-12/89
1765	GUADALUPE R., VICTORIA	5198	12/34-12/89
1774	COLETO CREEK RESERVOIR	494	2/80-12/89
1780	SAN ANTONIO R., SAN ANTONIO	41.8	3/39-12/89
1787	SALADO C., SAN ANTONIO, UPPER	137	10/60-12/89
1788	SALADO C., SAN ANTONIO, LOWER	189	10/60-12/89
1795	MEDINA LAKE	634	4/13-12/89
1808	MEDINA R., SOMERSET	967	10/70-12/89
1815	MEDINA R., SAN ANTONIO	1317	8/39-12/89
1818	SAN ANTONIO R., ELMENDORF	1743	10/62-12/89
1835	SAN ANTONIO R., FALLS CITY	2113	5/25-12/89
1839	CIBOLO C., BOERNE	68.4	3/62-12/89
1850	CIBOLO C., SELMA	274	4/46-12/89
1860	CIBOLO C., FALLS CITY	827	10/30-12/89
1865	ECLETO C., RUNGE	239	4/62-12/89
1885	SAN ANTONIO R., GOLIAD	3921	3/39-12/89
1888	GUADALUPE R., TIVOLI	10128	9/65-12/89
STREAMGAGES USED AS SECONDARY CONTROL POINTS			
1678	GUADALUPE R., SATTLER	1436	3/60-12/89
1769	COLETO C., SCHROEDER	357	10/78-12/89
1770	COLETO C., SCHROEDER	369	10/52-9/79
1775	COLETO C., VICTORIA	514	7/39-9/54, 6/78-12/89
1788.8	MEDINA R., BANDERA	427	10/82-12/89
1790	MEDINA R., PIPE CREEK	474	10/22-6/35, 10/52-9/82
1791	RED BLUFF C., PIPE CREEK	56.3	4/56-11/81
1800	MEDINA CANAL	N/A	4/22-4/34, 7/57-12/89
1805	MEDINA R., RIOMEDINA	650	2/53-9/73
1814	HELOTES C., HELOTES	15	6/68-12/89
1825	CALAVERAS C., ELMENDORF	77.2	10/54-9/71
WATERSHED CONTROL POINTS WITHOUT STREAMGAGES			
6	LAKE WOOD (H-5)	2103	1/80-12/89
17	OLMOS C., EDWARDS	8.3	N/A
22	DIVERSION LAKE SUBWATERSHED	15.6	N/A
24	DEEP C., EDWARDS	13.1	N/A
25	SAN GERONIMO C., EDWARDS	58.3	N/A
26	LEON C., EDWARDS	99.7	N/A
30	BRAUNIG LAKE	9.4	2/63-12/89
31	CALAVERAS LAKE	65.0	1/71-12/89
G	SINK, PURGATORY, YORK, AND ALLIGATOR CREEKS	94.0	N/A

GUADALUPE-SAN ANTONIO RIVER BASIN
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WATERSHED CONTROL POINT AND STREAMGAGE LOCATION MAP

FIGURE 4-1

at selected watershed control points. Additional watershed control points for ungaged watersheds were adopted to facilitate calculation of Edwards Aquifer recharge and are also shown in Figure 4-1. Summaries of monthly streamflow records were obtained from the Texas Water Commission (TWC) and directly from the USGS. Records from these gaging stations, with few exceptions, are classified by the USGS (Ref. 45) as "good" which means that 95 percent of the published daily discharges are within 10 percent of their true values.

An additional watershed control point was established at Lake Wood (H-5) because of its key location on the Guadalupe River just upstream of the San Marcos River confluence. Streamflow records at this location were estimated for the 1980-89 period using reports of water use for hydroelectric power generation and microfilmed spill logs maintained by the Guadalupe Blanco River Authority (GBRA). These spill logs contain detailed records of gate settings and headwater and tailwater depths during flood events which exceeded the turbine capacity and resulted in flow over the gates. Using a spillway rating table provided by GBRA with appropriate adjustments for tailwater levels (Ref. 34) and leakage, HDR developed a computer program which was applied to calculate monthly spill volumes. Combining these computed spill volumes with reported flows through the turbines, estimated gaged flows were obtained for the Guadalupe River at Lake Wood (H-5).

4.2 Reservoir Inflows

Historical reservoir inflows were computed for Canyon Lake (July, 1962 - December, 1989) and Calaveras Lake (February, 1971 - December, 1989) to supplement gaged streamflow records for the Guadalupe River and Calaveras Creek, respectively. Computation of historical inflow was based on the principle of continuity as formulated in the following simplified equation:

$$I_t = (Z_{t+1} - Z_t) + E_t + D_t + S_t - P_t \tag{4-1}$$

where:

I_t	=	Inflow
Z_{t+1}	=	End-of-Month Storage
Z_t	=	Beginning-of-Month Storage
E_t	=	Net Evaporation
D_t	=	Direct Diversion
S_t	=	Spill and/or Release
P_t	=	Imported Inflow

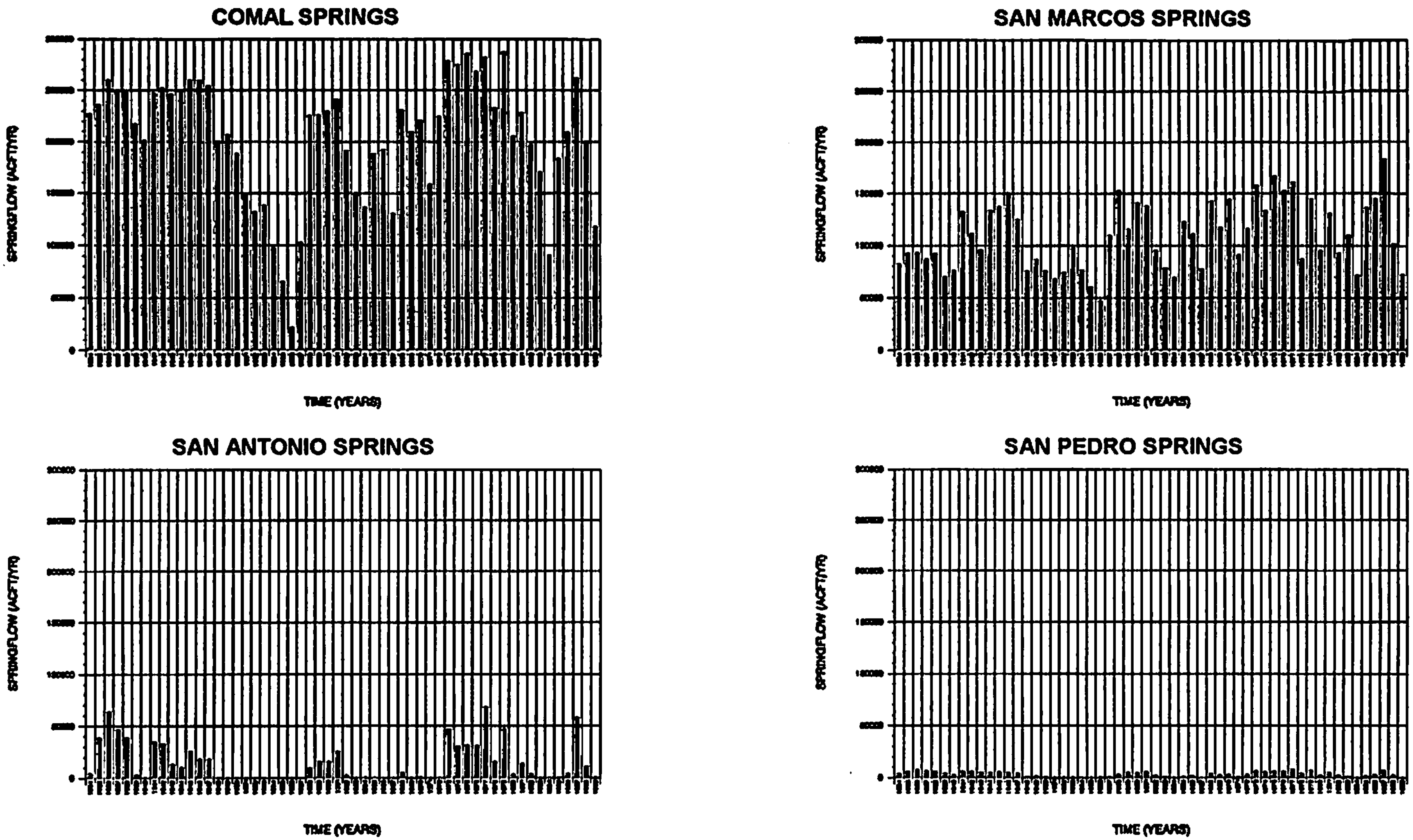
An utility program was developed to solve this equation for monthly inflow assuming the monthly storage change due to net evaporation is based on the surface area associated with the average storage volume for the month. Computed monthly inflow estimates less than zero were set equal to zero. The resultant historical reservoir inflows are comparable to gaged streamflows and were naturalized in the same manner.

Basic data for inflow computations was obtained from a variety of sources. Reservoir contents records for Canyon and Calaveras Lakes were obtained from USGS publications (Refs. 43, 44, and 45) and summary tables provided by City Public Service of San Antonio (CPS) (Ref. 5), respectively. Elevation-area-capacity tables from original reservoir mapping in 1947 and from a bathymetric survey conducted by the U.S. Army Corps of Engineers (USCE) in 1972 were used for Canyon Lake, while an elevation-area-capacity table dated 1970 (Ref. 30) was used for Calaveras Lake. Gross monthly water surface evaporation rates derived from Texas Water Development Board (TWDB) data as described in Section 3, were adjusted using records from nearby National Weather Service (NWS) or TWDB precipitation stations to obtain applicable monthly net evaporation rates. CPS provided monthly estimates of imported inflows (make-up water from the San Antonio River), releases, spills, and direct diversions (consumptive use in the form of forced evaporation) for Calaveras Lake. Gaged streamflow records for the Guadalupe River at Sattler (ID# 1678) were assumed to approximate the sum of all inflows passed through, releases from storage, and spills at Canyon Lake during the 1971-89 period.

4.3 Springflows

Four of the seven largest springs in Texas including Comal, San Marcos, San Antonio, and Hueco Springs are located within the Guadalupe - San Antonio River Basin (Ref. 1). Historical discharges from Comal, San Marcos, San Antonio, and San Pedro Springs which are located downstream of the Edwards Aquifer recharge zone were used directly in the streamflow naturalization process while flows from Hueco Springs which are located within the recharge zone were used in a different way. A more detailed discussion of the consideration of Hueco Springs is included in Section 6.1.3. Figure 4-2 provides an annual summary of historical springflow during the 1934-89 study period for four of the major springs.

Comal Springs which is the largest in Texas is located within the City of New Braunfels in Comal County and discharges an average of about 205,000 ac-ft/yr into the Comal River near the confluence with the Guadalupe River. Records provided by the USGS indicate that Comal Springs flowed continuously during the 1934-89 period with the



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GUADALUPE-SAN ANTONIO RIVER BASIN
RECHARGE ENHANCEMENT STUDY

HISTORICAL SPRINGFLOWS

FIGURE 4-2

exception of almost five months from June to November, 1956 during a severe drought period. Discharge from Comal Springs is highly correlated with water levels in the Bexar County Monitoring Well (J-17) as well as other regional wells in the Edwards formation. Analyses of tritium content in the water from Comal Springs reported by the Texas Department of Water Resources (TDWR) (Ref. 22) indicate that the majority of water discharging at Comal Springs entered the Edwards Aquifer as recharge more than 20 years previously.

San Marcos Springs which is the second largest in Texas is located within the City of San Marcos in Hays County and discharges an average of about 109,000 ac-ft/yr into the San Marcos River upstream of the confluence with the Blanco River. Monthly records of springflow were obtained from USGS publications (Ref. 45) for the 1956-89 period when flows were gaged. For the 1940-55 period, flow estimates were obtained from TWDB files and, for the 1934-39 period, estimated by linear interpolation between periodic USGS measurements. Springflow estimates obtained by interpolation agree reasonably well with annual values published by the USGS (Ref. 39). San Marcos Springs has flowed without interruption throughout the 1934-89 period. Analyses of tritium content indicates that "a large part of the water from San Marcos Springs did not come from the same source area as Comal Springs and that, on the average, the water from San Marcos Springs is much younger than the water from Comal Springs (Ref. 22)."

San Antonio and San Pedro Springs are both located within the City of San Antonio in Bexar County and discharge averages of about 14,400 ac-ft/yr and 3,640 ac-ft/yr, respectively, to the San Antonio River. Both of these springs have ceased to flow for extended periods during the 1934-89 study period. Periodic springflow measurements by the

USGS were correlated with water levels in the Bexar County Monitoring Wells J-17 (Fort Sam Houston, 1963-89) and 26 (Ed Steves & Sons, 1932-62) resulting in linear regression equations used to obtain estimates of historical monthly discharge from each of these springs. The regression equations based on piezometric water levels at J-17 are:

$$Q_{SA} = 6.8829(H_{J\text{-}17}) - 4629.93 \tag{4-2}$$

$$Q_{SP} = 0.3511(H_{J\text{-}17}) - 229.37 \tag{4-3}$$

where:

Q_{SA}	=	San Antonio Springflow (cfs)
Q_{SP}	=	San Pedro Springflow (cfs)
$H_{J\text{-}17}$	=	J-17 Well Level (ft-msl)

Coefficients of determination (r^2) for these equations ranged from 0.93 to 0.94 indicating that the equations could explain 93 to 94 percent of the variation in springflow. The J-17 water surface elevations at which the equations predict zero springflow are consistent with published spring elevations (Ref. 1) and estimated annual totals are in reasonable agreement with USGS estimates (Ref. 6).

4.4 Naturalization Methodology

Monthly natural streamflows for the 1934-89 period were developed by adjusting gaged streamflows and calculated reservoir inflows for the effects of historical water supply diversions, municipal and industrial return flows, and reservoir operations. Translation of the effects of upstream diversions and return flows to downstream locations was accomplished with the use of delivery equations representative of typical channel loss rates in each intervening reach. Derivation of delivery equations is described in Section 4.5.

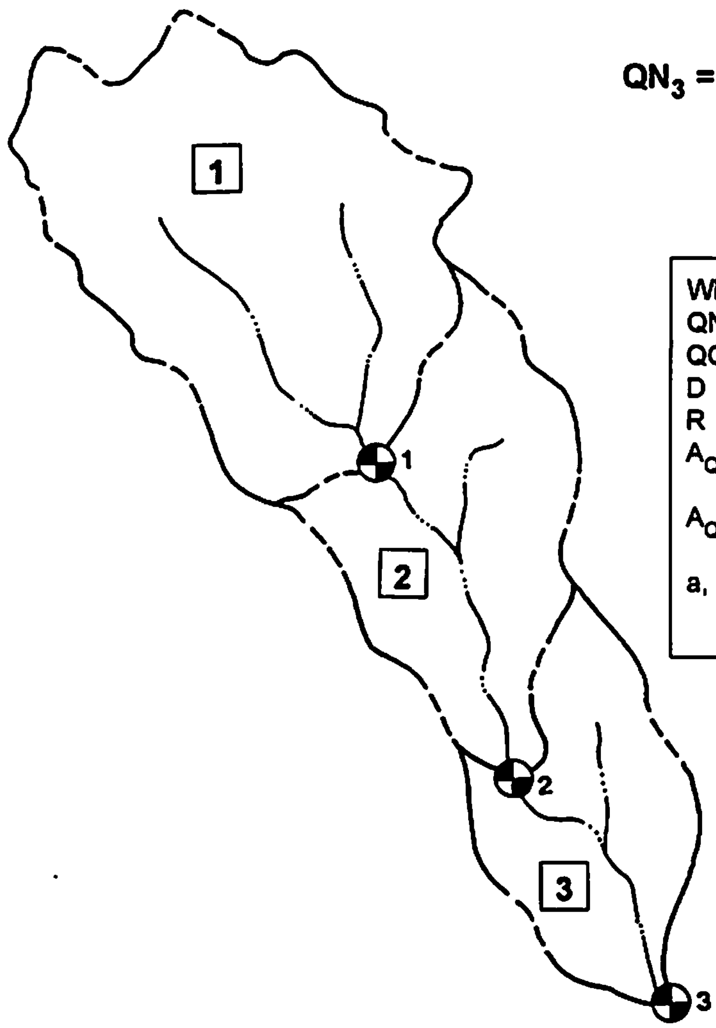
The streamflow naturalization methodology applied in this study is summarized in schematic and equation form in Figure 4-3. Historical monthly diversions of all use types as well as return flows were grouped by subwatershed as delineated by control point. The natural flow at the downstream end of an headwater subwatershed, such as Subwatershed 1 in Figure 4-3, is calculated by simply adding the historical diversions to and subtracting the historical return flows from the gaged streamflow at Control Point 1 (CP1). Natural flow at the downstream end of Subwatershed 2 (CP2) is equal to the gaged streamflow adjusted for local diversions and return flows which occurred in Subwatershed 2 plus the portion of the change in flow (from gaged to natural) at CP1 which arrives at CP2. In like manner, streamflows were naturalized at consecutive control points moving upstream to downstream through the entire river basin. The methodology employed to estimate channel losses in the reach from CP1 to CP2 is described in the following section of this report.

The streamflow naturalization methodology applied in this study was originally developed by HDR in the performance of a regional water supply planning study of the Nueces River Basin (Ref. 14) and is different from the more traditional methodology incorporated in previous natural streamflow databases and river basin models (Refs. 27 and 28). Traditionally, successive downstream gaged streamflows were adjusted for historical upstream diversions and return flows on a "one-to-one" basis to obtain natural streamflows, thereby neglecting differences between historical and natural channel losses. Application of traditional methodology generally results in higher estimates of natural flow. Potential errors resulting from this traditional technique were mitigated, in part, by the "one-to-one"

$$QN_1 = QG_1 + D_1 - R_1$$

$$QN_2 = QG_2 + D_2 - R_2 + \left(A_{QN_1} - A_{QG_1}\right)$$
$$A_{QN_1} = QN_1 - a_2 QN_1^{b_2}$$
$$A_{QG_1} = QG_1 - a_2 QG_1^{b_2}$$

$$QN_3 = QG_3 + D_3 - R_3 + \left(A_{QN_2} - A_{QG_2}\right)$$
$$A_{QN_2} = QN_2 - a_3 QN_2^{b_3}$$
$$A_{QG_2} = QG_2 - a_3 QG_2^{b_3}$$



WHERE:

QN	=	NATURAL STREAMFLOW
QG	=	GAGED STREAMFLOW
D	=	DIVERSIONS
R	=	RETURN FLOWS
A_{QN}	=	UPSTREAM NATURAL FLOW DELIVERED
A_{QG}	=	UPSTREAM GAGED FLOW DELIVERED
a, b	=	CHANNEL LOSS EQUATION COEFFICIENTS

LEGEND

- STREAMGAGE/CONTROL POINT
- WATERSHED BOUNDARY
- STREAM

GUADALUPE-SAN ANTONIO RIVER BASIN
RECHARGE ENHANCEMENT STUDY

HDR Engineering, Inc.

STREAMFLOW NATURALIZATION METHODOLOGY

FIGURE 4-3

adjustment of natural flows to account for full water rights diversions and applicable return flows in the evaluation of water available for appropriation. However, if full water rights use significantly exceeds historical water use (which is often the case), application of the traditional methodology can significantly underestimate both water availability and remaining downstream flows. In this study, quantitative assessment of the potential impacts of upstream recharge enhancement projects, and/or changes in historical release patterns from Canyon Lake, necessitated the application of a methodology incorporating the effects of intervening losses. Simply stated, impoundment and recharge of one acre-foot of runoff in the headwaters of the basin does not reduce inflow to the Guadalupe Estuary by one acre-foot. Accounting for channel losses as modelled in this study more accurately reflects the natural physical processes which affect streamflows throughout the basin.

4.5 Delivery Equations and Channel Loss Rates

A streamflow delivery equation was developed for each stream reach linking control points in the Guadalupe - San Antonio River Basin in order to estimate the percentage of water passing an upstream control point that arrives at the next downstream control point. The equations were derived using gaged streamflow records at the upstream and downstream control points along with calibrated estimates of runoff from the intervening area and include adjustments for intervening diversions and return flows. Previous streamflow studies conducted by the USGS (Ref. 41) have shown a direct logarithmic relationship between channel loss and streamflow, and this type of relationship was utilized to describe the channel loss characteristics in each stream segment in the Guadalupe - San

Antonio River Basin. The channel loss equations derived for each segment illustrate that as streamflow increases, the *volume* of channel loss increases and the *percentage* of upstream flow lost decreases.

Channel loss relationships were developed for selected stream segments by performing long-term comparisons of concurrent upstream and downstream gaged streamflow records using a modified Soil Conservation Service (SCS) curve number procedure (Refs. 18 & 19) and monthly areal precipitation to estimate intervening runoff arriving at the downstream gage. The first step in the derivation of the channel loss relationships was the estimation of appropriate SCS "map" curve numbers for each subwatershed which was accomplished by detailed review of county soil surveys. The resulting map curve numbers for each of the subwatersheds are summarized in Table 4-1. Using the modified SCS procedure, monthly intervening runoff is computed from areal precipitation using the following general equation:

$$QI = \left(\frac{640}{12}\right) A \frac{\left(P - \frac{200}{CN} + 2\right)^2}{\left(P + \frac{800}{CN} - 8\right)} \tag{4-4}$$

where

QI = Intervening Runoff (acre-feet/month);
A = Watershed Area (square miles);
P = Areal Precipitation (inches/month); and
CN = Calibrated SCS Curve Number.

A more detailed discussion of how the modified SCS procedure is applied for computing intervening runoff along with an example for a watershed over the recharge zone is presented in Section 6.

Table 4-1
Summary of SCS Map Runoff Curve Numbers for Watershed Control Points

Watershed Control Point		Intervening Drainage Area (Sq.Mi.)	SCS Map Runoff Curve Number
ID#	Stream Name, Location		
1670	Guadalupe River, Comfort	839	84.3
1675	Guadalupe River, Spring Branch	476	82.4
1677	Guadalupe River, Canyon Lake	117	82.7
1685	Guadalupe River, Above Comal River at New Braunfels	86	83.7
1690	Comal River, New Braunfels	130	86.5
1710	Blanco River, Wimberley	355	82.6
1713	Blanco River, Kyle	57	84.3
1720	San Marcos River, Luling	332[1]	83.4
1730	Plum Creek, Luling	309	83.7
1746	Peach Creek, Dilworth	460	76.4
1750	Sandies Creek, Westhoff	549	79.4
1758	Guadalupe River, Cuero	675	74.7
1765	Guadalupe River, Victoria	264	74.8
1774	Coleto Creek Reservoir, Victoria	494	73.8
1780	San Antonio River, San Antonio	41.8	83.0
1787	Salado Creek, San Antonio Upper Station	137	85.4
1788	Salado Creek, San Antonio Lower Station	52	78.0
1795	Medina Lake	634	83.6
1808	Medina River, Somerset	246[1]	80.7
1815	Medina River, San Antonio	242[1]	80.8
1818	San Antonio River, Elmendorf	195.2[2]	75.1
1835	San Antonio River, Falls City	305[3]	75.9
1839	Cibolo Creek, Boerne	68.4	82.9
1850	Cibolo Creek, Selma	205.6	83.1
1860	Cibolo Creek, Falls City	553	79.4
1865	Ecleto Creek, Runge	239	77.8
1885	San Antonio River, Goliad	742	76.4
1888	Guadalupe River, Tivoli	515	78.2
6	Guadalupe River, Lake Wood (H-5)	455	80.2
17	Olmos Creek, Edwards	8.3	85.6
22	Diversion Lake	15.6	85.6
24	Deep Creek, Edwards	13.1	85.6
25	San Geronimo Creek, Edwards	58.3	86.7
26	Leon Creek, Edwards	99.7	86.4
31	Calaveras Lake	65.0	81.5
G	Sink, Purgatory, York, Alligator Creeks	94.0	86.4

Notes:
1) Intervening area below the downstream edge of the recharge zone.
2) Includes Braunig Lake (ID# 30) drainage area.
3) Excludes Calaveras Lake drainage area.

The amount of channel loss in a given stream segment was computed for each month of concurrent record for the upstream and downstream gaging stations. Channel loss for each month was computed as:

$$Q_{Loss} = QG_1 + QI - QNH_2 \tag{4-5}$$

where:

Q_{Loss} = Channel Loss;
QG_1 = Upstream Gaged Flow;
QI = Intervening Runoff; and
QNH_2 = Downstream Flow Adjusted for Intervening Diversions and Return Flows.

Channel loss equations for each of the stream segments were derived based on the monthly estimates of channel loss as a function of monthly upstream flow. Months when losses were calculated to be less than zero or greater than the upstream flow were not included in the derivations. Calculated losses in these months represent extreme or impossible conditions which generally result from inaccuracies in estimating runoff for large intervening watersheds from monthly areal precipitation. The channel loss equations were derived using linear regression techniques for a log-log relationship of channel loss as a function of upstream flow. The standard form of the channel loss equation is expressed as:

$$Log_{10}(Q_{Loss}) = b\ Log_{10}(QG_1) + Log_{10}(a) \tag{4-6}$$

or

$$Q_{Loss} = a(QG_1)^b \tag{4-7}$$

where:

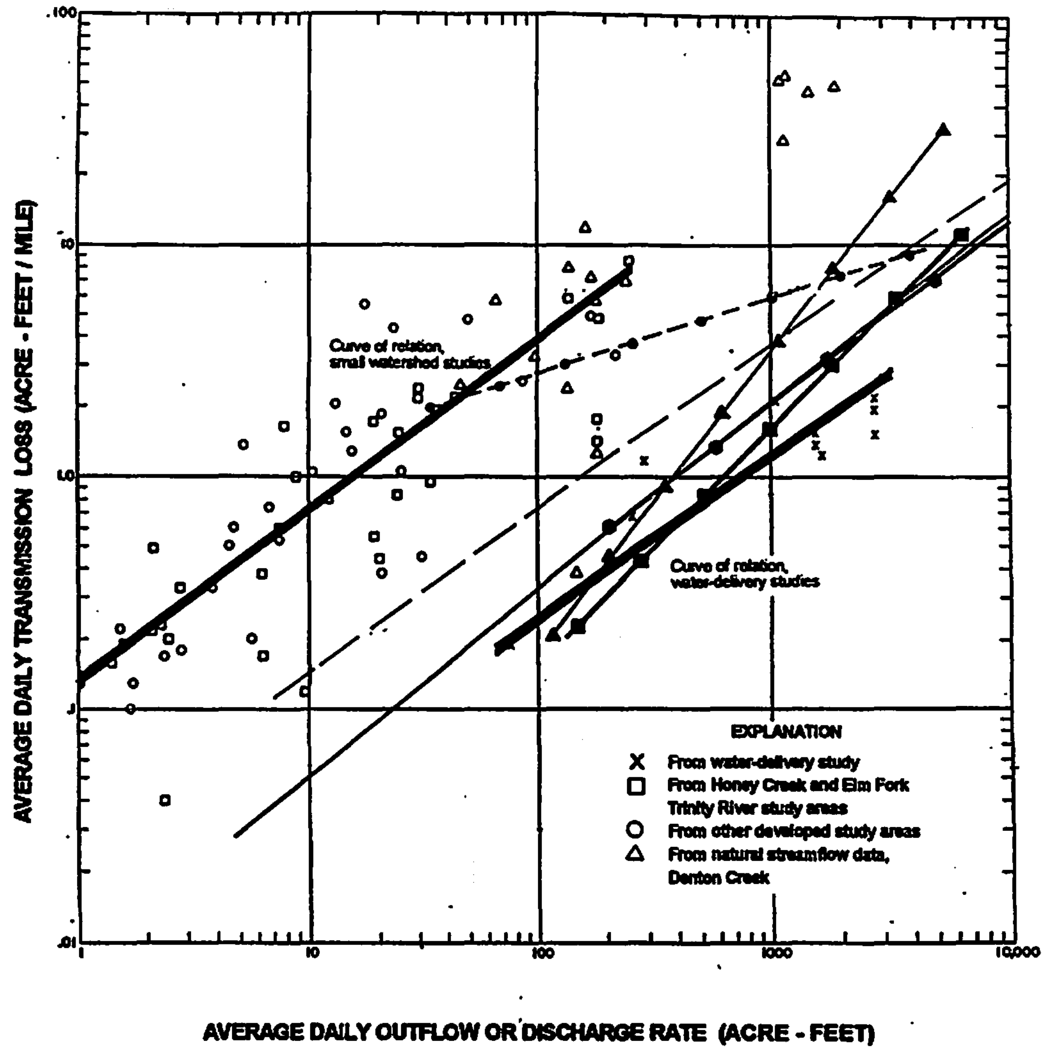
Q_{Loss} = Channel Loss (acre-feet/month);

QG_1 = Upstream Gaged Flow (acre-feet/month); and
a,b = Regression Coefficients.

For purposes of this study, the regression coefficients in the channel loss equation were retained only if they were significantly different from zero at the 90 percent confidence level based on the Students t Test (Ref. 12). The resulting regression equations for selected stream segments had coefficients of determination (r^2) ranging from 0.16 for the Blanco River at Wimberley to 0.37 for the San Antonio River at Goliad. For stream reaches where insufficient gaged data was available to compute meaningful channel loss equations, equations developed for nearby stream reaches were utilized with adjustments for median upstream flow.

Table 4-2 summarizes the channel loss equations applied for all stream segments in the Guadalupe - San Antonio River Basin. Figure 4-4 shows all channel loss equations computed with actual gaged data for the range of flows from which each was developed. Comparable regression lines for small watershed and water delivery studies conducted by the USGS (Ref. 41) are also presented for reference in Figure 4-4. The channel loss equations developed for stream segments in the Guadalupe - San Antonio River Basin, to a large extent, fall within the range of channel loss relationships found in the USGS studies. Generally, channel loss rates were found to be in the lower range for those stream segments upstream of the Edwards Aquifer recharge zone and in the plains and coastal prairies, while higher channel loss rates were found to occur in those segments crossing aquifer outcrops.

GUADALUPE RIVER BASIN



LEGEND:

GUADALUPE RIVER: COMFORT TO SPRING BRANCH
ID# 1670 TO ID# 1675 (70 MILES)

GUADALUPE RIVER: SPRING BRANCH TO CANYON LAKE
ID# 1675 TO ID# 1677 (14 MILES)

GUADALUPE RIVER: NEW BRAUNFELS TO LAKE WOOD (H-5)
ID# 1685 TO ID# 6 (79 MILES))

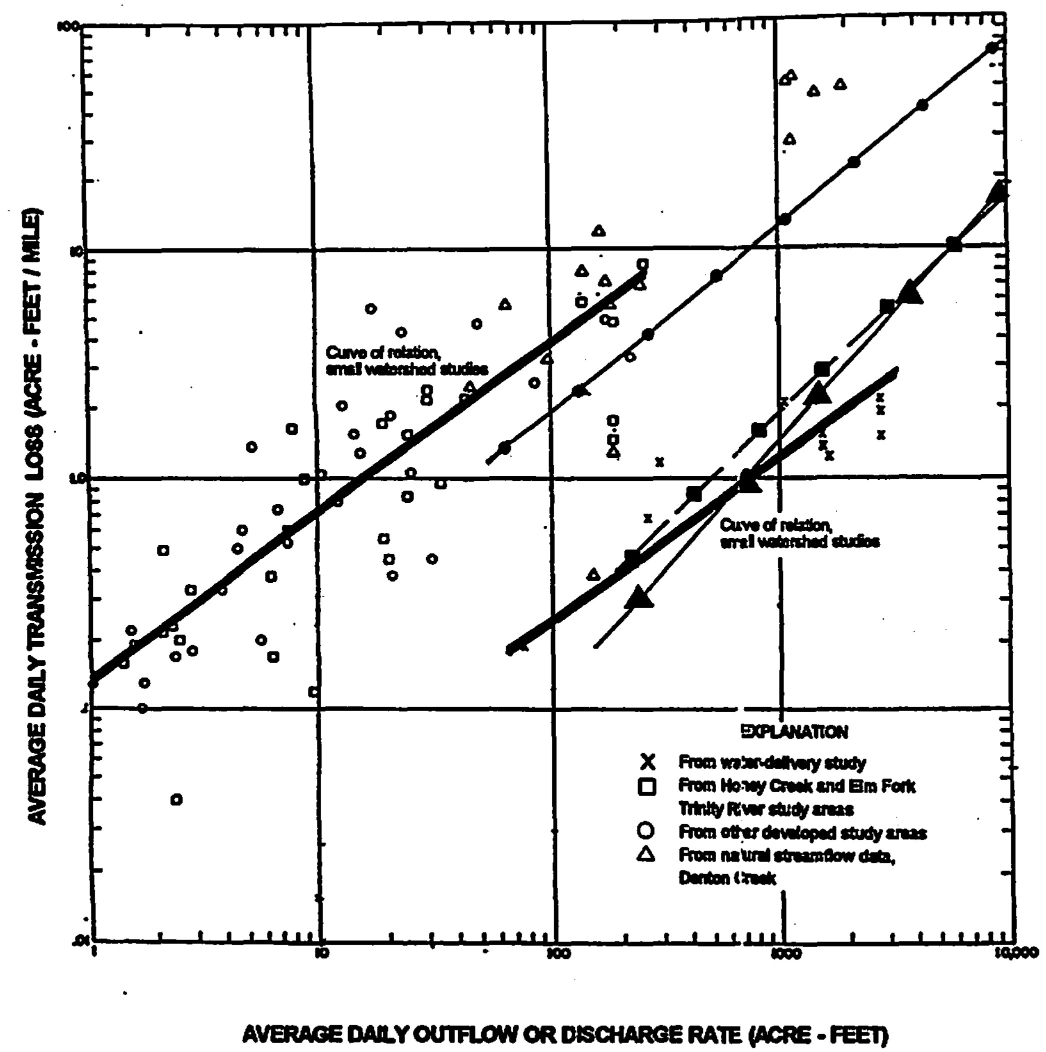
GUADALUPE RIVER: CUERO TO VICTORIA
ID# 1758 TO ID# 1765 (50 MILES)

BLANCO RIVER: WIMBERLEY TO KYLE
ID# 1710 TO ID# 1713 (16 MILES)

SAN MARCOS RIVER: SAN MARCOS TO LULING
ID# 1700 TO ID 1720 (42 MILES)

REFERENCE: U. S. GEOLOGICAL SURVEY, "HYDROLOGIC EFFECTS OF FLOODWATER - RETARDING STRUCTURES ON GARZA - LITTLE ELM RESERVOIR, TEXAS," WATER - SUPPLY PAPER 1984, 1970.

SAN ANTONIO RIVER BASIN



LEGEND:

MEDINA RIVER: SOMERSET TO SAN ANTONIO
ID# 1808 TO ID# 1815 (10 MILES)

SAN ANTONIO RIVER: ELMENDORF TO FALLS CITY
ID # 1818 TO ID# 1835 (42 MILES)

SAN ANTONIO RIVER: FALLS CITY TO GOLIAD
ID# 1835 TO ID #1885 (81 MILES)

GUADALUPE-SAN ANTONIO RIVER BASIN
RECHARGE ENHANCEMENT STUDY

SUMMARY OF CHANNEL LOSS ANALYSES

HDR Engineering, Inc.

FIGURE 4 - 4

Table 4-2
Summary of Channel Loss Equations

River Basin	Stream Segment Description	Upstream Control Point(s) ID#	Downstream Control Point ID#	Channel Loss Equation Coefficients[1] a	b
Guadalupe River Basin	Guadalupe River Comfort to Spring Branch	1670	1675	1.0000	0.7979
	Guadalupe River Spring Branch to Canyon Lake	1675	1677	1.0000	0.7150
	Guadalupe River Canyon Lake to New Braunfels	1677	1685	0.0000	0.0000
	Guadalupe River New Braunfels to Lake Wood	1690 1685	6	0.0771	1.0460
	Guadalupe River Lake Wood to Cuero	6,1720,1730 1746,1750	1758	0.4077	0.7801
	Guadalupe River Cuero to Victoria	1758	1765	1.0000	0.7801
	Guadalupe River Victoria to Tivoli	1765 1774	1888	0.7194	0.7801
	Blanco River Wimberley to Kyle	1710	1713	92.4272	0.3314
	San Marcos River San Marcos to Luling	1700 G	1720	0.0057	1.3161
San Antonio River Basin	Medina River Diversion Lake to Somerset	1795 22/24,25	1808	1.0000	0.7980
	Medina River Somerset to San Antonio	1808 26,17	1815	1.0000	0.7980
	San Antonio River San Antonio to Elmendorf	1815,1780 1788,30	1818	1.0111	0.7980
	San Antonio River Elmendorf to Falls City	1818 31/1825	1835	0.1727	0.9278
	San Antonio River Falls City to Goliad	1835 1860,1865	1885	0.0490	1.0880
	San Antonio River Goliad to Tivoli	1885	1888	0.0379	1.0880
	Cibolo Creek Boerne to Selma	1839	1850	1.0000	1.0000
	Cibolo Creek Selma to Falls City	1850	1860	0.5509	1.0000
	Salado Creek Upper Sta. to Lower Sta.	1787	1788	0.2944	1.0000

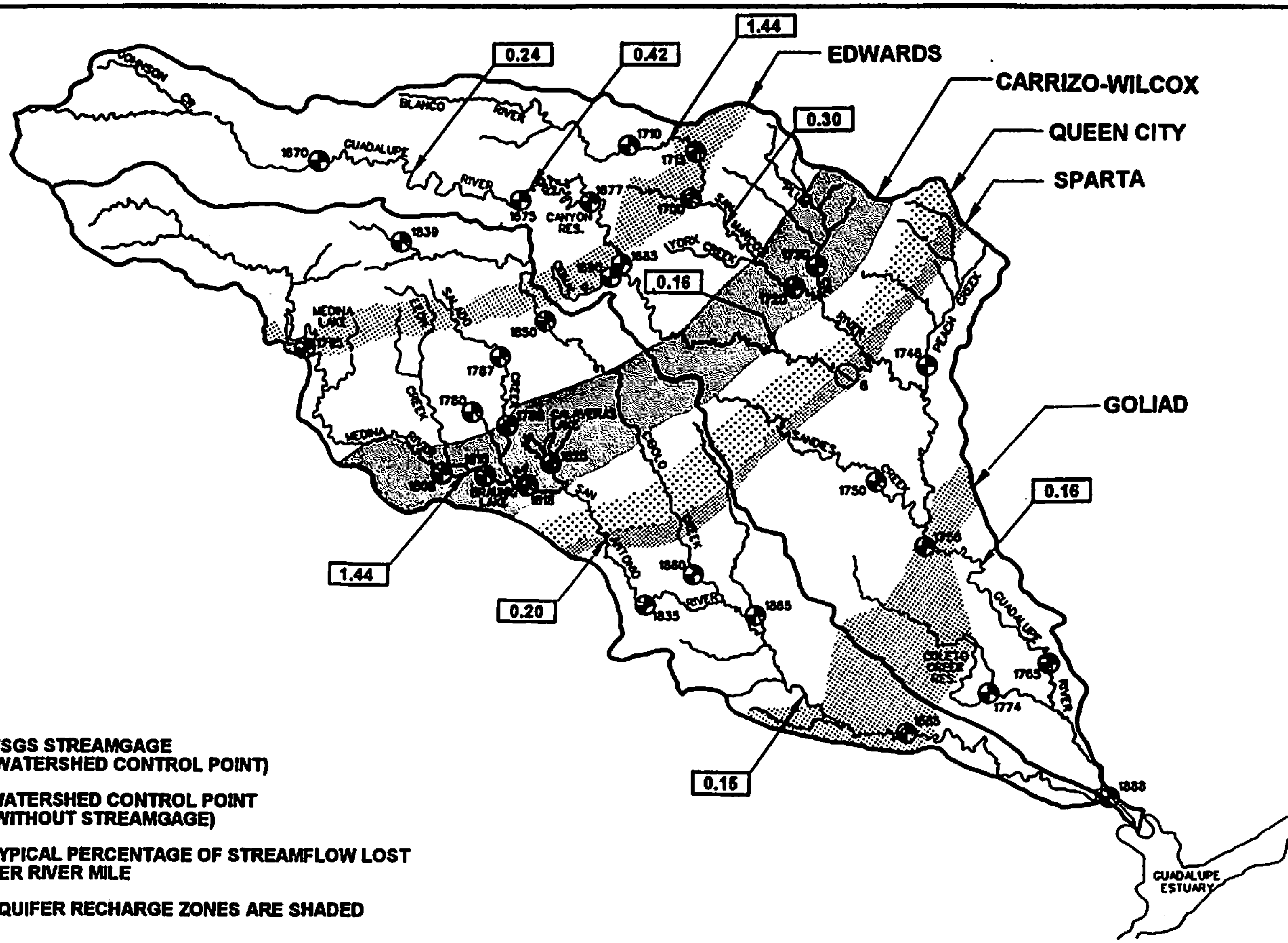
Notes:
1) Coefficients "a" and "b" for Channel Loss Equation expressed as: $Q_{Loss} = a(QG_1)^b$, where Q_{Loss} is the monthly channel loss in acre-feet and QG_1 is the total monthly flow at the upstream control points in acre-feet.

Figure 4-5 presents a summary of typical channel loss rates in percent per mile, based on average flow conditions for all stream segments where losses were calculated from gaged records. Channel loss rates outside of the Edwards Aquifer recharge zone ranged from 0.15 percent per mile to 1.44 percent per mile with the highest for the Medina River segment which crosses the Carizzo-Wilcox Aquifer outcrop. Generally, the lower channel loss rates were found to occur in those stream segments which do not traverse major aquifer outcrops or have short travel distances across these outcrop areas. Overall, channel loss rates downstream of the Edwards Aquifer recharge zone averaged 0.22 percent per mile in the Guadalupe - San Antonio River Basin as compared to 0.48 percent per mile in the Nueces River Basin (Ref. 14).

4.6 Completion of Streamflow Records

Streamflow records missing during the 1934-89 historical period were estimated for 24 streamflow gaging stations or control points located throughout the Guadalupe - San Antonio River Basin. Records were completed using multiple linear regression techniques based on available streamflow records, calibrated estimates of local runoff based on areal precipitation and curve number, or drainage area ratio based on available streamflow records in the same or an adjacent watershed. The equations used to estimate these missing monthly streamflow records are summarized in Table 4-3.

Generally, regression equations were developed to calculate missing flows from available upstream or downstream flows and estimates of intervening runoff. When suitable upstream or downstream flow records were not available, however, regression equations



Legend:

USGS STREAMGAGE (WATERSHED CONTROL POINT)

WATERSHED CONTROL POINT (WITHOUT STREAMGAGE)

0.05 TYPICAL PERCENTAGE OF STREAMFLOW LOST PER RIVER MILE

AQUIFER RECHARGE ZONES ARE SHADED

NOTE: ACTUAL CHANNEL LOSS RATES APPLIED IN THE GSA MODEL ARE COMPUTED EACH MONTH BASED ON THE VOLUME OF UPSTREAM FLOW.

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GUADALUPE-SAN ANTONIO RIVER BASIN RECHARGE ENHANCEMENT STUDY

TYPICAL CHANNEL LOSS RATES

FIGURE 4-5

Table 4-3
Estimation of Missing Streamflow Records

Control Point with Missing Records	Period of Missing Records	Equation	Length of Concurrent Records (Years)	Coefficient of Determination (r^2)
1670	1/34-5/39	$QG_{1670} = (QNH_{1675} - 0.8851\ QI_{1675})/1.0829$	50	.93
1677	1/34-6/62	$QNH_{1677} = 0.9274\ QG_{1675} + 0.8980\ QI_{1677} + 1225.5800$	27	.99
H-5	1/34-12/59	$QNH_{H\text{-}5} = 0.8002\ QG_{1685} + 1.2624\ QG_{1690} - 2254.6391$	10	.97
H-5	1/60-12/79	$QNH_{H\text{-}5} = 0.7646\ QG_{1685} + 1.2020\ QG_{1690} - 0.2587\ QI_{H\text{-}5}$	10	.98
1713	1/34-5/56	$QNH_{1713} = 1.0289\ QG_{1710} + 0.3844\ QI_{1713} + 1360.1090$	33	.98
1720	1/34-4/39	$QNH_{1720} = 1.1776\ QG_{1710} + 0.7441\ QG_{1730} + 1.1762\ QG_{1700} - 2673.7705$	50	.94
1746	1/34-7/59,10/79-12/89	$QN_{1746} = QI_{1746}$	---	---
1750	11/34-7/59	$QN_{1750} = 0.9596\ QN_{1860}$	31	.52
1758	12/35-12/63	$QG_{1758} = (QNH_{1765} - 1239.8739)/1.0461$	26	.99
1765	1/34-11/34	$QNH_{1765} = 1.0461\ QG_{1758} + 1239.8739$	26	.99
1774	1/34-6/39	$QN_{1774} = 770.9900\ P_{1774}^2 - 2657.9253\ P_{1774} + 3424.5904$	50	.78
1774	7/39-9/54	$QN_{1774} = QN_{1775}\ (494/514)_{D.A.R.}$	---	---
1774	10/54-9/78	$QN_{1774} = QN_{1770}\ (494/369)_{D.A.R.}$	---	---
1774	10/78-12/89	$QN_{1774} = QN_{1769}\ (494/357)_{D.A.R.}$	---	---

Definition of Terms: QG = Gaged Flow   QN = Natural Flow   P = Areal Precipitation
QNH = Gaged Flow Adjusted for Local Diversions and Return Flows
QI = Intervening or Potential Runoff Calculated Using Modified SCS Procedure
D.A.R. = Drainage Area Ratio R_N = Natural Recharge

Units: Acre-Feet/Month: QG, QN, QNH, QI, R_N Inches/Month: P

Table 4-3
Estimation of Missing Streamflow Records

Control Point with Missing Records	Period of Missing Records	Equation	Length of Concurrent Records (Years)	Coefficient of Determination (r^2)
1780	1/34-2/39	$QN_{1780} = 1.0910\ QG_{S.A.SPRING} + 6.6831\ QG_{RECHARGE\ ZONE} + 0.3556\ QI_{1780} + 1206.3234$	51	.87
1788	1/34-2/39	$QN_{1788} = 1.6024\ QN_{1787} + 0.1319\ QI_{1788} + 1479.5876$	29	.84
1788	3/39-9/60	$QNH_{1788} = 0.7510\ QN_{1780}$	29	.52
1790	7/35-9/42	$QN_{1790} = 0.4325\ QN_{1675}$	30	.75
1790	10/42-9/52	$QN_{1790} = 0.4443\ QN_{1670} + 1.1155\ QN_{1980}$	30	.87
1795	1/34-3/56,12/81-9/82	$QN_{1795} = QN_{1790}\ (634/474)_{D.A.R.}$	---	---
1795	4/56-11/81	$QN_{1795} = (QN_{1790} + QN_{1791})\ [634/(474+56.3)]_{D.A.R.}$	--	---
1795	10/82-12/89	$QN_{1795} = QN_{17888}\ (634/427)_{D.A.R.}$	---	---
1805	1/34-12/89	$QN_{1805} = QN_{1795} + QI_{1805} - R_{N1805} - 10\hat{}(0.3314\ \log QN_{1795} + 1.9658)$	---	---
1808	1/34-7/39	$QNH_{1808} = 1.1787\ QG_{1805} + 0.2179\ QI_{1808} + 2787.7344$	19	.90
1808	8/39-9/70	$QG_{1808} = (QNH_{1815} - 959.2566 - 0.1303\ QI_{1815})/1.0833$	19	.99
1815	1/34-7/39	$QNH_{1815} = 1.3496\ QG_{1805} + 4650.5164$	50	.83
1818	1/34-9/54	$QG_{1818} = QNH_{1835}/1.0942$	27	.97

Definition of Terms: QG = Gaged Flow QN = Natural Flow P = Areal Precipitation
QNH = Gaged Flow Adjusted for Local Diversions and Return Flows
QI = Intervening or Potential Runoff Calculated Using Modified SCS Procedure
D.A.R. = Drainage Area Ratio R_N = Natural Recharge

Units: Acre-Feet/Month: QG, QN, QNH, QI, R_NInches/Month: P

Table 4-3
Estimation of Missing Streamflow Records

Control Point with Missing Records	Period of Missing Records	Equation	Length of Concurrent Records (Years)	Coefficient of Determination (r^2)
1818	10/54-9/62	$QG_{1818} = (QNH_{1835} - 5.3685\ QG_{CL} - 1839.0573)/0.9960$	27	.98
Braunig Lake	1/34-12/89	$QN_{BL} = QN_{CL}(9.4/65)_{D.A.R.}$		
Calaveras Lake	1/34-9/54,1/69-12/70	$QG_{CL} = 0.0527\ QNH_{1825} - 555.0354$	14	.61
Calaveras Lake	10/54-12/68	$QN_{CL} = QN_{1825}\ (65/77.2)_{D.A.R.}$	---	---
1839	1/34-6/35,10/52-2/62	$QN_{1839} = 0.1772\ QI_{1675} + 0.0122\ QN_{1790} - 367.9174$	21	.80
1839	7/35-9/52	$QN_{1839} = 0.1466\ QI_{1675}$	28	.76
1850	1/34-3/46	$QNH_{1850} = 0.3768\ QG_{1839} + 0.4070\ QI_{1850} - 1701.6080$	28	.64
1865	1/34-2/39	$QN_{1865} = 0.2875\ QN_{1860}$	27	.42
1865	3/39-3/62,10/89-12/89	$QG_{1865} = (QNH_{1885} - 1.0815\ QG_{1835} - 0.3649\ QG_{1860})/4.0338$	27	.93
1885	1/34-2/39	$QNH_{1885} = 0.9962\ QG_{1835} + 1.7361\ QG_{1860} + 2622.1322$	51	.83

Definition of Terms: QG = Gaged Flow QN = Natural Flow P = Areal Precipitation
QNH = Gaged Flow Adjusted for Local Diversions and Return Flows
QI = Intervening or Potential Runoff Calculated Using Modified SCS Procedure
D.A.R. = Drainage Area Ratio R_N = Natural Recharge

Units: Acre-Feet/Month: QG, QN, QNH, QI, R_N Inches/Month: P were developed from available natural flows in one or more adjacent watersheds or by other means. Table 4-3 indicates the length of concurrent record on which each regression equation was based which averaged 2.2 times the length of missing records. Coefficients of determination (r^2) for the regression equations ranged from 0.42 to 0.99, with the average, weighted by dependent mean, being about 0.94.

Runoff estimates for the ungaged coastal area in the Guadalupe - San Antonio River Basin were required to develop a natural flow record at the Saltwater Barrier near Tivoli (ID# 1888). The ungaged area includes the 515 square mile intervening area upstream of the Saltwater Barrier, and downstream of the San Antonio River at Goliad (ID# 1885), Coleto Creek at Coleto Creek Reservoir near Victoria (ID# 1774), and the Guadalupe River at Victoria (ID# 1765). Ungaged runoff estimates for the coastal area were available from past studies by Espey, Huston & Associates, Inc. (EH&A) (Ref. 10) and the TDWR (Ref. 24) for the 1940-82 period. EH&A ungaged runoff estimates were significantly less than those developed by the TDWR but appeared more consistent with independent partial record estimates developed by HDR using drainage area ratios and modified SCS procedures. Hence, the EH&A ungaged runoff estimates were adopted for use in this study. For the period prior to 1940, monthly ungaged runoff estimates were computed using areal precipitation and a linear regression relationship based on EH&A ungaged runoff and areal precipitation during the 1940-82 period. Ungaged runoff after 1982 was estimated by application of modified SCS procedures (discussed in Section 4.5) using the Coleto Creek watershed above Coleto Creek Reservoir (ID# 1774) as a partner area. Estimated runoff for the ungaged, 515 square mile intervening area above the Saltwater Barrier averaged

221,734 ac-ft/yr for the 1934-89 period. Although this area drains about five percent of the basin, it contributes about 11.4 percent of the average annual natural flow for the entire Guadalupe - San Antonio River Basin.

4.7 Trends in Annual Streamflow

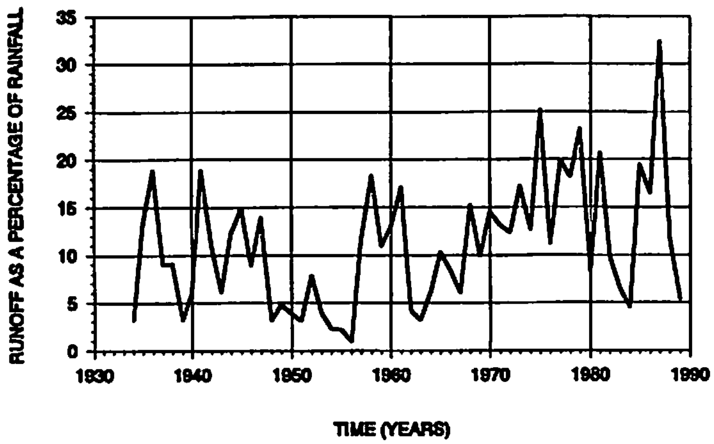
It is not uncommon for streamflows to be influenced over time by various changes occurring within a river basin which are not directly considered in the streamflow naturalization process. Examples of these types of changes potentially applicable to the Guadalupe - San Antonio River Basin include: 1) Increasing use of groundwater from the Edwards Aquifer which, in turn, may reduce the discharge of certain springs; 2) Urbanization which may increase surface runoff; and 3) Changes in land use, vegetative cover, or farming techniques which may either increase or decrease runoff. While changes in springflow are considered in the application of the GSA Model, urbanization and other land use changes are generally assumed to be of insufficient magnitude on a basin-wide scale to warrant similar consideration. Climatic changes such as global warming may also affect the frequency and intensity of precipitation events and other factors which may influence streamflows. This section summarizes statistical analyses of long-term rainfall and natural streamflow data conducted to detect the presence of potentially significant trends.

The detection of historical trends in streamflow is an inexact science, as is estimation of future trends. Although numerous physical and statistical methods exist, none are truly deterministic due to the stochastic nature of variations in rainfall and runoff in a watershed the size of the Guadalupe - San Antonio River Basin. In order to evaluate possible changes in the relationship between streamflow and areal precipitation with respect to time, standard statistical tests were performed on the annual series of natural runoff as a percentage of rainfall at three locations. These locations included the Guadalupe River near Spring Branch (ID# 1675), Guadalupe River at Victoria (ID# 1765), and San Antonio River at Goliad (ID# 1885). These locations were selected to be somewhat representative of inflows to Canyon Lake, Guadalupe River Basin runoff, and San Antonio River Basin runoff, respectively. Figure 4-6 presents annual runoff expressed as a percentage of rainfall at each of these locations.

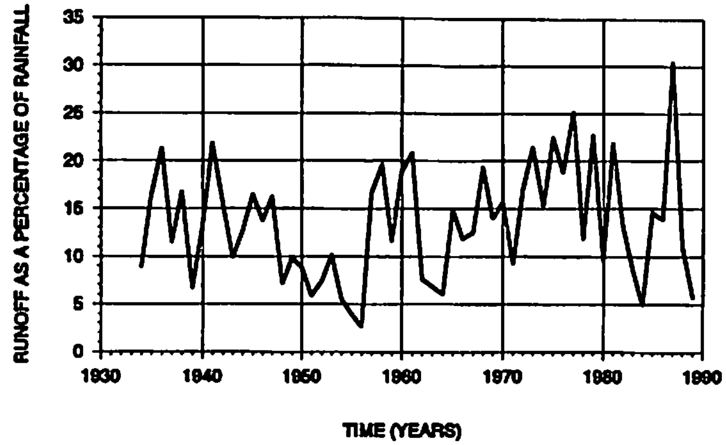
The statistical tests applied included the non-parametric Kendall Tau (Ref. 15) and Turning Points (Ref. 47) tests, as well as linear regression of runoff percentage versus time and sample partitioning which are classified as parametric tests. Sample partitioning, in this case, simply involved subdivision of the 56-year historical period into halves so that the means and variances from the earlier and later subperiods could be compared to one another. Review of the series for each of the selected locations indicates that the annual values may reasonably be assumed normally distributed. Statistical significance was assumed at the 90 percent confidence level for these tests. Table 4-4 summarizes the results of the trend tests for selected watersheds.

A trend which could be statistically significant was detected for the Guadalupe River near Spring Branch, while no significant indications of trend were detected for the Guadalupe River at Victoria or the San Antonio River at Goliad. It is interesting that no truly significant indications of trend were noted for the Victoria and Goliad locations as pumpage and urbanization in the San Antonio area increased dramatically during the

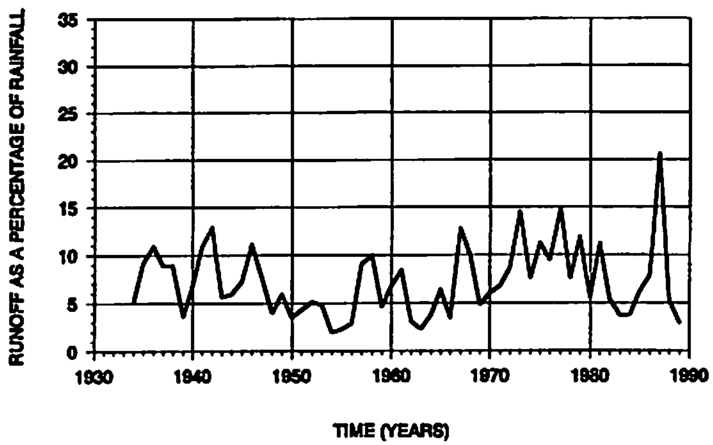
GUADALUPE RIVER NEAR SPRING BRANCH



GUADALUPE RIVER AT VICTORIA



SAN ANTONIO RIVER AT GOLIAD



GUADALUPE-SAN ANTONIO RIVER BASIN
RECHARGE ENHANCEMENT STUDY

ANNUAL RUNOFF/RAINFALL FOR SELECTED WATERSHEDS

HDR

HDR Engineering, Inc.

FIGURE 4-6

Table 4-4
Statistical Trend for Selected Watersheds[1]

Statistical Test	Test Type	Indication of Statistically Significant Trend[2]		
		Guadalupe River, Spring Branch	Guadalupe River, Victoria	San Antonio River, Goliad
Kendall Tau	Non-parametric	Yes	No	No
Turning Points	Non-parametric	No	No	Yes[5]
Linear Regression[3], t Distribution	Parametric	Yes	No	No
Sample Partitioning[4], Mean Comparison, t Distribution	Parametric	Yes	No	No
Sample Partitioning[4], Variance Comparison, F Distribution	Parametric	No	No	Yes[6]

[1]Tests based on annual series of natural streamflow as a percentage of areal precipitation.
[2]Statistical significance assumed at the 90% confidence level.
[3]Linear regression of natural streamflow as a percentage of areal precipitation versus time. These percentages are assumed to be normally distributed.
[4]56-year historical period partitioned into 1934-61 and 1962-89 sub-periods
[5]Affirmative indication more likely a result of serial correlation than long-term trend.
[6]Affirmative indication a result of including maximum (1987) observation.

1934-89 historical period. Indications were detected that runoff, as a percentage of rainfall upstream of Canyon Lake, has been increasing with time based on the Kendall Tau, linear regression, and mean comparison tests. For example, runoff as a percentage of rainfall for the Guadalupe River near Spring Branch averaged almost 9 percent for the 1934-61 period and more than 13 percent for the 1962-89 period. While this difference can be explained, in part, by greater average areal precipitation in the later period, it is interesting to note that average natural runoff for the later period exceeded that for the earlier period by an amount greater than the difference in average annual rainfall assuming that 100 percent of the difference in average rainfall became runoff. Without a full understanding of the physical causes of apparently increasing runoff above Canyon Lake, whether they be changes in land use practices, climate (including the magnitude and frequency of extreme events), or other factors, there is no reasonable assurance that the historical trend will continue into the future. For these reasons, no adjustments to natural streamflows for apparent trends in runoff were made in this study.

5.0 RIVER BASIN MODEL DEVELOPMENT

The development of the Guadalupe - San Antonio River Basin (GSA) *Model* included building selected features into a computer code to accomplish the following tasks:

- Estimation of natural and enhanced Edwards Aquifer recharge;
- Simulation of the operations of existing and proposed reservoirs subject to various Edwards Aquifer pumpage/springflow and surface water rights scenarios; and
- Calculation of water potentially available at selected locations subject to various Edwards Aquifer pumpage/springflow and surface water rights scenarios.

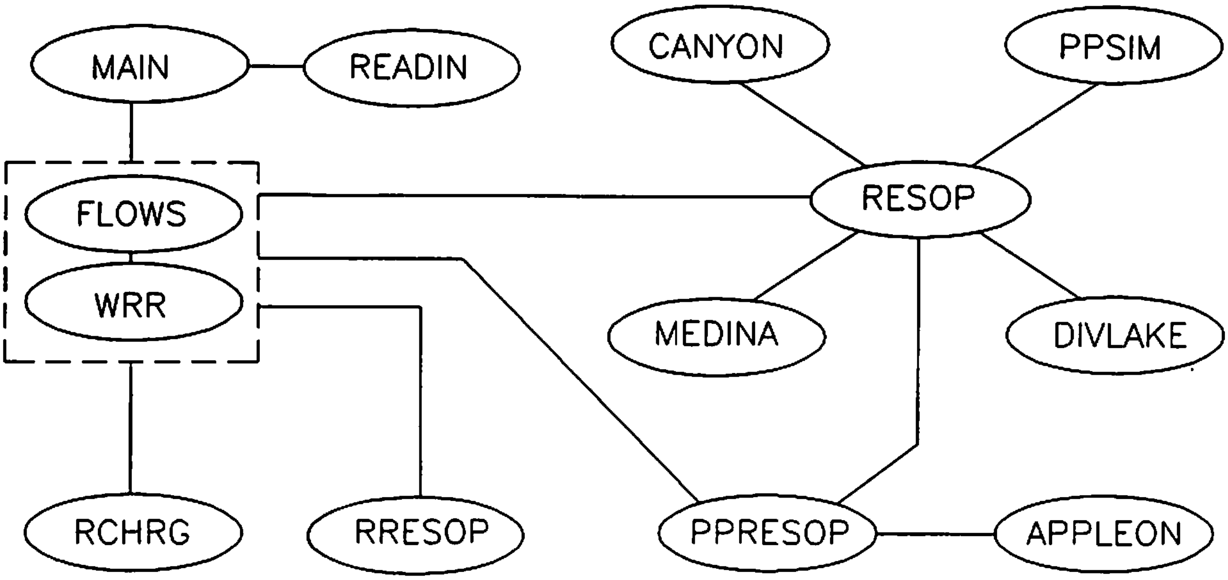
The structure of the model is based on the physical characteristics, water rights, and hydrologic phenomena which exist within the basin with monthly computations simulating the movement of water throughout the basin. The GSA Model was completed in two primary stages: 1) Development of input databases such as natural streamflows which are described in the preceding sections; and 2) Computer program code development and pertinent assumptions which are addressed in this section.

5.1 General Organization

The computer program code for the GSA Model is in the FORTRAN programming language as are many similar models currently in use such as RESOP-II (Ref. 26) and SIMYLD-II (Ref. 29) and is compatible with the Nueces River Basin Models previously developed by HDR (Refs. 13 and 14). The GSA Model was compiled and debugged using Microsoft FORTRAN, Version 5.1 (Ref. 17) and is sufficiently generic that it can be compiled and executed on mainframe, micro, and many personal computers. The program code was written in subroutines which are program segments intended to simulate a specific process or perform a related sequence of calculations. Thirteen of the most significant subroutines in the GSA Model are shown in Figure 5-1 along with connecting lines indicating their relationships and a brief definition of the function of each subroutine. Comments and variable definitions were interspersed throughout the program code to facilitate understanding of computational logic and sequencing. A listing of the FORTRAN code for the GSA Model is included in Appendix G (Volume III).

5.2 Basic Computational Procedures

The GSA Model employs a monthly time step proceeding with flow calculations in an upstream to downstream order simulating recharge, channel losses, water rights, return flows, and reservoir operations. Changes in upstream flow from the natural flow at each control point are translated to the next downstream control point using the delivery equations described in Section 4.5. Calculations are performed at each of the 38 Watershed Control Points located throughout the river basin as shown in Figure 4-1 beginning in the headwaters of the Guadalupe River near Comfort (ID# 1670), continuing downstream to Victoria (ID# 1765), moving to the headwaters of the San Antonio River Basin near Medina Lake (ID# 1795), continuing downstream to Goliad (ID# 1885), and finally combining flows from both the Guadalupe and San Antonio Rivers at the Saltwater Barrier near Tivoli (ID# 1888). These control points were generally established at streamflow gaging stations, existing reservoirs, and other locations near the downstream limits of the Edwards Aquifer recharge zone.



SUBROUTINE	PRIMARY FUNCTION
MAIN	Input/Output File Management
READIN	Control Parameters and Data Input
FLOWS	Streamflow and Water Delivery Simulation
WRR	Water Rights Release Determination
RCHRG	Natural Recharge Calculation
RRESOP	Recharge Reservoir Operations and Recharge Calculation
RESOP	Reservoir Operations
CANYON	Canyon Lake Contents Simulation
PPSIM	Power Plant Reservoir Contents Simulation
MEDINA	Medina Lake Contents Simulation and Recharge Calculation
DIVLAKE	Diversion Lake Contents Simulation and Recharge Calculation
PPRESOP	Power Plant Reservoir Operations
APPLEON	Leon Creek to Applewhite Reservoir Diversion

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GUADALUPE-SAN ANTONIO RIVER BASIN RECHARGE ENHANCEMENT STUDY

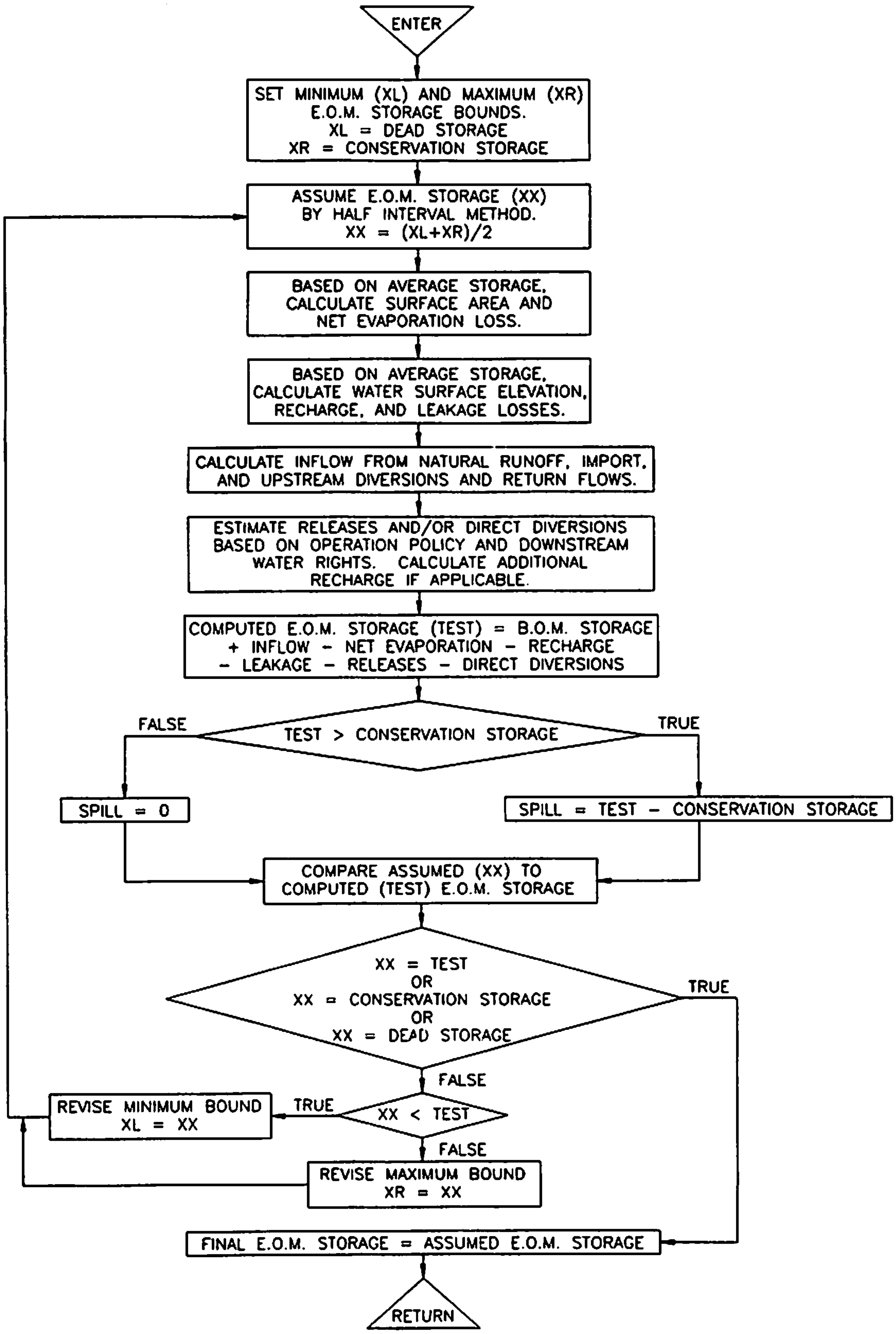
KEY MODEL SUBROUTINES

FIGURE 5-1

Monthly simulation of reservoir contents can be somewhat more complicated than estimation of streamflow and recharge for control points without reservoirs. Volume fluxes affecting reservoir storage include inflow, net evaporation, recharge, leakage, direct diversions, releases, and spills. As net evaporation, recharge, and leakage are calculated from the water surface area or elevation associated with the average storage for a given month, a simultaneous solution for these fluxes is necessary to obtain an accurate estimate of end-of-month storage. This solution is obtained using the Half-Interval Method (Ref. 3) as illustrated in Figure 5-2 which depicts the reservoir contents simulation procedure employed by the GSA Model in the form of a flowchart. Elevation-area-capacity relationships for existing reservoirs and potential recharge enhancement projects were obtained from published sources or developed from available topographic mapping. Tables summarizing these relationships are included in Appendix H (Volume III).

5.3 Water Rights

The GSA Model is capable of simulating diversion rights for consumptive water use and non-consumptive hydropower generation rights as well as reservoir storage rights. Diversion rights were grouped according to use type between control points and exercised in accordance with typical monthly percentages of the authorized annual diversion depending on water availability. River diversions for power plant cooling reservoir make-up were assumed to be exercised only when needed to maintain a desired cooling surface and were limited to authorized annual amounts. In order to accurately determine monthly inflow passage and/or releases from Canyon Lake, it was necessary to group diversion rights



GUADALUPE-SAN ANTONIO RIVER BASIN
RECHARGE ENHANCEMENT STUDY

RESERVOIR CONTENTS SIMULATION PROCEDURE

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FIGURE 5-2

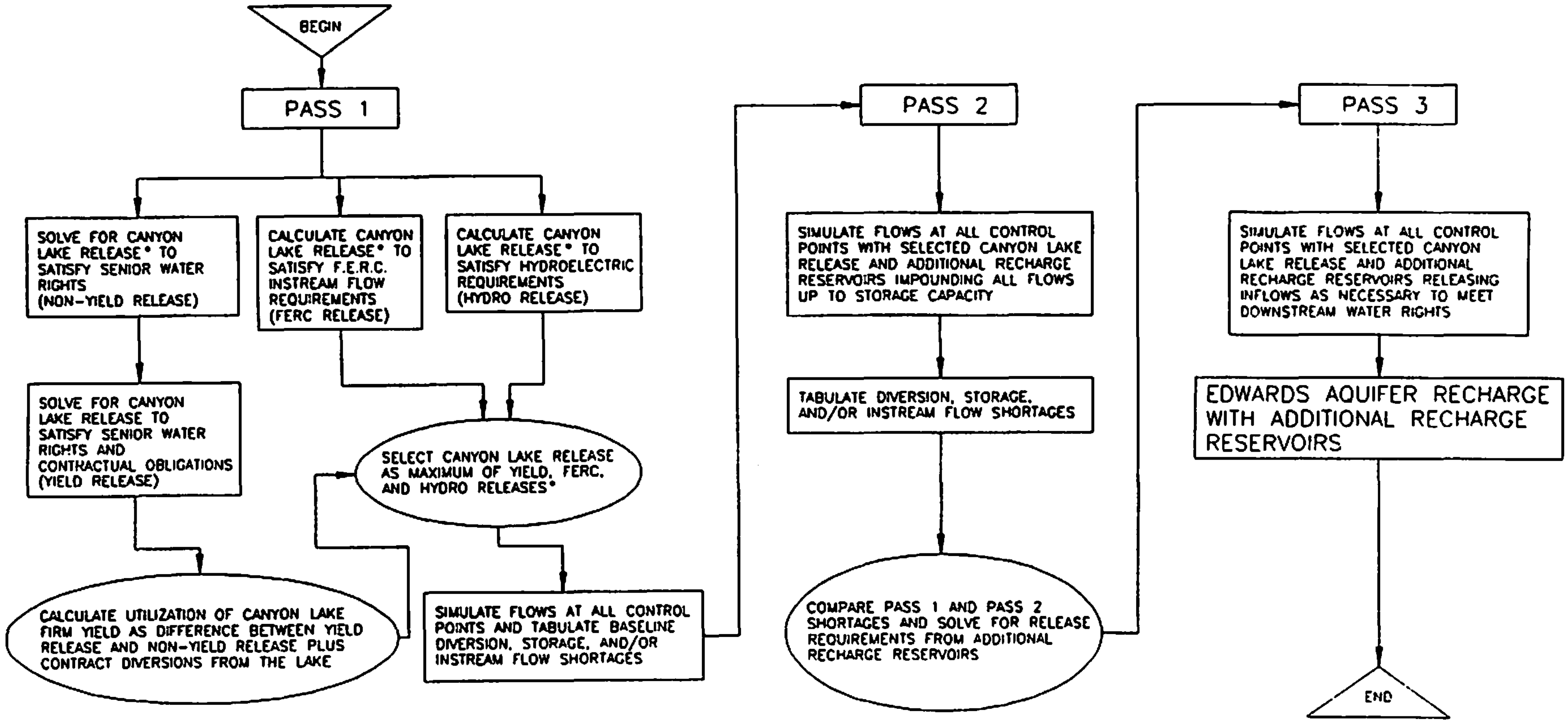
throughout the Guadalupe - San Antonio River Basin into three classes: 1) Rights senior to Canyon Lake; 2) Contractual obligations under Guadalupe-Blanco River Authority (GBRA) rights in Canyon Lake; and 3) Rights junior to Canyon Lake. The senior industrial diversion rights (300 cfs) held by Central Power & Light (CP&L) for non-consumptive, once-through cooling were modelled as an instream flow requirement to meet all nonconsumptive 'rights in the lower basin at or below the control point located on the Guadalupe River near Victoria.

A desired hydropower flowrate in cubic feet per second (cfs) representative of streamflow entering Lake Dunlap on the Guadalupe River is an interactive input for each execution of the GSA Model. Non-consumptive hydropower rights other than those held by GBRA for a series of small dams on the Guadalupe River between New Braunfels and the San Marcos River confluence were not included in the GSA Model. It was assumed that the hydropower rights of Seguin Municipal Utilities which are generally satisfied by GBRA hydropower operations would be subordinated to the same extent as those held by GBRA based on inflows to Lake Dunlap. Rights held by New Braunfels Utilities downstream of Comal Springs and Aquarena Springs Corporation downstream of San Marcos Springs were not included because surface water availability at neither of these locations would be significantly affected by any of the identified recharge enhancement projects. Major hydropower rights held by the City of Gonzales and John L. McNeill were neglected because their Certificates of Adjudication specify that they would be subordinated to any future rights to use the waters of the Guadalupe River for municipal, industrial, irrigation, and/or mining purposes. Rights held by Hydraco Power Inc. on the San Marcos

River were officially abandoned by permit amendment issued August 20, 1990.

Major reservoir storage rights are handled in the GSA Model much as they have traditionally been handled in river basin models developed by the Texas Department of Water Resources (Refs. 27 and 28). Monthly reservoir inflows are required to be passed to the extent necessary to satisfy senior downstream water rights, but flows impounded in previous months may remain in storage. No reservoir inflows are passed for junior water rights. Similarly, potential recharge enhancement reservoirs or diversion projects are not allowed to impound or divert, respectively, unless the downstream reservoir is full and spilling.

Computation of water potentially available for recharge or diversion for other purposes from selected locations without adversely affecting downstream water rights is accomplished by the GSA Model using a three-pass process. A flowchart summarizing this three-pass process is presented in Figure 5-3. In the first pass, operational releases from Canyon Lake (which may include both inflow passage and release from storage) and make-up diversions for Coleto Creek, Braunig, and Calaveras Lakes are determined, flows are simulated at all control points, and any shortages (failures to satisfy diversion or storage rights or any specified instream flow requirements) are tabulated. Operational releases from Canyon Lake, make-up diversions for power plant cooling reservoirs, and operational guidelines assumed for Medina Lake are presented in Sections 5.4, 5.5, and 5.6, respectively. In the second pass, additional recharge or diversion projects are included and shortages are tabulated for the entire river basin assuming full impoundment or diversion of inflows and



* NON-YIELD, FERC, AND/OR HYDRO RELEASES ARE LIMITED TO CANYON LAKE INFLOWS.

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GUADALUPE-SAN ANTONIO RIVER BASIN RECHARGE ENHANCEMENT STUDY

RIVER BASIN MODEL FLOWCHART

FIGURE 5-3

considering applicable evaporation losses at the additional project locations. If these shortages exceed those determined in the first pass, the GSA Model solves for the portion of inflow at each additional project which must be passed in order to satisfy all downstream water rights to the extent they were satisfied in the first pass. Any inflows which may be impounded or diverted without impacting downstream water rights are assumed to be available for recharge enhancement or other purposes. In the third and final pass, flows are simulated at all control points with the selected Canyon Lake release and additional projects passing inflows as necessary for downstream water rights and enhanced recharge of the Edwards Aquifer is computed.

5.4 Canyon Lake

One of the most critical and complicated aspects of GSA Model development was the determination of operational releases (inflow pass through and/or releases from storage) from Canyon Lake in order to satisfy senior water rights, contractual obligations, hydropower requirements, and Federal Energy Regulatory Commission (FERC) guidelines. Simulation of these operational releases is important so that the GSA Model can compute reasonably accurate estimates of recharge enhancement with identified projects or water potentially available for diversion at selected stream locations.

As indicated in Figure 5-3, the first step in evaluating Canyon Lake operations is the calculation of firm yield utilization by determination of the arithmetic difference between monthly "non-yield" and "yield" releases. The non-yield release is limited to monthly inflow at Canyon Lake and represents the quantity of water which would have to be passed to satisfy senior water rights only. The yield release may include both inflows and storage and represents the quantity of water which would have to be released to satisfy contractual obligations in full (with the exception of CP&L at Coleto Creek which is delivered only as needed) and senior water rights to the extent they could be satisfied with the non-yield release. It is assumed in the GSA Model that releases must be sufficient to deliver full contracted amounts to the points of diversion so that any losses in delivery are a part of the utilization of the firm yield or authorized diversion rights at Canyon Lake. Hydropower requirements and FERC guidelines are not considered in the calculation of yield utilization because they result in essentially non-consumptive use of water.

The firm yield of Canyon Lake is a complex function of many interrelated assumptions including hydropower subordination, Edwards Aquifer pumpage and resultant springflow, reservoir operation policy, point(s) of diversion, channel losses incurred in delivery, and type of use in addition to the highly variable hydrologic factors of inflow and net evaporation. Although calculation of Canyon yield was not within the scope of this study, it was necessary to account for the full utilization of senior rights associated with Canyon Lake in order to determine quantities of water potentially available for recharge enhancement with the implementation of new projects. Hence, GBRA contractual obligations were honored in full and any portion of the firm annual yield which remained unutilized was removed from Canyon Lake in December of each year simulated. When calculating firm yield utilization specifically for the estimation of water potentially available at Canyon Lake, however, unutilized firm annual yield was not removed from Canyon Lake. Yield estimates used in this study were obtained from a study sponsored by GBRA and completed in 1993 by EH&A (Ref. 7). While the yield estimates from the GBRA study do not reflect the effects of channel losses on water deliveries or the effects of some future drought management plan for the Edwards Aquifer on springflows, they are the best presently available.

The second step in the modelling of Canyon Lake operations is the calculation of inflow passage necessary to comply with FERC guidelines (Ref. 11). These guidelines specify instream flow minima of 100 cfs (June-January) and 120 cfs (February-May) to be maintained in non-drought conditions to the extent inflows as measured at the USGS streamflow gage located near Spring Branch (ID# 1675) are available. In the event of two consecutive months of inflow less than 90 cfs, drought conditions apply and the instream flow requirement is reduced to passage of inflows up to 90 cfs until the end-of-month reservoir level exceeds 909.0 ft-msl. For consistency with respect to water rights, the GSA Model uses inflows to the lake rather than those measured near Spring Branch. The remaining provisions of the FERC guidelines are included in the GSA Model and the required volume of inflow passed is referenced in Figure 5-3 as the "FERC" release.

The third step in the modelling of Canyon Lake operations is calculation of inflow passage for hydropower generation which is referenced in Figure 5-3 as the "hydro" release. The GSA Model determines Canyon Lake inflow passage necessary to maintain a user-specified desired flowrate near Lake Dunlap based on the sum of monthly flows at control points located on the Guadalupe and Comal Rivers near New Braunfels. There are no releases from Canyon Lake storage strictly for the purpose of hydropower generation.

Ultimately, the maximum of the yield, FERC, and hydro releases is selected as the monthly operational release from Canyon Lake and flows are simulated at all control points throughout the river basin. These flows and any observed diversion, storage, and/or instream flow shortages become the baseline relative to which the potential impacts of recharge enhancement or diversion projects are measured using the GSA Model. Guidelines for the release of flood storage in Canyon Lake were not incorporated in the GSA Model. Rather, it was assumed that all flood flows would be discharged during the same month in which they entered Canyon Lake to ensure a conservative estimate of water potentially available for recharge enhancement.

5.5 Power Plant Reservoirs

Coleto Creek Reservoir, Calaveras Lake, and Braunig Lake serve as sources of circulating flow for the dissipation of heat resulting from the operations of three existing power plants. Consumptive use of water at these power plant reservoirs or cooling ponds is the result of forced evaporation due to heat loading. Forced evaporation is a volume of water loss typically calculated from the megawatt hours of electricity generated and is accounted for separately from natural evaporation occurring at the free water surface. Each of these reservoirs is located on a stream tributary to the Guadalupe or San Antonio River and has an estimated or permitted annual consumptive use rate which is supplemented by permitted annual make-up diversions from the nearby river.

It is generally desirable to maintain power plant reservoirs at or near the normal pool level because the efficiency of heat dissipation increases with the size of the available mixing volume. Therefore, the power plant reservoir operation policy coded into the GSA Model first solves for the desired monthly volume of make-up water in addition to local inflows necessary to maintain a full reservoir subject to forced and natural evaporation losses and any required instream flow releases. The GSA Model then calculates flow available in the river after satisfying instream flow requirements at the specified source location for make-up diversions and transfers the necessary portion of this available flow to the reservoir. Cumulative annual make-up diversions associated with each power plant reservoir are tracked in the GSA Model and these river diversions are suspended for the remainder of the calendar year when the permitted annual maximum has been withdrawn.

Consumptive use by Central Power and Light (CP&L) at Coleto Creek Reservoir was assumed equal to the permitted rate of 12,000 ac-ft/yr distributed in accordance with the typical monthly industrial water use pattern presented in Figure 2-5. Make-up diversions are made from the Guadalupe River between Cuero (ID# 1758) and Victoria (ID# 1765) and are obtained under a permitted run-of-the-river right of 20,000 ac-ft/yr supplemented, when necessary, by a contractual agreement with GBRA for water from Canyon Lake averaging about 6,000 ac-ft/yr. As the run-of-the-river rights were obtained through a purchase and transfer of West Side Calhoun County Navigation District rights, originally located near Tivoli, make-up diversions under these rights are not permitted unless there is concurrent flow over the Saltwater Barrier (ID# 1888). It was assumed that CP&L rights for make-up water for Coleto Creek Reservoir would take precedence over the CP&L rights to use the waters of the Guadalupe River near Victoria up to approximately 300 cfs for non-consumptive, once-through cooling purposes. These provisions are included in the GSA Model along with the required passage of Coleto Creek inflows up to 5 cfs. The contractual agreement with GBRA for supplementary make-up water is rather complex and all provisions therein were not included in the GSA Model. Make-up diversions made under the GBRA contract are, however, reflected in the monthly utilization of the firm yield of Canyon Lake as computed by the GSA Model. The simulated maximum annual make-up diversion under the GBRA contract was approximately 19,000 ac-ft in 1956 which is consistent with the results of the original study in support of the CP&L permit application (Ref. 33).

For Braunig and Calaveras Lakes, respective maximum consumptive use rates of 10,500 ac-ft/yr and 16,000 ac-ft/yr (based on future plant expansions) as well as maximum make-up diversion rates of 12,000 ac-ft/yr and 36,900 ac-ft/yr provided by San Antonio City Public Service were used in the GSA model. Make-up diversions for both lakes are made from the San Antonio River upstream of the control point (ID# 1818) located near Elmendorf and are limited by a minimum instream flow requirement of 10 cfs. Return flows from the City of San Antonio which enter the river upstream of Elmendorf are typically sufficient to satisfy both the make-up water needs of the power plant reservoirs and the instream flow requirements.

Although the construction of Applewhite Reservoir has been abandoned, the associated diversion and storage rights are still held by the City of San Antonio and were included in the GSA Model. Rights associated with Applewhite Reservoir were modelled similarly to the power plant reservoirs with a consumptive use of 70,000 ac-ft/yr at the lake and an annual maximum make-up diversion of 12,300 ac-ft from Leon Creek. In accordance with the Certificate of Adjudication, Applewhite inflows up to 4 cfs were passed downstream and make-up diversions from Leon Creek were not allowed to impair the desired instream flow of 10 cfs for the Medina River at San Antonio (ID# 1815).

5.6 Medina and Diversion Lakes

Medina Lake and Diversion Lake storage is simulated on a monthly timestep in the GSA Model in accordance with the reservoir contents simulation procedure detailed in Figure 5-2. Recharge and leakage curves developed by EH&A (Ref. 9) for each of the reservoirs were expressed mathematically and included in the program code. Estimates of recharge and leakage at each lake are calculated by the GSA Model using these curves and the water surface elevation associated with average contents for each month simulated. The majority of the water rights associated with the lakes including the 67,830 ac-ft/yr irrigation rights held by Bexar-Medina-Atascosa Water Control and Improvement District (BMA) were assumed to be diverted from Diversion Lake into the Medina Canal. Releases from Medina to Diversion Lake were based on the operational objective of sustaining a Diversion Lake level about five feet below the spillway during irrigation season to minimize losses and maintain diversion efficiency. In all simulations, full or partial water rights were assumed to be exercised in every year to the extent storage was available in Medina and Diversion Lakes to satisfy those rights.

5.7 Pumpage/Springflow Simulation

Pumpage or withdrawal of water from the Edwards Aquifer affects storage and water levels within the formation which, in turn, affect springflows. The GSA Model does not directly simulate this process, however, it is capable of simulating the effects of changes in aquifer pumpage and historical springflows on streamflows throughout the Guadalupe - San Antonio River Basin below the springs. Changes from historical springflows were determined for a range of pumpage scenarios through application of the Texas Water Development Board (TWDB) Edwards Aquifer Model (Ref. 23) using historical monthly recharge calculated by HDR. The assistance of TWDB Staff in geographical distribution of HDR historical recharge estimates; modification of the Edwards Model to include new relationships for estimation of San Antonio and San Pedro springflows and Edwards Aquifer flux in the Hueco Springs area; and generation of springflow sequences subject to historical and to three fixed annual pumpage rates is acknowledged and appreciated.

5.8 Recharge Reservoirs

The operations of recharge reservoirs with respect to water rights are simulated in the GSA Model in a manner consistent with that described in Section 5.3. Recharge reservoir inflows are passed to the extent necessary to satisfy downstream rights to the extent they would have been satisfied without the new recharge enhancement projects. When multiple recharge enhancement projects are considered, the user specifies the sequence of projects from which inflows will be passed to mitigate any additional downstream shortages.

Recharge occurring with reservoirs is calculated in the GSA Model by the specification of a recharge release rate and/or a direct recharge rate. The recharge release rate is generally specified for reservoirs located upstream of the recharge zone and is equal to the threshold rate at which the Edwards Aquifer will accept recharge from the streambed across the outcrop. The direct recharge rate may be the percolation rate through the bottom of a reservoir and/or the diversion rate for injection to the Edwards Aquifer in an adjacent watershed. Evaporation losses are computed at all recharge reservoirs with the exception of smaller projects located atop the recharge zone which have monthly direct percolation rates in excess of reservoir storage capacity.

For recharge reservoirs located upstream of the outcrop, recharge is calculated as the sum of the losses across the recharge zone and diversions for injection. For recharge reservoirs located over the outcrop, recharge is calculated as the sum of natural recharge (without the reservoir), percolation, and diversions for injection. All estimates of recharge are limited to the monthly volume of runoff physically available at or above the project site plus any carryover storage from previous months.

The GSA Model calculates recharge in basins where Soil Conservation Service Flood Retardation Structures (SCS/FRS) are present as the sum of natural recharge adjusted for water rights and return flows plus recharge enhancement components associated with the normal and active pools of the SCS/FRS. As described in greater detail in Section 6.2.1 of this report, 100 percent and 70 percent of the volume of water impounded in the respective normal and active pools of the SCS/FRS is assumed to recharge the Edwards Aquifer. Under scenarios in which the principal spillway outlets are closed, it is assumed that 100 percent (rather than 70 percent) of the water impounded in the former active pool (between the principal and emergency spillway levels) contributes to recharge. Evaporation losses are not simulated for SCS/FRS because data collected on these structures indicates that they drain in a matter of days or a few weeks.

5.9 Verification

Verification of the GSA Model and the natural streamflow sequences was accomplished through reproduction of historical gaged flows and recharge estimates for each control point. More specifically, the GSA Model was verified by simulating the effects of historical diversions and return flows on the natural streamflows developed for each control point. The result of this simulation should be reproduction of the gaged streamflows and historical recharge estimates, if the model is functioning correctly. Agreement with the gaged flows and historical recharge estimates was virtually exact with some very minor discrepancies arising from the limited use of integer variables in the model. Further verification of all model simulation capabilities was accomplished through extensive manual checking of intermediate computations and final output summaries.

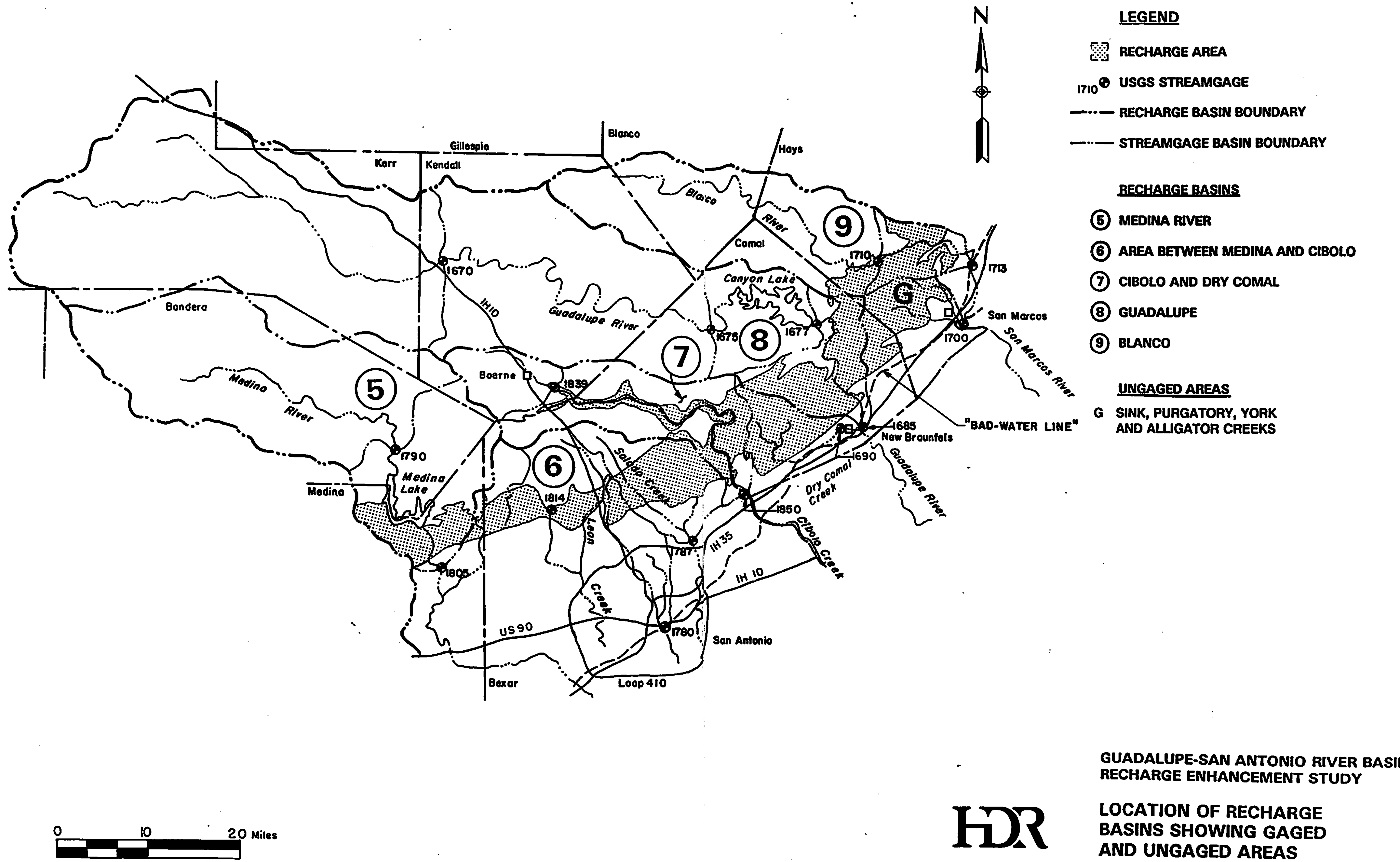
6.0 HISTORICAL RECHARGE

Estimates of recharge to the Edwards Aquifer for the five major recharge basins in the Guadalupe - San Antonio River Basin were calculated for the 56-year period from 1934 through 1989. The boundaries of the five recharge basins are shown in Plate 1. These recharge basin boundaries are the same as those utilized by the U.S. Geological Survey (USGS) in their annual report (Ref. 39) prepared in cooperation with the Edwards Underground Water District (EUWD). Drainage areas and corresponding percentages of the total drainage area included in each recharge basin are summarized in Table 6-1. Gaged areas total about 2,838 square miles above and within the recharge zone, and partially gaged and ungaged areas total about 554 square miles. Methodologies applied in the calculation of recharge in gaged, partially gaged, and ungaged areas are detailed in the following sections.

Table 6-1
Recharge Basin Drainage Areas

Recharge Basin[1]	Drainage Area (square miles)	Percent of Total
5. Medina River	634	18%
6. Area between Medina River and Cibolo Creek	330	10%
7. Cibolo Creek and Dry Comal Creek	404	12%
8. Guadalupe River	1,518	45%
9. Blanco River and Upper San Marcos River	506	15%
Total	3,392	100%

Notes:
1. Recharge Basins 1 through 4 are located in the Nueces River Basin (Refs. 39 and 45).



GUADALUPE-SAN ANTONIO RIVER BASIN
RECHARGE ENHANCEMENT STUDY

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LOCATION OF RECHARGE BASINS SHOWING GAGED AND UNGAGED AREAS

PLATE 1

6.1 Recharge in Gaged Areas

In the Guadalupe - San Antonio River Basin, there are three streams that recharge the Edwards Aquifer which are gaged both upstream and immediately downstream of the recharge zone. These streams include the Blanco River, Cibolo Creek, and the Guadalupe River. Figure 6-1 is a schematic diagram showing typical gage locations relative to the recharge zone.

Historical recharge in gaged areas was calculated on a monthly time step in accordance with the following equation:

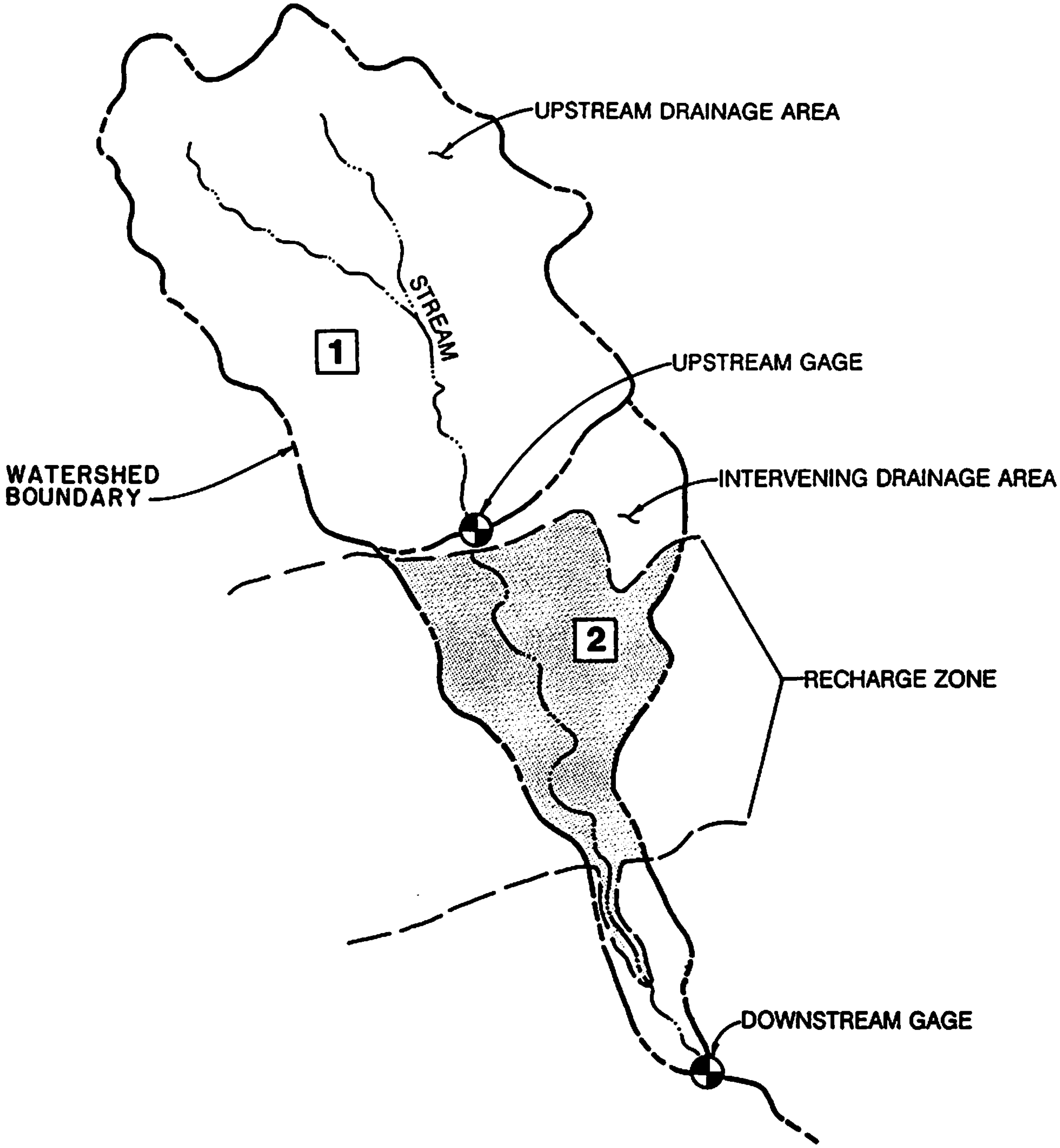
$$R = QG_1 + QI - QNH_2 \tag{6-1}$$

where:

R = Recharge;
QG_1 = Upstream Gaged Flow;
QI = Intervening Runoff; and
QNH_2 = Downstream Flow Adjusted for Intervening Diversions and Return Flows.

Intervening runoff is the most difficult parameter to quantify in the above equation because it cannot be measured directly and must be estimated from available data such as gaged streamflow, precipitation, and watershed characteristics. In the calculation of recharge, intervening runoff may also be called potential runoff as it represents the volume of runoff which would have arrived at the downstream gage if the intervening area were not over the recharge zone.

The method employed to estimate potential runoff for the intervening area is a variation of the SCS runoff curve number procedure (Refs. 18 and 19) developed by HDR



GUADALUPE-SAN ANTONIO RIVER BASIN
RECHARGE ENHANCEMENT STUDY

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SCHEMATIC OF TYPICAL GAGED AREA NEAR RECHARGE ZONE

FIGURE 6-1

for the calculation of recharge in the Nueces River Basin. This procedure takes into account differences in soil-cover complexes as well as differences in precipitation between upstream gaged and intervening areas. Applying this procedure, potential intervening runoff is expressed as:

$$QI = \left(\frac{640}{12}\right) A \frac{\left(P - \frac{200}{CN} + 2\right)^2}{\left(P + \frac{800}{CN} - 8\right)} \quad (6\text{-}2)$$

where:

QI = Potential Intervening Runoff (acre-feet/month);
A = Watershed Area (square miles);
P = Aerial Precipitation (inches/month); and
CN = SCS Curve Number.

The first step in the application of the SCS runoff curve number procedure was the selection of a runoff curve number (CN) for each major soil-cover complex in a watershed using SCS soils reports. The curve numbers were then weighted by area to arrive at a composite average CN for each watershed (see Table 4-1). Under the SCS procedure, CN also varies with antecedent moisture conditions (AMC). The average CN (AMC_{II}) increases with wet antecedent moisture conditions (AMC_{III}) and decreases with dry conditions (AMC_{I}). The higher the CN, the more runoff is produced for a given rainfall amount.

In calculating monthly intervening runoff, the CN for the intervening area was calibrated for antecedent moisture conditions as reflected in a gaged partner area. It is assumed in this methodology that AMC and storm rainfall patterns in the gaged partner area are reasonably indicative of those in the ungaged or intervening area. Using natural runoff and areal precipitation for the partner area, Equation 6-2 is solved each month for CN and the magnitude of this CN, relative to the AMC_{II} CN, is used to adjust the AMC_{II} CN and obtain a calibrated CN for the ungaged or intervening area. This calibration procedure is necessary to justify application of SCS methods on a monthly rather than storm event basis. Potential intervening runoff is then calculated using Equation 6-2 with precipitation and the calibrated CN for the intervening area.

Following is an example illustrating the procedures used for estimating potential intervening runoff and calculating recharge for July, 1987 in the Blanco River Basin (see Table 6-2). The Blanco River is gaged upstream of the recharge zone near Wimberley (ID# 1710). The watershed area at this location is 355 square miles with an average (AMC_{II}) CN of 82.6. Utilizing relationships defined by the SCS, the AMC_{I} and AMC_{III} curve numbers were computed to be 66.60 and 91.61, respectively. The Blanco River is also gaged downstream of the recharge zone near Kyle (ID# 1713). The intervening area is 57 square miles and has an estimated AMC_{II} CN of 84.3 with corresponding AMC_{I} and AMC_{III} curve numbers of 69.28 and 92.51, respectively. Natural runoff from the watershed above Wimberley, which serves as the partner area for the intervening area, was 25,978 acre-feet (25,950 acre-feet gaged) or 1.37 inches for the month of July, 1987. Areal precipitation in July, 1987 totalled 4.13 inches and 2.80 inches for the upstream and intervening areas, respectively. Based on rainfall of 4.13 inches and the corresponding runoff volume of 1.37 inches, a CN of 69.32 which is between AMC_{I} and AMC_{II}, was calculated for the upstream gaged area. By interpolation, using the AMC_{I} and AMC_{II} curve numbers for the intervening

Table 6-2
Example Calculation of Potential Intervening Runoff for the Blanco River Basin

Data	Blanco River near Wimberley ID# 1710 (Partner Area)	Blanco River near Kyle ID# 1713 (Intervening Area)
Drainage Area	355 sq.mi.	57 sq.mi
AMC_{II} CN	82.60	84.30
AMC_{I} CN	66.60	69.28
AMC_{III} CN	91.61	92.51
July, 1987 Rainfall	4.13 inches	2.80 inches
July, 1987 Runoff	25,978 ac-ft[1]	2,086 ac-ft[2]
July, 1987 Runoff	1.37 inches	0.69 inches
July, 1987 CN	69.32[2]	71.87[4]

Notes:
1) Natural runoff at ID# 1710 of 25,978 ac-ft is the sum of 25,950 ac-ft (gaged) and 28 ac-ft (diversions).
2) Potential intervening runoff estimate. Actual gaged flow at ID# 1713, adjusted for diversions and return flows, was 26,450 ac-ft.
3) Computed CN based on rainfall and runoff of 4.13 inches and 1.37 inches, respectively.
4) Calibrated CN based on interpolation between AMC_{I} CN and AMC_{II} CN.

area, a CN of 71.87 was computed for the intervening area. Applying Equation 6-2 using monthly rainfall of 2.80 inches and the calibrated curve number of 71.87, a potential runoff estimate of 0.69 inches or 2,086 acre-feet was computed for the intervening area. The flow measured at the streamflow gage downstream of the recharge zone (ID# 1713) was 26,450 acre-feet after adjustments for diversions and return flows in the intervening area. This downstream flow represents the portion of total runoff originating upstream of the recharge zone and in the intervening area that did not contribute to recharge. The recharge estimate for the Blanco River Basin for July, 1987 was then computed by using Equation 6-1 expressed as:

$$R_{1713} = QG_{1710} + QI - QNH_{1713} \quad (6\text{-}3)$$

where:

R_{1713} = Recharge for Blanco River Basin;
QG_{1710} = Upstream Gaged Flow for Blanco River at Wimberley (ID# 1710);
QI = Potential Intervening Runoff for the Area Between Wimberley (ID# 1710) and Kyle (ID# 1713); and
QNH_{1713} = Downstream Flow for Blanco River at Kyle (ID# 1713) Adjusted for Intervening Diversions and Return Flows.

Inserting values for July, 1987 recharge was computed as:

$$R_{1713} = 25{,}950 + 2{,}086 - 26{,}450 = 1{,}586 \text{ ac-ft}$$

6.1.1 Blanco River Basin

Recharge in the Blanco River Basin was computed utilizing the streamflow gaging stations located upstream of the recharge zone near Wimberley (ID# 1710) and downstream of the recharge zone near Kyle (ID# 1713). The upstream gaging station was in service for the entire 1934-89 period while the downstream gaging station was in service only during the 1956-89 period. Streamflow at the downstream gaging station prior to 1956 was estimated by standard multiple linear regression techniques utilizing the upstream gaged flow and the estimated intervening runoff (see Table 4-3). Estimates of potential runoff for the 57 square mile intervening area over the recharge zone were made using the Blanco River watershed above Wimberley as a partner area.

Average annual recharge for the Blanco River Basin for the 1934-89 period was 27,018 ac-ft which represents 4.3 percent of the total average annual recharge to the Edwards Aquifer. The minimum annual recharge estimate was 12,224 ac-ft in 1956 and the maximum annual recharge estimate was 53,952 ac-ft in 1975.

6.1.2 Cibolo Creek Basin

Recharge in the Cibolo Creek Basin was computed utilizing the streamflow gaging stations located upstream of the recharge zone near Boerne (ID# 1839) and downstream of the recharge zone near Selma (ID# 1850). The upstream gaging station was in service for the 1962-89 period and the downstream gaging station was in service for the 1946-89 period. Streamflow at the upstream gaging station for the period prior to 1962 was estimated using relationships based on the intervening runoff for the Guadalupe River at Spring Branch (ID# 1765) and streamflow as measured on the Medina River near Pipe Creek (ID# 1790). Streamflow data at the downstream gaging station for the period prior to 1946 was estimated using estimated upstream gaged flow (ID# 1839) and potential runoff for the Cibolo Creek intervening area. Table 4-3 summarizes the methods used to predict the missing streamflow records. Estimates of potential runoff for the 205.6 square mile intervening area over the recharge zone were made using the Cibolo Creek watershed above Boerne as a partner area. Accuracy of recharge estimates prior to 1962 may be limited by the accuracy of estimated flows at the upstream and downstream gaging stations. The large difference in drainage area between the upstream partner area (68.4 sq.mi.) and the intervening area over the recharge zone (205.6 sq.mi.) may also affect the accuracy of recharge estimates for the Cibolo Creek Basin.

Average annual recharge for the Cibolo Creek Basin for the 1934-89 period was 63,880 ac-ft which represents 10.2 percent of the total average annual recharge to the Edwards Aquifer. The minimum annual recharge estimate was 1,683 ac-ft in 1956 and the maximum annual recharge estimate was 149,136 ac-ft in 1958.

6.1.3 Guadalupe River Basin

Recharge in the Guadalupe River Basin was computed using the streamflow gaging stations located upstream of the recharge zone near Sattler (ID# 1678) and downstream of the recharge zone at New Braunfels (ID# 1685). Streamflow records are available for the downstream gaging station for the 1934-89 period, however, records for the upstream gaging station exist only for the 1962-89 period. Streamflow at the upstream gaging station prior to 1962 was estimated using a relationship with the Guadalupe River at Spring Branch (ID# 1675) and the intervening runoff between the Spring Branch and Sattler gages (see Table 4-3). Intervening runoff estimates for the area over the recharge zone between the Sattler and New Braunfels gaging stations were developed utilizing the Blanco River watershed above Wimberley (ID# 1710) as a partner area.

In addition to upstream and downstream gaged flows and potential intervening runoff, there is an exchange of water or flux between the Edwards Aquifer and the Guadalupe River occurring in this reach which affects the calculation of recharge. Initially, it was theorized that Hueco Springs was the primary component of this flux, but literature review (Refs. 1 and 22) and preliminary regression analyses using periodic discharge measurements indicate that flows from Hueco Springs are probably influenced by a combination of local recharge, regional Edwards Aquifer levels, and possible flow from the Guadalupe River.

In order to obtain an estimate of historical and/or simulated recharge occurring in this reach, it was necessary to isolate the steady component of flux driven by regional Edwards Aquifer levels from the transient components associated with local recharge and flow from the Guadalupe River. It is expected that the regional Edwards Aquifer level flux component would be affected by changes from historical pumpage rates to a greater degree than would the transient, local components. Hence, estimates of Edwards Aquifer flux in this reach of the Guadalupe River were developed by subtracting downstream flow from upstream flow during each of the 94 months when intervening runoff was insignificant and flows in the previous month were below average. These estimates of flux were then correlated to the corresponding monthly average well level at the Bexar County Monitoring Well (J-17) resulting in a linear relationship of flux as a function of well level. A linear relationship was assumed based on similar linear relationships found for San Antonio, San Pedro, and Comal springflow as a function of J-17 level. The resulting relationship is plotted in Figure 6-2 and is expressed as:

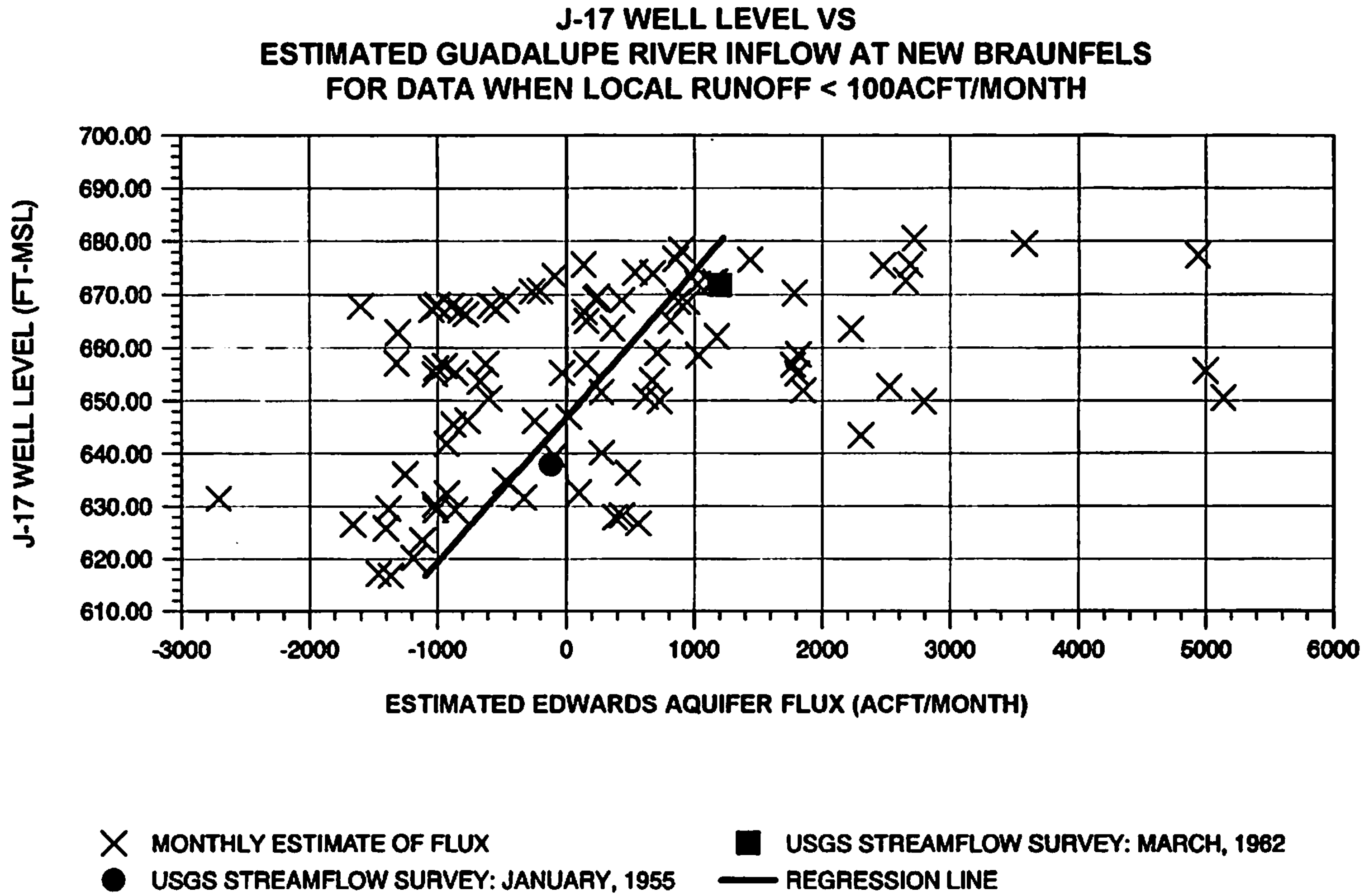
$$Q_E = 36.31\ (H_{J-17}) - 23{,}486 \qquad (6\text{-}4)$$

where:

Q_E = Edwards Aquifer Flux (ac-ft/month); and
H_{J-17} = Average Monthly J-17 Well Level (ft-msl).

Statistical significance of the regression equation and coefficients was confirmed by F and t tests (Ref. 4), respectively. The coefficient of determination (r^2), however, was 0.16 indicating that only 16 percent of the variation in flux is explained by the regression equation.

Streamflow surveys performed by the USGS (Refs. 38 and 40) for the reach between the Sattler and New Braunfels gaging stations were completed during January, 1955 and March, 1962. The average monthly J-17 well levels for these two periods were 637.8 ft-msl and 671.7 ft-msl, respectively. The January, 1955 streamflow survey showed a net loss



GUADALUPE-SAN ANTONIO RIVER BASIN
RECHARGE ENHANCEMENT STUDY

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ESTIMATED EDWARDS AQUIFER FLUX NEAR HUECO SPRINGS

FIGURE 6-2

of about 120 acre-feet per month (2 cfs) in the reach, while the March, 1962 streamflow survey showed a net gain of 1200 acre-feet per month (20 cfs). These two surveys are identified in Figure 6-2 and, in general, appear to support the derived relationship of J-17 well level versus Edwards Aquifer flux. The regression equation indicates that this segment of the Guadalupe River changes from a gaining to a losing reach with respect to water in the Edwards Aquifer when the J-17 well level falls below about 647 ft-msl.

Using the derived relationship, Edwards Aquifer flux was computed for each month during the 1934-89 period based on average monthly J-17 well levels. Recharge for the Guadalupe River Basin was then calculated using the following equation:

$$R_{1685} = QG_{1677} + QI - (QNH_{1685} - Q_E) \qquad (6\text{-}5)$$

where:

R_{1685} = Recharge for Guadalupe River Basin;
QG_{1677} = Upstream Gaged Flow for Guadalupe River at Sattler (ID# 1678);
QI = Potential Intervening Runoff for Area Between Sattler (ID# 1678) and New Braunfels (ID #1685);
QNH_{1685} = Downstream Flow for Guadalupe River at New Braunfels (ID# 1685) Adjusted for Intervening Diversions and Return Flows; and
Q_E = Edwards Aquifer Flux.

Average annual recharge for the Guadalupe River Basin for the 1934-89 period was 11,255 ac-ft which represents 1.8 percent of the total average annual recharge to the Edwards Aquifer. The minimum annual recharge estimate was 0 ac-ft in 1965 and 1977 and the maximum annual recharge estimate was 37,170 ac-ft in 1936. Accuracy of the Edwards Aquifer flux and recharge estimates for the Guadalupe River Basin may be somewhat limited by the accuracy of the flow estimates at Sattler during dry periods prior to 1962.

Even considering the maximum error possible in these flow estimates, recharge in the Guadalupe River Basin accounts for about 7.0 percent of the total recharge during 1956. Hence, the findings of this study do not support the past assumption that the Guadalupe River does not contribute recharge in significant quantities (Ref. 42). In fact, the findings of this study suggest that recharge from the Guadalupe River becomes increasingly significant when aquifer levels are lowered.

6.2 Recharge in Partially Gaged and Ungaged Basins

Partially gaged and ungaged areas which contribute to Edwards Aquifer recharge in the Guadalupe - San Antonio River Basin include portions of the Dry Comal, Salado, Leon, Helotes, Government, San Geronimo, Sink, Purgatory, York, and Alligator Creek watersheds. The last four of these areas have been grouped and are referenced herein as the Upper San Marcos River. All of these areas are headwater watersheds which lie primarily on the Edwards Aquifer recharge zone and have no gages located upstream of the recharge zone. Dry Comal and Salado Creeks are gaged at locations just below the downstream limits of the recharge zone, Helotes Creek has been gaged within the recharge zone in recent years, and the remaining watersheds listed above are ungaged in or near the recharge zone. Without upstream gage records, the calculation of recharge is highly dependent on estimates of potential runoff which reflect the soil types, slopes, and land use characteristics of each area. Hence, potential runoff in each of these areas was computed using the modified SCS procedure described in Section 6.1 which includes monthly calibration to an adjacent gaged watershed. Calculation of recharge in each of these partially gaged and ungaged watersheds is described in the following subsections.

6.2.1 Dry Comal Creek Basin

The Dry Comal Creek Basin is an area of about 130 square miles upstream of the USGS streamflow gaging station on the Comal River at New Braunfels (ID# 1690) the majority of which is located on the Edwards Aquifer recharge zone. Published records for this gaging station include the discharge of Comal Springs, however, the USGS has performed hydrograph separations on a daily basis throughout the entire 1934-89 study period to obtain estimates of surface runoff exclusive of springflow and provided these estimates to HDR. The surface runoff estimates were then adjusted by HDR to account for reported historical diversions and return flows. Potential runoff for the Dry Comal Creek Basin was estimated using the Blanco River watershed above Wimberley (ID# 1710) as a partner area and historical recharge was calculated in accordance with the following equation:

$$R_{1690} = QI_{1690} - QNH_{1690} \tag{6-6}$$

where:

R_{1690} = Recharge for Dry Comal Creek Basin;
QI_{1690} = Potential Runoff for Dry Comal Creek Basin; and
QNH_{1690} = Surface Runoff for Comal River at New Braunfels (ID# 1690) Adjusted for Upstream Diversions and Return Flows.

Average annual recharge for the Dry Comal Creek Basin for the 1934-89 period was 46,259 ac-ft which represents 7.2 percent of the total average annual recharge to the Edwards Aquifer. The minimum annual recharge estimate was 3,971 ac-ft in 1939 and the maximum annual recharge estimate was 121,146 ac-ft in 1973.

There are a total of five SCS/FRS located in the Dry Comal Creek Basin controlling runoff from 57.4 percent of the watershed with aggregate normal pool capacity of 709 ac-ft and active pool capacity of 18,265 ac-ft. Soil Conservation Service records indicate that these SCS/FRS were completed between June, 1956 and April, 1981. Clearly, the SCS/FRS have the effect of enhancing recharge through both direct percolation and steady release of impounded waters while performing their primary flood control function. The Dry Comal Creek Basin is the primary source of gaged surface runoff data for watersheds located directly over the Edwards Aquifer recharge zone in the Guadalupe - San Antonio River Basin and is an important partner area. For this reason, it was necessary to remove the SCS/FRS effects from the gaged data and obtain estimates of natural recharge which could be used to estimate recharge in ungaged basins. Furthermore, it was necessary to simulate the effects of these structures as if they were in place throughout the study period in order to obtain recharge and streamflow baselines for the consideration of potential recharge enhancement projects.

In order to assess the recharge characteristics of the SCS/FRS, it was postulated that historical recharge (R) is comprised of natural recharge (R_N) and additional components associated with the normal pool (R_{NP}) and active pool (R_{AP}) as defined in the following equations (in which, for clarity, the control point ID# 1690 is not shown):

$$R = R_N + R_{NP} + R_{AP} \tag{6-7}$$

$$R_{NP} = c_1(A_c/A)(QI - R_N) \leq c_{NP}\ (NP) \tag{6-8}$$

$$R_{AP} = c_2[(A_c/A)(QI - R_N) - R_{NP}] \leq c_{AP}\ (AP) \tag{6-9}$$

where:

R = Historical Recharge;
R_N = Natural Recharge;
R_{NP} = SCS/FRS Normal Pool Recharge;
R_{AP} = SCS/FRS Active Pool Recharge;
QI = Potential Runoff;
A_c = Watershed Area Controlled;
A = Total Watershed Area;
c_{NP} = Normal Pool Recharge Coefficient;
c_{AP} = Active Pool Recharge Coefficient;
NP = Aggregate Normal Pool Storage; and
AP = Aggregate Active Pool Storage.

Assuming that potential runoff, historical recharge, area controlled, and SCS/FRS physical characteristics were known for the 1956-89 period, reasonable estimates for natural recharge and the recharge coefficients were sought in the following manner. First, an approximation of natural monthly recharge for the 1956-89 period was obtained from a linear regression relationship between natural and potential runoff based on available data prior to SCS/FRS construction. The normal pool recharge coefficient was assumed equal to 1.0 which implies that 100 percent of water impounded within the normal pools of the SCS/FRS will contribute to recharge neglecting evaporation. Historical monthly recharge was then computed based on the postulated equations using various assumed values for the active pool recharge coefficient. An assumed active pool recharge coefficient of 0.70 resulted in the least error in estimating historical recharge during the 1981-89 period when all structures were in place. This result indicates that approximately 70 percent of the runoff temporarily impounded by the SCS/FRS ultimately contributes to recharge neglecting evaporation. Hence, normal and active pool recharge coefficients of 1.00 and 0.70, respectively, were adopted for the Dry Comal Creek Basin SCS/FRS and consistent monthly estimates of natural recharge and runoff were computed using Equations 6-6 through 6-9.

6.2.2 Salado Creek Basin

The Salado Creek Basin is an area of about 137 square miles upstream of the USGS streamflow gaging station on Salado Creek (Upper Station) at San Antonio (ID# 1787) the majority of which is located on the Edwards Aquifer recharge zone. Available gaged streamflows for the 1960-89 period were adjusted for reported upstream diversions and return flows and potential runoff was estimated using the Blanco River watershed above Wimberley (ID# 1710) as a partner area. The curve number used in the estimation of potential runoff for the Salado Creek was increased with respect to time to reflect the gradual urbanization of the watershed. Historical recharge for the 1960-89 period was computed in accordance with the following equation:

$$R_{1787} = QI_{1787} - QNH_{1787} \qquad \textbf{(6-10)}$$

where:

R_{1787} = Recharge for Salado Creek Basin;
QI_{1787} = Potential Runoff for Salado Creek Basin; and
QNH_{1787} = Surface Runoff for Salado Creek at San Antonio (ID# 1787) Adjusted for Upstream Diversions and Return Flows.

Historical recharge for the 1934-59 period when gaged streamflow records on Salado Creek are unavailable was computed using the following equation:

$$R_{1787} = QI_{1787}(R_{N\,1690}/QI_{1690}) \qquad \textbf{(6-11)}$$

where:

$R_{N\,1690}$ = Natural Recharge for Dry Comal Creek Basin; and
QI_{1690} = Potential Runoff for Dry Comal Creek Basin.

Average annual recharge for the Salado Creek Basin for the 1934-89 period was 44,014 ac-ft which represents 6.9 percent of the total average annual recharge to the Edwards Aquifer. The minimum annual recharge estimate was 6,783 ac-ft in 1955 and the maximum annual recharge estimate was 117,150 ac-ft in 1973.

As of 1989, there were a total of 12 SCS/FRS located in the Salado Creek Basin controlling runoff from 58.7 percent of the watershed with aggregate normal pool capacity of 1809 ac-ft and active pool capacity of 28,847 ac-ft. Soil Conservation Service records indicate that these SCS/FRS were completed between March, 1971 and April, 1987. These structures as well as one additional SCS/FRS completed in December, 1991 have the effect of enhancing recharge through both direct percolation and steady release of impounded waters while performing their primary flood control function. For reasons identical to those stated with respect to Dry Comal Creek (Section 6.2.1), it was necessary to quantify and remove the SCS/FRS effects and obtain monthly estimates of natural streamflow and recharge. Employing the methodology described for the Dry Comal Creek Basin, an active pool coefficient of 0.63 resulted in the least error in estimating historical recharge during the 1971-80 period before urbanization significantly affected the Salado Creek watershed. Hence, normal and active pool recharge coefficients of 1.00 and 0.63, respectively, were adopted for the Salado Creek Basin SCS/FRS and consistent monthly estimates of natural recharge and runoff were computed.

6.2.3 Upper San Marcos River Basin

The Upper San Marcos River recharge basin includes Sink and Purgatory Creeks which feed the headwaters of the San Marcos River near San Marcos Springs, as well as the portion of York and Alligator Creek watersheds over the recharge zone. No gaged streamflow data has been published for the basin, therefore, natural recharge that occurred in this basin was estimated using the relationship of natural recharge to potential runoff in the nearby Dry Comal Creek Basin. Potential runoff estimates for the Upper San Marcos River Basin were developed by application of modified SCS procedures and Equation 6-2 using the Blanco River watershed above Wimberley (ID# 1710) as a partner area. Natural recharge in the Upper San Marcos River Basin was computed using the following equation:

$$R_{N\,1700} = QI_{1700}\left(\frac{R_{N\,1690}}{QI_{1690}}\right) \tag{6-12}$$

where:

$R_{N\,1700}$ = Natural Recharge for Upper San Marcos River Basin;
QI_{1700} = Potential Runoff for Upper San Marcos River Basin;
$R_{N\,1690}$ = Natural Recharge for Dry Comal Creek Basin; and
QI_{1690} = Potential Runoff for Dry Comal Creek Basin.

Six SCS/FRS were constructed on the recharge zone in the Upper San Marcos River Basin during the 1963-89 period which provide a total of 751 ac-ft of normal pool storage and 20,926 ac-ft of active pool storage. Historical recharge enhancement due to SCS/FRS in the Upper San Marcos River Basin was estimated by application of techniques developed for assessment of SCS/FRS in the Dry Comal and Salado Creek watersheds. Normal and active pool coefficients of 1.00 and 0.70, respectively, were used. Natural recharge was combined with estimated recharge enhancement due to the SCS/FRS to obtain the total historical recharge for the Upper San Marcos River Basin.

Historical recharge in the Upper San Marcos River Basin during the 1934-89 period averaged 37,505 ac-ft/yr, comprising 5.8 percent of the total average annual recharge to the Edwards Aquifer. The minimum annual recharge estimate was 3,868 ac-ft in 1939 and the maximum annual recharge estimate was 92,668 ac-ft in 1981.

6.2.4 Leon, Helotes, Government, and San Geronimo Creeks

Recharge estimates for the portions of the Leon, Helotes, Government, and San Geronimo Creek watersheds upstream and over the recharge zone were developed for the 1934-89 period. These watersheds were ungaged during the study period, with the exception of Helotes Creek which was gaged (ID# 1814) during the 1968-89 period. Recharge estimates were developed by considering the basins as a group and included the intervening area over the recharge zone between Medina Lake and Diversion Lake and the subwatersheds over the recharge zone adjacent to the Diversion Lake watershed. The combined area totals 193 square miles of which 106 square miles is upstream of the recharge zone and 87 square miles is on the recharge zone. Composite curve numbers were determined for the areas upstream of and on the recharge zone and monthly potential runoff estimates were developed for both of these areas using the Cibolo Creek watershed near Boerne (ID# 1839) as a partner area.

For the area on the recharge zone, recharge was computing using the ratio of natural recharge to potential runoff for the Salado Creek Basin expressed as follows:

$$R_{NZ} = QI_Z \left(\frac{R_{N\,1787}}{QI_{1787}} \right) \qquad (6\text{-}13)$$

where:

R_{NZ} = Natural Recharge for Area On Recharge Zone;
QI_Z = Potential Runoff for Area On Recharge Zone;
$R_{N\,1787}$ = Natural Recharge for Salado Creek Basin; and
QI_{1787} = Potential Runoff for Salado Creek Basin.

For the area upstream of the recharge zone, recharge during the 1968-89 period was computed utilizing measured data from the Helotes Creek gaging station (ID# 1814). The Helotes Creek gaging station measures runoff from an area that is predominantly upstream of the recharge zone, but overlies the recharge zone in the vicinity of the gage. Using the Cibolo Creek watershed near Boerne (ID# 1839) as a partner area, monthly potential runoff estimates were developed for the Helotes Creek watershed. Recharge for the Helotes Creek Basin was computed as the difference between potential and measured runoff at the gaging station. The monthly ratio of recharge to potential runoff for the Helotes Creek Basin was then used to compute recharge for the entire 106 square mile area upstream of the recharge zone in accordance with the following equation:

$$R_U = QI_U \left(\frac{R_{1814}}{QI_{1814}} \right) \qquad (6\text{-}14)$$

R_U = Recharge for Area Upstream of Recharge Zone;
QI_U = Potential Runoff for Area Upstream of Recharge Zone;
R_{1814} = Recharge for Helotes Creek Basin; and
QI_{1814} = Potential Runoff for Helotes Creek Basin.

For the period prior to 1968, when the Helotes Creek gaging station was not in service, recharge estimates for the area upstream of the recharge zone were based on respective averages developed for the Helotes and Salado Creek Basins. For the 1968-89 period, recharge in the Helotes Creek Basin averaged about 61 percent of potential runoff while natural recharge averaged about 85 percent of potential runoff in the adjacent Salado Creek Basin. Therefore, the ratio of recharge to potential runoff for the area upstream of the recharge zone (including the Helotes Creek Basin) averaged about 71 percent (61/85) of that for the Salado Creek Basin. This percentage was used to compute monthly recharge estimates for the area upstream of the recharge zone for the 1934-67 period based on natural recharge and potential runoff in the adjacent Salado Creek Basin in accordance with the following equation:

$$R_U = 0.71\ QI_U \left(\frac{R_{N\,1787}}{QI_{1787}} \right) \qquad \textbf{(6-15)}$$

where:

R_U = Recharge for Area Upstream of Recharge Zone;
QI_U = Potential Runoff for Area Upstream of Recharge Zone;
$R_{N\,1787}$ = Natural Recharge for Salado Creek Basin; and
QI_{1787} = Potential Runoff for Salado Creek Basin.

San Geronimo Creek Dam was constructed at the downstream edge of the recharge zone by the Edwards Underground Water District for the purpose of enhancing recharge to the Edwards Aquifer. Incremental recharge provided by this structure was obtained from TWC monthly water use reports prepared by the EUWD and added to the recharge estimates computed for the areas upstream of and on the recharge zone.

Average annual recharge for the Leon, Helotes, Government and San Geronimo Creek Basins for the 1934 - 89 period was 44,260 ac-ft which represents 6.9 percent of the total average annual recharge to the Edwards Aquifer. The minimum annual recharge estimate was 2,056 acre-feet in 1955 and the maximum annual recharge estimate was 109,881 acre-feet in 1986.

6.3 Medina and Diversion Lakes

Estimation of monthly Edwards Aquifer recharge occurring at Medina and Diversion Lakes is very different from the procedures used in other watersheds as it is based on relationships with reservoir stages. Medina and Diversion Lakes have been in place throughout the 1934-89 study period and have been operated primarily to supply water for irrigation through a distribution canal beginning at Diversion Lake. In addition to diversions for water supply and net evaporation losses, storage in these reservoirs is affected by percolation or recharge as well as leakage through the dams. It was assumed that reasonable estimates of recharge, leakage, and net evaporation could be based on the elevation or water surface area associated with the average reservoir contents in each month.

Key records used in the calculation of historical recharge include Medina Lake contents (1913-89) and gaged flows for the Medina River at Riomedina (ID# 1805) (1953-73) and for the Medina Canal (1922-35, 1957-89). Additional diversion records for the Medina Canal were obtained from an Espey, Huston & Associates, Inc. (EH&A) report (Ref. 9) for the 1940-56 period and estimated by HDR for the 1935-39 period. Elevation-area-capacity tables for Medina and Diversion Lakes were obtained from published reports (Refs. 25 and 35) and are included in Appendix H (Volume III).

Calculation of historical monthly recharge at Medina Lake and leakage at Medina Dam was accomplished using the reservoir stage associated with average monthly contents and recharge and leakage curves developed by EH&A (Ref. 9). Historical recharge at Diversion Lake, however, was somewhat more difficult to calculate in the absence of contents records. When gaged streamflow records were available for the Medina River at Riomedina (ID# 1805), they were assumed equal to the sum of leakage and spills from Diversion Lake, average monthly lake level was estimated from the EH&A leakage curve, and recharge was calculated from the EH&A recharge curve using the average lake level. When gaged streamflows were not available below Diversion Dam, average monthly lake level was estimated by iterative mass balance calculations considering runoff below Medina Dam, leakage and releases from Medina Lake, Medina Canal diversions, and net evaporation losses. Releases from Medina to Diversion Lake were based on the operational objective of maintaining Diversion Lake at a level about five feet below the spillway during irrigation season to minimize losses and maintain diversion efficiency.

Average annual recharge at Medina and Diversion Lakes for the 1934-89 period was 41,833 ac-ft which represents 6.5 percent of the total average annual recharge of the Edwards Aquifer. Approximately 64 percent of the historical average recharge is attributable to Medina Lake. The minimum annual recharge estimate was 10,256 ac-ft in 1951 and the maximum annual recharge estimate was 53,275 ac-ft in 1936.

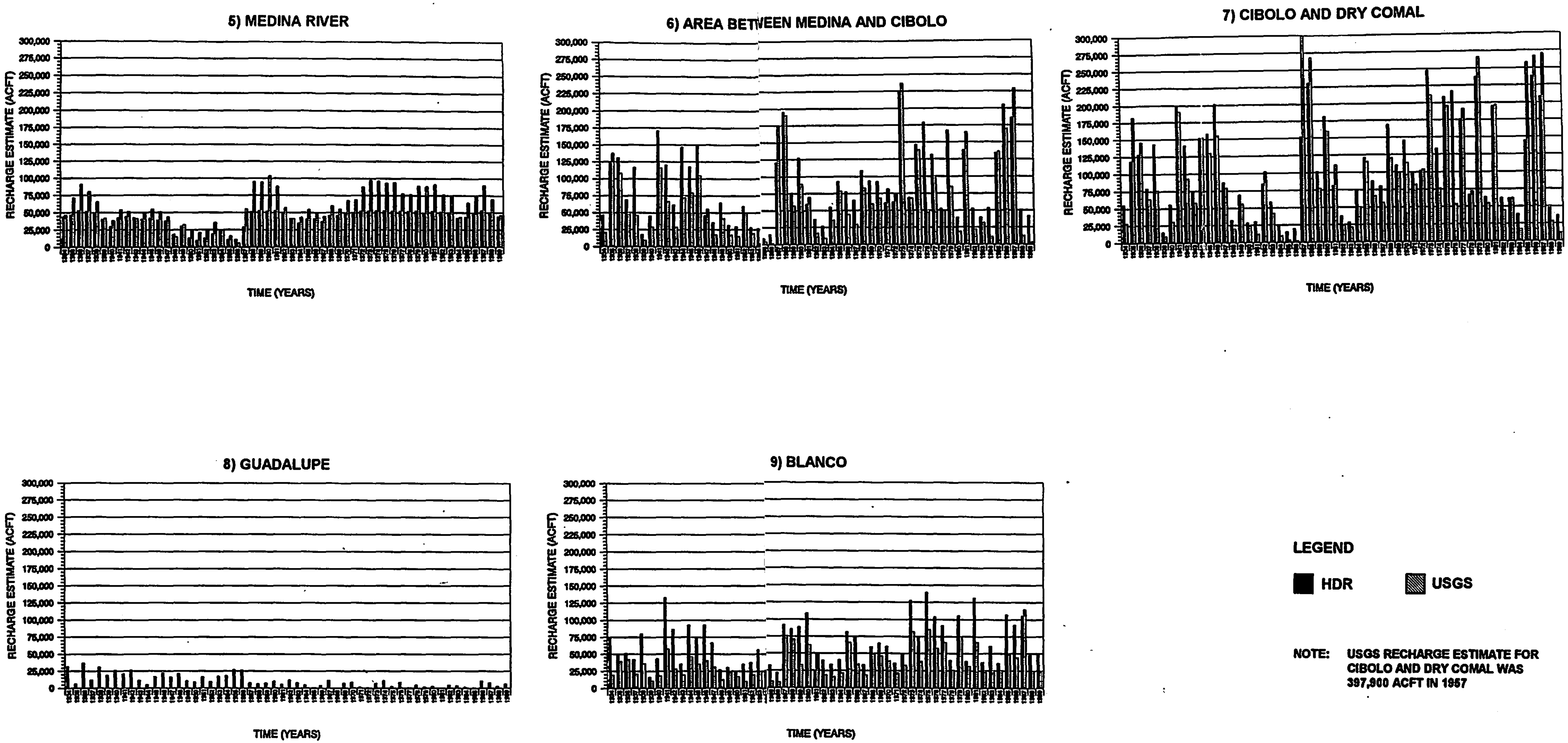
6.4 Comparison of Edwards Aquifer Recharge Estimates

Historical Edwards Aquifer recharge estimates for the watersheds within the Guadalupe - San Antonio River Basin were compared to the USGS recharge estimates for the 1934-89 period. This comparison revealed that the USGS average recharge estimate of 270,000 ac-ft/yr is about 15 percent less than the average of 316,000 ac-ft/yr computed by HDR. Although this difference in the long-term average is only marginally significant considering the complexity of the physical processes involved, important differences do exist in the geographical distribution of recharge among the various recharge basins.

In order to understand the differences between the USGS and HDR estimates, key methodologies and assumptions must be considered. The principal difference between the HDR and USGS methods of calculating recharge is in estimating potential runoff directly over the recharge zone. Reasonable estimates of flow in this area are necessary to accurately calculate recharge. The methods employed by the USGS assume that potential runoff over the recharge zone is equal to runoff from the area upstream of the recharge zone (or other partner area) adjusted for drainage area size and precipitation differences if precipitation differs by more than 20 percent. More specifically, USGS methods assume that runoff varies linearly with precipitation when adjusting for precipitation differences and that soil-cover complex is identical in both the area upstream of and the area directly over the recharge zone. Methods applied by HDR are based on Soil Conservation Service (SCS) procedures which account for differences in soil-cover complex as well as differences in rainfall regardless of relative magnitude. Other general differences between the HDR and USGS methodologies include consideration of historical diversions and return flows. HDR accounts for such diversions and return flows, while the USGS does not. Selections of partner areas for use in estimating the potential runoff for intervening or ungaged areas also differ for some recharge basins.

Figure 6-3 presents a comparison of annual HDR and USGS recharge estimates for the 1934-89 period for each of the five recharge basins identified in Plate 1. Recharge estimated by the USGS in the Medina River Basin averaged 45.3 percent higher than the average of 41,833 ac-ft/yr computed by HDR. Both sets of recharge estimates for the Medina River Basin are based on stage-recharge relationships for Medina and Diversion Lakes. The recharge estimates computed by HDR were based on stage-recharge relationships developed by Espey, Huston and Associates (Ref. 9) which have been shown to reasonably approximate historical lake levels at Medina Lake, while the USGS recharge estimates were based on stage-recharge relationships developed by Lowry (Ref. 42). USGS recharge estimates were higher than HDR estimates due to the differences in the stage-recharge relationships used.

Recharge estimated by the USGS for the area between the Medina River and Cibolo Creek averaged 23.3 percent lower than the average of 88,274 ac-ft/yr computed by HDR. This area includes the Leon, Helotes, Government, San Geronimo, and Salado Creek Basins. HDR also included the intervening area between Medina Lake and Diversion Lake in this basin which, in part, accounts for the higher recharge estimates computed by HDR. It is noted that neither HDR or the USGS (Ref. 42) included an area of about 12 square miles over the Edwards Aquifer recharge zone in the Medina Lake watershed in the recharge calculations. If this area were considered and experienced recharge comparable



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RECHARGE ENHANCEMENT STUDY

COMPARISON OF HISTORICAL RECHARGE ESTIMATES FOR FIVE RECHARGE BASINS

FIGURE 6-3

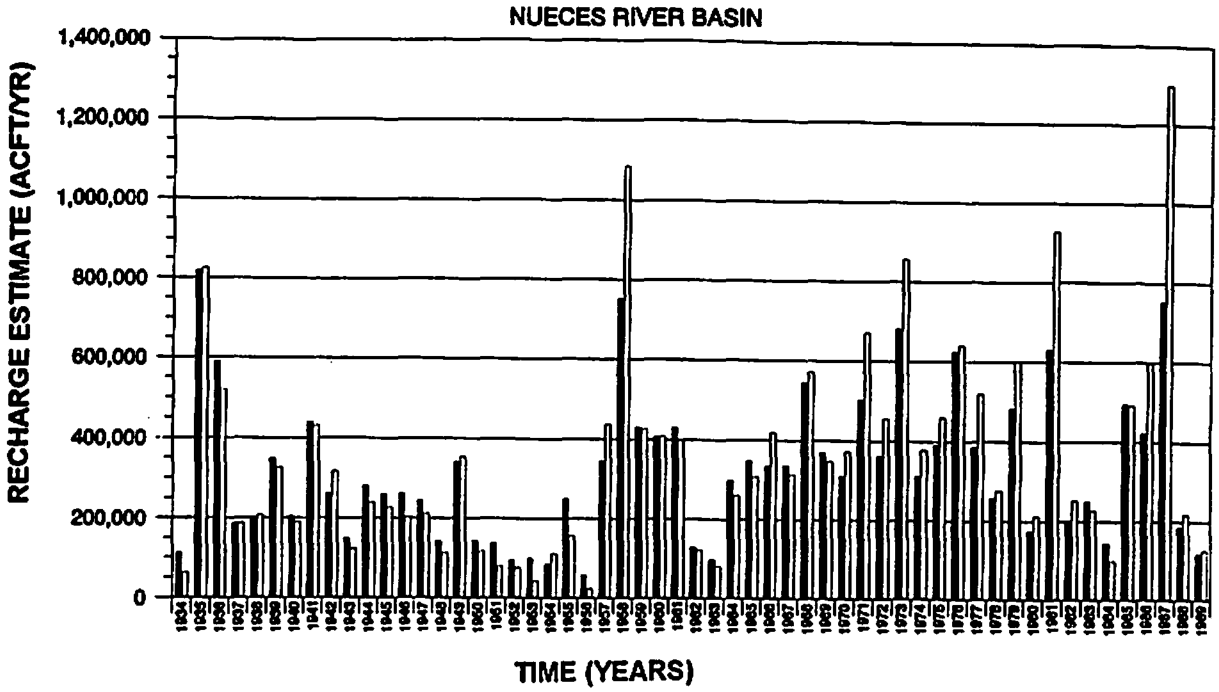
to adjacent watersheds over the recharge zone, HDR estimates of average annual recharge to the entire Edwards Aquifer might be increased by about 3,000 ac-ft (0.46 percent). Other differences in methodology include an accounting for enhanced recharge due to existing structures in the San Geronimo and Salado Creek Basins and the inclusion of urbanization effects on potential runoff in the Salado Creek Basin by HDR. All of these factors contribute to HDR producing higher average annual recharge estimates for this basin than the USGS.

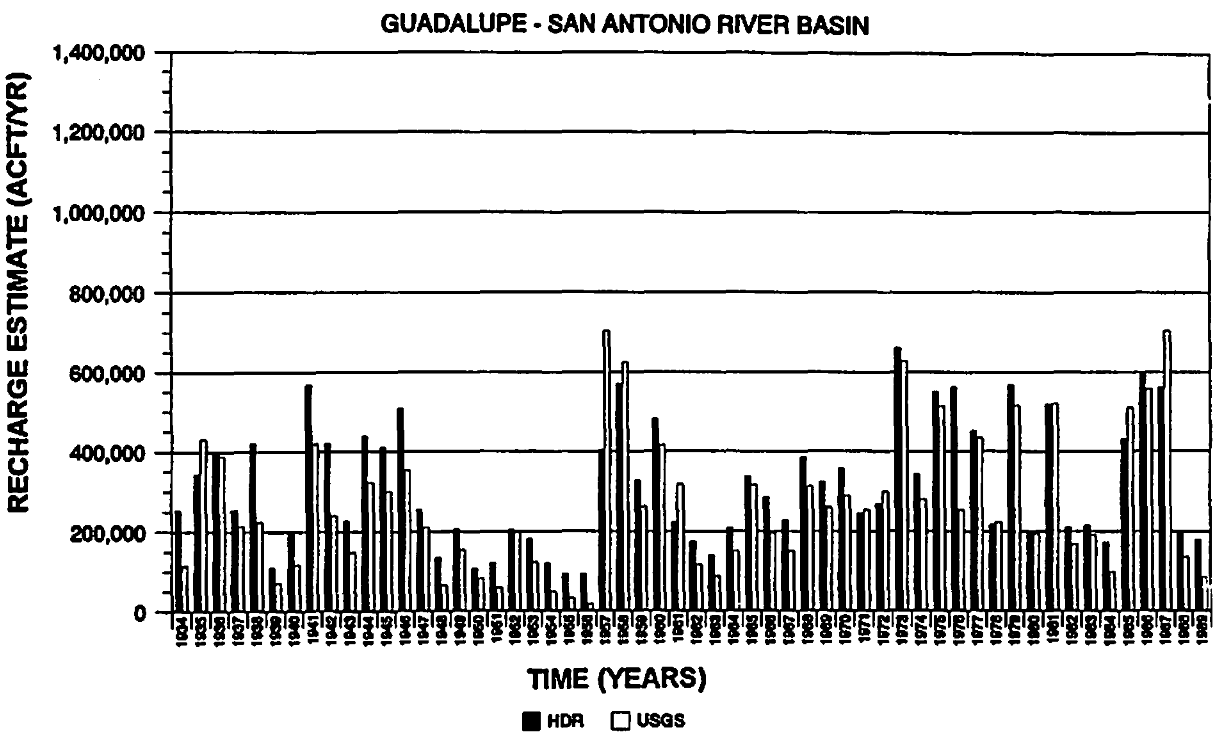
HDR and USGS average annual recharge estimates for the Cibolo Creek and Dry Comal Creek Basin differ significantly, especially during drought periods. The average recharge estimate of 104,045 ac-ft/yr by the USGS was 5.5 percent lower than the 110,139 ac-ft/yr average recharge estimate computed by HDR. During the 1947 to 1956 drought period, average USGS recharge was 35,250 ac-ft/yr which is 21.8 percent less than the HDR average of 45,050 ac-ft/yr. Large differences were evident during wet years where the USGS recharge estimates were, in many cases, substantially higher than those computed by HDR. The higher HDR average recharge estimate for this basin is partially attributed to HDR accounting for enhanced recharge due to existing structures in the Dry Comal Creek Basin and due to a difference in selection of partners areas for intervening runoff estimates. For the Dry Comal Creek Basin, the USGS used the intervening area for the Guadalupe River between Canyon Lake and New Braunfels (ID# 1685) as a partner area while the Blanco River watershed near Wimberley (ID# 1710) was used in the HDR estimates. The intervening area between Canyon Lake and New Braunfels lies primarily over the recharge zone which may produce lower estimates of potential runoff resulting in lower recharge estimates for the Dry Comal Creek Basin by the USGS.

In the Guadalupe River Basin, below Canyon Lake and above New Braunfels, recharge estimates were computed only by HDR. The USGS considers recharge to be insignificant in this reach. Although, the average recharge of 11,255 ac-ft/yr in the Guadalupe River Basin is not great, it can be a significant component of Edwards Aquifer recharge when aquifer levels are low.

HDR and USGS average annual recharge estimates for the Blanco River Basin, which includes the Blanco and Upper San Marcos River Basins, were significantly different. Average recharge of 37,758 ac-ft/yr estimated by the USGS was 41.5 percent lower than the average of 64,523 ac-ft/yr computed by HDR. During the 1947-56 drought period, recharge estimated by the USGS averaged 17,030 ac-ft/yr, some 53.0 percent less than the HDR average of 36,260 ac-ft/yr. The difference in the recharge estimates is partially attributable to HDR accounting for recharge enhancement due to existing SCS/FRS and to the selection of partner areas. Similarly to the Dry Comal Creek Basin, the USGS used the intervening area for the Guadalupe River between Canyon Lake and New Braunfels (ID# 1685) as one of their partner areas, while HDR used the Blanco River Watershed near Wimberley (ID# 1710). Utilizing the Guadalupe River intervening area which is over the recharge zone is believed to produce low potential runoff estimates resulting in lower recharge estimates by the USGS.

Figure 6-4 presents a comparison of the historical Edwards Aquifer recharge computed by the USGS and HDR for the Guadalupe - San Antonio River Basin and also for the Nueces River Basin, which was previously studied by HDR (Ref 14). Table 6-3





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RECHARGE ENHANCEMENT STUDY

COMPARISON OF HISTORICAL EDWARDS AQUIFER RECHARGE BY RIVER BASIN

FIGURE 6-4

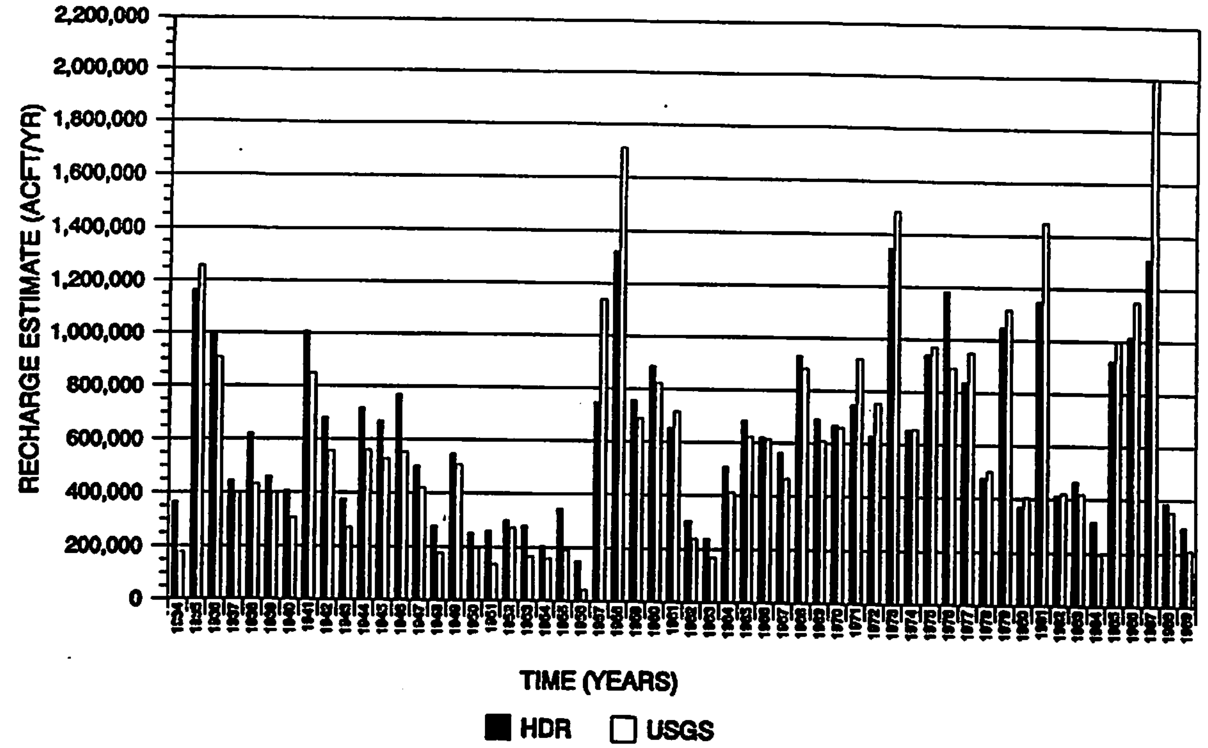
and Appendix I (Volume III) present the geographical distribution of estimated average annual recharge for various recharge basins within the Nueces, San Antonio, and Guadalupe River Basins. It is interesting to note that the recharge estimated by HDR for the Nueces River Basin proved to be consistently lower than the recharge reported by the USGS. This was also the case in the westernmost watershed of the Guadalupe - San Antonio River Basin (Medina River). However, in the eastern watersheds, the HDR recharge estimates were substantially higher than the USGS estimates.

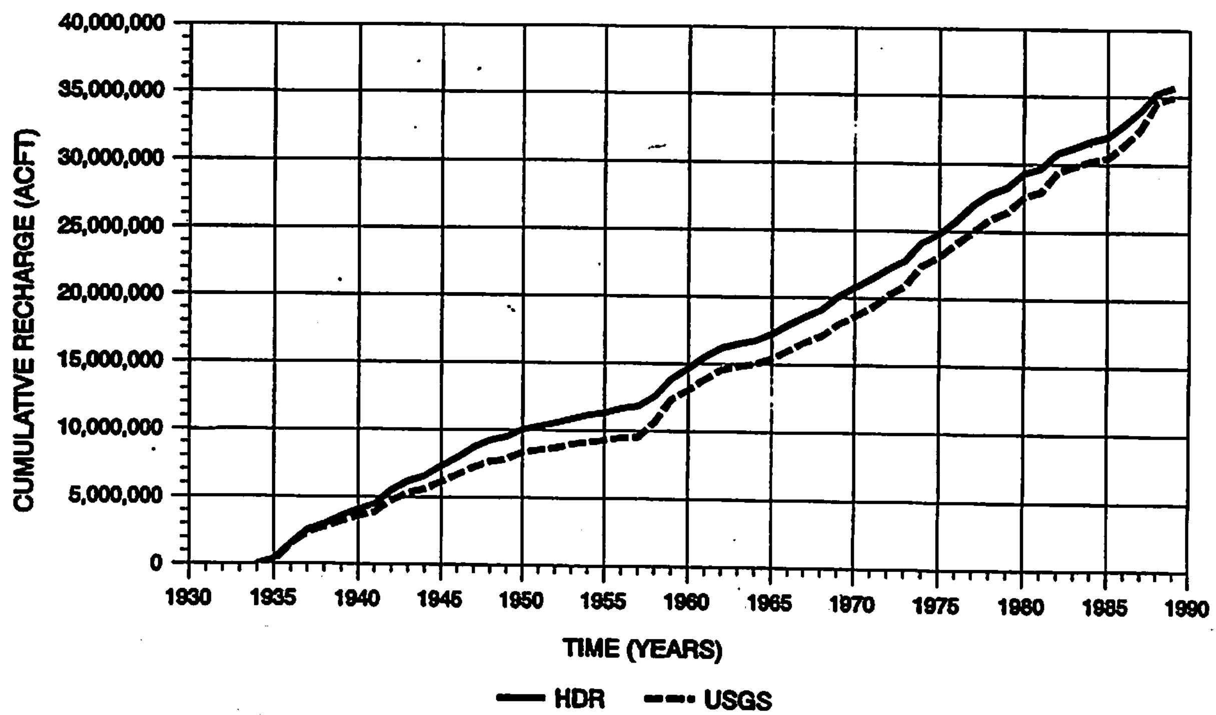
The modified geographical distribution of historical recharge reflected in the HDR estimates could have a significant effect on calibration of existing Edwards Aquifer models. The Texas Water Development Board (TWDB) used the HDR recharge estimates instead of the USGS estimates in various simulations to assess the effects of these new recharge estimates might have on the predictive capability of the TWDB Edwards Aquifer Model. Preliminary comparisons of simulated versus actual Bexar County monitoring well (J-17) levels and Comal and San Marcos springflows obtained from the TWDB model using the HDR recharge estimates generally show improved correlation as compared to simulations using the USGS recharge estimates. Additional improvement in simulated versus actual performance would be expected if the TWDB model were re-calibrated using the new recharge estimates.

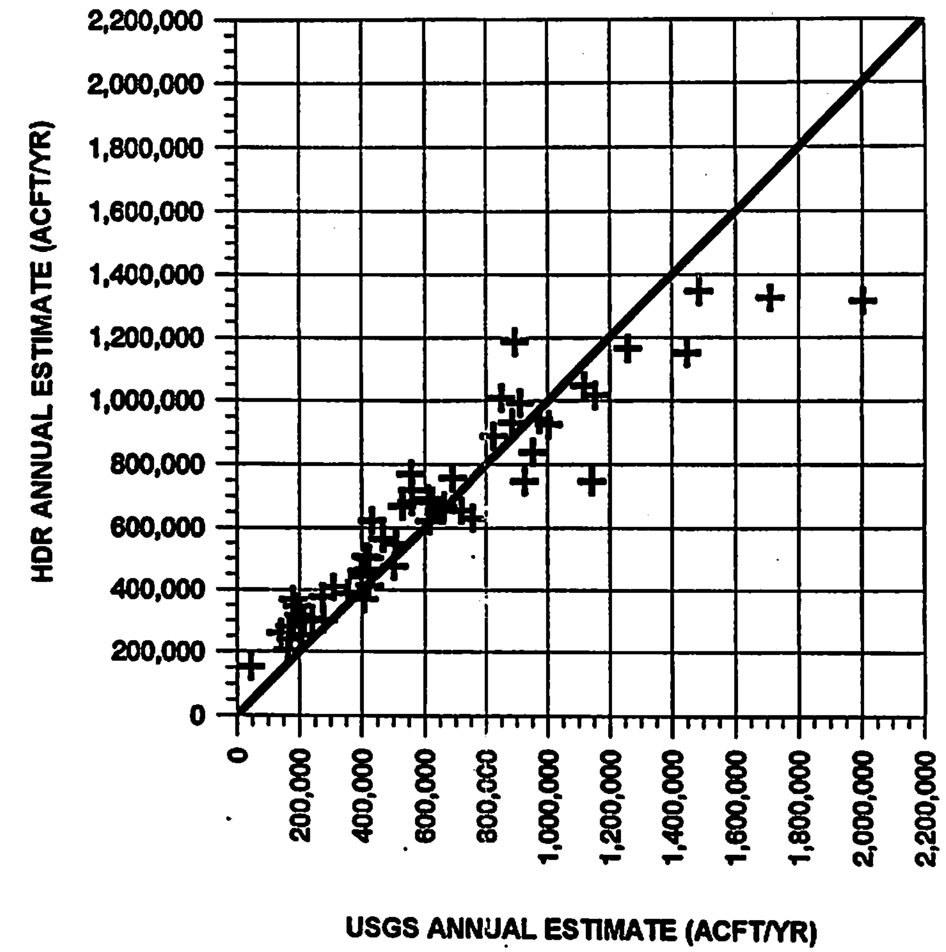
River Basin	Recharge Basin	HDR Recharge Estimate (Ac-Ft/Yr)	USGS Recharge Estimate (Ac-Ft/Yr)	Difference (Ac-Ft/Yr)	Percent Difference
Nueces	1. Nueces - W. Nueces	88,744	104,509	15,765	17.8%
	2. Frio - Dry Frio	111,739	117,454	5,715	5.1%
	3. Sabinal	32,581	38,307	5,726	17.6%
	4. Between Sabinal & Medina	92,998	97,404	4,406	4.7%
	SUBTOTAL	326,062	357,674	31,612	9.7%
San Antonio	5. Medina	41,833	60,780	18,947	45.3%
	6. Between Medina & Cibolo	88,274	67,705	-20,569	-23.3%
	7. Cibolo - Dry Comal	110,139	104,045	-6,094	-5.5%
	SUBTOTAL	240,246	232,530	-7,716	-3.2%
Guadalupe	8. Guadalupe	11,255	0	-11,255	-100.0%
	9. Blanco	64,523	37,758	-26,765	-41.5%
	SUBTOTAL	75,778	37,758	-38,020	-50.2%
	TOTAL	642,086	627,962	-14,124	-2.2%

Table 6-3
Summary of Historical Edwards Aquifer Recharge by Basin

Figure 6-5 presents three comparisons of total recharge to the Edwards Aquifer, including both the Nueces and Guadalupe - San Antonio River Basins. This comparison shows that the previous USGS estimate of about 628,000 ac-ft/yr for the entire aquifer is about two percent lower than the estimate of about 642,000 ac-ft/yr computed by HDR. However, for individual watersheds in the eastern sections of the aquifer, the differences are much more significant with the largest difference occurring in the Guadalupe and Blanco River Basins where the average USGS recharge estimate is about 50 percent less than the HDR estimate. Considering the proximity of these eastern watersheds to Comal and San Marcos Springs, the disparate recharge estimates could have a significant effect on efforts







GUADALUPE-SAN ANTONIO RIVER BASIN
RECHARGE ENHANCEMENT STUDY

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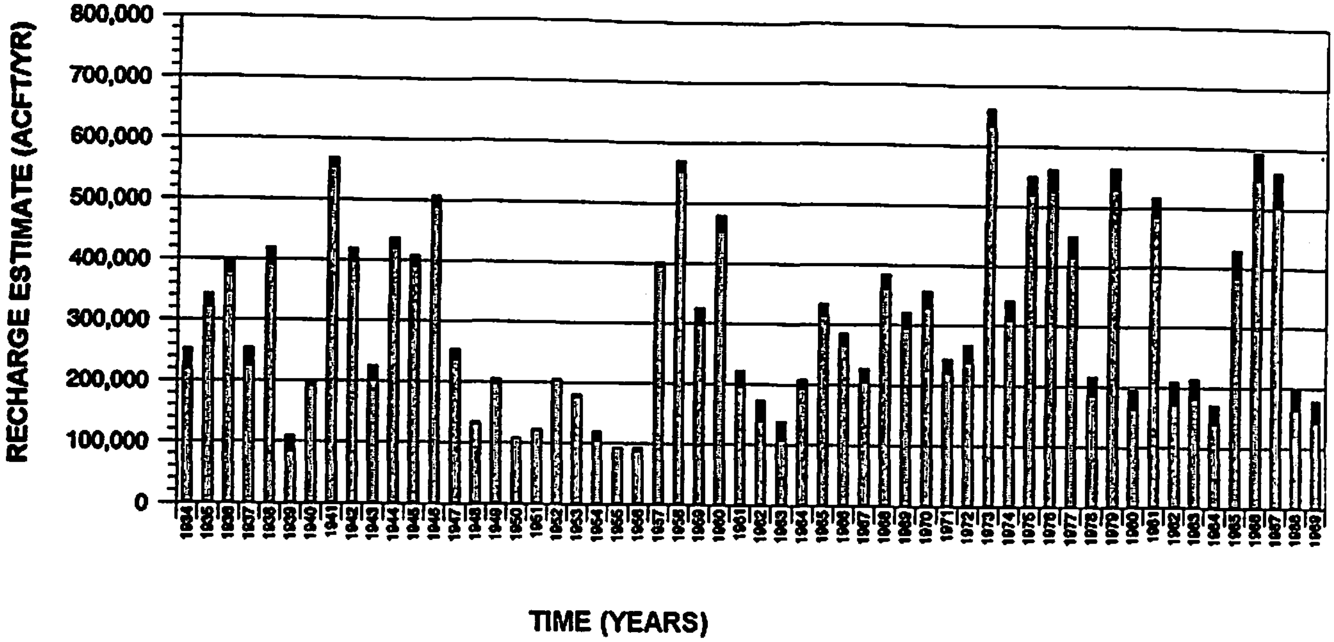
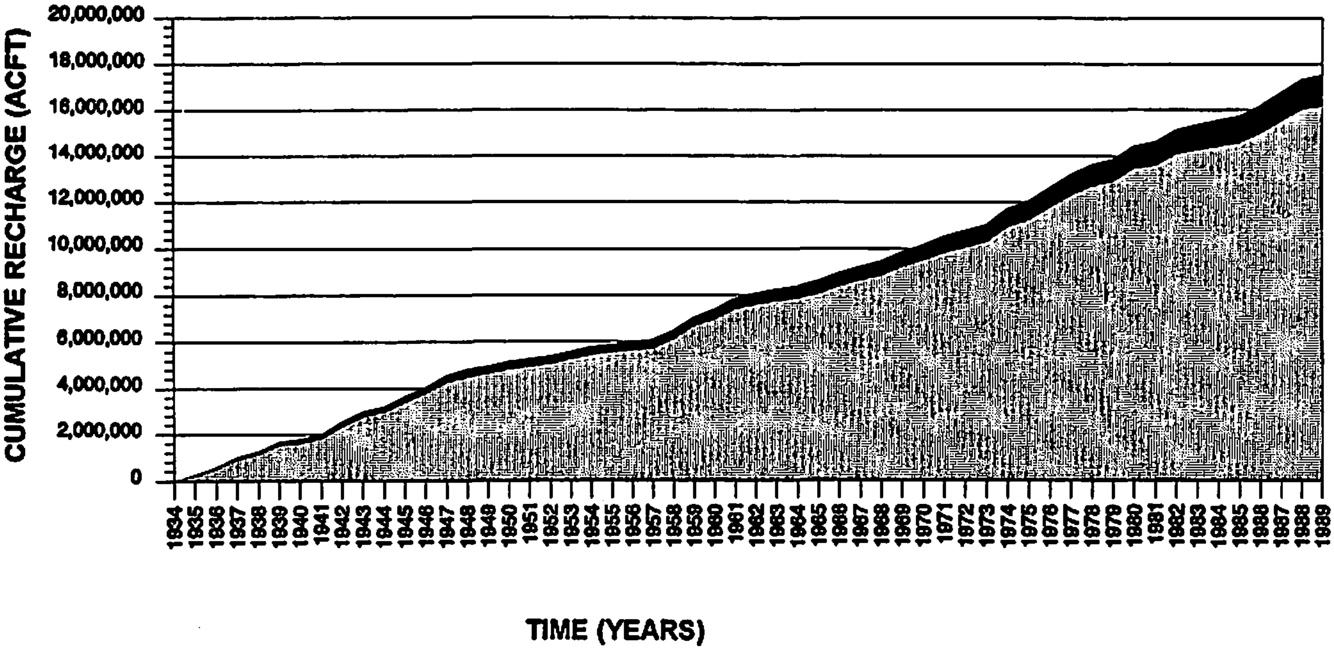
COMPARISON OF HISTORICAL EDWARDS AQUIFER RECHARGE

FIGURE 6-5

to accurately predict springflows. Overall, the USGS annual recharge estimates are lower than the estimates computed by HDR for dry and average years; however, for wet years, the USGS estimates are significantly higher than the HDR estimates.

Throughout the historical period, various reservoir structures have been constructed in the Guadalupe - San Antonio River Basin atop the Edwards Aquifer recharge zone which have enhanced the natural recharge to the aquifer. These structures include Medina Lake (constructed in 1911), San Geronimo Creek Dam, and various SCS Flood Retardation Structures (SCS/FRS) in the Salado Creek, Dry Comal Creek and Upper San Marcos River (including York Creek) watersheds. An estimate of the natural recharge to the Edwards Aquifer in the Guadalupe - San Antonio River Basin was developed in order to approximate the effects of these structures. The average annual natural recharge in the Guadalupe River Basin is estimated to be about 291,000 ac-ft as compared to the historical recharge of about 316,000 ac-ft, an 8.6 percent increase. Figure 6-6 traces the annual and cumulative historical recharge in the Guadalupe - San Antonio River Basin for the 1934-89 period and identifies the portion attributable to man-made structures in existence at the time.





NATURAL RECHARGE

HISTORICAL RECHARGE ENHANCEMENT

HDR

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GUADALUPE-SAN ANTONIO RIVER BASIN
RECHARGE ENHANCEMENT STUDY

COMPARISON OF NATURAL AND HISTORICAL EDWARDS AQUIFER RECHARGE

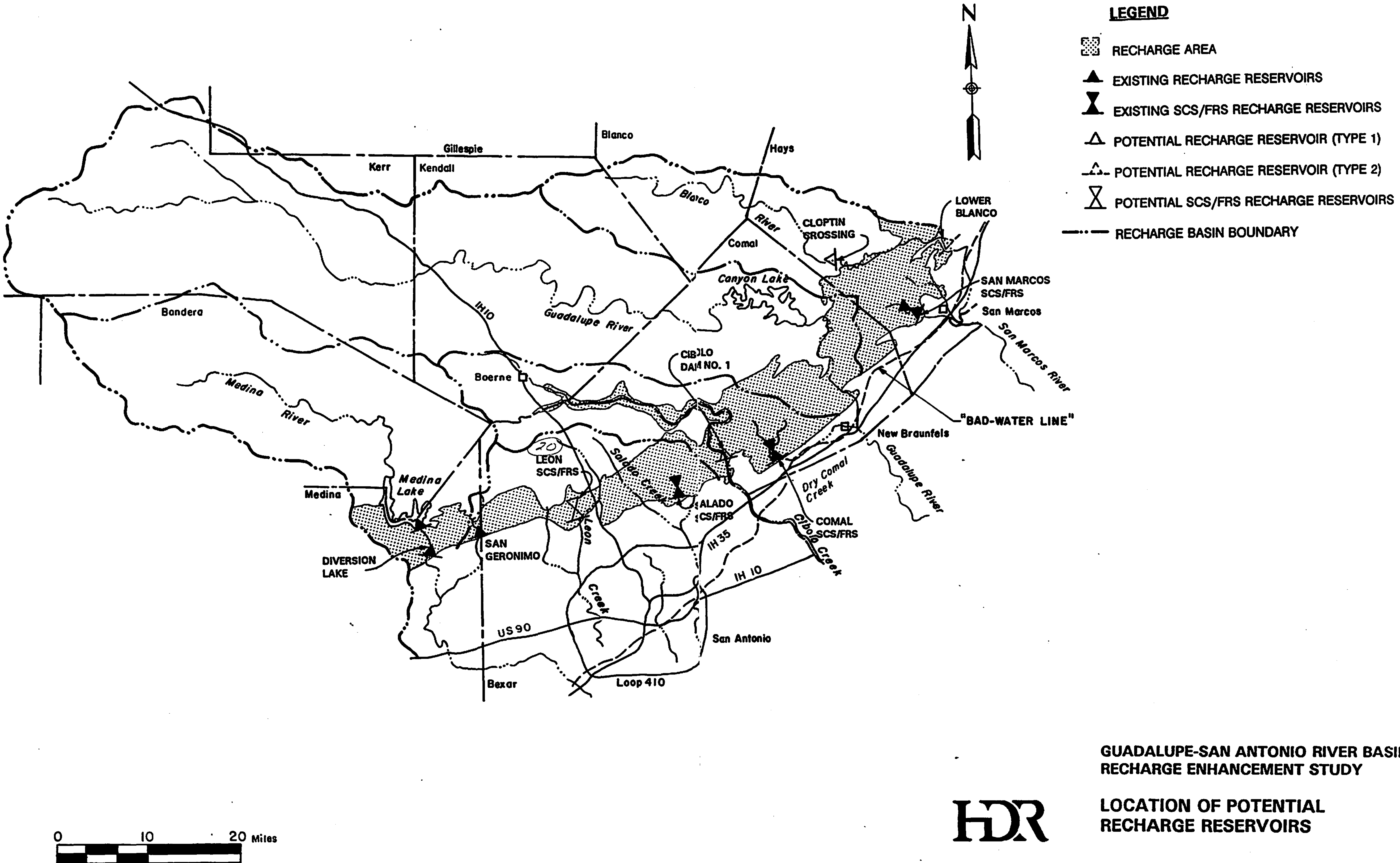
FIGURE 6-6

7.0 POTENTIAL RECHARGE ENHANCEMENT PROJECTS

7.1 Identification of Potential Projects

The approximate locations of all potential recharge reservoirs and existing reservoirs which contribute to the recharge of the Edwards Aquifer in the Guadalupe - San Antonio River Basin are shown in Plate 2. Although the Cloptin Crossing and Cibolo Dam No. 1 projects have been identified and examined in previous studies (Refs. 36 and 8, respectively), other potential recharge reservoirs were sited in the course of this study without detailed consideration of economic, geologic, environmental, or other factors of human interest. The express purpose of the projects selected for analysis in this study was the determination of the theoretical maximum additional recharge attainable. The reader is cautioned that this study was performed to assess the potential for recharge enhancement in the Guadalupe - San Antonio River Basin subject to the current state of water supply development and without regard for proposed water resource developments or environmental needs. Any use of the results of this study should be appropriately qualified in accordance with the following abbreviated list of factors, each of which, when applied, may serve to reduce the amount of recharge enhancement potential reported herein:

- Smaller projects dictated by economics;
- Water requirements for more valuable supply alternatives;
- Water requirements for environmental needs;
- Reuse of treated wastewater effluent;
- Limited recharge enhancement during severe drought;
- Site geology and/or regional hydrogeology; and



GUADALUPE-SAN ANTONIO RIVER BASIN
RECHARGE ENHANCEMENT STUDY

LOCATION OF POTENTIAL
RECHARGE RESERVOIRS

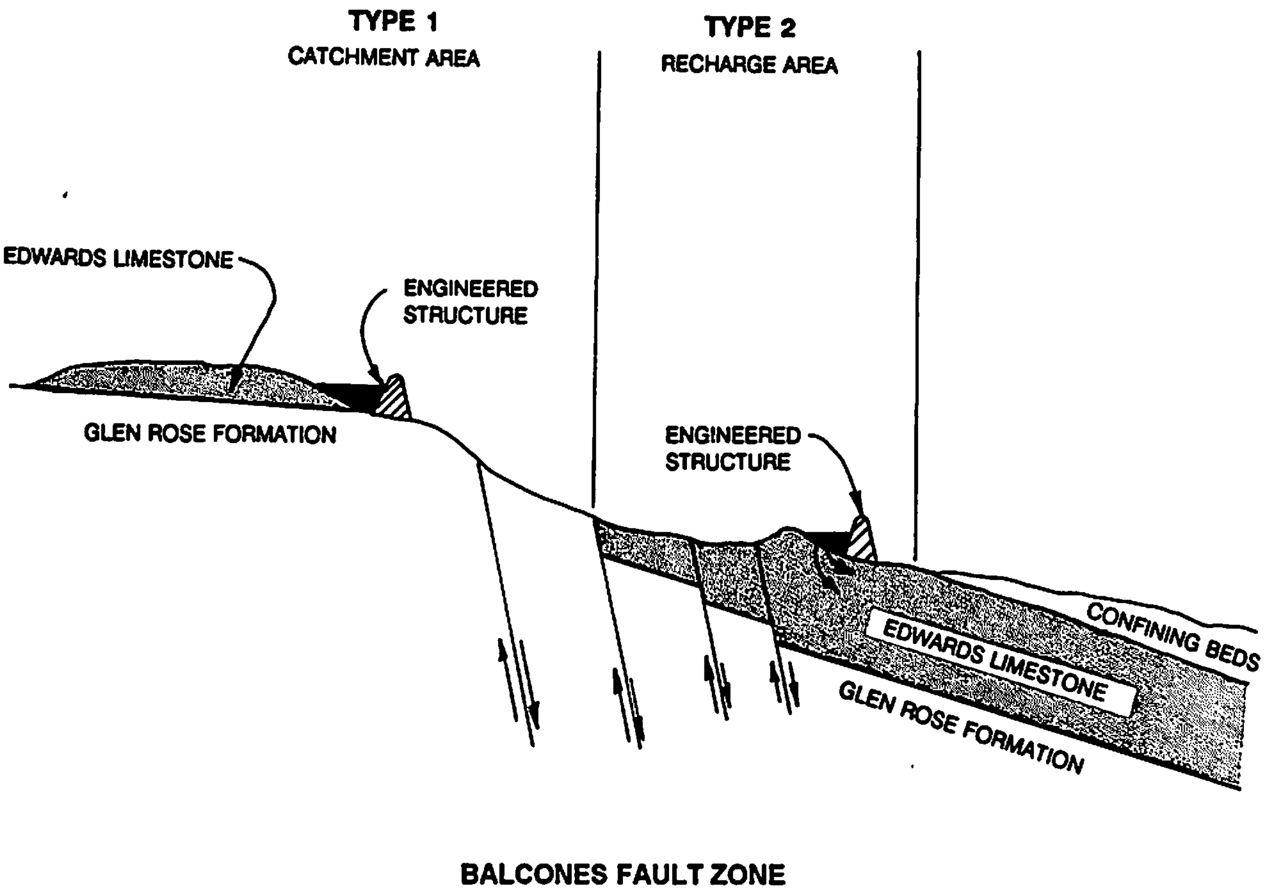
PLATE 2

- Location of recharge enhancement relative to demand centers and/or springs.

The effect of each of these factors on recharge enhancement potential may be measured in subsequent studies when suitable criteria for the application of each is established.

The two general types of recharge reservoirs considered are illustrated in Figure 7-1. Type 1 or "catch and release" reservoirs are located upstream of the recharge zone and are operated to release water at the maximum recharge rate of the downstream channel. Carryover storage from one month to the next is frequent in Type 1 reservoirs so net evaporation losses are included in the simulation of reservoir contents. Cloptin Crossing Reservoir is the only Type 1 project considered in this study. Type 2 or "direct percolation" reservoirs are located within the recharge zone and recharge directly through the bottom of the reservoir. For smaller Type 2 projects, the entire storage volume will usually drain within a period of less than one month and evaporation losses are not calculated. Cibolo Dam No. 1 and Lower Blanco Reservoir are the only Type 2 projects considered individually in this study. Due to relatively low natural recharge rates along the Blanco River, direct diversions from either the Cloptin Crossing or Lower Blanco Reservoir for injection to the aquifer and/or transfer to the adjacent upper San Marcos River watershed were modelled in order to more efficiently recharge water impounded in these reservoirs. Since the Lower Blanco Reservoir will normally have carryover storage, net evaporation losses were calculated.

Existing Soil Conservation Service Flood Retardation Structures (SCS/FRS) constructed in the recharge zone, exhibit characteristics of both Type 1 and Type 2



GUADALUPE-SAN ANTONIO RIVER BASIN
RECHARGE ENHANCEMENT STUDY

TYPES OF RECHARGE RESERVOIRS

HDR Engineering, Inc.

FIGURE 7-1

reservoirs in that both controlled releases and direct percolation serve to drain storage which has been temporarily impounded. In this study, SCS/FRS reservoirs are grouped by watershed for calculation of recharge, and net evaporation losses are assumed negligible due to the rapid rate at which storage is typically evacuated from these reservoirs. Analyses of hydrologic data from the Salado Creek and Dry Comal Creek watersheds indicates that, on the average, approximately 100 percent and 70 percent of the water stored in the normal and active pools, respectively, contributes to recharge. If the recharge characteristics of the SCS/FRS were not incorporated in their original design, it is possible that restriction and/or closure of reservoir outlets could enhance recharge without adversely affecting the flood control function of these projects.

7.2 Scenarios and Assumptions

Potential recharge enhancement projects considered in this study have been generally classified and grouped into "Structural" and/or "Operational" programs. The various potential recharge enhancement projects have been classified and grouped in this way simply for organized presentation in this report. Projects classified as "Structural" involve the development of additional storage through new reservoir construction, while those classified as "Operational" involve modification of existing structures, acquisition of existing water rights, or re-activation of a project found to be economically unfeasible. Structural recharge enhancement projects analyzed include the following:

- Enlargement of the existing San Geronimo Creek Recharge Dam and/or development of additional storage upstream.
- Development of a program of small SCS/FRS in the Leon, Helotes, and Government Creek watersheds similar to that in the Salado Creek watershed.

- Cibolo Dam No. 1 on Cibolo Creek near Selma.
- One additional SCS/FRS in the Dry Comal Creek watershed.
- Lower Blanco project on the Blanco River near Kyle.

Operational recharge enhancement projects analyzed include the following:

- Acquisition of irrigation rights at Medina and Diversion Lakes for diversion and injection to the Edwards Aquifer.
- Modification or closure of SCS/FRS outlets in the Salado Creek, Dry Comal Creek, and upper San Marcos River watersheds.
- Cloptin Crossing project on the Blanco River near Wimberley.

Potential recharge enhancement with the Structural Program in place was calculated subject to two water rights and three Edwards Aquifer pumpage/springflow scenarios. The two water rights scenarios include full use of permitted water rights and reported use for 1988. Simulations under the Full Water Rights Scenario are based on the following assumptions:

- All rights and contracts divert full authorized amounts.
- Permitted annual diversions and contractual obligations from Canyon Lake total 50,000 ac-ft.
- Flow requirement of 600 cfs at Lake Dunlap for hydroelectric power generation.
- Annual consumptive use (forced evaporation) at Braunig, Calaveras, and Coleto Creek Lakes based on estimated full potential power generation.
- Return flows in each stream segment equal to those reported for 1988.

Simulations under the 1988 Water Usage Scenario are based on the following assumptions:

- All rights and contracts divert amounts reported for 1988. Diversion and storage rights associated with Applewhite Reservoir and the Leon Creek Diversion are excluded from this scenario.

- Permitted annual diversions and contractual obligations from Canyon Lake total 50,000 ac-ft.

- Flow requirement of 0 cfs at Lake Dunlap assuming full subordination of hydroelectric power generation.

- Annual consumptive use (forced evaporation) at Braunig, Calaveras, and Coleto Creek Lakes equal to that reported for 1988.

- Return flows in each stream segment equal to those reported for 1988.

The three Edwards Aquifer pumpage/springflow scenarios considered in this study assumed fixed annual use of water directly from the aquifer totalling 250,000 ac-ft, 400,000 ac-ft, or 450,000 ac-ft. With the assistance of the TWDB, monthly springflow sequences were calculated for Comal, San Marcos, San Antonio, and San Pedro Springs utilizing their model of the Edwards Aquifer. The TWDB modified the Edwards Aquifer model in order to include HDR estimates of historical recharge in both the Nueces and Guadalupe - San Antonio River Basins and to estimate aquifer discharge to the Guadalupe River near Hueco Springs.

7.3 Structural Program

The results of recharge enhancement calculations for the Structural Program are summarized in Tables 7-1 and 7-2 for long-term average and drought conditions, respectively. Long-term average (1934-89) Guadalupe - San Antonio River Basin recharge enhancement due to the listed new reservoirs totalled approximately 48,300 ac-ft/yr (an

Table 7-1
Recharge Enhancement with Structural Program for Average Conditions (1934-89)

Recharge Basin	New Reservoirs	Maximum Storage (Ac-Ft)	Historical[1] Average Annual Recharge (Ac-Ft/Yr)		Recharge Enhancement With Structural Program (Ac-Ft/Yr)[3]					
					Pumpage Scenario 1 250,000 Ac-Ft/Yr		Pumpage Scenario 2 400,000 Ac-Ft/Yr		Pumpage Scenario 3 450,000 Ac-Ft/Yr	
			Full Water Rights	1988 Water Usage	Full Water Rights	1988 Water Usage	Full Water Rights	1988 Water Usage	Full Water Rights	1988 Water Usage
5) Medina River			40,610	42,250						
6) Area between Medina River and Cibolo Creek			85,550	85,550						
	San Geronimo	3,500			1,715	3,550	1,715	3,550	1,715	3,550
	Leon Creek FRS[2]	25,200			5,230	6,120	5,205	6,120	5,205	6,120
7) Cibolo Creek and Dry Comal Creek			113,965	114,300						
	Cibolo Dam	10,000			8,485	8,520	8,485	8,520	8,485	8,520
	Dry Comal FRS	2,075			1,335	1,335	1,335	1,335	1,335	1,335
8) Guadalupe River			11,255	11,255						
9) Blanco River			68,135	68,295						
	Lower Blanco	35,230			31,610	31,715	31,515	31,650	31,495	31,640
Recharge Enhancement (Ac-Ft/Yr)[3]					48,375	51,240	48,255	51,175	48,235	51,165
Total Recharge (Ac-Ft/Yr)			319,515	321,650	367,890	372,890	367,770	372,825	367,750	372,815
Percent Increase in Historical[1] Recharge					15.1%	15.9%	15.1%	15.9%	15.1%	15.9%
Total Spring Flow (Ac-Ft/Yr)			340,850		382,815		264,925		226,960	

Notes: 1) Historical Recharge is adjusted for existing structures and includes Medina Lake, San Geronimo Dam, and SCS/FRS programs in place for the entire period.
2) Leon Creek FRS includes an SCS/FRS program in the Leon Creek, Helotes Creek, and Government Creek watersheds.
3) Development of these projects will likely require compromises in size, location, mitigation of wildlife habitat, and other factors which may reduce the actual recharge enhancement attainable relative to the theoretical amounts reported herein.

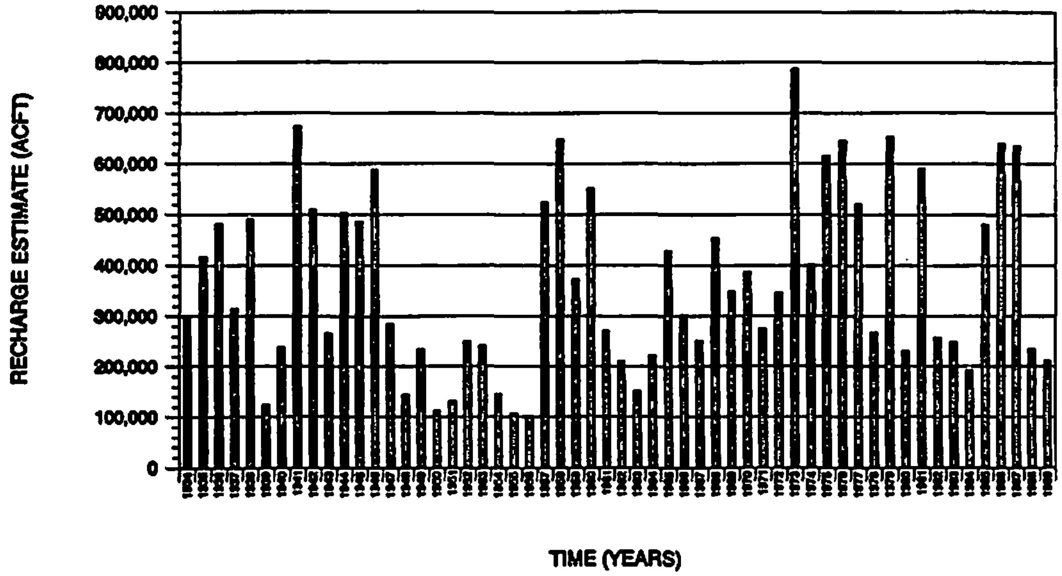
Table 7-2
Recharge Enhancement with Structural Program for Drought Conditions (1947-56)

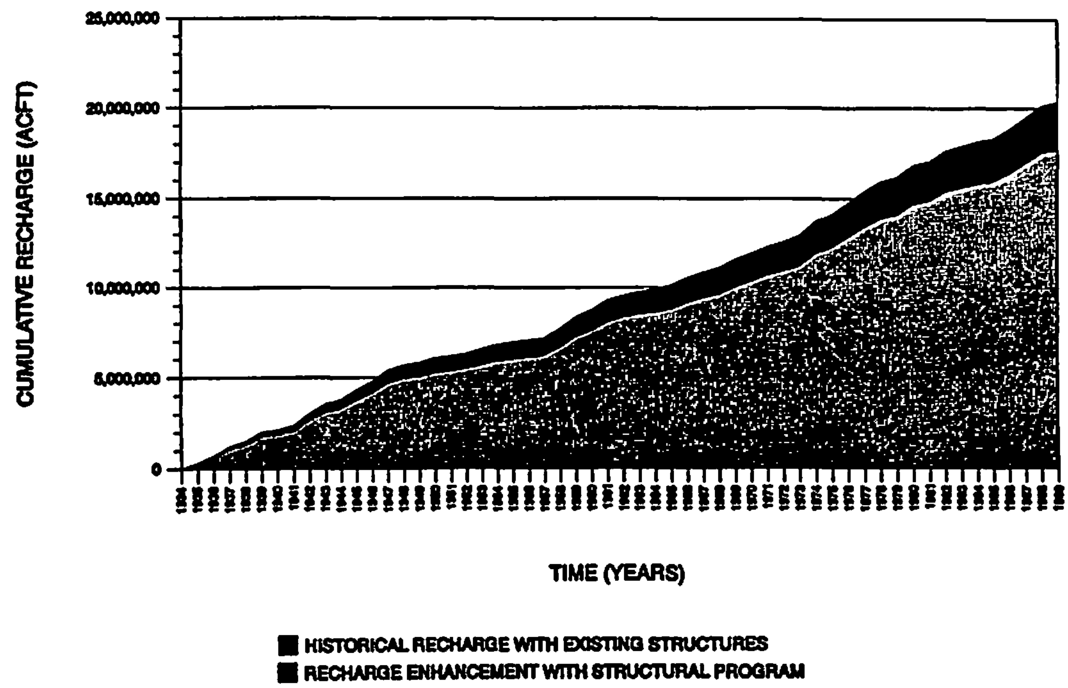
Recharge Basin	New Reservoirs	Maximum Storage (Ac-Ft)	Historical[1] Average Annual Recharge (Ac-Ft/Yr)		Recharge Enhancement With Structural Programs (Ac-Ft/Yr)[3]					
					Pumpage Scenario 1 250,000 Ac-Ft/Yr		Pumpage Scenario 2 400,000 Ac-Ft/Yr		Pumpage Scenario 3 450,000 Ac-Ft/Yr	
			Full Water Rights	1988 Water Usage	Full Water Rights	1988 Water Usage	Full Water Rights	1988 Water Usage	Full Water Rights	1988 Water Usage
5) Medina River			11,755	12,370						
6) Area between Medina River and Cibolo Creek			33,705	33,705						
	San Geronimo	3,500			560	785	560	785	560	785
	Leon Creek FRS[2]	25,200			1,950	2,395	1,815	2,395	1,815	2,395
7) Cibolo Creek and Dry Comal Creek			52,735	52,990						
	Cibolo Dam	10,000			1,265	1,265	1,265	1,265	1,265	1,265
	Dry Comal FRS	2,075			520	525	520	525	520	525
8) Guadalupe River			17,595	17,595						
9) Blanco River	Lower Blanco	35,230	37,355	37,725	19,850	20,105	19,515	19,850	19,465	19,835
Recharge Enhancement (Ac-Ft/Yr)[3]					24,145	25,075	23,675	24,820	23,625	24,805
Total Recharge (Ac-Ft/Yr)			153,145	154,385	177,290	179,460	176,820	179,205	176,770	179,190
Percent Increase in Historical[1] Recharge					15.8%	16.2%	15.5%	16.1%	15.4%	16.1%
Total Springflow (Ac-Ft/Yr)			230,970		203,800		96,980		66,425	

Notes: 1) Historical Recharge is adjusted for existing structures and includes Medina Lake, San Geronimo Dam, and SCS/FRS programs in place for the entire period.
2) Leon Creek FRS includes an SCS/FRS program in the Leon Creek, Helotes Creek, and Government Creek watersheds.
3) Development of these projects will likely require compromises in size, location, mitigation of wildlife habitat, and other factors which may reduce the actual recharge enhancement attainable relative to the theoretical amounts reported herein.

increase of 15.1 percent over the historical recharge) under the Full Water Rights Scenario and 51,200 ac-ft/yr (an increase of 15.9 percent over the historical recharge) under the 1988 Water Usage Scenario. Drought average (1947-56) recharge enhancement due to the listed new reservoirs totalled approximately 24,000 ac-ft/yr (an increase of 15.7 percent over the historical recharge) under the Full Water Rights Scenario and 25,000 ac-ft/yr (an increase of 16.1 percent over the historical recharge) under the 1988 Water Usage Scenarios. As is apparent in Tables 7-1 and 7-2, recharge enhancement with new structures is not very sensitive to either the assumed Edwards Aquifer pumpage/springflow scenario (with minor exceptions) or to the degree of water rights utilization. Recharge enhancement is typically limited by the volumes of runoff reaching each site and the physical capability to impound and recharge that runoff. Figure 7-2 presents annual and cumulative recharge of the Edwards Aquifer in the Guadalupe - San Antonio River Basin for the 1934-89 period, illustrating the relative magnitudes of baseline historical recharge with existing structures and enhanced recharge with the Structural Program subject to the Full Water Rights Scenario. Figure 7-3 provides a similar illustration focusing on annual recharge estimates during the 1947-56 drought period. See Appendix J (Volume III) for summaries of annual recharge by control point.

It is interesting to note that about 65 percent of the potential additional recharge under average conditions and over 80 percent of the potential additional recharge under drought conditions is a result of the Lower Blanco Reservoir. This reservoir is the largest in the Structural Program with an assumed maximum storage volume of 35,230 ac-ft. Due to the limited recharge rates observed in this portion of the Blanco River, net evaporation losses were considered, and direct diversions to the upper San Marcos River watershed for injection or





NOTES:
PUMPAGE SCENARIO 3: 450,000 ACFT/YR
FULL WATER RIGHTS SCENARIO

GUADALUPE-SAN ANTONIO RIVER BASIN
RECHARGE ENHANCEMENT STUDY

STRUCTURAL PROGRAM
RECHARGE ENHANCEMENT

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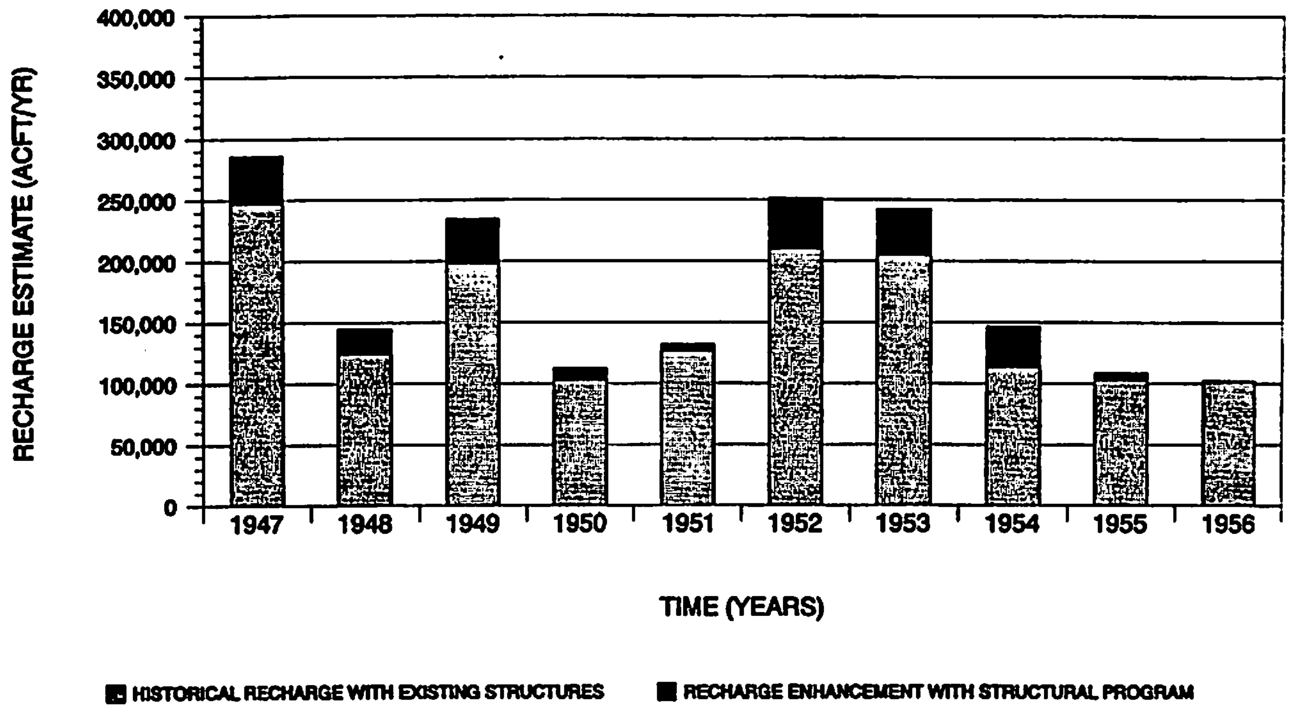
FIGURE 7-2



NOTES:
PUMPAGE SCENARIO 3: 450,000 ACFT/YR
FULL WATER RIGHTS SCENARIO

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GUADALUPE-SAN ANTONIO RIVER BASIN
RECHARGE ENHANCEMENT STUDY

STRUCTURAL PROGRAM DROUGHT RECHARGE ENHANCEMENT

FIGURE 7-3

natural recharge were assumed, in order to obtain the full recharge enhancement potential at this site. The Lower Blanco Reservoir is also quite efficient with respect to minimization of losses to evaporation. The free water surface area exposed to evaporative losses at maximum storage for this project is one-third less than that for the same storage volume at the upstream Cloptin Crossing site.

Tables 7-1 and 7-2 also reveal the significant differences in recharge enhancement potential in the San Geronimo and Leon Creek watersheds subject to each water rights scenario. Long-term average combined recharge enhancement in these two watersheds totals about 6,920 ac-ft/yr (an increase of 8.1 percent over the historical recharge) under the Full Water Rights Scenario and 9,670 ac-ft/yr (an increase of 11.3 percent over the historical recharge) under the 1988 Water Usage Scenario. This difference of 2,730 ac-ft/yr in recharge enhancement is a result of the exclusion of Applewhite Reservoir and the Leon Creek Diversion from the 1988 Water Usage Scenario.

7.4 Operational Program

Potential recharge enhancement with the Operational Program added to the Structural Program was calculated subject to the Full Water Rights Scenario previously described and springflows resulting from a fixed annual pumpage of 450,000 ac-ft from the Edwards Aquifer. Simulations for the Operational Program include all projects from the Structural Program except the Lower Blanco Reservoir which would not likely be feasible in conjunction with the Cloptin Crossing project. Long-term average (1934-89) Guadalupe - San Antonio River Basin recharge enhancement under the Operational Program totalled approximately 123,060 ac-ft/yr (an increase of 38.5 percent over the historical recharge) and drought average (1947-56) recharge enhancement totalled approximately 66,300 ac-ft/yr (an increase of 43.3 percent over the historical recharge). Table 7-3 provides a side-by-side comparison of potential recharge enhancement in each recharge basin for the Operational Programs. Figure 7-4 presents annual and cumulative recharge of the Edwards Aquifer in the Guadalupe-San Antonio River Basin for the 1934-89 period, illustrating the relative magnitudes of baseline historical recharge with existing structures and enhanced recharge with the Operational Program subject to the Full Water Rights Scenario. Figure 7-4 provides a similar illustration, focusing on annual recharge estimates during the 1947-56 drought period.

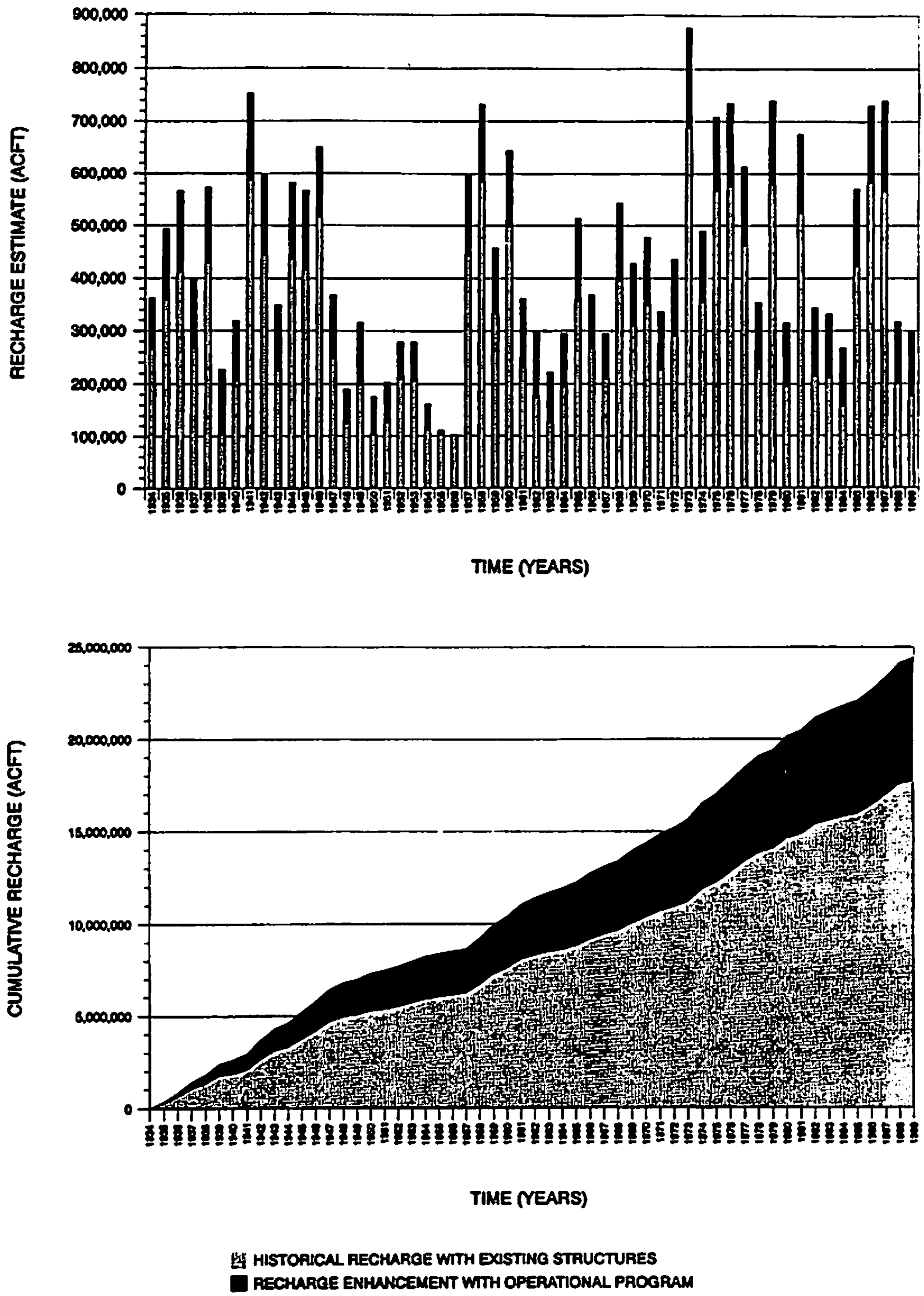
An average of approximately 55,395 ac-ft/yr (45.0 percent of the long-term average recharge enhancement under the Operational Program) could be available for diversion and injection to the Edwards Aquifer by acquisition of Medina and Diversion Lake irrigation rights totalling 67,830 ac-ft/yr. Such diversions were assumed to be accomplished on a monthly schedule similar to that for irrigation use so that historical recharge estimates for Medina and Diversion Lakes would be unaffected. Figure 7-6 summarizes annual quantities of surface water available for diversion under these rights and clearly illustrates that diversions would be severely limited during drought due to depletion of storage in Medina Lake. Although recharge enhancement averaged 20,935 ac-ft/yr during the 1947-56 drought period, water available during the 1954-56 period averaged only 3,735 ac-ft/yr.

The Cloptin Crossing Reservoir project was found to be economically unfeasible by the U.S. Army Corps of Engineers in 1979 and was placed in a deferred category (Ref 37). Simulations indicate, however, that is could provide significant recharge enhancement in both

Table 7-3
Recharge Enhancement with Structural and Operational Programs

Recharge Basin	Operational Projects	Historical[1] Recharge (Ac-Ft/Yr)		Recharge Enhancement (Ac-Ft/Yr)[2,5]			
				Structural Program		Structural and Operational Programs[3]	
		Average (1934-89)	Drought (1947-56)	Average (1934-89)	Drought (1947-56)	Average (1934-56)	Drought (1947-56)
5) Medina River		40,610	11,755				
	Irrigation Purchase					55,395	20,935
6) Area between Medina River and Cibolo Creek		85,550	33,705	6,920	2,375	6,920	2,375
	Salado Creek FRS					485	0
7) Cibolo Creek and Dry Comal Creek		113,965	52,735	9,820	1,785	9,820	1,785
	Dry Comal FRS					1,145	390
8) Guadalupe River		11,255	17,595				
9) Blanco River		68,135	37,355	31,495	19,465		
	Cloptin Crossing					48,275	40,690
	San Marcos FRS					1,020	125
Recharge Enhancement (Ac-Ft/Yr)[5]				48,235	23,625	123,060	66,300
Total Recharge (Ac-Ft/Yr)		319,515	153,145	367,750	176,770	442,575	219,445
Percent Increase in Historical[1] Recharge				15.1%	15.4%	38.5%	43.3%
Estuarine Inflow (Ac-Ft/Yr) and Percent Reduction[4]		1,548,395	514,065	-2.0%	-2.7%	-3.4%	-3.2%

Notes:
1) Historical Recharge is adjusted for existing structures and includes Medina Lake, San Geronimo Dam, and SCS/FRS programs in place for the entire period.
2) Recharge Enhancement based on Pumpage Scenario 3 (450,000 Ac-Ft/Yr) and Full Water Rights Scenario.
3) Includes all projects from the Structural Program except Lower Blanco Reservoir.
4) Estuarine inflows and percent reductions are based on flows at the Saltwater Barrier near Tivoli subject to Pumpage Scenario 3 (450,000 ac/ft-yr). Figures shown reflect no increase in return flows and/or springflows due to recharge enhancement.
5) Development of these projects will likely require compromises in size, location, mitigation of wildlife habitat, and other factors which may reduce the actual recharge enhancement attainable relative to the theoretical amounts reported herein.



NOTES:
PUMPAGE SCENARIO 3: 450,000 ACFT/YR
FULL WATER RIGHTS SCENARIO

GUADALUPE-SAN ANTONIO RIVER BASIN
RECHARGE ENHANCEMENT STUDY

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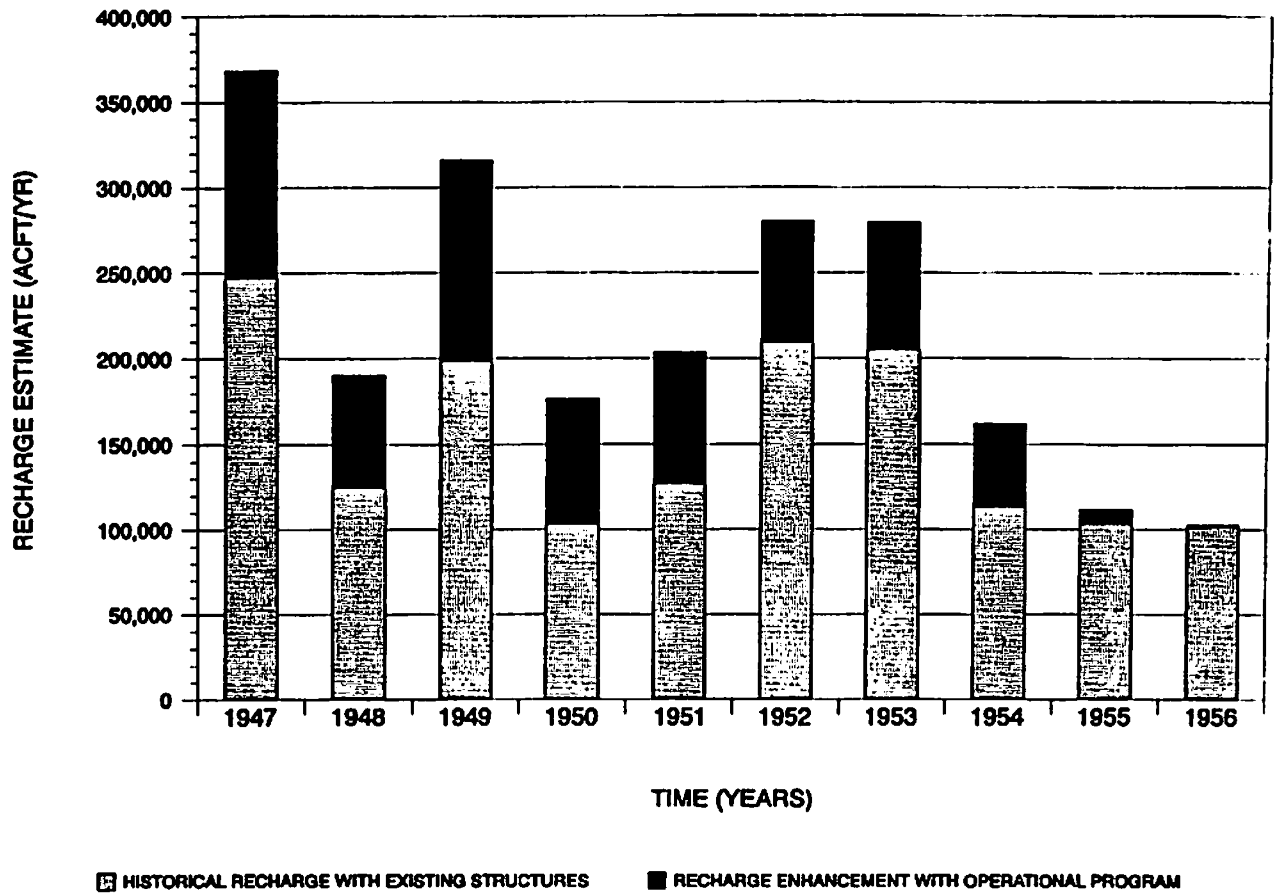
OPERATIONAL PROGRAM
RECHARGE ENHANCEMENT

FIGURE 7-4



NOTES:
PUMPAGE SCENARIO 3: 450,000 ACFT/YR
FULL WATER RIGHTS SCENARIO

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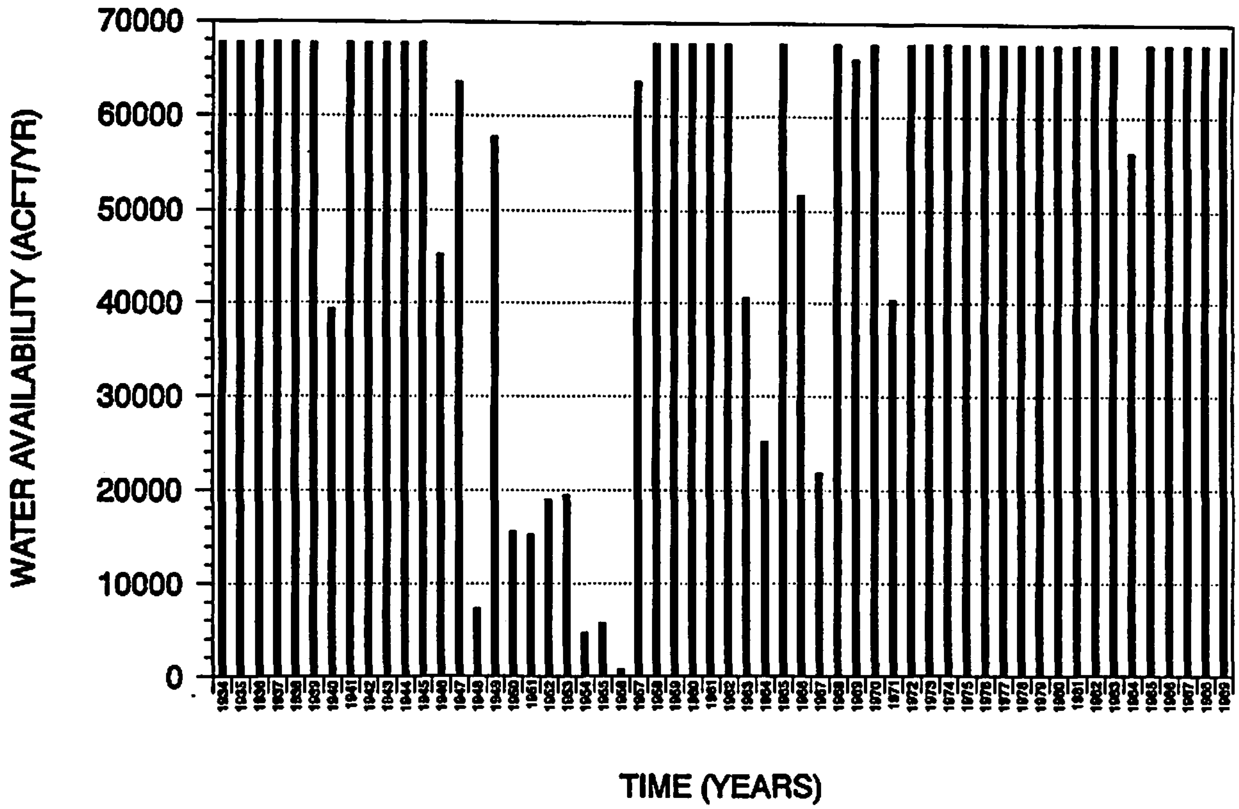
GUADALUPE-SAN ANTONIO RIVER BASIN
RECHARGE ENHANCEMENT STUDY

OPERATIONAL PROGRAM DROUGHT RECHARGE ENHANCEMENT

FIGURE 7-5



IRRIGATION RIGHTS = 67,830 ACFT/YR

HDR Engineering, Inc.

GUADALUPE-SAN ANTONIO RIVER BASIN
RECHARGE ENHANCEMENT STUDY

MEDINA AND DIVERSION LAKE WATER AVAILABILITY UNDER IRRIGATION RIGHTS

FIGURE 7-6

average times and during severe drought periods. Comparing the Cloptin Crossing Reservoir with the previously discussed Lower Blanco Reservoir reveals that the Cloptin Crossing Reservoir could provide 53 percent and 109 percent more recharge enhancement under average and drought conditions, respectively. However, the conservation storage of Cloptin Crossing Reservoir (283,400 ac-ft) is eight times that of the Lower Blanco Reservoir and the assumed diversion rate from Cloptin Crossing for injection to the Edwards Aquifer was more than four times that assumed for the Lower Blanco Reservoir. More detailed economic and hydrologic analyses will be necessary to evaluate the relative merits of these alternative projects.

As indicated in Table 7-3, an additional measure of recharge enhancement could be obtained through closure of SCS/FRS outlets in the watersheds where SCS/FRS programs are in place. It is estimated that, on the average, the existing SCS/FRS programs increase recharge in the Guadalupe - San Antonio River Basin by 12,760 ac-ft/yr (4.0 percent) over that which would occur naturally. Closure of SCS/FRS outlets in the Salado Creek, Dry Comal Creek (including the outlet of the additional SCS/FRS included in the Structural Program), and upper San Marcos River watersheds could contribute an additional 2,650 ac-ft/yr (0.8 percent) on the average. Further investigation of design assumptions and regulatory constraints associated with closing or modifying the outlets of existing SCS/FRS projects is necessary to assess feasibility.

8.0 WATER POTENTIALLY AVAILABLE AT SELECTED LOCATIONS

The Guadalupe - San Antonio River Basin Model was used to estimate monthly quantities of water potentially available at the following locations:

- San Marcos River Below the Blanco River Confluence;
- Guadalupe River Below the Comal River Confluence; and
- Canyon Lake.

Calculations were performed subject to two general scenarios selected to present the reasonable range of water potentially available during average and drought conditions without consideration of instream flow and/or estuarine inflow requirements:

Scenario 1: Full utilization of existing water rights based on springflows resulting from a fixed Edwards Aquifer pumpage rate of 450,000 ac-ft/yr. Water potentially available under this scenario is comparable to unappropriated flow.

Scenario 2: Utilization of existing water rights to the extent reported in 1988 based on springflows resulting from a fixed Edwards Aquifer pumpage rate of 250,000 ac-ft/yr. Diversion of water potentially available under this scenario implicitly assumes that it would be necessary to purchase existing water rights which were not used in 1988.

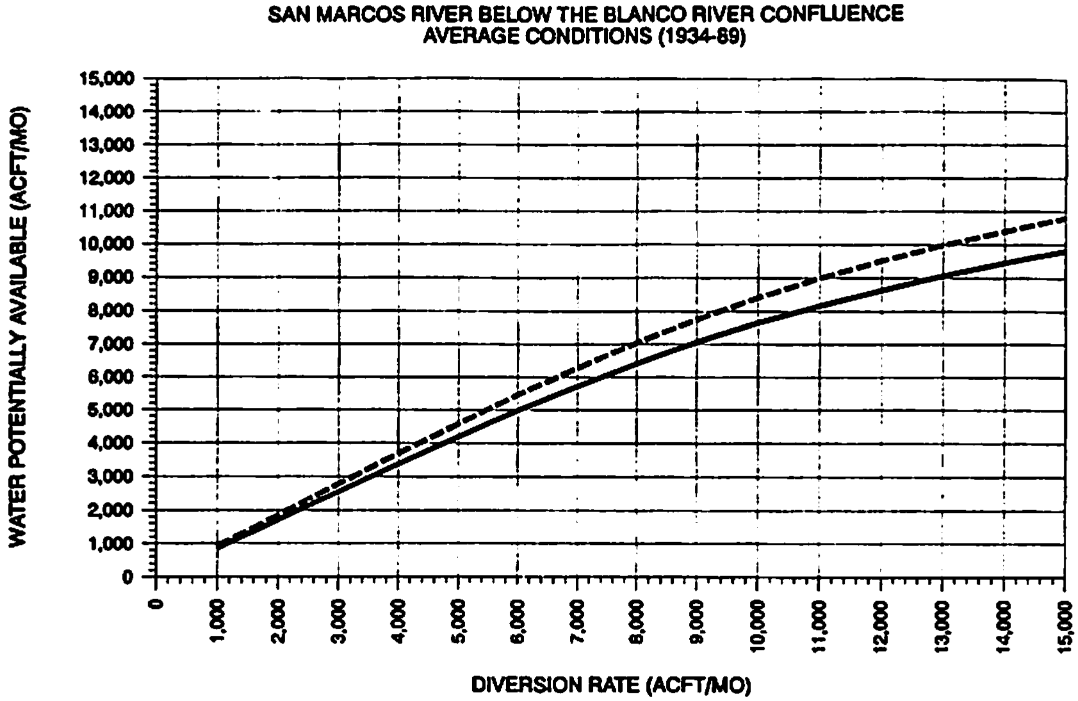
Average quantities of water potentially available which are reported herein are theoretical maximums and may be subject to significant reductions due to economic, environmental, structural, and political limitations.

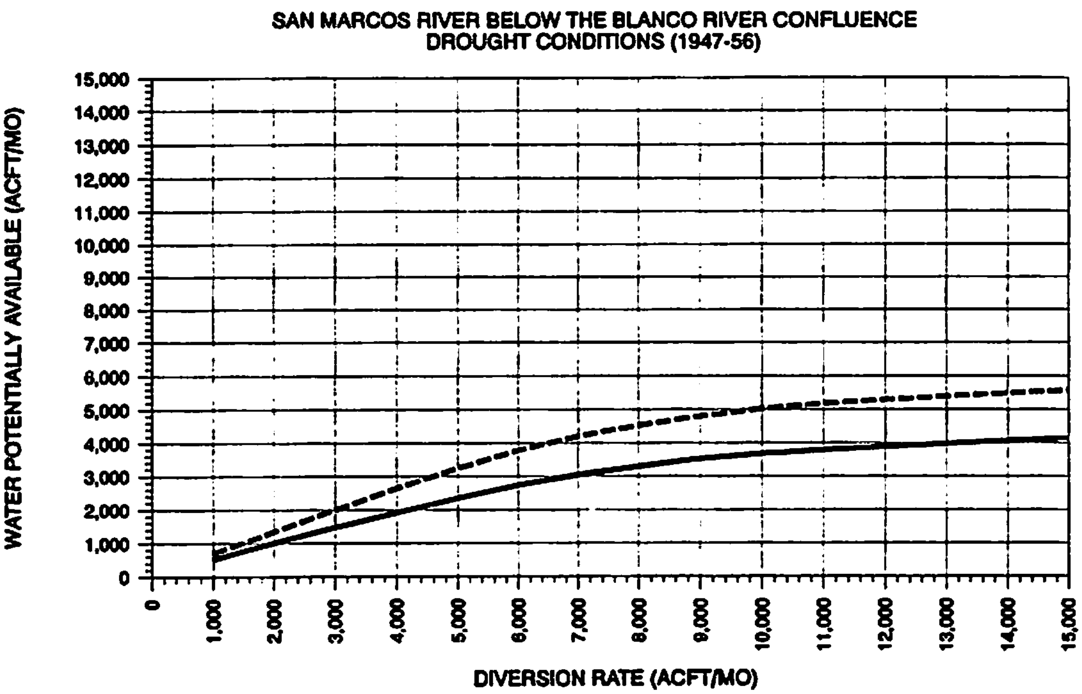
8.1 San Marcos River

Figure 8-1 presents estimates of water potentially available at the selected location on the San Marcos River based on diversion rates ranging from 1,000 ac-ft/month (17 cfs) to 15,000 ac-ft/month (250 cfs). Operating under Scenario 1 with a 6,000 ac-ft/month (100 cfs) diversion rate, for example, a long-term average of approximately 5,000 ac-ft/month (60,000 ac-ft/yr) and a drought average of approximately 2,750 ac-ft/month (33,000 ac-ft/yr) might be available. While increased quantities of water potentially available could be obtained under Scenario 2 or by increasing diversion rate, Figure 8-1 reveals that availability does not increase uniformly with diversion rate and does, in fact, begin to approach a maximum. Furthermore, it is important to note that there would be no water available at this location under either scenario approximately 13 percent and 45 percent of the time subject to average and drought conditions, respectively. Monthly summaries of theoretical maximum quantities of water potentially available under Scenarios 1 and 2 are included in Appendix K (Volume III).

8.2 Guadalupe River

Figure 8-2 presents estimates of water potentially available on the Guadalupe River below the Comal River confluence based on diversion rates ranging from 1,000 ac-ft/month (17 cfs) to 15,000 ac-ft/month (250 cfs). Operating under Scenario 1 with a 6,000 ac-ft/month (100 cfs) diversion rate, a long-term average of only about 1,250 ac-ft/month (15,000 ac-ft/yr) and a drought average of only about 250 ac-ft/month (3,000 ac-ft/yr) might be available. Under this scenario, no water would be available at the selected location





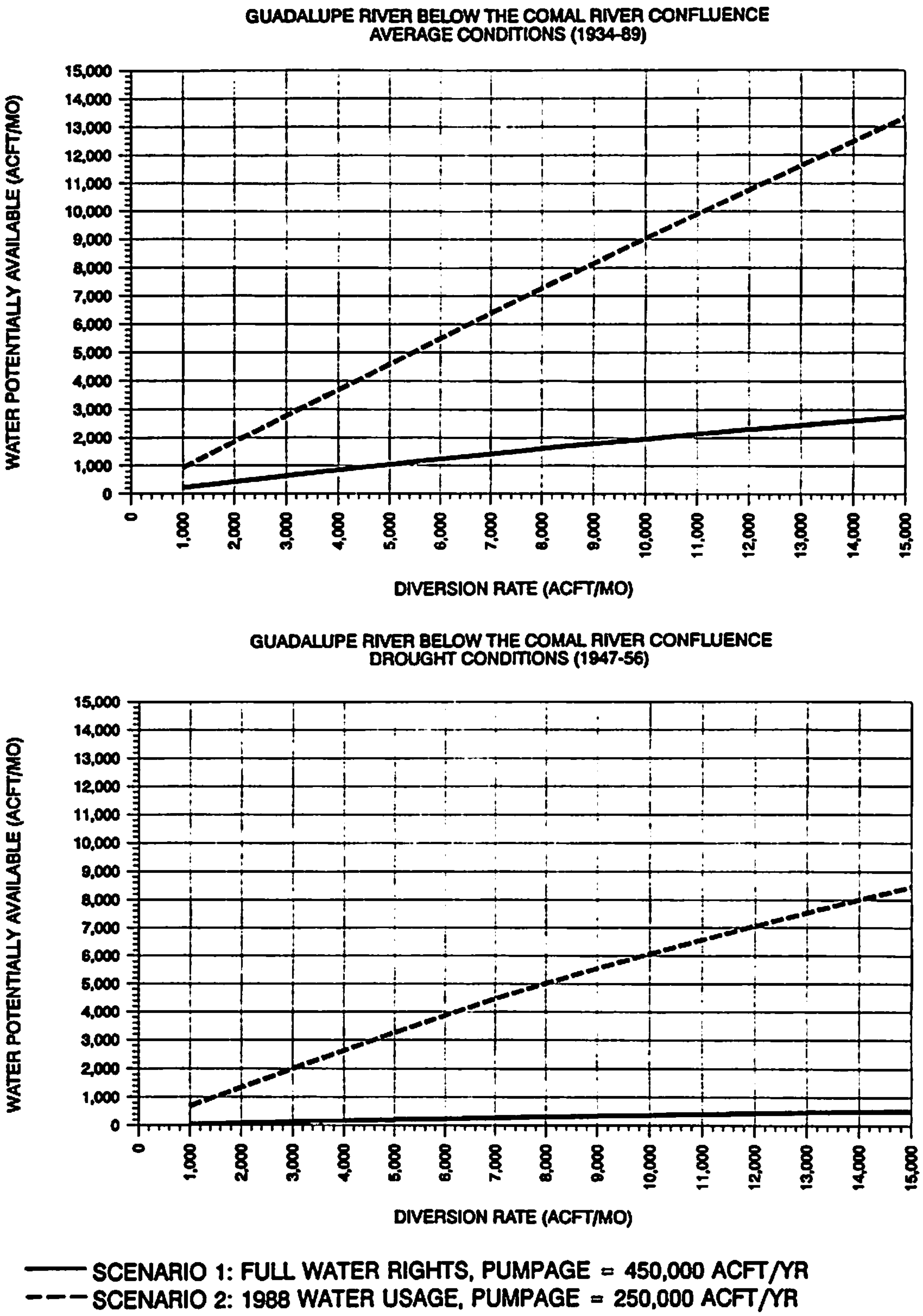
—— SCENARIO 1: FULL WATER RIGHTS, PUMPAGE = 450,000 ACFT/YR
– – – SCENARIO 2: 1988 WATER USAGE, PUMPAGE = 250,000 ACFT/YR

GUADALUPE-SAN ANTONIO RIVER BASIN
RECHARGE ENHANCEMENT STUDY

HDR Engineering, Inc.

WATER POTENTAILLY AVAILABLE
SAN MARCOS RIVER

FIGURE 8 -1



GUADALUPE-SAN ANTONIO RIVER BASIN
RECHARGE ENHANCEMENT STUDY

HDR Engineering, Inc.

WATER POTENTAILLY AVAILABLE GUADALUPE RIVER

FIGURE 8-2

between 78 percent and 95 percent of the time subject to average and drought conditions, respectively. For the same diversion rate under Scenario 2, however, about 5,500 ac-ft/month (66,000 ac-ft/yr) and 3,900 ac-ft/month (46,800 ac-ft/yr) might be available subject to average and drought conditions, respectively. Under Scenario 2, no water would be available at the selected location between 12 percent and 44 percent of the time subject to average and drought conditions, respectively. Estimates of water potentially available in the Guadalupe River are significantly more sensitive to assumptions regarding Edwards Aquifer pumpage/springflow and water rights utilization than are those for the San Marcos River. Monthly summaries of theoretical maximum quantities of water potentially available under Scenarios 1 and 2 are included in Appendix K (Volume III).

8.3 Canyon Lake

Development of estimates of water potentially available (unutilized firm yield) from Canyon Lake was substantially more complex than the estimation of water potentially available at selected stream locations. The added complexity is attributable to the complicated relationship between the firm yield of Canyon Lake and Edwards Aquifer pumpage and resulting springflows, subordination of hydroelectric rights, and losses in delivery of inflows passed through or storage released from Canyon Lake in fulfillment of downstream obligations. For the purposes of this study, utilization of Canyon yield is comprised of releases and direct diversions from the lake and is defined to be the difference between the volume necessary to meet senior water rights and the volume necessary to meet both senior water rights and contractual obligations. The GSA Model does not make releases from Canyon Lake storage to meet senior downstream water rights. Water potentially available or unutilized firm yield is, for purposes of this study, defined to be the annual difference between firm yield and utilization.

A previous study (Ref. 7) sponsored by the Guadalupe - Blanco River Authority (GBRA) indicates that the firm yield based on historical springflows, full water rights, and subordination of GBRA hydroelectric rights to 600 cfs is about 50,000 ac-ft/yr which is consistent with the permitted annual diversion from Canyon Lake. Operating under Scenario 1 and meeting all current contractual obligations (with the exception of make-up water for Coleto Creek Reservoir which was delivered as needed), utilization of Canyon firm yield was estimated to average approximately 30,500 ac-ft/yr with a maximum utilization of about 47,900 ac-ft in 1956 and a typical utilization of about 28,200 ac-ft/yr when no releases for Coleto Creek Reservoir were necessary. Hence, an average of approximately 19,500 ac-ft/yr is potentially available at Canyon Lake under the existing diversion right of 50,000 ac-ft/yr. Comparing contractual obligations which total about 25,000 ac-ft/yr (excluding Central Power & Light at Coleto Creek Reservoir) with the typical utilization of 28,200 ac-ft/yr indicates that, on the average, about 3,200 ac-ft/yr or 11 percent is lost in delivery. In the event of further subordination of GBRA hydroelectric rights, the firm yield of Canyon Lake would increase and additional quantities of water from Canyon Lake could become available.

9.0 CONCLUSIONS

Significant study findings and conclusions are as follows:

1) The potential for recharge enhancement estimated in this report is a theoretical maximum and, on more detailed review, will likely be subject to significant reductions due to economic, environmental, structural, and political limitations. When analyzed as a part of a total regional water resources program, there may be other types of water resource projects which provide greater benefits than some of the projects identified in this report.

2) Recharge of the Edwards Aquifer in the Guadalupe - San Antonio River Basin may be increased by an average of about 123,000 ac-ft/yr if all Structural and Operational projects identified in this report (with the exception of the Lower Blanco Reservoir) are implemented and all water rights are honored. This represents an increase of about 38.5 percent in the historical average recharge. Recharge during the 10-year drought period from 1947 through 1956 could be increased by about 66,300 ac-ft/yr or 43.3 percent of the historical average during this period.

3) If the Structural and Operational programs identified (with the exception of the Lower Blanco Reservoir) are fully implemented, inflows to the Guadalupe Estuary could be reduced by an average of about 53,200 ac-ft/yr. The construction of only the Structural Program (which includes the Lower Blanco Reservoir and excludes the Cloptin Crossing Reservoir) could reduce inflows by about 31,000 ac-ft/yr. These figures represent between 3.4 and 2.0 percent of the average annual flow of the Guadalupe and San Antonio Rivers into the Guadalupe Estuary. Note that these average estuarine inflow reductions do not reflect potential increases in return flow and/or springflow associated with recharge enhancement.

4) Estimates of recharge enhancement associated with the structural and operational programs are not very sensitive to the various aquifer pumpage/springflow scenarios or to the degree of water rights utilization. Recharge enhancement is typically limited by the volume of runoff reaching each site and the physical capability to impound and recharge that runoff.

5) Potentially significant quantities of water may be available in the San Marcos River below the Blanco River confluence, in the Guadalupe River below the Comal River confluence, and in Canyon Lake for recharge enhancement or other uses. Theoretical maximum quantities of water available have been presented in this report for a range of assumptions as to Edwards Aquifer pumpage/springflow and utilization of existing water rights. As water is not available at these locations in each and every month, storage would be required to sustain a firm supply.

6) Methods used in this study to calculate historical recharge to the Edwards Aquifer result in estimates that differ from previous estimates by the USGS. In particular, there are significant differences at Medina Lake and Diversion Lake (HDR estimates are lower), the area between the Medina River and Cibolo Creek (HDR estimates are higher), and the upper San Marcos River watershed (HDR estimates are higher). In addition, the methods used in this study show that significant recharge does occur in the Guadalupe River Basin where previous estimates by the USGS do not consider recharge in this basin.

10.0 RECOMMENDATIONS

The findings of this study indicate that recharge to the Edwards Aquifer may be substantially enhanced by the construction of additional recharge structures and/or changes in existing operational and institutional constraints. In order to determine whether these projects and/or operational changes are truly feasible and to quantify potential benefits to well yields and springflows, the following additional work is recommended:

1) Information developed in this study should be analyzed as a part of a total regional water resources program which compares the relative merits of recharge enhancement to other water supply options. After the role of recharge is determined in the regional water resources planning effort, selected recharge projects should be carried forward for additional detailed study.

2) The Texas Water Development Board model of the Edwards Aquifer should be recalibrated using the recharge values developed in this study and used to evaluate the various recharge options under consideration for the Nueces and Guadalupe - San Antonio River Basins to determine benefits to well yields and springflows.

3) Significant numbers of additional streamgages and raingages should be added to the hydrologic data collection network to more accurately calculate recharge in ungaged areas and to significantly improve the accuracy of recharge estimates in areas directly over the recharge zone. A state-of-the-art recharge calculation methodology for the Edwards Aquifer should be developed which utilizes the additional streamgages and raingages and incorporates appropriate elements of the USGS and HDR procedures. It is expected that consideration of these state-of-the-art recharge estimates will result in significant improvement in aquifer model calibration.

4) The TWDB Edwards Aquifer model and the surface water/recharge models of the Nueces and Guadalupe - San Antonio River Basins should be combined into one model to fully evaluate recharge enhancement options and to aid in the evaluation of various aquifer and surface water management alternatives.

5) Benefit/cost analyses of recharge projects (and/or operational changes) should be performed in detailed studies considering economic, environmental, geological, institutional, and structural feasibility of individual projects as well as combinations of projects.

6) Special hydrologic studies addressing the following specific items should be undertaken in support of improved recharge estimates:

- Field studies of Medina Lake and Diversion Lake to better understand and define relationships between reservoir levels and recharge and leakage rates;
- Field studies of water exchange rates between the Edwards Aquifer and the Guadalupe River downstream of Canyon Lake over a range of aquifer water levels;
- Refinement of firm yield estimates for Canyon Lake to include consideration of water delivery losses in conjunction with Edwards Aquifer pumpage/springflow scenarios and potential subordination of hydroelectric rights;
- Consideration of new geologic mapping of Bexar, Comal, and Hays Counties nearing completion by the USGS which should result in improved recharge zone definition and more accurate recharge basin drainage areas; and
- Investigation of the possibility of calculating historical total daily flow estimates (including flows which are not springflows) for the USGS San Marcos River springflow gage to provide more accurate historical recharge estimates for the upper San Marcos River watershed. This is similar to the procedure used at the USGS Comal River gage.

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