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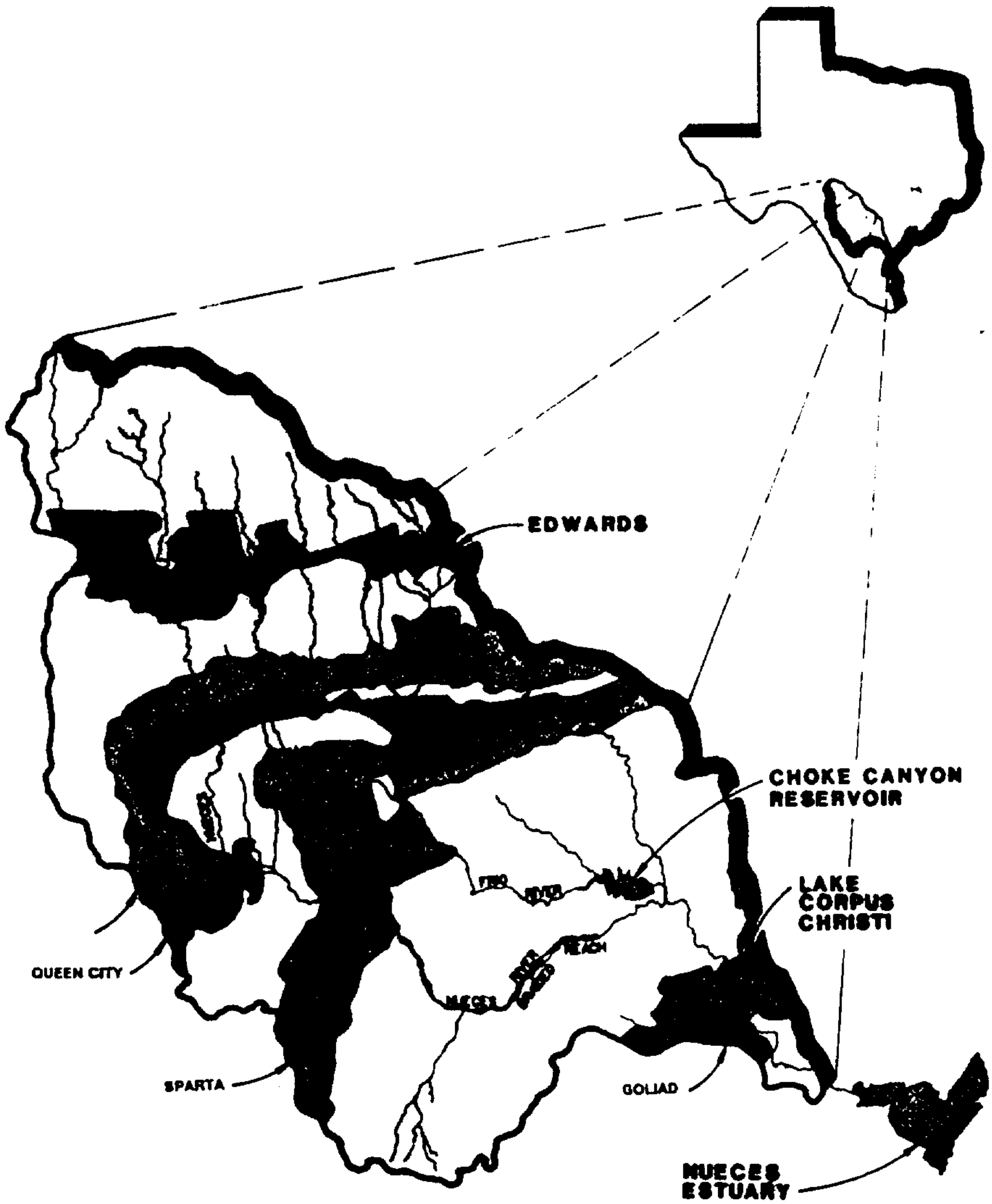
Regional Water Supply Planning Study - Phase I

Nueces River Basin

Volume II - Technical Report



Nueces River Authority

City of Corpus Christi

Edwards Underground Water District

South Texas Water Authority

Texas Water Development Board

HDR

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REGIONAL WATER SUPPLY PLANNING STUDY

NUECES RIVER BASIN

VOLUME II - TECHNICAL REPORT

Prepared for

Nueces River Authority
City of Corpus Christi
Edwards Underground Water District
South Texas Water Authority
Texas Water Development Board

by

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May, 1991

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Nueces River Basin

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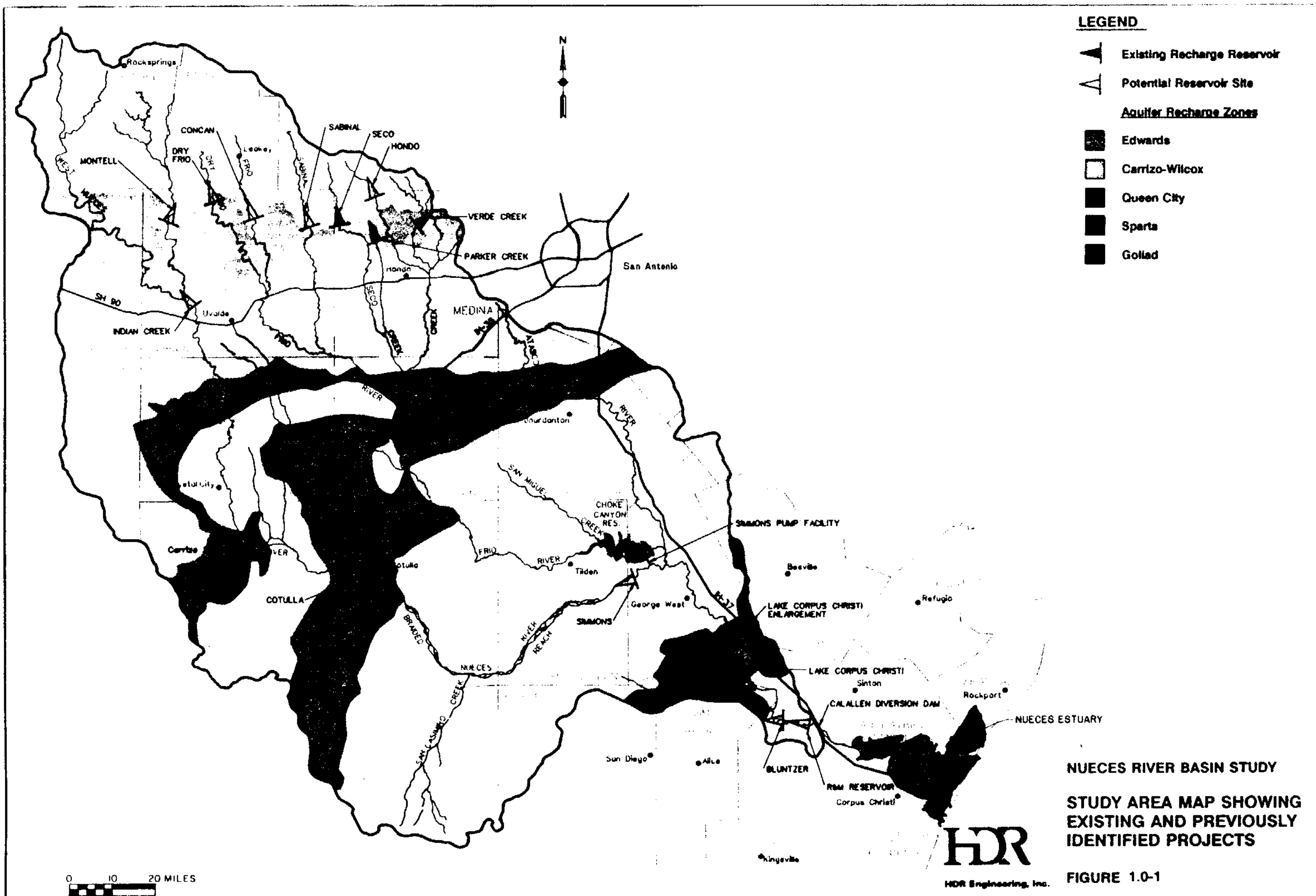
1.0 INTRODUCTION

The study area consists primarily of the Nueces River Basin, which covers an area of approximately 17,000 square miles in South Texas, as shown in Figure 1.0-1. Several entities interested in the potential development of additional water supplies in the basin, along with the Texas Water Development Board (TWDB), have jointly participated in the performance of this study. These four entities are:

Nueces River Authority (Authority);
City of Corpus Christi;
Edwards Underground Water District (EUWD); and
South Texas Water Authority (STWA).

Over the past several decades, increasing water demands on the Edwards Aquifer have raised concerns about the ability of the aquifer to meet these demands without causing social, economic, and environmental problems. The headwaters of the Nueces River Basin contribute about 57 percent of the total volume of surface water recharge to the San Antonio portion of the Edwards Aquifer. Streams crossing the Edwards Aquifer recharge zone lose a significant portion of their flow through faults and solution cavities in the limestone formations. A large portion of the runoff from the headwater area, however, occurs during storms which exceed the capacity of the recharge zone. It has been suggested that, if recharge enhancement structures were constructed, aquifer water levels, well yields, and springflows would benefit.



NUECES RIVER BASIN STUDY

STUDY AREA MAP SHOWING EXISTING AND PREVIOUSLY IDENTIFIED PROJECTS

FIGURE 1.0-1

The concept of building recharge structures is not new. In 1964, the U.S. Army Corps of Engineers (COE) identified numerous potential sites for recharge projects. Since 1974, the Edwards Underground Water District has undertaken the construction of three small recharge projects in the basin. The locations of the EUWD recharge projects as well as the locations of those projects identified by the COE (and others) are shown in Figure 1.0-1.

1.1 Description of Nueces River Basin

The Nueces River Basin is a highly complex geohydrologic environment of ground water and surface water. Streams throughout the basin cross no less than five major aquifer recharge zones as shown in Figure 1.0-1. The most significant of these is the Edwards Aquifer recharge zone where an average 326,000 acre-feet per year enters the aquifer. Other aquifer recharge zones include the Carrizo-Wilcox, Queen City-Bigford, Sparta-Laredo, and Goliad. Although flows entering each of these aquifers are not as great on an annual basis as flows entering the Edwards, these recharge zones can significantly affect channel loss rates.

A unique feature of the Nueces River is an 81 mile long section commonly referred to as the "braided reach." The braided reach begins about 15 miles downstream of Cotulla where the single channel of the river transitions to a system of interconnected braided channels. These interconnected channels continue to about 12 miles upstream of Simmons. Studies performed by the U.S. Geological Survey (USGS) (Ref. 69) show significant stream flow losses occur in this reach.

Annual precipitation in the basin generally increases from west to east with the westernmost portion of the basin receiving about 21 inches and the easternmost portion about 32 inches. The topography within the basin varies from extremely steep slopes in the hill country upstream of the Edwards Aquifer recharge zone to generally mild or flat topography downstream of the Edwards. The steep slopes and thin soil characteristics typical of the hill country result in this area producing the greatest runoff volume per unit area of watershed in the basin. In the hill country portion of the basin, about 13 percent of annual precipitation contributes to runoff. Outside of the hill country, annual runoff volumes generally vary between 2 percent and 5 percent of annual precipitation. Average and median annual streamflow in the Nueces River Basin are about 631,000 acre-feet and 421,000 acre-feet, respectively, as measured at Lake Corpus Christi for the 1934 through 1989 period. This represents about 3 percent of the average annual basin-wide precipitation.

Land use within the basin is almost entirely related to agricultural uses, with 10 percent classified as cropland, 6 percent pastureland, and 84 percent rangeland (Ref. 36 & 37). The largest municipality located within the basin is the City of Uvalde, which has a population of approximately 16,650 (Ref. 35).

1.2 Previous Hydrologic and Water Supply Studies

Numerous studies have been performed by the U.S. Geological Survey (USGS) and others to define relationships between ground and surface water resources throughout the basin. These studies have focused on: 1) Measuring channel losses and gains for eight stream segments crossing the Edwards recharge zone (Ref. 68); 2) Estimating channel losses through the braided reach of the Nueces River (Ref. 69); 3) Estimating channel losses and gains below Lake Corpus Christi on the Nueces River (Ref. 64); 4) Estimating seepage losses from Lake Corpus Christi (Ref. 44); and 5) estimating natural recharge to the Edwards Aquifer (Ref. 66 & 67). These studies as well as the 1983 U.S. Bureau of

Reclamation Report (Ref. 47 & 49) and the 1964 U.S. Army Corp of Engineers (USCE) Report (Ref. 53) were the primary published references for this study. Summaries of previous water supply studies from which significant reservoir sites in the Nueces and adjoining River Basins were identified are included in Appendix B.

1.3 Other Considerations of Recharge Enhancement

Approximately 98 percent of the drainage area of the Nueces River Basin is located upstream of the Choke Canyon Reservoir/Lake Corpus Christi System (CC/LCC System). The locations of these two reservoirs are shown in Figure 1.0-1. The CC/LCC System is operated by the City of Corpus Christi, with the majority of water being diverted from the system at the Calallen Diversion Dam located 35 miles downstream of Lake Corpus Christi. At this location, the water is diverted from the river and distributed to various municipal and industrial users. The CC/LCC System is the primary source of municipal and industrial water supply for a significant portion of the Texas Coastal Bend. Reductions in the inflows to these two reservoirs that could result from the construction of additional recharge projects is an important consideration in the evaluation of any recharge enhancement program.

Ongoing studies of the Nueces Estuary, which includes Nueces, Corpus Christi, Oso, and Redfish Bays and a portion of the Laguna Madre have shown that freshwater inflows play an important role in the productivity and viability of the estuary. Reduction of inflow to the Nueces Estuary that could result from the construction of additional recharge structures is also an important consideration.

1.4 Study Objectives

The primary objectives of this study are listed below and were accomplished through the development and application of a computer model of the Nueces River Basin.

* Determination of the potential for increasing artificial recharge to the Edwards Aquifer through construction of additional recharge structures in the Nueces River Basin;

* Calculation of the firm yield of the Choke Canyon Reservoir/Lake Corpus Christi System with and without additional recharge structures; and

* Quantification of the potential impacts of additional recharge structures on inflows to the Nueces Estuary.

Additional objectives of the study included:

* Independent evaluation of U.S. Geological Survey (USGS) estimates of historical natural recharge to the Edwards Aquifer from the Nueces River Basin;

* Estimation of future water demands for the Nueces River Basin through the year 2040 with emphasis on estimating future demands of the CC/LCC service area;

* Evaluation of the firm yield of the CC/LCC System with respect to its ability to meet future demands through the year 2040; and

* Development of recommendations for additional study.

2.0 WATER USE AND WATER RIGHTS

2.1 Historical Surface Water Use

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

For this study, the Nueces River Basin is subdivided into 4 major reaches for convenience of discussion and presentation. These reaches and associated drainage areas are presented in Figure 2.1-1 and are described as follows:

Reach 1 - Extends from basin headwaters to the downstream edge of the Edwards Aquifer recharge zone including areas upstream of the nearby USGS streamflow gaging stations on the Nueces, Frio, and Sabinal Rivers and on Hondo and Seco Creeks.

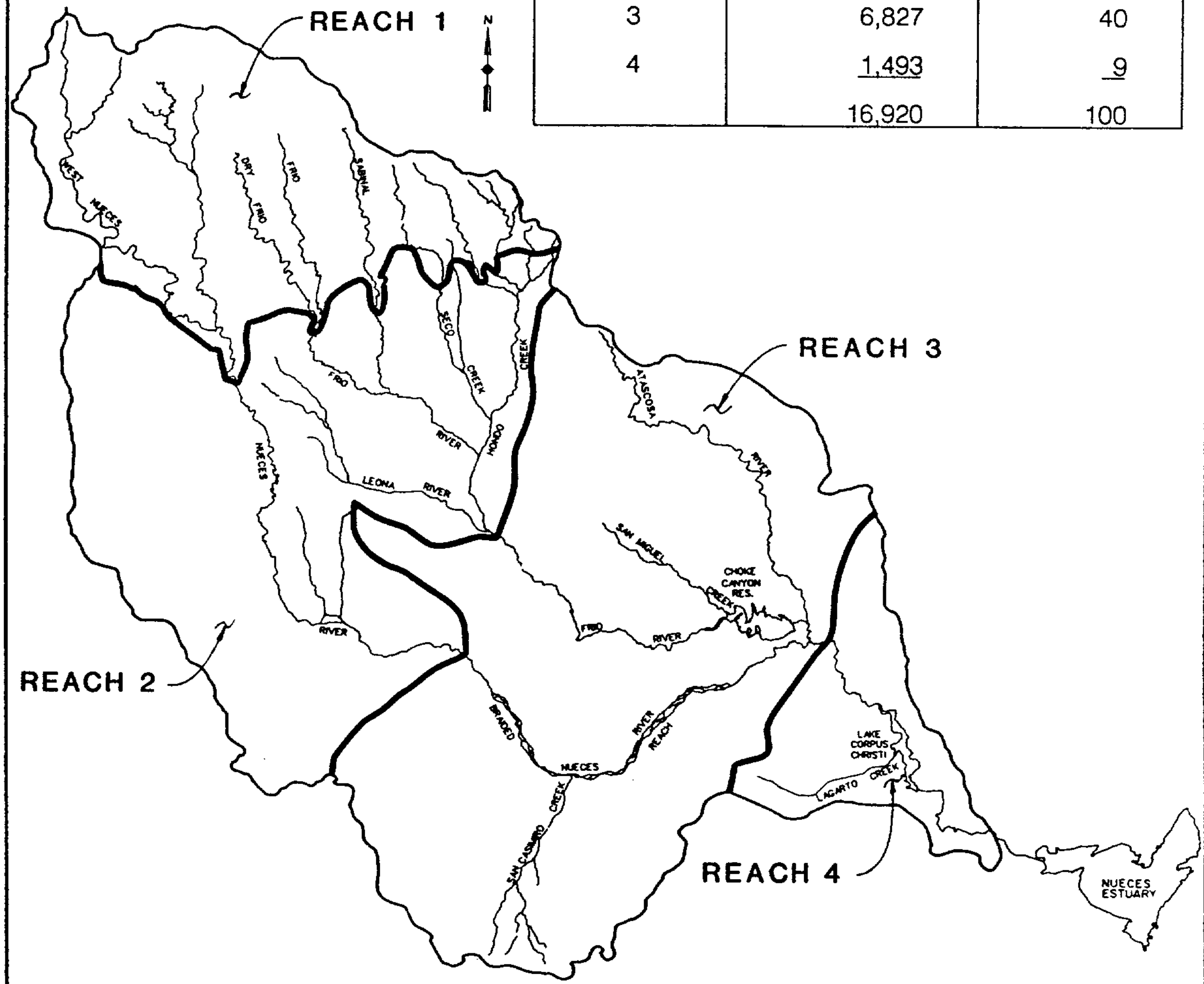
Reach 2 - Extends from the lower end of Reach 1 to the USGS streamflow gaging stations located near Interstate Highway 35 on the Nueces River at Cotulla and the Frio River near Derby.

Reach 3 - Extends from the lower end of Reach 2 to the USGS streamflow gaging station on the Nueces River near Three Rivers.

Reach 4 - Extends from the lower end of Reach 3 to Calallen Dam.

Records of historical surface water use as reported by individual water rights owners have been tabulated by the Texas Water Commission (TWC) staff. These records are comprised of annual totals from 1915 to 1955 and monthly totals from 1955 through 1988. The records are further categorized by designated type of use, including municipal, industrial, irrigation, mining, and recharge. HDR obtained surface water use records for the

Drainage Area of Model Reaches		
Reach Number	Drainage Area (Sq. Mi.)	Percentage of Basin
1	3,306	20
2	5,294	31
3	6,827	40
4	1,493	9
	16,920	100



NUECES RIVER BASIN STUDY

BASIN MODEL REACHES

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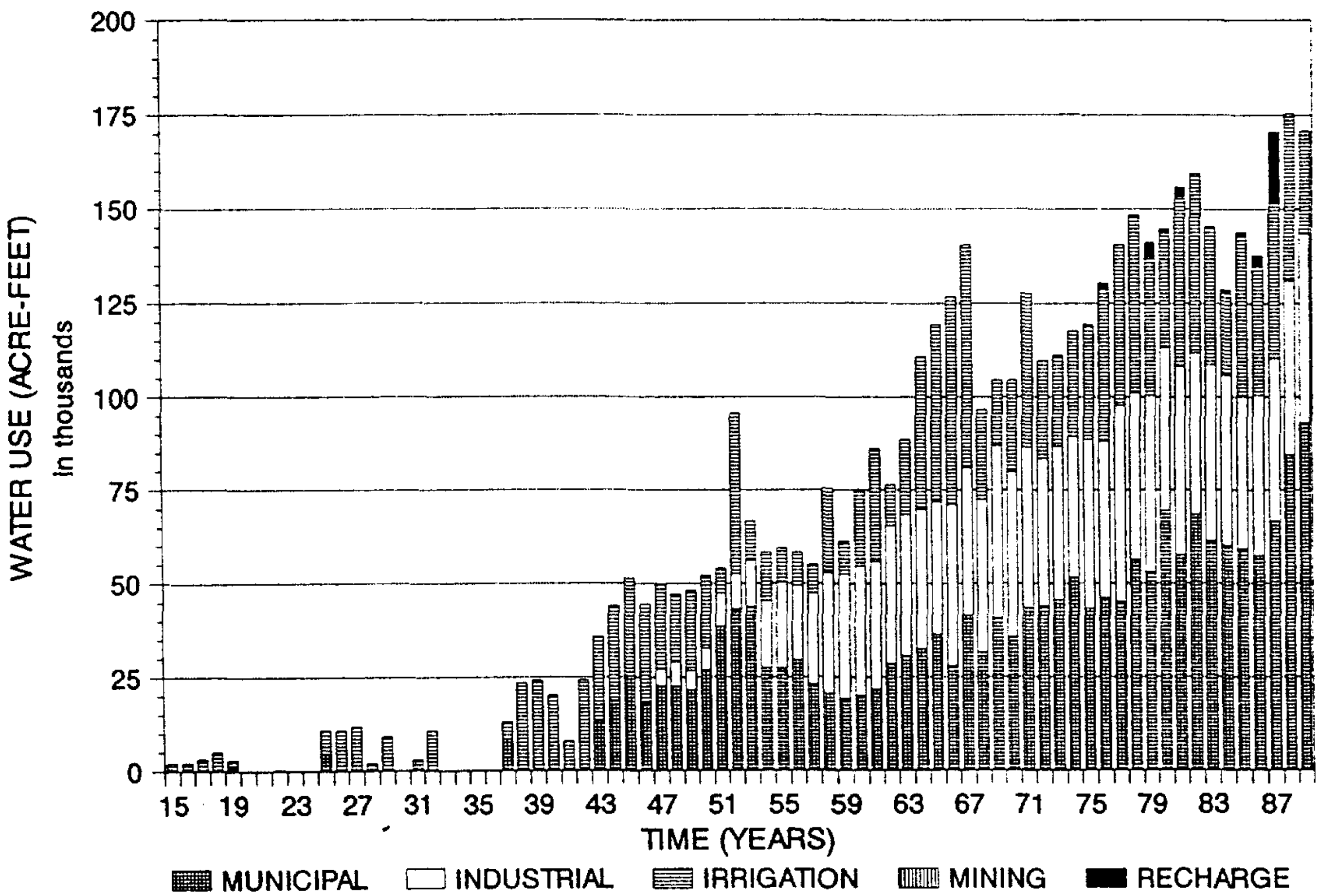
FIGURE 2.1-1

1915-88 period from the TWC in digital format and researched reports from individual rights owners authorized to divert at least 50 acre-feet per year to estimate 1989 use. Figure 2.1-2 and Table 2.1-1 summarize historical surface water use by type of use for the entire Nueces River Basin. Figure 2.1-3 and Table 2.1-2 summarize historical surface water use according to type of use for each reach within the basin. Comprehensive tables of annual surface water use broken down by type of use for each reach and the entire basin are included in Appendix C (Volume III).

Water use is highly variable from month to month depending upon the type of use and geographic location. Typical monthly percentages of annual water demand were calculated for municipal, industrial, and irrigation use types for each major reach within the basin where significant use has occurred. Surface water use for mining was assumed, for modelling purposes, to occur uniformly throughout the year. Reported monthly water use data for the 1955 to 1988 period provided by TWC was used for calculation of the monthly percentages presented in Figure 2.1-4.

As is apparent in Figure 2.1-4, municipal water demand peaks during the summer months at between about 10 percent and 13 percent of annual use, with summer demand percentages increasing as one moves upstream. Significant industrial water demand exists only in Reach 4, and the calculated monthly percentages are very similar to the municipal percentages for Reach 4. Significant water use for irrigation has occurred in each major reach, with peak monthly demands ranging from about 11 percent (Reach 2) to about 21 percent (Reach 4) of annual use. In the lower portion of the basin (Reaches 3 and 4), irrigation demand peaks in May, while monthly irrigation demand does not peak until June or July in Reaches 1 and 2.



NUECES RIVER BASIN STUDY

HISTORICAL SURFACE WATER USE NUECES RIVER BASIN

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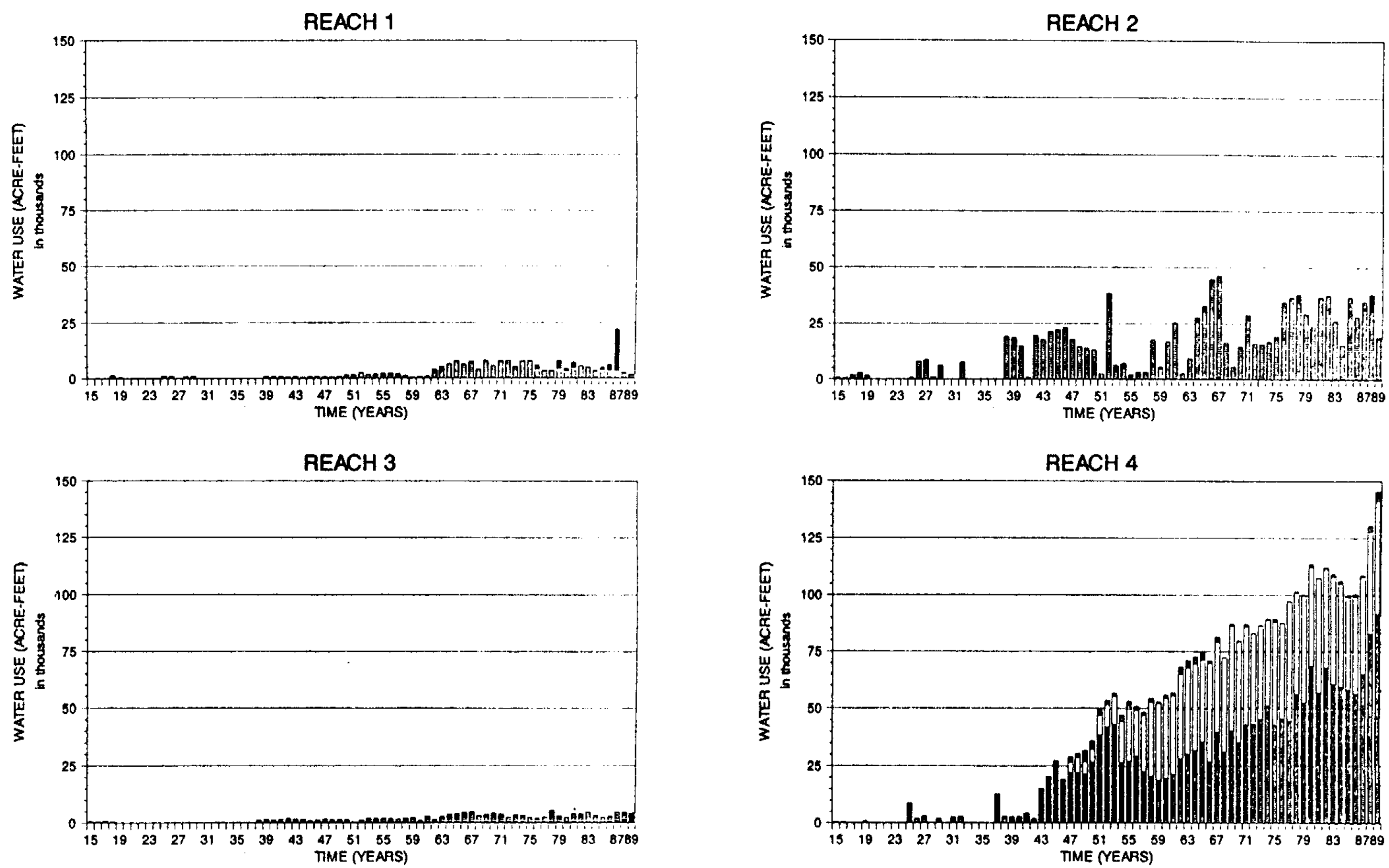
FIGURE 2.1-2

Table 2.1-1 Historical Surface Water Use Nueces River Basin				
Type of Use	Average Use* (Ac-Ft-Year)	Percentage of Average Use	Maximum Use (Ac-Ft/Yr)	Year of Max. Use
Municipal	63,785	42.5	93,113	1989
Industrial	45,241	30.1	52,585	1977
Irrigation	37,978	25.3	59,339	1967
Mining	42	0.0	74	1983
Recharge	3,218	2.1	19,160	1987
Total	150,264	100.0		

*Average use based on 1979-88 period.

Table 2.1-2 Historical Surface Water Use by Model Reach Nueces River Basin				
Type of Use	Percentage of Basin Average Use*			
	Reach 1	Reach 2	Reach 3	Reach 4
Municipal	0.4	0.1	0.9	98.6
Industrial	0.0	0.3	0.2	99.5
Irrigation	9.5	80.2	7.8	2.5
Mining	0.0	8.1	0.0	91.9
Recharge	100.0	0.0	0.0	0.0
All Uses	4.7	20.4	2.4	72.5

*Average use based on 1979-88 period.



LEGEND

MUNICIPAL INDUSTRIAL IRRIGATION MINING RECHARGE

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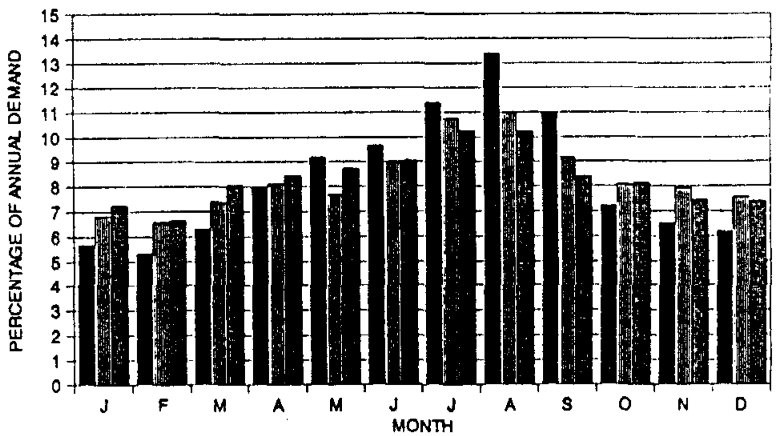
NUECES RIVER BASIN STUDY

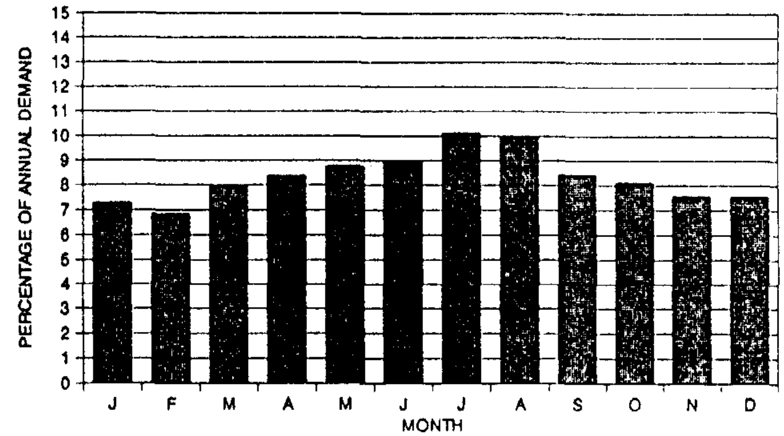
HISTORICAL SURFACE WATER USE BY REACH

FIGURE 2.1-3

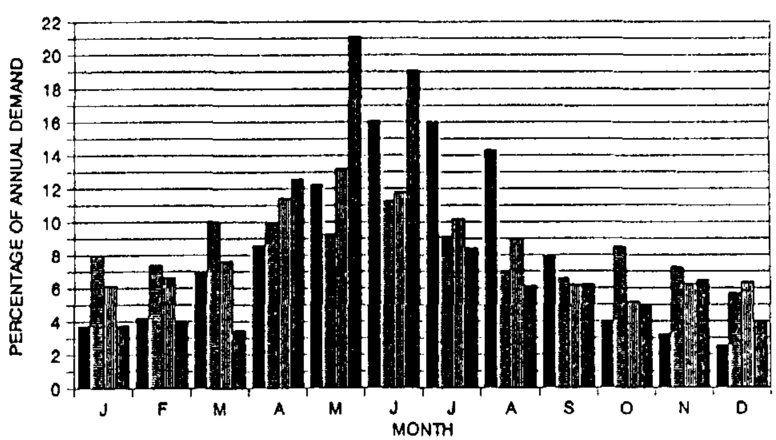
MUNICIPAL WATER USE



INDUSTRIAL WATER USE



IRRIGATION WATER USE



LEGEND

REACH 1 REACH 2 REACH 3 REACH 4

NUECES RIVER BASIN STUDY

MONTHLY PERCENTAGES OF ANNUAL SURFACE WATER DEMAND

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FIGURE 2.1-4

The typical monthly percentages of annual water demand presented in Figure 2.1-4 and discussed above were used to disaggregate annual diversion totals reported prior to 1955 in order to approximate monthly totals, which were used to adjust gaged streamflows to develop a natural streamflow database for the Nueces River Basin model. These monthly demand percentages are also included in the model in order to accurately simulate typical monthly diversion patterns for water rights according to type of use and geographic location and to accurately estimate the firm yield of the CC/LCC System.

2.2 Water Rights

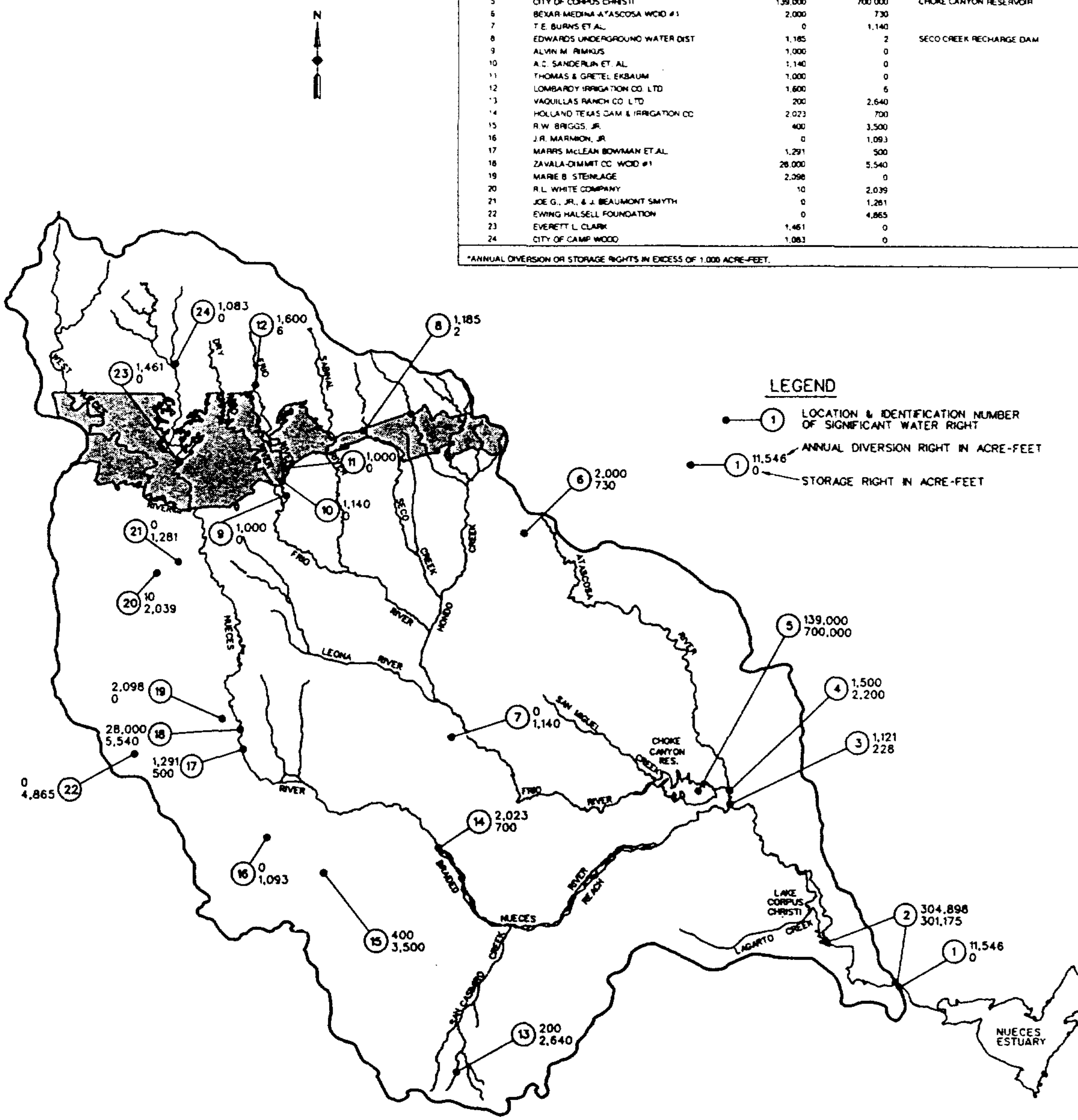
The Texas Water Commission maintains a master listing of all water rights and applications for water rights within the state. A current listing of all water rights and applications in the Nueces River Basin was extracted from the master listing, sorted by river order number (downstream to upstream), and included as Appendix D in Volume III of this report. Water rights in terms of authorized diversion for the entire basin are summarized by type of use in Table 2.2-1. As is apparent in Table 2.2-1, municipal and industrial water rights are the dominant types of use in the basin, totaling over 85 percent of all authorized diversion rights. Authorized municipal and industrial diversion rights of the City of Corpus Christi comprise almost 84 percent of total basin diversion rights. The Edwards Underground Water District owns all currently authorized diversion rights for recharge, which comprise less than 1 percent of total basin diversion rights.

There are a total of 24 owners of storage or annual diversion rights in excess of 1,000 acre-feet. The geographic location of each of these significant water rights is shown in Figure 2.2-1 along with a listing of the associated diversion and storage rights. The sum of these diversion rights represents almost 95 percent of total diversion rights in the Nueces River Basin.

Table 2.2-1 **Summary of Water Rights by Type of Use**		
Type of Use	**Authorized Diversion (Ac-Ft/Year)**	**Percent of Total Authorized Diversion**
Municipal		
A. City of Corpus Christi (et. al)	215,142	
B. Others	6,933	
Subtotal-Municipal	222,075	41.9
Industrial		
A. City of Corpus Christi (et. al)	228,530	
B. Other	368	
Subtotal-Industrial	228,898	43.2
Irrigation		
A. Zavala-Dimmit Co. WID #1	27,996	
B. Others	48,761	
Subtotal-Irrigation	76,757	14.5
Mining	16	0.0
Recharge	2,290	0.4
Other	10	0.0
TOTALS	530,046	100%

SIGNIFICANT WATER RIGHTS*				
IDENT. NO.	OWNER	DIVERSION RIGHTS (AC-FT/YR)	STORAGE RIGHTS (AC-FT)	NOTES
1	NUECES COUNTY WCID #3	11,546	0	
2	CITY OF CORPUS CHRISTI	304,898	300,000 1,175	LAKE CORPUS CHRISTI CALALLEN RESERVOIR
3	DIAMOND SHAMROCK REFINING	1,121	228	
4	CITY OF THREE RIVERS	1,500	2,200	
5	CITY OF CORPUS CHRISTI	139,000	700 000	CHOKE CANYON RESERVOIR
6	BEXAR-MEDINA-ATASCOSA WCID #1	2,000	730	
7	T.E. BURNS ET AL.	0	1,140	
8	EDWARDS UNDERGROUND WATER DIST	1,185	2	SECO CREEK RECHARGE DAM
9	ALVIN M. RIMKUS	1,000	0	
10	A.C. SANDERLIN ET. AL.	1,140	0	
11	THOMAS & GRETEL EKBAUM	1,000	0	
12	LOMBARDY IRRIGATION CO. LTD	1,600	6	
13	VAQUILLAS RANCH CO. LTD	200	2,640	
14	HOLLAND TEXAS DAM & IRRIGATION CO	2,023	700	
15	R.W. BRIGGS, JR.	400	3,500	
16	J.R. MARMION, JR.	0	1,093	
17	MARRS McLEAN BOWMAN ET.AL.	1,291	500	
18	ZAVALA-DIMMIT CO. WCID #1	28,000	5,540	
19	MARIE B. STEINLAGE	2,098	0	
20	R.L. WHITE COMPANY	10	2,039	
21	JOE G., JR., & J. BEAUMONT SMYTH	0	1,281	
22	EWING HALSELL FOUNDATION	0	4,865	
23	EVERETT L. CLARK	1,461	0	
24	CITY OF CAMP WOOD	1,083	0	

*ANNUAL DIVERSION OR STORAGE RIGHTS IN EXCESS OF 1,000 ACRE-FEET.



NUECES RIVER BASIN STUDY

SIGNIFICANT WATER RIGHTS LOCATION MAP

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FIGURE 2.2-1

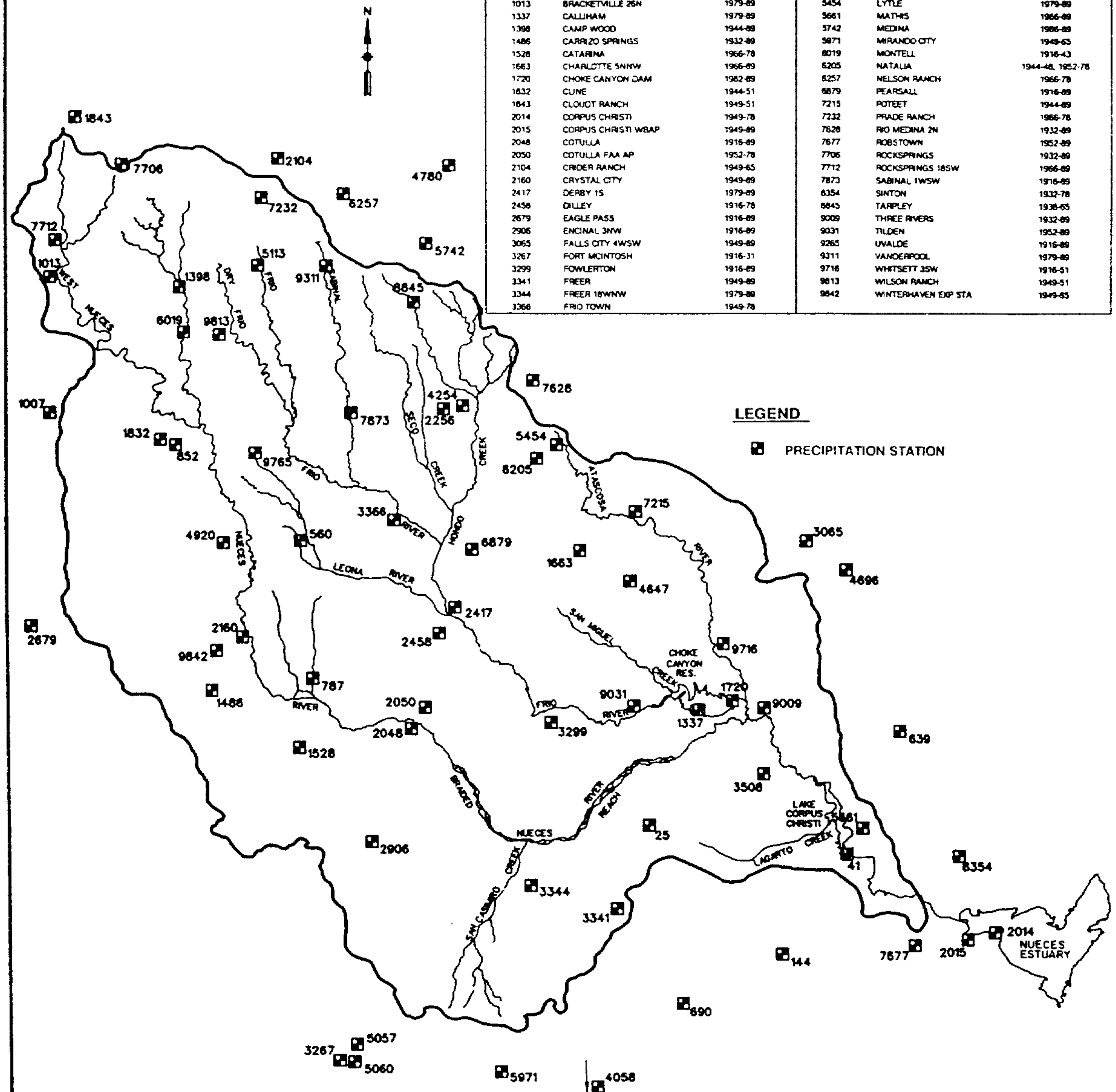
3.0 CLIMATOLOGICAL DATA

3.1 Precipitation

Precipitation data from approximately 70 stations was used in the development of areal precipitation for the 1916 to 1989 historical period for each of 29 subwatersheds comprising the entire Nueces River Basin. The geographic location of each of these stations is presented in Figure 3.1-1. Inset in Figure 3.1-1 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 sources of historical precipitation data were stations supported by the National Weather Service (NWS) and the Texas Water Development Board (TWDB); however, supplementary records obtained from local observers and the U.S. Geological Survey (USGS) were also used. Monthly areal precipitation for each of the 29 subwatersheds in the Nueces River Basin is summarized for reference in tables included in Appendix E (Volume III).

Areal precipitation for each watershed was developed by applying the Thiessen Method (Ref. 70) in which individual stations become the centers of polygonal areas constructed by drawing the perpendicular bisectors of lines connecting the stations. Watershed boundaries are superimposed on the polygons and Thiessen weights are calculated for each station and watershed based on the percentage of the watershed area within the polygonal subarea. Areal precipitation is then computed as the sum of the products of the measured station precipitation and the associated Thiessen weight. Missing monthly precipitation totals at any given station were estimated by review of daily records for that station and the nearest active station. Missing daily values were replaced with values from the nearest active station, and the estimated monthly total was calculated by summing the daily values.

NWS AND TWDB PRECIPITATION STATIONS					
STATION NUMBER	STATION NAME	PERIOD OF RECORD USED IN STUDY	STATION NUMBER	STATION NAME	PERIOD OF RECORD USED IN STUDY
25	ACKER RANCH	1979-89	3508	GEORGE WEST	1916-89
41	WESLEY SEALE DAM	1966-89	4056	HEBRONVILLE	1916-48, 1952-89
144	ALICE	1916-48, 1952-89	4254/4256	HONDO & HONDO WSMO AP	1916-89
560	BATESVILLE	1966-89	4647	JOURDANTON	1949-89
639	BEEVILLE 5NE	1916-89	4696	KARNES CITY	1932-89
690	BENAVIDES 72	1966-89	4780	KERRVILLE	1916-48
787	BIG WELLS	1916-89	4920	LA PRYOR	1916-78
852	BLEWETT 5NW	1966-78	5057/5060	LAREDO WB AP & #2	1949-89
1007	BRACKETTVILLE	1916-89	5113	LEAKEY	1952-89
1013	BRACKETVILLE 26N	1979-89	5454	LYTLE	1979-89
1337	CALLIHAM	1979-89	5661	MATHIS	1966-89
1398	CAMP WOOD	1944-89	5742	MEDINA	1966-89
1486	CARRIZO SPRINGS	1932-89	5971	MIRANDO CITY	1949-65
1528	CATARINA	1966-78	6019	MONTELL	1916-43
1663	CHARLOTTE 5NNW	1966-89	6205	NATALIA	1944-48, 1952-78
1720	CHOKE CANYON DAM	1982-89	6257	NELSON RANCH	1966-78
1832	CLINE	1944-51	6879	PEARSALL	1916-89
1843	CLOUDT RANCH	1949-51	7215	POTEET	1944-89
2014	CORPUS CHRISTI	1949-78	7232	PRADE RANCH	1966-78
2015	CORPUS CHRISTI WBAP	1949-89	7628	RIO MEDINA 2N	1932-89
2048	COTULLA	1916-89	7677	ROBSTOWN	1952-89
2050	COTULLA FAA AP	1952-78	7706	ROCKSPRINGS	1932-89
2104	CRIDER RANCH	1949-65	7712	ROCKSPRINGS 18SW	1966-89
2160	CRYSTAL CITY	1949-89	7873	SABINAL 1WSW	1916-89
2417	DERBY 1S	1979-89	8354	SINTON	1932-78
2458	DILLEY	1916-78	8845	TARPLEY	1938-65
2679	EAGLE PASS	1916-89	9009	THREE RIVERS	1932-89
2906	ENCINAL 3NW	1916-89	9031	TILDEN	1952-89
3065	FALLS CITY 4WSW	1949-89	9265	UVALDE	1916-89
3267	FORT MCINTOSH	1916-31	9311	VANDERPOOL	1979-89
3299	FOWLERTON	1916-89	9716	WHITSETT 3SW	1916-51
3341	FREER	1949-89	9813	WILSON RANCH	1949-51
3344	FREER 18WNW	1979-89	9842	WINTERHAVEN EXP STA	1949-65
3366	FRIO TOWN	1949-78			



NUECES RIVER BASIN STUDY

PRECIPITATION STATION LOCATION MAP

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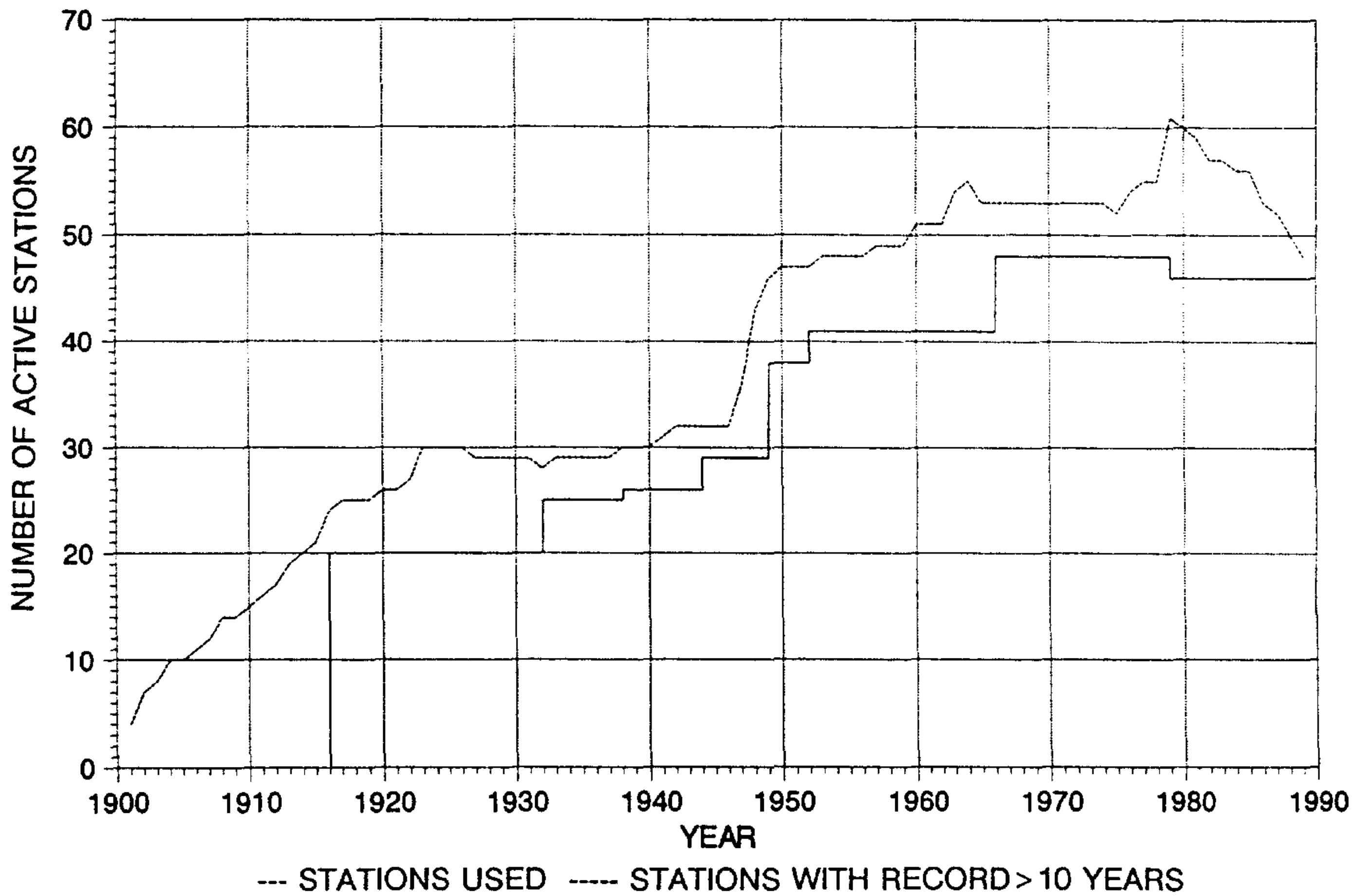
FIGURE 3.1-1

Because computed Thiessen weights for a given watershed can change significantly with the addition or deletion of precipitation stations, the 1916 to 1989 historical period was divided into 8 subperiods based on the availability of records at key stations. Figure 3.1-2 presents the number of stations used in each subperiod as well as the total number of precipitation stations having a period of record greater than 10 years which were active in each year of the 1901 to 1989 period. The actual number of stations used to compute areal precipitation during a particular subperiod ranged from a minimum of 20 during the 1916 to 1931 period up to a maximum of 48 during the 1966 to 1978 period.

3.2 Net Evaporation

Net evaporation is generally defined to be the difference between gross free water surface evaporation and direct precipitation on the water surface and is typically expressed in inches or feet. As 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 from the surface of a reservoir. Evaporation pans have been maintained at various locations throughout the state since the turn of the century by numerous federal and state agencies, municipalities, and local interests. The TWDB has compiled much of the available historical pan evaporation data (Ref. 40) and has developed monthly reservoir evaporation rates for the entire state by one degree quadrangles of latitude and longitude (Ref. 42) for the 1940 to 1988 period.

Monthly net evaporation rates for the 1934 to 1989 period were needed in this study to accurately calculate historical inflows to Choke Canyon Reservoir and Lake Corpus



NUECES RIVER BASIN STUDY

PRECIPITATION STATION AVAILABILITY AND USE

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FIGURE 3.1-2

Christi and to simulate lake level fluctuations in these reservoirs as well as in potential recharge reservoirs. The evaporation rates used in this study for the 1940 to 1988 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 potential recharge reservoirs and for 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 to 1939 period and for 1989 were computed from available pan evaporation records adjusted by pan coefficients recommended by the TWDB (Ref. 42) and by coincident measured precipitation. Tables summarizing historical net evaporation rates used in this study are included in Appendix F (Volume III).

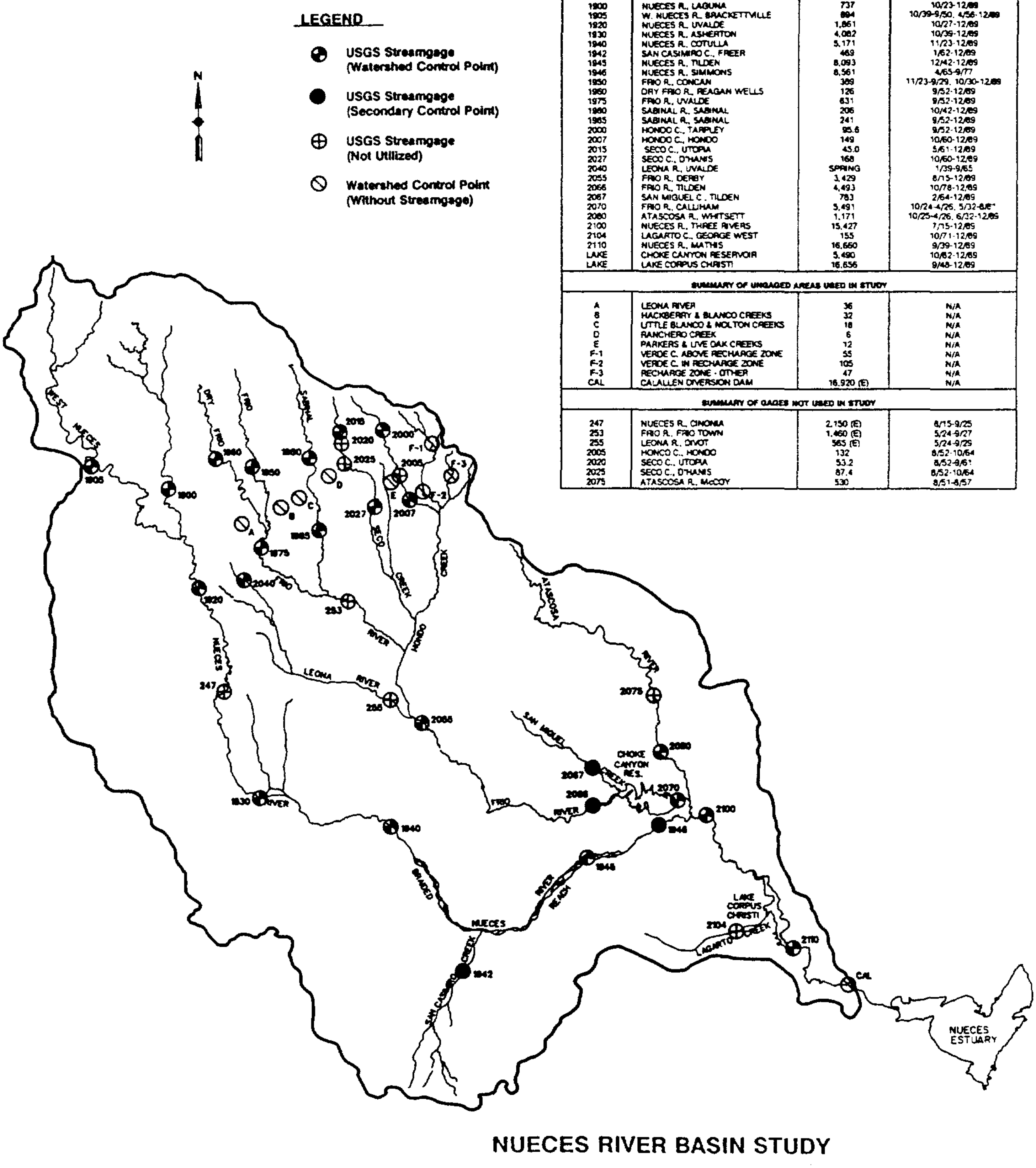
4.0 NATURAL STREAMFLOW DEVELOPMENT

The compilation of accurate estimates of historical natural streamflow is the key prerequisite to the development of a useful model of the Nueces River Basin. Natural streamflow is defined to be 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 and reservoir operations. Once an historical natural streamflow database is complete, the potential effects of future water rights diversions and additional recharge reservoir construction may be accurately quantified. This chapter presents the steps involved in the development of natural streamflows for selected locations throughout the Nueces River Basin. Natural streamflow summary tables for each control point in the model are included in Appendix G in Volume III.

4.1 Streamflow Data Collection

Records of streamflow in the Nueces River Basin have been collected at numerous streamflow gaging stations maintained by the U.S. Geological Survey (USGS), some since 1915. Figure 4.1-1 indicates the location, drainage area, and period of record of each station used in this study, as well as for several stations which were not used due to limited period of record. Summaries of monthly gaged streamflow were obtained from the Texas Natural Resources Information System, water resources data summaries (Ref. 32 & 60), and directly from the USGS. The records from the gaging stations in the Nueces River Basin are generally classified by the USGS as "good," which means that about 95 percent of the daily discharges reported are within 10 percent of the true values.

SUMMARY OF GAGED WATERSHED AREAS USED IN STUDY			
REFERENCE NUMBER	LOCATION	DRAINAGE AREA (SQ. MI.)	PERIOD OF RECORD
1900	NUECES R., LAGUNA	737	10/23-12/89
1905	W. NUECES R., BRACKETTVILLE	894	10/39-9/50, 4/56-12/89
1920	NUECES R., UVALDE	1,861	10/27-12/89
1930	NUECES R., ASHERTON	4,082	10/39-12/89
1940	NUECES R., COTULLA	5,171	11/23-12/89
1942	SAN CASIMIRO C., FREER	469	1/62-12/89
1945	NUECES R., TILDEN	8,093	12/42-12/89
1946	NUECES R., SIMMONS	8,561	4/65-9/77
1950	FRIO R., CONCAN	389	11/23-9/29, 10/30-12/89
1960	DRY FRIO R., REAGAN WELLS	126	9/52-12/89
1975	FRIO R., UVALDE	631	9/52-12/89
1980	SABINAL R., SABINAL	206	10/42-12/89
1985	SABINAL R., SABINAL	241	9/52-12/89
2000	HONDO C., TARPLEY	95.6	9/52-12/89
2007	HONDO C., HONDO	149	10/60-12/89
2015	SECO C., UTOPIA	45.0	5/61-12/89
2027	SECO C., D'HANIS	168	10/60-12/89
2040	LEONA R., UVALDE	SPRING	1/39-9/65
2055	FRIO R., DERBY	3,429	8/15-12/89
2066	FRIO R., TILDEN	4,493	10/78-12/89
2067	SAN MIGUEL C., TILDEN	783	2/64-12/89
2070	FRIO R., CALLIHAM	5,491	10/24-4/26, 5/32-6/81
2080	ATASCOSA R., WHITSETT	1,171	10/25-4/26, 6/32-12/89
2100	NUECES R., THREE RIVERS	15,427	7/15-12/89
2104	LAGARTO C., GEORGE WEST	155	10/71-12/89
2110	NUECES R., MATHIS	16,660	9/39-12/89
LAKE	CHOKE CANYON RESERVOIR	5,490	10/82-12/89
LAKE	LAKE CORPUS CHRISTI	16,656	9/48-12/89
SUMMARY OF UNGAGED AREAS USED IN STUDY			
A	LEONA RIVER	36	N/A
B	HACKBERRY & BLANCO CREEKS	32	N/A
C	LITTLE BLANCO & NOLTON CREEKS	18	N/A
D	RANCHERO CREEK	6	N/A
E	PARKERS & LIVE OAK CREEKS	12	N/A
F-1	VERDE C. ABOVE RECHARGE ZONE	55	N/A
F-2	VERDE C. IN RECHARGE ZONE	105	N/A
F-3	RECHARGE ZONE - OTHER	47	N/A
CAL	CALALLEN DIVERSION DAM	16,920 (E)	N/A
SUMMARY OF GAGES NOT USED IN STUDY			
247	NUECES R., CINONIA	2,150 (E)	8/15-9/25
253	FRIO R., FRIO TOWN	1,460 (E)	5/24-9/27
255	LEONA R., DIVOT	565 (E)	5/24-9/25
2005	HONCO C., HONDO	132	8/52-10/64
2020	SECO C., UTOPIA	53.2	8/52-9/61
2025	SECO C., D'HANIS	87.4	8/52-10/64
2075	ATASCOSA R., McCOY	530	8/51-8/57



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WATERSHED CONTROL POINT AND STREAMGAGE LOCATION MAP

FIGURE 4.1-1

All of the streamflow gaging stations having a period of record in excess of 13 years were used as watershed control points in the computer model of the basin. Accurate calculation of recharge to the Edwards Aquifer necessitated the selection of additional watershed control points for several ungaged watersheds. The locations of these ungaged watershed control points are indicated in Figure 4.1-1. Development of synthetic historical runoff for the ungaged areas is discussed in Chapter 6. A total of 29 watershed control points were ultimately included in the Nueces River Basin model and several more were used in streamflow database development.

4.2 Reservoir Inflows

Historical reservoir inflows were computed for Choke Canyon Reservoir (October, 1982 - December, 1989) and Lake Corpus Christi (September, 1948 - December, 1989) to supplement gaged streamflow records for the Frio River at Calliham and the Nueces River near Mathis, respectively. Computation of historical inflows was based on the principle of continuity as formulated in the following simplified equation:

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

where:

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

Basic data sets for inflow computations, including end-of-month contents, outflow, precipitation, and pan evaporation, were obtained from U.S. Bureau of Reclamation (USBR) Monthly Water Supply Reports and Operators Daily Logs provided by the City of Corpus Christi. Gross monthly water surface evaporation rates derived from TWDB data as discussed in Chapter 3 were used in net evaporation rate calculations for years prior to 1989, and adjusted pan evaporation data was used for calendar year 1989. Elevation-area-capacity relationships representative of conditions in 1948 (Ref. 19), 1959 (Ref. 41), 1972 (Ref. 14), and 1987 were used for Lake Corpus Christi. An elevation-area-capacity table dated June 1, 1983 provided by the City of Corpus Christi for Choke Canyon Reservoir was used to supplement the USBR Monthly Water Supply Reports. Spills and releases from Lake Corpus Christi were assumed equal to the concurrent gaged streamflow reported by the USGS for the Nueces River near Mathis. Records of direct diversions from Lake Corpus Christi for the Alice Water Authority, Beeville Water Supply District, and City of Mathis were obtained from the Texas Water Commission. Computed historical inflows to the reservoirs were naturalized in the same manner as gaged streamflows.

4.3 Streamflow Naturalization Methodology

Monthly natural streamflows for the 1934 through 1989 period were developed by adjusting gaged streamflows and calculated reservoir inflows for the effects of historical water supply diversions and reservoir operations. Translation of the effects of upstream diversions to downstream control points was accomplished with the use of delivery factors representative of typical channel loss rates in each intervening reach. Natural streamflows at selected control points during portions of the 1934 to 1989 period when gaged records do not exist were subsequently estimated using multiple linear regression techniques. Derivation of delivery factors and missing flow records are detailed in Sections 4.4 and 4.5, respectively, of this Chapter.

The streamflow naturalization methodology applied in the performance of this study is summarized in schematic and equation form in Figure 4.3-1. Historical monthly diversions of all use types were grouped by watershed as delineated by control point. The natural flow at the base of headwater watersheds, such as Watershed 1 in Figure 4.3-1, is calculated by simply adding the historical diversions to the gaged streamflow at Control Point 1 (CP1). Natural flow at the base of Watershed 2 (CP2) is equal to the gaged streamflow plus the local diversions in Watershed 2 plus the change in flow at CP1 due to diversions in Watershed 1 delivered to CP2. The delivery factor from CP1 to CP2 is simply the average percentage of the flow passing CP1 which reaches CP2. In like manner, streamflows were naturalized at consecutive control points moving upstream to downstream through the entire basin. It was not necessary to consider return flows in the streamflow naturalization process because return flows from agricultural operations are very minor or non-existent, and all significant municipal and industrial return flows occur downstream of Calallen Dam or in another basin.

It should be noted that the streamflow naturalization methodology used in this study is significantly different from the more traditional methodology applied by the Texas Water Commission (TWC, formerly Texas Department of Water Resources, Ref. 33). Traditionally, upstream historical diversions have been effectively added to successive downstream gaged streamflows on a "one-to-one" basis to obtain natural streamflow which inherently neglects

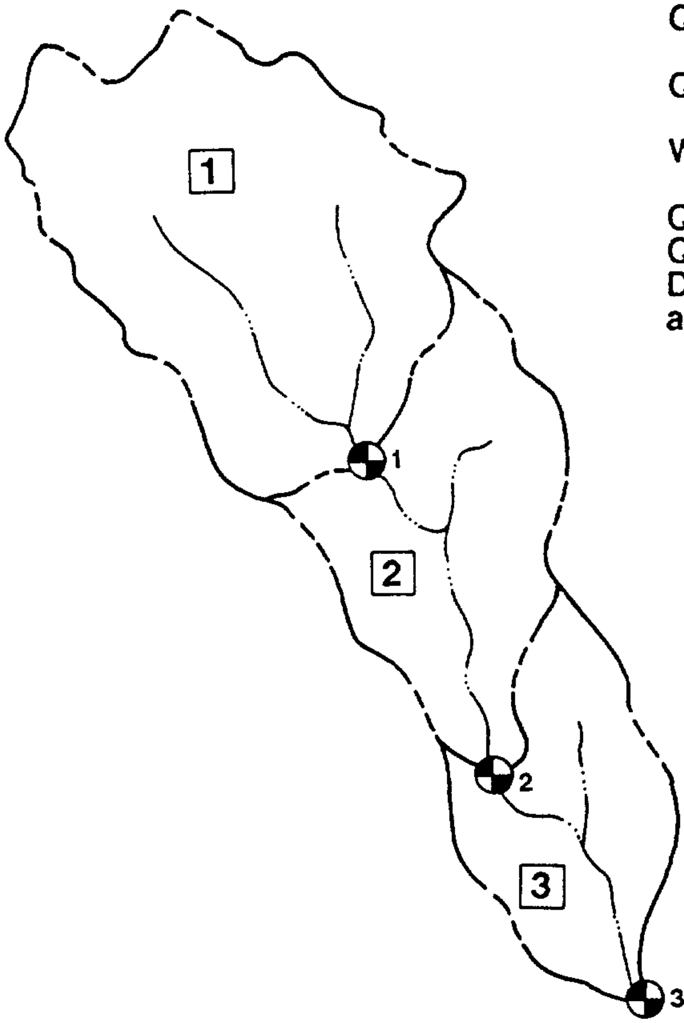
$$QN_1 = QG_1 + D_1$$

$$QN_2 = QC_2 + D_2 + a_2(QN_1 - QG_1)$$

$$QN_3 = QC_3 + D_3 + a_3(QN_2 - QG_2)$$

WHERE:

QN	=	NATURAL STREAMFLOW
QG	=	GAGED STREAMFLOW
D	=	REPORTED DIVERSIONS
a	=	DELIVERY FACTOR



LEGEND

STREAMGAGE/CONTROL POINT

WATERSHED BOUNDARY

STREAM

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STREAMFLOW NATURALIZATION METHODOLOGY

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FIGURE 4.3-1

intervening channel losses. The errors resulting from this traditional technique are mitigated in part by the "one-to-one" reduction of natural flows to account for full water rights diversions in the evaluation of water availability for appropriation. In this study, quantitative assessment of the potential impact of upstream recharge structures on downstream water rights, including those of the City of Corpus Christi in the CC/LCC System, necessitated development of a methodology incorporating the significant effects of intervening losses. Simply stated, impoundment and recharge of one acre-foot of runoff near Uvalde does not reduce inflow to Lake Corpus Christi by one acre-foot. Natural streamflows developed in this study for the Nueces River near Three Rivers are compared with those provided by the TWC in Section 4.6 of this Chapter.

4.4 Delivery Factors and Channel Loss Rates

A streamflow delivery factor representing the percentage of water passing an upstream control point that arrives at the next downstream control point was estimated for each stream reach linking control points in the Nueces River Basin. Delivery factors used in the model are summarized in Table 4.4-1 by stream reach. The factors presented in Table 4.4-1 were derived using two primary methods depending upon location or major reach within the basin. Delivery factors in Reach 1, where intervening watersheds between upstream and downstream control points are relatively small, were obtained using stepwise multiple linear regression. In Reaches 2, 3, and 4, where intervening watersheds are substantially larger and channel loss rates are of great consequence in this study, delivery factors were derived using rainfall/runoff techniques in conjunction with gaged streamflow records. Each of these primary methods is discussed in the following sub-Sections.

Table 4.4-1 Summary of Delivery Factors by Stream Reach			
	Reach Reference Numbers		
Stream	From	To	Delivery Factor
Nueces River	1900	1920	0.95
West Nueces River	1905	1920	0.97
Nueces River	1920	1930	0.53
Nueces River	1930	1940	0.74
Nueces River	1940	1945	0.65
Nueces River	1945	2100	0.82
Frio River	1950	1975	0.51
Dry Frio River	1960	1975	0.78
Frio River	1975	2055	0.51
Sabinal River	1980	1985	0.84
Sabinal River	1985	2055	0.51
Seco Creek	2015	2027	0.51
Seco Creek	2027	2055	0.51
Hondo Creek	2000	2007	0.77
Hondo Creek	2007	2055	0.51
Verde Creek	F-1	F-2	0.77
Verde Creek	F-2	2055	0.51
Misc. Ungaged	A,B,C,D,E & F-3	2055	0.51
Frio River	2055	2070	0.66
Frio River	2070	2100	0.95
Atascosa River	2080	2100	0.90
Nueces River	2100	2110	0.74
Nueces River	2110	CAL	0.93

4.4.1 Reach 1 - Multiple Linear Regression

Stepwise multiple linear regression techniques were used to estimate delivery factors for gaged stream reaches in Reach 1 which include the Nueces, Frio, and Sabinal Rivers and Hondo and Seco Creeks. The delivery factor for Verde Creek, which is ungaged, was assumed equal to that derived for adjacent Hondo Creek due to comparable soil-cover complex, intervening drainage area size, and geographic proximity. Using these regression techniques, candidate independent variables were evaluated individually for significance and retained if they significantly improved estimates of the dependent variable. The general form of the regression equation was assumed to be as follows:

$$QNH = a\,(QG) + b\,(QI) + c$$

where:

QNH	=	Downstream Gaged Flow Adjusted for Diversions in Intervening Area
QG	=	Upstream Gaged Flow
QI	=	Estimated Flow from Intervening Area
a,b&c	=	Regression Coefficients

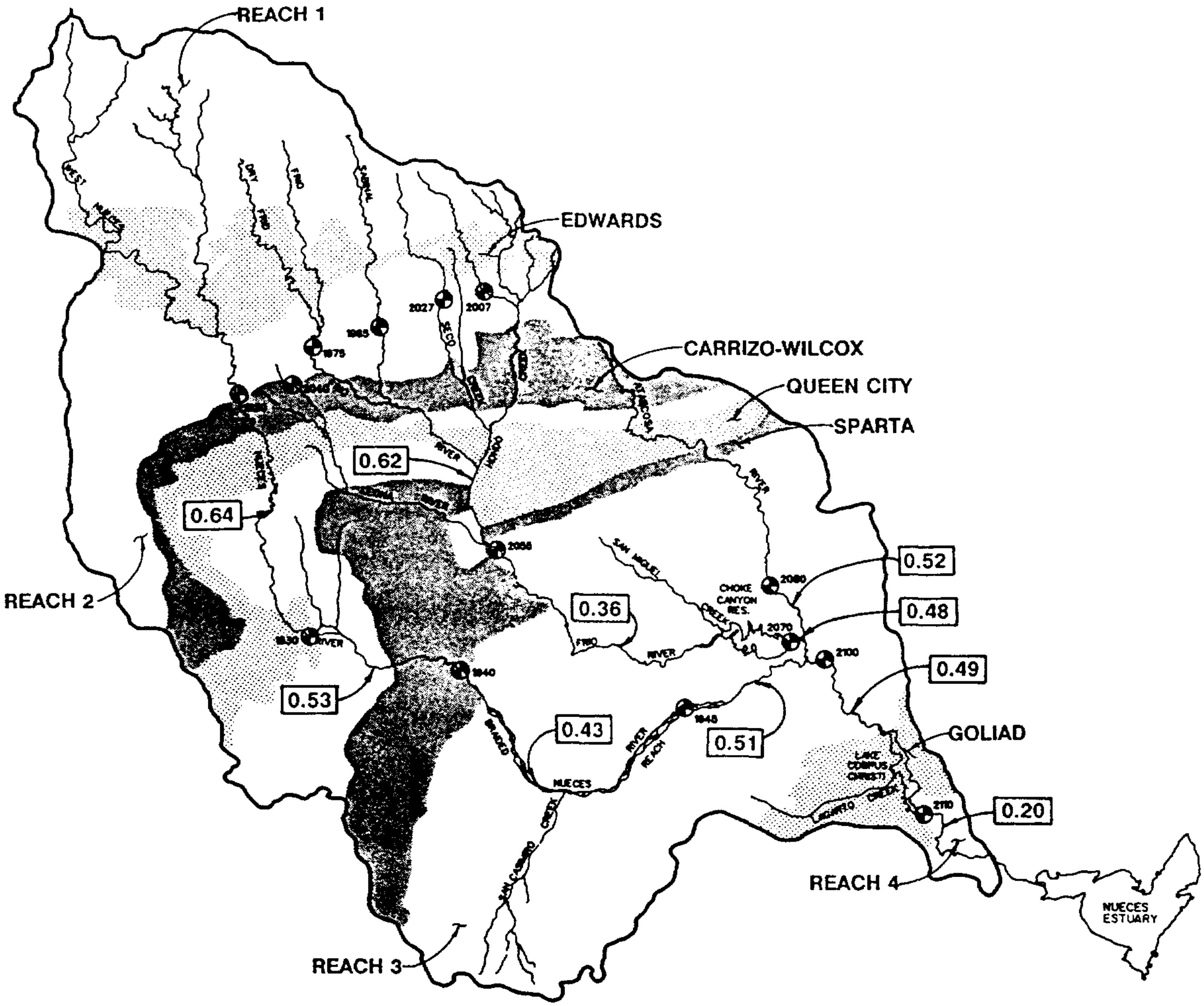
If two upstream gaged flow records exist above any one downstream gage, records from each upstream gage were included as independent variables for the period of concurrent record. The estimated flow from the intervening area, QI, is calculated monthly based on soil-cover complex, antecedent moisture conditions, and local precipitation as described in Chapter 6. For the purposes of this study, only independent variables or regression coefficients significant at the 90 percent confidence level based on the Students t Test (Ref. 11) were retained in the regression equations. The coefficient "a" associated with upstream gaged flow, QG, approximates the long-term average delivery factor for upstream gaged flow to the downstream gage location.

The five resulting regression equations for stream reaches in Reach 1 had coefficients of determination, r^2, ranging from 0.96 for the Nueces River to 0.57 for Seco Creek. The coefficient of determination of 0.96 for the Nueces River implies that 96 percent of the variation in the flow recorded at the gage below Uvalde can be explained by the regression equation. A weighted average r^2 for the equations representative of Reach 1 is 0.91 based on the dependent (downstream) mean monthly flow for each stream.

In Reach 1, upstream gaged flow and estimated intervening flow were significant in each of the five equations with the exception of the Frio River, where the intervening flow was not statistically significant. Well levels at the City of Uvalde well were also considered as candidate independent variables in developing regression equations for the Nueces and Frio Rivers. Consideration of well levels did not significantly improve estimates of downstream flow when all months with concurrent upstream and downstream flow records were considered in the regression analyses. The USGS (Ref. 68) found well levels along with upstream flow and a time/cumulative volume variable to be significant in one regression analysis of the Nueces River obtaining an r^2 of 0.89 using 103 data points. Runoff from the intervening watershed, however, was not directly considered by the USGS. The regression equation selected in this study was based on 536 data points, included both upstream and intervening flow, and resulted in an r^2 of 0.96. Several of the regression equations developed for Reach 1 were also used to estimate missing flow records as described in Section 4.5 of this Chapter.

4.4.2 Reaches 2, 3, and 4 - Rainfall/Runoff Techniques

Delivery factors or channel loss rates for stream segments in Reaches 2, 3, and 4 were calculated by performing long-term comparisons of concurrent upstream and downstream gaged streamflows using a modified SCS curve number procedure (Ref. 17 & 18) and monthly areal precipitation to estimate intervening runoff arriving at the downstream gage. The resulting channel loss rates for each stream segment are presented in Figure 4.4-1. Channel loss rates



LEGEND

USGS STREAMGAGE (WATERSHED CONTROL POINT)

0.64 PERCENTAGE OF STREAMFLOW LOST PER RIVER MILE

AQUIFER RECHARGE ZONES ARE SHADED.

NOTE: CHANNEL LOSS RATE OF 0.52 PERCENT/MILE FOR THE FRIO RIVER BELOW THE EDWARDS AQUIFER RECHARGE ZONE IS ASSUMED REASONABLE FOR THE LEONA RIVER, HONDO CREEK, AND SECO CREEK.

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CHANNEL LOSS RATES

FIGURE 4.4-1

upstream of Lake Corpus Christi ranged from a minimum of 0.36 percent per mile on the Frio River from Derby to Choke Canyon Reservoir to a maximum of 0.64 percent per mile on the Nueces River from Uvalde to Asherton. The average loss rate of 0.20 percent per mile on the Nueces River from Lake Corpus Christi to Calallen Dam was based on field measurements reported by the USGS and TWDB (Ref. 64) and is representative of the loss rate during periods of normal water deliveries with minimal intervening flows. Channel losses in the "braided reach" of the Nueces River between Cotulla and Tilden averaged 0.43 percent per mile, which is within the range of loss rates reported for this segment by the USGS (Ref. 69). Loss rates developed throughout Reaches 2 and 3 compared well with the results of water-delivery studies reported by the USGS (Ref. 59). As is apparent in Figure 4.4-1, channel loss rates were generally higher in stream segments crossing aquifer recharge zones. Table 4.4-2 summarizes composite estimates of the percentage of upstream flow lost for four reaches of significant interest.

Table 4.4-2
Summary of Channel Losses Downstream of Edwards Aquifer Recharge Zone

River Reach	Reach Length (miles)	Percentage of Upstream Flow Lost
Nueces River between Uvalde and Lake Corpus Christi	291.4	84.5
Frio River between Edwards Aquifer Recharge Zone and Choke Canyon Reservoir	173.7	66.3
Frio and Nueces Rivers between Choke Canyon Reservoir and Lake Corpus Christi	63.3	29.7
Nueces River between Lake Corpus Christi and Calallen Dam	35	7.0

The first step in the derivation delivery factors downstream of the Edwards aquifer recharge zone was estimation of appropriate SCS "map" curve numbers for each subwatershed. This was accomplished by detailed review of available county soil surveys (Refs. 20 through 31) and adjustment to account for typical antecedent moisture condtions (Ref. 18). The resulting map curve numbers are summarized in Table 4.4-3. Six gaged headwater watersheds, including the Nueces, Frio, Sabinal, and Atascosa Rivers and San Miguel and San Casimiro Creeks, were analyzed to obtain a relationship between the "map" curve number and the "volumetric" curve number. The volumetric curve number is defined herein to be the curve number for which long-term average gaged runoff equals that computed from monthly areal precipitation using the following general equation:

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

where:

Q_{CN}	=	Calculated Runoff (Acre-Feet)
A	=	Watershed Area (Square Miles)
P	=	Areal Precipitation (Inches)
CN	=	Volumetric Curve Number

The following relationship ($r^2 = 0.91$) was obtained by simple linear regression of map and volumetric curve number for the headwater watersheds:

$$CN = 0.728\ (CN_m) - 0.271$$

where:

CN	=	Volumetric Curve Number
CN_m	=	Map Curve Number

Table 4.4-3 Summary of Runoff Curve Numbers Downstream of the Edwards Aquifer Recharge Zone		
Streamgage/Control Point		Map Curve Number
Reference Number	Location	
1930	Nueces River near Asherton	52.5
1940	Nueces River at Cotulla	50.5
1942	San Casimiro Creek near Freer	57
1945	Nueces River near Tilden	51.5
1946	Nueces River at Simmons	54
2055	Frio River near Derby	56
2067	San Miguel Creek near Tilden	55
2070	Frio River at Calliham	52.5
2080	Atascosa River at Whitsett	57.5
2100	Nueces River near Three Rivers	58
2110	Nueces River near Mathis	59.5

Using this relationship, volumetric curve numbers were calculated from map curve numbers for each subwatershed and intervening runoff arriving at the downstream gage location was estimated on a monthly basis from areal precipitation using the preceding general equation. The percentage of flow passing the upstream control point and arriving at the downstream control point was computed for each month of concurrent record. Actual delivery factors were then computed using average upstream, intervening, and downstream flow volumes from only those months when losses were between 0 and 100 percent. Months when losses were calculated to be greater than or equal to 100 percent (intervening flow exceeds measured downstream flow) and months when no losses were calculated (measured downstream flow minus intervening flow exceeds measured upstream flow) were not included in the averages. Calculated losses in these months represent extreme or impossible conditions which generally result from inaccuracies inherent in estimating runoff for large intervening watersheds on the basis of monthly areal precipitation and estimated curve numbers.

4.5 Missing Streamflow Records

Streamflow records missing during the 1934 to 1989 historical period were estimated for 14 streamflow gaging stations located throughout the Nueces River Basin using multiple linear regression techniques. Regression equations were generally derived from natural flows for nearby gaged subwatersheds; however, local runoff estimates based on areal precipitation and curve number were used when appropriate and statistically significant. Well levels from the City of Uvalde well were used to extend the springflow records of the Leona River near its origin. The synthesis of streamflow records for the 8 ungaged subwatershed control points located near the Edwards aquifer recharge zone with a total drainage area of 256 square miles (less than 2 percent of the basin) is discussed in Chapter 6.

The regression equations used to estimate missing monthly streamflow records are summarized in Table 4.5-1 along with the coefficients of determination (r^2) and lengths of concurrent record on which the equations are based. In general, the equations were developed to calculate missing natural flow directly from natural flow in upstream or adjacent subwatersheds as well as local runoff in order to be consistent with the upstream to downstream streamflow naturalization process. Calculated negative monthly flow values from the regression equations were set to zero. Missing gaged streamflows were calculated at two locations on the Nueces River (Asherton = 1930 and Tilden = 1945) because equations based on downstream flow records provided more accurate estimates. Missing gaged streamflows were also calculated at one location on the Frio River (Calliham = 2070) because local historical diversions were insignificant. More than one regression equation was used for control points on Hondo Creek (2000) and Seco Creek (2015) because the availability of additional flow records in adjacent subwatersheds improved the estimates of missing streamflow. The length of the concurrent records on which the regression equations were based averaged 3.5 times the length of the

Table 4.5-1 Estimation of Missing Streamflow Records				
Reference Number of Control Point/Streamgage with Missing Records	**Period of Missing Records**	**Regression Equation**	**Length of Concurrent Records (Years)**	**Coefficient of Determination (r^2)**
1905	1/34-9/39, 10/50-3/56	$QN_{1905} = 0.5738\ QN_{1900} - 3322$	44	0.53
1930	1/34-9/39	$QG_{1930} = (QNH_{1940} - 0.1361\ QI_{1940})/1.1623$	50	0.90
1945	1/34-11/42	$QG_{1945} = (QNH_{2100} - 0.8340\ QG_{2070} - 1.2805\ QG_{2080} - 0.1146\ QI_{2100} + 485)/1.0032$	47	0.98
1960	1/34-8/52	$QN_{1960} = 0.2643\ QN_{1950} + 0.0345\ QN_{1900} - 249$	37	0.78
1975	1/34-8/52	$QN_{1975} = 0.5137\ QN_{1950} + 0.7844\ QN_{1960} - 3540$	37	0.80
1980	1/34-9/42	$QN_{1980} = 0.6865\ QN_{1950} - 1101$	47	0.81
1985	1/34-8/52	$QN_{1985} = 0.8394\ QN_{1980} + 0.6839\ QI_{1985} - 1812$	37	0.93
2000	1/34-9/42	$QN_{2000} = 0.4164\ QN_{1950} - 782$	37	0.65
2000	10/42-8/52	$QN_{2000} = 0.6088\ QN_{1980}$	37	0.83
2007	1/34-8/52	$QN_{2007} = 0.7690\ QN_{2000} + 0.3276\ QI_{2007} - 1377$	29	0.81
2015	1/34-9/42	$QN_{2015} = 0.1975\ QN_{1950} - 516$	28	0.72
2015	10/42-8/52	$QN_{2015} = 0.2799\ QN_{1980}$	28	0.86
2015	9/52-4/61	$QN_{2015} = 0.3073\ QN_{2000} - 0.0927\ QN_{1980}$	28	0.94
2027	1/34-9/60	$QN_{2027} = 0.5074\ QN^{*}_{2015} + 0.1176\ QI^{*}_{2027} - 781$	28	0.57
2040	1/34-12/38,10/65-12/89	$QN_{2040} = 136.85\ W_{uv} - 118{,}131.1$	17**	0.92
2070	3/81-9/82	$QG_{2070} = 0.8879\ QG_{2066} + 0.5342\ QG_{2067} + 1765$	9	0.99
2110	1/34-8/48	$QNH_{2110} = 1.0390\ QG_{2100} + 0.0621\ QI_{2110} - 2040$	41	0.98

Definition of Terms: QG = Gaged Flow QN = Natural Flow QNH = Gaged Flow Adjusted for Local Diversions QI = Intervening Runoff Calculated from Precipitation W_{uv} = Well Level at Uvalde

Units: Acre-Feet/Month: QG, QN, QNH, and QI Feet-Mean Sea Level: W_{uv}

*Drainage areas adjusted to reflect entire Seco Creek watershed above Edwards aquifer recharge zone.

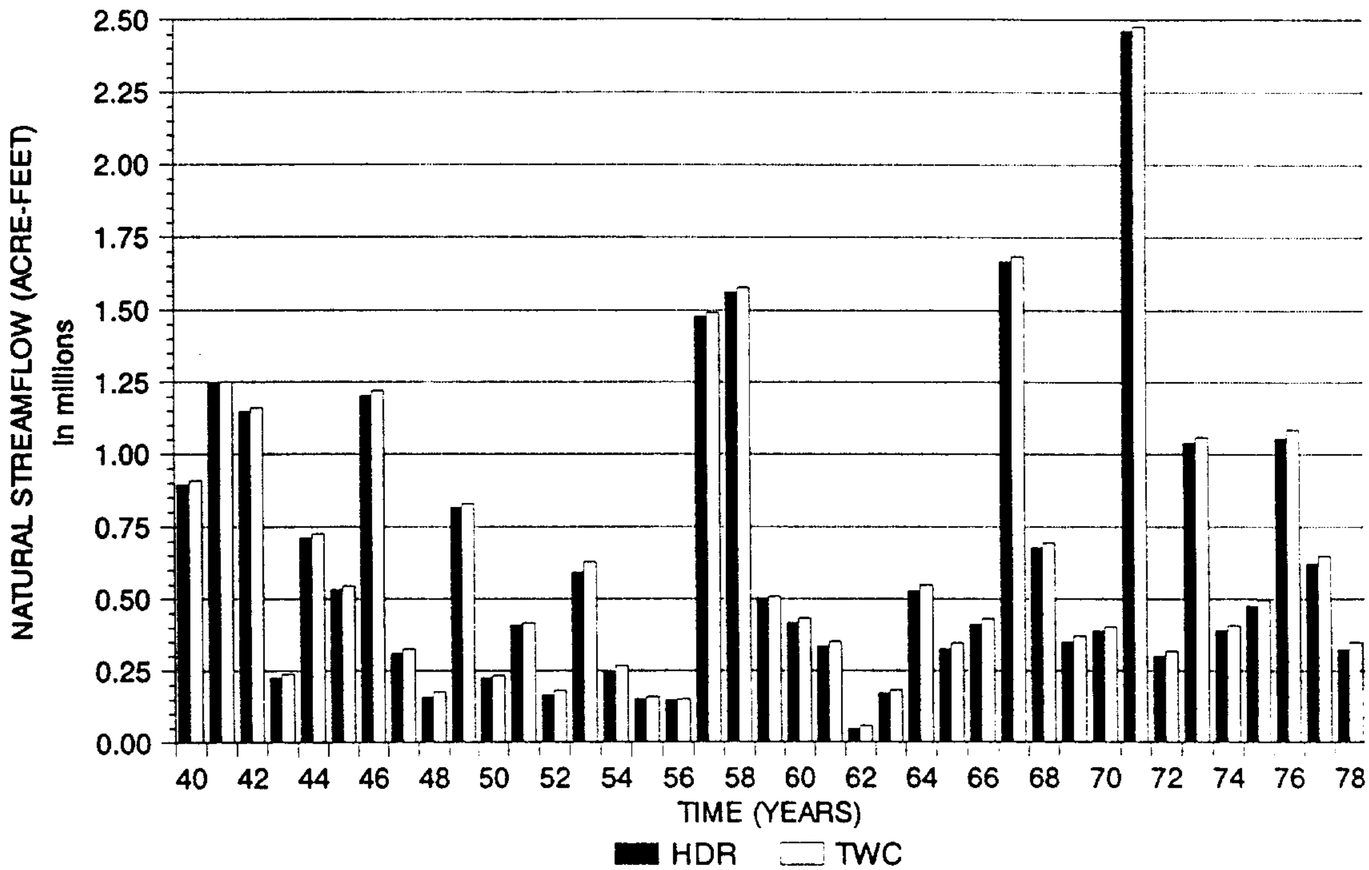
**Length of concurrent record based on non-zero flow valves at Leona River Spring Flow gage (2040). Spring ceased flow for extended periods during the 1/39-9/64 period.

estimated records. Coefficients of determination for the regression equations ranged from 0.53 to 0.99, with the average weighted by dependent mean being 0.94.

4.6 Comparison with Texas Water Commission Natural Streamflows

Natural streamflows developed in the performance of this study were compared to those used by the Texas Water Commission in their water availability computer model. Figure 4.6-1 presents both HDR and TWC natural streamflows for the Nueces River near Three Rivers for the 1940 to 1978 historical period selected by the TWC. As is apparent in Figure 4.6-1, agreement between the two data sets is quite good with the TWC flows always being slightly greater than those used by HDR. The magnitudes of the annual differences between the HDR and TWC flows generally increased with time, as did historical diversions during the same period. Differences between the TWC and HDR flows, however, average only 2.4 percent of the average natural streamflow.

The differences in natural streamflow are due to differences in the streamflow naturalization methodologies applied. The TWC adjusted gaged streamflows for historical diversions on a one-to-one basis throughout the basin, while HDR used delivery factors to translate the effects of historical diversions to downstream gages. A brief analysis of average historical water use (1940 to 1978) in each subwatershed of the basin applying HDR delivery factors indicates that more than 90 percent of the average difference between HDR and TWC flows is attributable to the use of delivery factors. The remainder of the difference may be attributable to alternative procedures for estimating missing flow records and/or historical diversions, as well as historical adjustments by the TWC to account for minor reservoirs, and



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NUECES RIVER BASIN STUDY

COMPARISON OF NATURAL STREAMFLOWS FOR THE NUECES RIVER NEAR THREE RIVERS

FIGURE 4.6-1

other factors.

It is believed that use of the HDR natural streamflows and delivery factors accurately represents the response of the basin to authorized diversion rights and potential implementation of recharge enhancement projects. Use of the TWC procedures is reasonable in basins where authorized diversion rights approximate historical diversions. In the Nueces River Basin, however, underestimation of inflows to the CC/LCC System would result because authorized diversion rights significantly exceed historical diversions, particularly in the early portion of the 1934-1989 period.

5.0 TRENDS IN STREAMFLOW CHARACTERISTICS

In relatively arid watersheds, like the Nueces River Basin, it is not uncommon for streamflow characteristics to be influenced over time by changes occurring in the watershed. Examples of these changes may include: 1) Farming techniques intended to reduce runoff such as furrow diking, contour plowing, and terracing; 2) Allowing previously farmed land to revert to pasture or rangeland; 3) Increased groundwater use resulting in lowering of the water table which, in turn, reduces the baseflow of streams and increases natural channel losses; 4) Increased prevalence of certain types of vegetation which enhance evapotransporation losses; and 5) Construction of farm ponds and other water control structures. Each of the above changes tends to decrease runoff, while the converse of the above items may tend to increase runoff. Climatic changes such as global warming may also affect the frequency and intensity of precipitation events, wind speed and direction, temperature, and other factors which, in turn, influence streamflow characteristics. This chapter describes previous studies addressing potential runoff trends in the basin and summarizes analyses of long-term rainfall and natural streamflow data to ascertain the presence of significant trends.

5.1 Previous Studies by the Bureau of Reclamation

Studies undertaken by the U. S. Bureau of Reclamation (USBR) in the early 1960's (Ref. 47, 49, & 51) included the development of estimates of inflows to Choke Canyon Reservoir subject to Year 2010 watershed conditions. These studies indicated that future inflows to Choke Canyon Reservoir were expected to be about 5 percent to 9 percent less than those which occurred historically due to watershed changes. Specifically, these included changes in land management practices (such as contour plowing and terracing), construction of farm ponds, and construction of other water control structures. A review of the streamflow and rainfall data available to the USBR in the early 1960's indicates that the adjustment may have appeared reasonable at that time. Moving averages of runoff as a percentage of rainfall for the 1934 through 1956 period of record available to the USBR exhibit a decreasing trend in the percentage of rainfall arriving as runoff at the Choke Canyon reservoir site. Statistical analyses performed by HDR based on the 1934 to 1989 period indicate that no such "trend" persists to the present. With respect to inflows at Lake Corpus Christi, the USBR studies indicated that no adjustments to historical inflows were necessary.

5.2 Status of Studies of Effects of Brush Control on Water Supply

Approximately 90 percent of the Nueces River Basin is presently in rangeland and pastureland (Ref. 36 & 37). Of the rangeland total, approximately 57 percent has canopy or cover of brush and woody species greater than 11 percent, with about 14 percent having brush canopy of more than 30 percent. Predominant species making up this cover are mesquite, pricklypear, and blackbrush.

It has been observed, and in some cases measurement has shown, that after brush control was applied to watersheds, springs and creeks of local and neighboring areas began to flow. Among the notable examples are Rocky Creek in Tom Green and Irion Counties, the Bridgeford Ranch in Nolan County, the Chaparrosa Ranch in Zavala County, and on ranches in the Fredericksburg/Kerrville area (Ref. 45). Quantitative information about potential changes in aquifer recharge and streamflows resulting from brush management programs is not adequate to determine whether or not brush management is a viable and feasible water development tool. In order to obtain such information, the Texas Water Development Board, Texas A&M University, the Texas State Soil and Water Conservation Board, the U.S. Soil Conservation Service, the Edwards Underground Water District, and others are funding studies to measure the effects of brush management on water yield from rangeland watersheds. Two of the study sites are located within the Nueces Basin. One is located at Lyles Ranch about 18.6 miles southwest of Uvalde and the other at Annadale Ranch about 19.8 miles northeast of Uvalde near Concan. A third site is located at the LaCopita Ranch near Alice in Jim Wells County within the Nueces-Rio Grande Coastal Basin.

The study sites were chosen to obtain information about the effects of management of different species of brush upon water yields. At the Lyles Ranch, the species being studied are honey mesquite and blackbrush. In this study, 0.6 hectare plots within nine watersheds have been equipped with instruments to measure precipitation, soil moisture, runoff, and sediment transport from the experimental plots. By comparing the results from treated and untreated plots, estimates can be made of the effects of treatment. The study is presently in the data collection phase and will require several years of observation before conclusions can be reached.

At the Annadale Ranch near Concan, nine watersheds ranging in size from 4 to 6 hectares have been instrumented to measure precipitation, runoff, and sediment loss. The species of interest at this site are live oak and ash juniper. As in the case of the Lyles

Ranch, this study is in the data collection stage.

At the LaCopita Ranch, the first year of water budget data indicates that runoff and deep percolation may increase by 1.18 inches when mesquite-dominated mixed brush complexes are replaced with herb-dominated species (Ref. 9). Data collection and analyses are also continuing at this site.

Limited observations indicate a beneficial relationship between brush management and water yield in Texas, including the Nueces and adjacent Nueces-Rio Grande Coastal Basin. The results of the studies mentioned above should soon provide useful quantitative information about the potential quantities of water that might be expected per unit of watershed treated.

5.3 Cropland Acreage

Annual records have been maintained by the Texas Department of Agriculture since 1970 for acres of planted cropland within each county. These records are summarized in Table 5.3-1 by 5-year increments for each of the counties with significant cropland acreage. Although total cropland within the basin represents 10 percent of the land area, planted cropland in the counties located upstream of Lake Corpus Christi has varied from about 5 percent in 1970, 1975, and 1980 to about 6 percent of the total drainage area in 1985.

Planted cropland can vary significantly from year to year depending on many factors, including Federal farm subsidies. Since the percentage of cropland in the basin is small, it is doubtful that planting practices significantly affect streamflows except in localized watersheds where cropland acreage is significant.

Table 5.3-1 Planted Cropland Acreage by County between 1970 and 1985				
	Acres Planted			
County	**1970**	**1975**	**1980**	**1985**
A. Upstream of Lake Corpus Christi				
Medina*	144,550	120,000	113,900	136,000
Atascosa*	109,950	86,300	78,950	131,000
Frio	60,250	92,700	78,500	113,000
Live Oak*	82,100	71,200	68,400	95,000
Uvalde	85,930	82,980	102,700	112,000
Zavala	50,200	64,950	58,400	58,000
Subtotal A	532,980	518,130	500,850	645,000
B. Downstream of Lake Corpus Christi				
Nueces**	338,500	332,000	366,800	321,000
San Patricio**	262,800	275,500	259, 600	189,000
Subtotal B	601,300	607,500	626,400	510,000

*Acreages shown are for entire county even though small portion of county is outside of Nueces Basin.

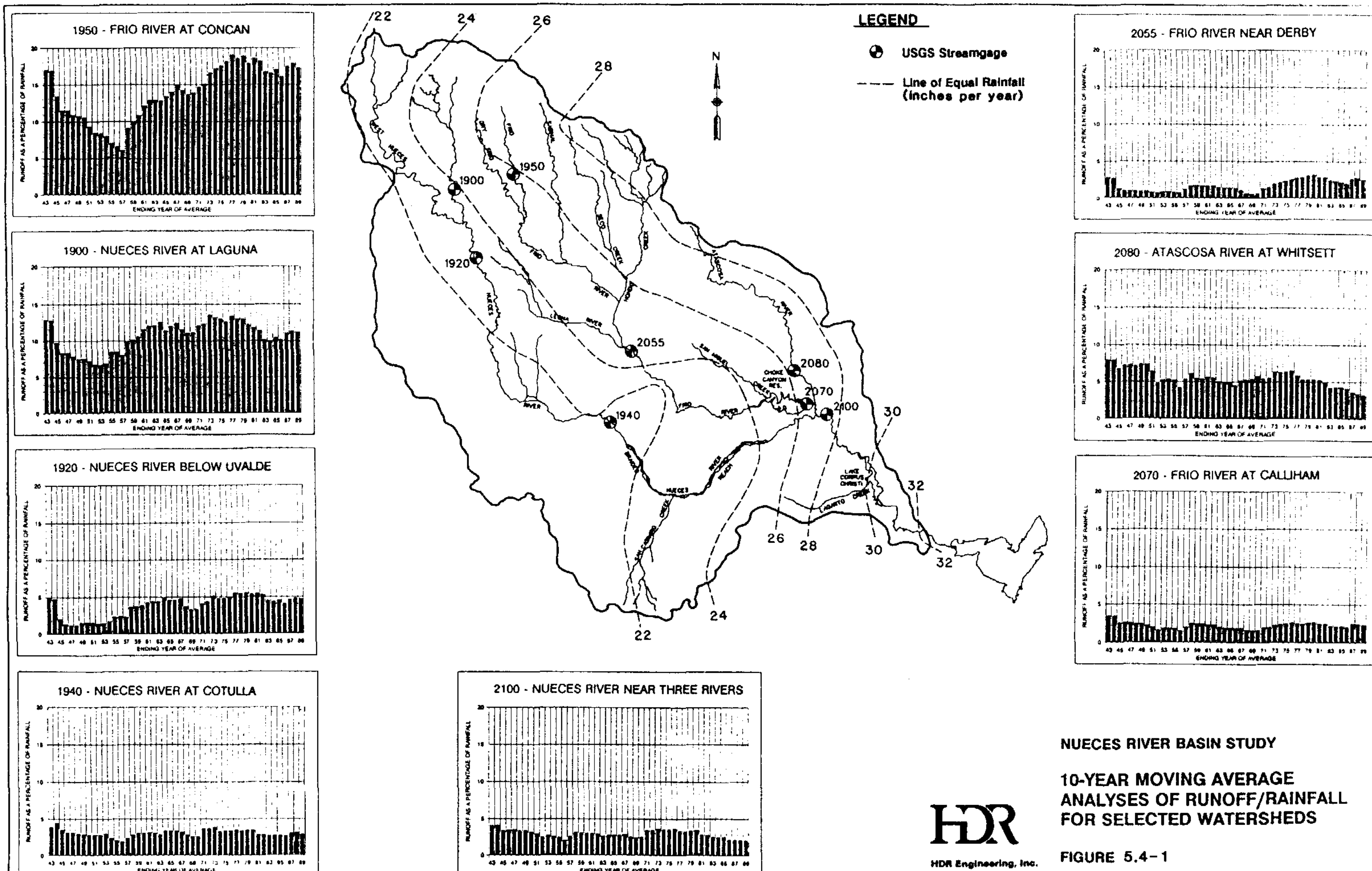
**Acreages shown are for entire county even though most of county is outside of Nueces Basin.

5.4 Summary of Trend Analyses

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 basin the size of the Nueces River Basin. In a qualitative attempt to identify potential trends in selected portions of the basin, 10-year moving average analyses of rainfall and runoff were performed for watersheds upstream of 8 long-term streamflow gaging stations. For these analyses, annual rainfall and runoff totals (expressed in inches over the watershed area) were tabulated, with a 10-year average calculated after each annual shift in the series. The entire 56-year period from 1934 through 1989 was used, resulting in 47 ten-year averages with ending years from 1943 through 1989. Figure 5.4-1 presents moving averages of runoff expressed as a percentage of rainfall at each of the 8 selected stations.

Upon review of Figure 5.4-1, it appears that runoff as a percentage of rainfall in the four most upstream watersheds in the basin is generally increasing during the period considered. These include the gages on the Nueces River at Laguna and below Uvalde, and on the Frio River at Concan and near Derby. Runoff percentages at the next downstream gaging stations (i.e., Nueces River at Cotulla and Frio River at Calliham), however, do not exhibit this increasing trend and appear generally uniform throughout the period. Since rainfall and runoff values for these two watersheds include the upper four watersheds, it is possible that a negative or decreasing trend may exist in the intervening watersheds which is masked by the apparently increasing runoff from the upstream areas. Runoff percentages for the other two watersheds (i.e., Atascosa River at Whitsett and Nueces River near Three Rivers) apparently exhibit negative trends in runoff over the period.

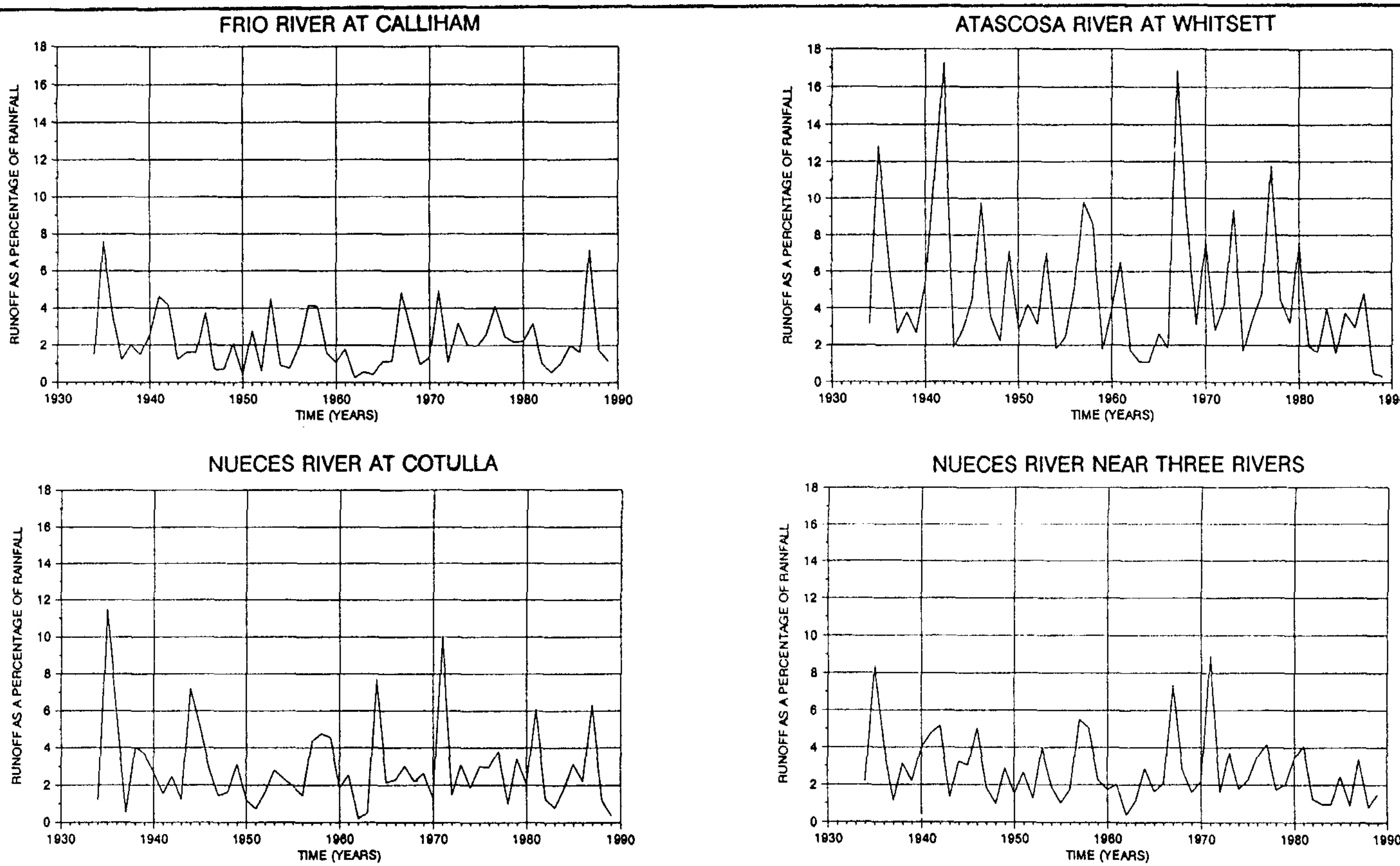
In order to more quantitatively evaluate possible changes in the relationship between rainfall and runoff with respect to time in the Nueces River Basin, several standard statistical tests were performed. Testing with the primary intent of detecting decreasing trends in runoff as a percentage of rainfall was conducted for the Frio River at Calliham (Choke Canyon Reservoir), Nueces River at Cotulla and near Three Rivers, and Atascosa River at Whitsett. These stations were selected due to their proximity to the CC/LCC System and preliminary indications of trend noted in the moving average analyses. Figure



NUECES RIVER BASIN STUDY

10-YEAR MOVING AVERAGE ANALYSES OF RUNOFF/RAINFALL FOR SELECTED WATERSHEDS

FIGURE 5.4-1



NUECES RIVER BASIN STUDY

ANNUAL RUNOFF/RAINFALL SERIES FOR SELECTED WATERSHEDS

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FIGURE 5.4-2

5.4-2 presents the annual series at each of these four locations.

The statistical tests applied included the non-parametric Kendall Tau (Ref. 12) and Turning Points (Ref. 71) tests. These non-parametric tests were applied to the annual series of runoff as a percentage of rainfall because the annual series are not believed to be normally distributed. Parametric tests, including simple regression of runoff percentage versus time and sample partitioning, were performed after log transformation of the series. Sample partitioning, in this case, simply involved subdividing 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. Table 5.4.-1 summarizes the results of these tests.

Table 5.4-1
Summary of Statistical Tests for Significant Trends in Streamflow

		Indication of Statistically Significant Trend[1]			
Statistical Test	**Test Type**	**Choke Canyon Reservoir**	**Nueces River, Three Rivers**	**Nueces River, Cotulla**	**Atascosa River, Whitsett**
Kendall Tau	Non-parametric	No	Yes[4]	No	Yes[4]
Turning Points	Non-parametric	No	No	No	No
Simple Regression, t Distribution[2]	Parametric	No	Yes[4]	No	Yes
Sample Partitioning, Mean Comparison, t Distribution[3]	Parametric	No	No	No	Yes[4]
Sample Partitioning, Variance Comparison, F Distribution[3]	Parametric	No	No	No	Yes

[1] Statistical significance assumed at the 90 percent confidence level.
[2] Simple regression of the natural logarithm of natural streamflow as a percentage of rainfall versus time. These percentages are assumed to be log-normally distributed.
[3] 56-year period partitioned into 1934-1961 and 1962-1989 sub-periods.
[4] Although indications of trend are significant at the 90 percent confidence level, they are not significant at the 95 percent confidence level.

Trends which could be statistically significant were detected for the Atascosa River and the Nueces River near Three Rivers, while inflows to Choke Canyon Reservoir and the Nueces River at Cotulla exhibited no trends. As noted in Table 5.4-1, however, the results of most tests which indicated decreasing runoff trends for the Atascosa River and the Nueces River near Three Rivers are not statistically significant at the 95 percent confidence level. Differences in mean and variance between the 1934 to 1961 and 1962 to 1989 periods were only statistically significant for the Atascosa River.

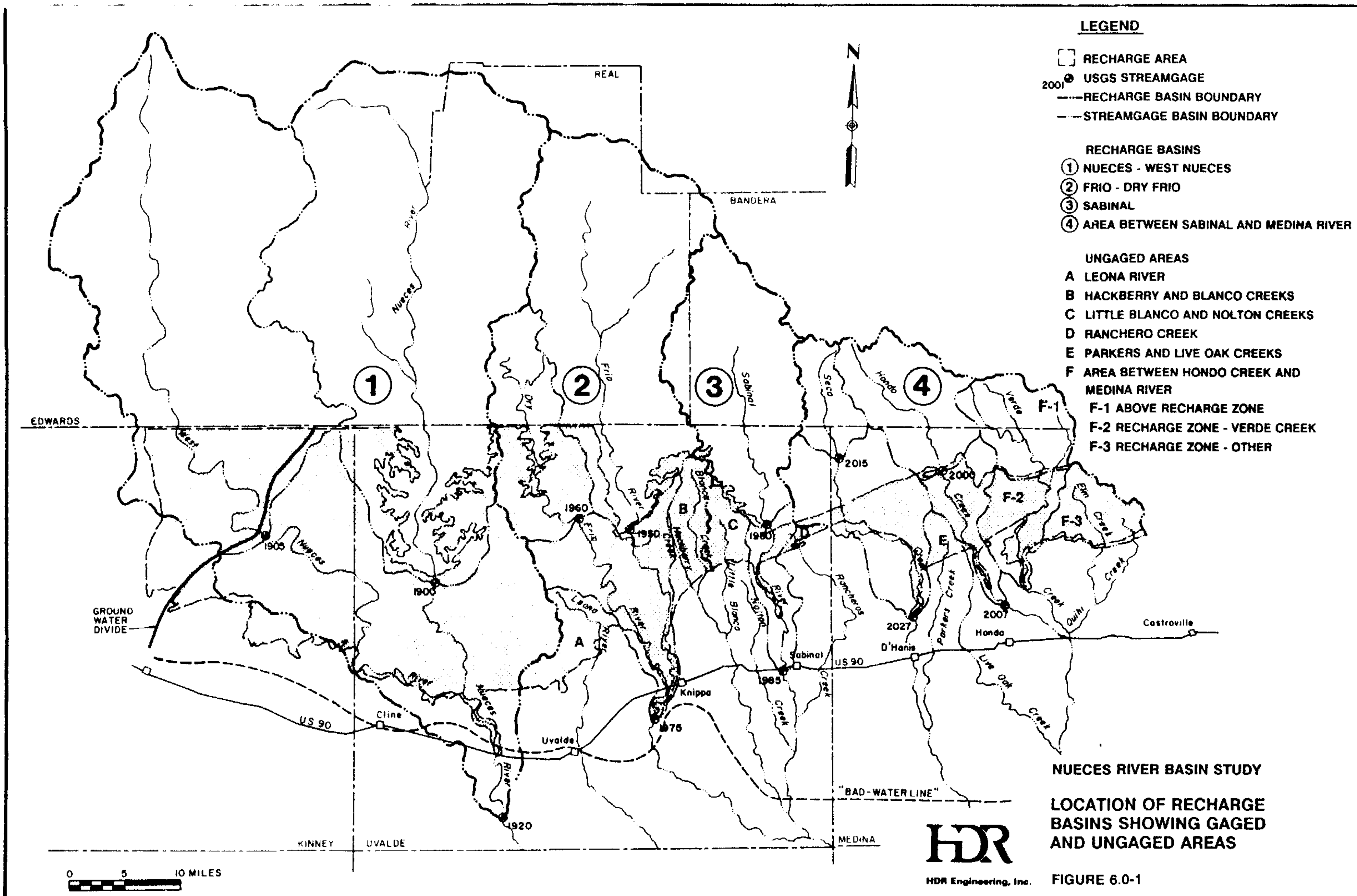
Ultimately, interpretation of the results of the statistical tests indicates that the Atascosa River may be the only watershed exhibiting a truly significant decreasing trend in runoff per unit of precipitation. The overall significance of this apparent trend is somewhat diminished by the fact that the Atascosa River watershed above Whitsett represents only about 7 percent of the contributing basin area above Lake Corpus Christi. Without a full understanding of the physical causes of apparently decreasing runoff from the Atascosa River watershed, whether they be agricultural practices, climatic changes, or other factors, one has no reasonable assurance that the observed historical trend will continue into the future. For these reasons, no adjustments to historical streamflows for apparent trends in runoff were made in this study.

6.0 HISTORICAL RECHARGE

Estimates of annual recharge to the Edwards Aquifer for the four major recharge basins within the Nueces Basin were calculated for the 56-year period from 1934 through 1989. Calculations were first performed for each of the areas with stream gages. Recharge estimates were then made for each of the ungaged areas and combined with the estimates for the gaged areas to obtain a total for each of the four recharge basins. The locations of gaged and ungaged areas are shown on Figure 6.0-1. The boundaries of the four recharge basins are the same as those utilized by the U.S. Geological Survey (USGS) in their annual report (Ref. 66) 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 6.0-1. Table 6.0-2 summarizes drainage areas for all gaged and ungaged areas. Gaged areas total about 3,050 square miles above and within the recharge zone, and ungaged areas total about 256 square miles. In the recharge zone proper, about 30 percent of the area is ungaged.

Table 6.0-1
Drainage Areas of Recharge Basins

Recharge Basin	Drainage Area (Square Miles)	Percent of Total
1. Nueces - W. Nueces	1,861	56
2. Frio - Dry Frio	699	21
3. Sabinal	265	8
4. Area Between Sabinal and Medina	481	15
TOTAL	3,306	100%



NUECES RIVER BASIN STUDY

LOCATION OF RECHARGE BASINS SHOWING GAGED AND UNGAGED AREAS

HDR
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FIGURE 6.0-1

Table 6.0-2
Summary of Gaged and Ungaged Drainage Areas In Edwards Recharge Area

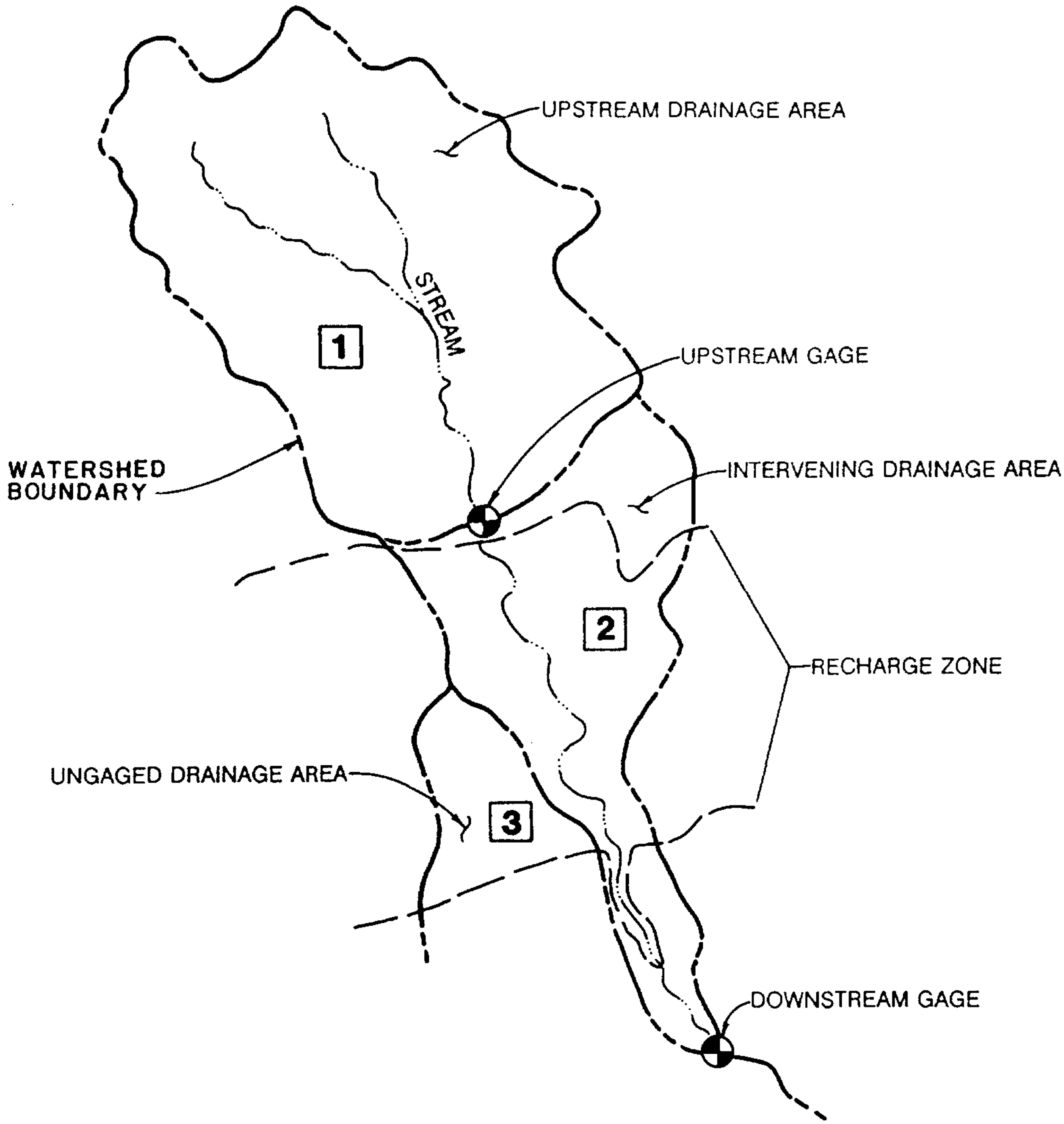
Recharge Basin	Gaged Areas	Drainage Area (Square Miles)	Ungaged Areas	Drainage Area (Square Miles)
1. Nueces-W. Nueces	W. Nueces near Brackettville	694		
	Nueces at Laguna	737	NONE	
	Nueces below Uvalde	430*		
		1,861		0
2. Frio - Dry Frio	Dry Frio near Reagan Wells	126	A - Leona River	36
	Frio at Concan	389	B - Hackberry & Blanco	32
	Frio below Dry Frio near Uvalde	116*		
		631		68
3. Sabinal	Sabinal near Sabinal	206	C - L. Blanco & Nolton	18
	Sabinal at Sabinal	35*	D - Ranchero Cr.	6
		241		24
4. Area Between Sabinal and Medina	Seco near Utopia	45	E - Parkers & Live Oak	12
	Seco near D'Hanis	123*	F-1 - Above Recharge	55
	Hondo near Tarpley	96	F-2 - In Recharge-Verde	50
	Hondo near Hondo	53*	F-3 - In Recharge-Other	47
		317		164
TOTALS		3,050		256

*Represents total intervening drainage area between downstream and upstream gages as reported in the 1988 USGS annual report. Of this total, the following drainage areas were estimated to be downstream of areas contributing to the recharge zone based on the 1983 intensive surveys by the USGS: Sabinal--seven square miles and Hondo--two square miles. A portion of the Nueces River watershed above the Uvalde gage is also located below the recharge zone; however, it was not necessary to compute this drainage area for purposes of this study since it was not necessary to compute recharge for an adjacent ungaged area. Drainage areas for gaged areas are taken from the 1988 USGS annual report. Drainage areas for ungaged areas are taken from 1978 USGS report "Method of Estimating Natural Recharge to the Edwards Aquifer in the San Antonio Area, Texas."

Procedures detailing how recharge calculations were performed for both gaged and ungaged areas are included in the following sections.

6.1 Recharge in Gaged Areas

In the Nueces River Basin portion of the Edwards Aquifer recharge zone, there are 12 stream gages operated by the USGS which were utilized to calculate recharge. The locations of these gages are shown on Figure 6.0-1 along with drainage area boundaries and general limits of the recharge zone. Seven of these gages can be classified as upstream gages (i.e., gages upstream of the recharge zone) and the other five as downstream gages. A schematic diagram showing typical gage locations is included as Figure 6.1-1. All but one of the seven upstream gages are located near the upstream boundary of the recharge zone and are generally unaffected by losses to the aquifer. The gage on the West Nueces River near Brackettville is the one exception, as it is located within the recharge zone. Consultation with the USGS (Ref. 62) indicates that losses occurring above this gage generally recharge that portion of the Edwards which flows to the southwest and not toward the San Antonio area. Therefore, losses which occur upstream of the West Nueces gage were not calculated for this study. Losses occurring downstream of the West Nueces gage were calculated and included in estimates of recharge.



NUECES RIVER BASIN STUDY

SCHEMATIC OF TYPICAL GAGED AND UNGAGED AREAS NEAR RECHARGE ZONE

HDR Engineering, Inc.

FIGURE 6.1-1

Because all of the gages were not in place during the entire 1934 through 1989 period, it was necessary to extend monthly streamflow estimates at many of the gages. For the upstream gages with missing records, this was accomplished utilizing standard linear regression methods in which monthly flows were estimated based on a relationship with a long-term partner gage (or gages). For downstream gages with missing records, this was accomplished during the process of developing recharge estimates by using a multiple linear regression method in which monthly downstream flows were calculated as a function of upstream flow and intervening flow.

In gaged areas, historical recharge is calculated in accordance with the following equation:

$$R = QG_1 + QI - QNH_2$$

where:

R = Recharge;
QG_1 = Upstream Gaged Flow;
QI = Estimated Flow in Intervening Areas; and
QNH_2 = Downstream Flow Adjusted for Diversions in Intervening Area.

The term, QI, in the above equation which is most difficult to quantify is the estimated flow in the intervening area over the recharge zone. Reasonable estimates of flow in this area are necessary to accurately calculate recharge. The method employed by the USGS to estimate intervening flows assumes that it is equal to the upstream gaged flood flow adjusted for drainage area size and precipitation differences. The USGS assumes that precipitation varies linearly with runoff in adjusting for precipitation differences. The USGS method is reasonable only if the runoff potential of the soil-cover complex and the precipitation are about the same in both the upstream and intervening areas.

A review of the Soil Conservation Service (SCS) Soils Surveys for Uvalde, Bandera, and Medina Counties (Ref. 21, 25, & 30; comparable soils reports for Kinney, Edwards, and Real Counties do not exist) was conducted to determine if the runoff potential of soils in the recharge area is similar to the runoff potential of soils in upstream areas. These reports show significant differences in runoff potential due to differences in the soil-cover complex. Differences in the soil-cover complex result from differences in soil grain size (clayey versus sandy soils), topography (hills versus level fields), and land use (rangeland versus cultivated fields). As a result of this review, as well as review of rainfall and runoff relationships contained in Chapter 5, it is believed that the drainage area ratio method utilized by the USGS is not the most appropriate method to estimate runoff in the intervening area. Based on the information contained in the SCS soils reports, it was decided that a variation of the SCS runoff curve number procedure (Ref. 17 & 18) could be utilized to obtain more accurate estimates of intervening flow. This procedure takes into account differences in soil-cover complexes as well as differences in precipitation.

The first step in the application of the SCS runoff curve number procedure is the selection of a runoff curve number (CN) for each major soil-cover complex in a watershed. The curve numbers are then weighted by area to arrive at a composite average CN for each watershed. Under the SCS procedure, the curve number also varies with antecedent moisture conditions (AMC). The curve number increases with wet antecedent moisture conditions and decreases with dry conditions. The higher the curve number, the more runoff is produced for a given rainfall amount.

In calculating monthly flows for the intervening areas, an average curve number (CN) was calculated for all gaged (and ungaged) watersheds using the SCS soils reports. A summary of curve numbers for each watershed based on average antecedent moisture conditions (AMC II) is provided in Table 6.1-3. The CN was adjusted each month based on antecedent moisture conditions as reflected in the corresponding upstream gage flow. This calculation was based on the relationship of monthly rainfall and precipitation excess expressed in inches of runoff for the upstream drainage area. In those instances when more runoff than rainfall occurred as a result of storms occurring near the end of the previous month or high base flow conditions, a CN based on average moisture conditions was used for the intervening area.

After the curve number for the intervening area is adjusted to reflect antecedent moisture conditions for a given month, runoff is calculated based on applying the curve number to the monthly rainfall for the intervening area. Using the SCS procedure in this manner automatically adjusts for differences in precipitation between the upstream and intervening drainage areas. Since the SCS method works in terms of inches of total runoff at the upstream gage (the baseflow component of which is actually delayed infiltration from the upstream drainage area), use of the SCS method indirectly accounts for infiltration or deep percolation in the intervening area.

In calculating recharge, the USGS makes adjustments for rainfall differences only if monthly rainfall totals for the upstream and intervening areas differ by more than 20 percent. In months when this is the case, the USGS adjusts estimated flows in the intervening areas by a direct ratio of the rainfall totals for the upstream area and the

Table 6.1-3
Summary of Runoff Curve Numbers for Gaged and Ungaged Areas Near the Recharge Zone

Recharge Basin	Gaged Areas	Curve Number*	Ungaged Areas	Curve Number*
1. Nueces-W. Nueces	W. Nueces near Brackettville	N/A		
	Nueces at Laguna	87	NONE	
	Nueces below Uvalde	84		
2. Frio - Dry Frio	Dry Frio near Reagan Wells	N/A	A - Leona River	82
	Frio at Concan	88	B - Hackberry & Blanco	88
	Frio below Dry Frio near Uvalde	84.5		
3. Sabinal	Sabinal near Sabinal	85.5	C - L. Blanco & Nolton	86.5
	Sabinal at Sabinal	81.5	D - Ranchero Cr.	84
4. Area Between Sabinal and Medina	Seco near Utopia	87	E - Parkers & Live Oak	89
	Seco near D'Hanis	84	F-1 - Above Recharge	84
	Hondo near Tarpley	85	F-2 - In Recharge-Verde	84.5
	Hondo near Hondo	83.5	F-3 - In Recharge-Other	87.5
TOTALS				

*Based on SCS Soil Surveys for Uvalde, Medina, and Bandera Counties with areas outside these counties estimated on the basis of geologic maps and topography. CN shown is based on antecedent moisture condition II.

intervening area. For example, in a month when the flood flow at the upstream gage is 300 acre-feet per square mile and 7.00 inches of rain were recorded in the upstream area, with 3.50 inches recorded in the intervening area, runoff in the intervening area is calculated as: (3.50/7.00)x300, or 150 acre-feet per square mile. If the SCS procedure is applied to the previous example, and if the upstream and intervening areas have the same curve number, runoff in the intervening area would be estimated at 123 acre-feet per square mile or 18 percent less than the USGS. If the curve number in the intervening area is 4 percent less than the curve number for the adjusted upstream area (as is usually the case), runoff by the SCS method would be calculated at 107 acre-feet per square mile or a total of 29 percent less than the USGS. In months when rainfall amounts vary significantly, the USGS method will either overestimate or underestimate flows for the intervening areas.

6.2 Recharge in Ungaged Areas

All of the ungaged areas, with the exception of the upper Verde Creek drainage area, are located directly over the recharge zone. The locations of all these areas are shown on Figure 6.0-1. Recharge calculations for ungaged areas are based on monthly recharge in an adjacent gaged area. The grouping of ungaged areas with adjacent gaged areas is as previously indicated in Table 6.0-2.

Recharge calculations for ungaged areas were performed utilizing two equations for different types of flow conditions. The first equation was utilized in those months when flow was not recorded at the adjacent downstream gage. For this condition, the following equation represents recharge in the ungaged area:

$$R_3 = Q_3$$

where:

R_3 = Recharge in Ungaged Area; and
Q_3 = Estimated Flow in Ungaged Area.

Estimates of monthly flows for the ungaged areas were developed using the same SCS procedure as utilized in the adjacent intervening gaged areas. Curve numbers for each ungaged area were adjusted for antecedent moisture conditions for each month as calculated at the adjacent upstream gage. Rainfall for the ungaged areas was assumed to be equal to rainfall in the adjacent intervening area, with the exception of the Verde Creek area for which composite rainfall data was developed.

In months when the flow at the adjacent downstream gage was not zero, a second equation was utilized. In these months, recharge in the ungaged area was assumed to be proportional to recharge in the intervening gaged area adjusted for flow differences based on curve number and drainage area. The following equation represents this condition:

$$R_3 = \left(\frac{Q_3}{QI_a}\right) RI$$

where:

R_3 = Recharge in Ungaged Area;
Q_3 = Estimated Flow in Ungaged Area;
QI_a = Estimated Flow in Intervening Area directly over Recharge Zone; and
RI = Recharge in Intervening Area

The USGS procedure for estimating runoff in ungaged areas is similar, with recharge in ungaged areas assumed to be proportional to recharge in the adjacent gaged areas. One significant difference between the two procedures is the way in which flows are estimated for the ungaged area. The USGS utilizes a drainage area adjustment with an adjacent gage to develop flows, while HDR estimates flows for the ungaged areas on the basis of differences in the soil-cover complex (or curve number) with an adjacent upstream gage.

6.3 Recharge in the Verde Creek Area

The Verde Creek watershed is the only ungaged watershed which has a significant drainage area (55 square miles) located upstream of the recharge zone. It was felt that a more accurate estimate of recharge could be obtained for the Verde Creek watershed by treating it like a gaged watershed rather than like an ungaged area because the other ungaged areas are located entirely over the recharge zone. Monthly flow estimates for Verde Creek for the upstream and two intervening areas were developed based on the SCS procedure as previously described with average curve numbers for each watershed adjusted for antecedent moisture conditions as calculated at the upper Hondo gage. These curve numbers were then applied to monthly rainfall to calculate flows for the three subwatersheds in the Verde Creek watershed (see areas F-1, F-2, and F-3 on Figure 6.0-1). Flows at the downstream limit of the recharge zone in area F-2 (established by the 1983 intensive survey by the USGS to be where Verde Creek crosses Highway 173) were estimated by using the regression equation developed for Hondo Creek. This equation estimates downstream flows on the basis of upstream flows and intervening flows. After estimates of both upstream and downstream flows were developed, the same procedure as described in Section 6.1 was utilized to estimate the combined recharge for areas F-1 and F-2 in the Verde Creek watershed. In the ungaged area F-3, the same procedures as described in Section 6.2 were used to calculate recharge with area F-2 utilized as the adjacent intervening area.

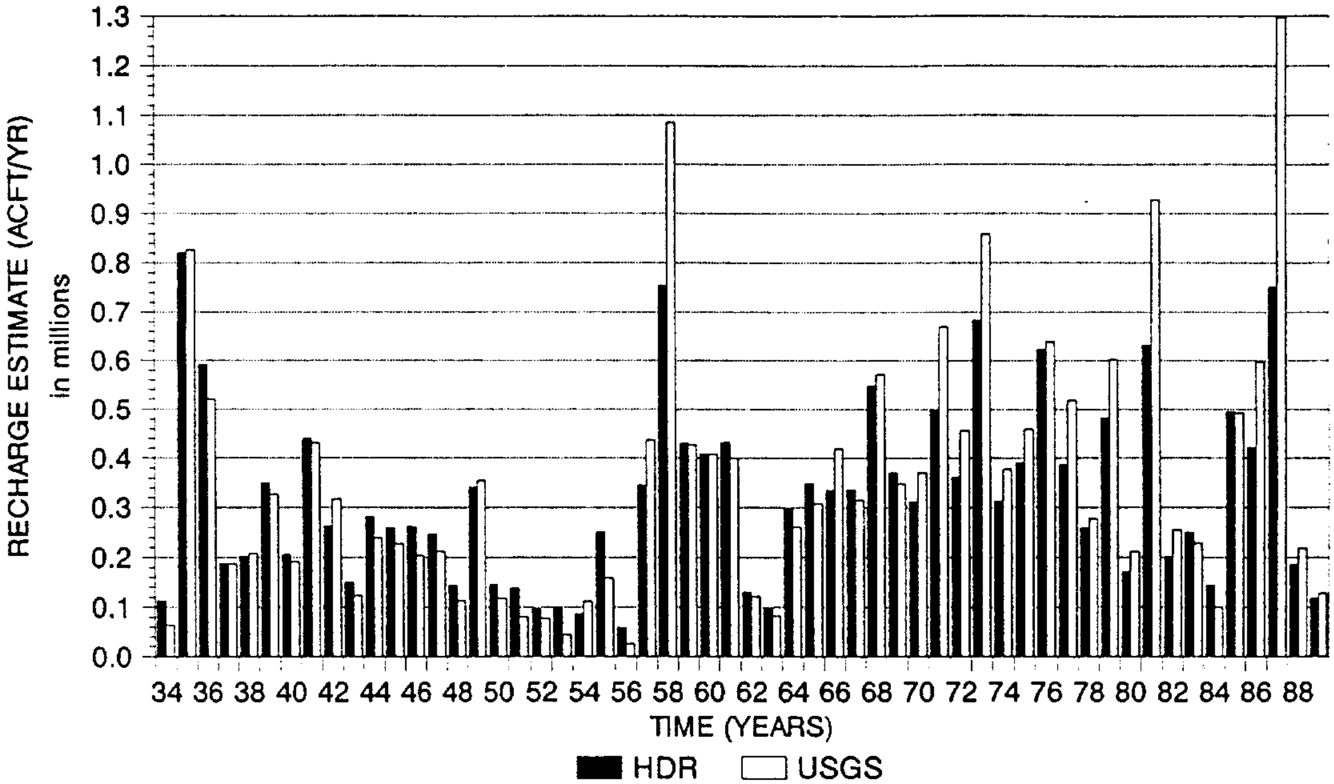
6.4 Comparison of Recharge Estimates

For each of the four recharge basins, average annual recharge volumes for the 1934 through 1989 period were calculated and compared to the USGS recharge estimates for the same period. This comparison is summarized in Table 6.4-1, which shows that the combined USGS estimates for the entire basin for the 56-year period are about 10 percent higher than HDR's estimates. Recharge estimates for the Nueces-W.Nueces and Sabinal showed the largest differences with the USGS long-term averages for these basins being approximately 18 percent higher than HDR's estimates. USGS estimates for the Frio-Dry Frio and remaining basins are approximately 5 percent higher. Much larger differences exist, however, for selected periods within this 56-year period. Figures 6.4-1 and 6.4-2, respectively, present historical and volumetric comparisons of recharge estimates for the entire Nueces River Basin. Figures 6.4-3 and 6.4-4, respectively, present historical and volumetric comparisons of recharge estimates for each of the four designated recharge basins.

Table 6.4-1 Comparison of Recharge Estimates			
Recharge Basin	**Average Annual Recharge (Ac-Ft per Year)**		**Percent Difference**
	HDR	USGS	
1. Nueces-W. Nueces	88,744	104,509	17.8
2. Frio-Dry Frio	111,739	117,454	5.1
3. Sabinal	32,581	38,307	17.6
4. Area Between Sabinal and Medina	92,998	97,404	4.9
TOTAL	326,062	357,674	9.7

To determine where differences exist between the USGS and HDR estimates, two separate analyses were performed. The first analysis consisted of a comparison of years with similar flow ranges. The 56-year annual totals were ranked from lowest to highest (based on HDR flow estimates) and then subdivided into four groups. The results of this analysis are summarized in Table 6.4-2.

Table 6.4-2 Comparison of Ranked Recharge Estimates			
HDR Annual Flow Groupings	**Average Annual Recharge (Ac-Ft per Year)**		**Percent Difference**
	HDR	USGS*	
Lowest 25%	121,059	99,924	-17.5
Second Lowest 25%	239,731	227,450	-5.1
Second Highest 25%	358,700	406,986	+13.5
Highest 25%	584,759	696,336	+19.1
*USGS flows corresponding to HDR flow groupings			



NUECES RIVER BASIN STUDY

COMPARISON OF HISTORICAL EDWARDS AQUIFER RECHARGE FOR NUECES RIVER BASIN

HDR

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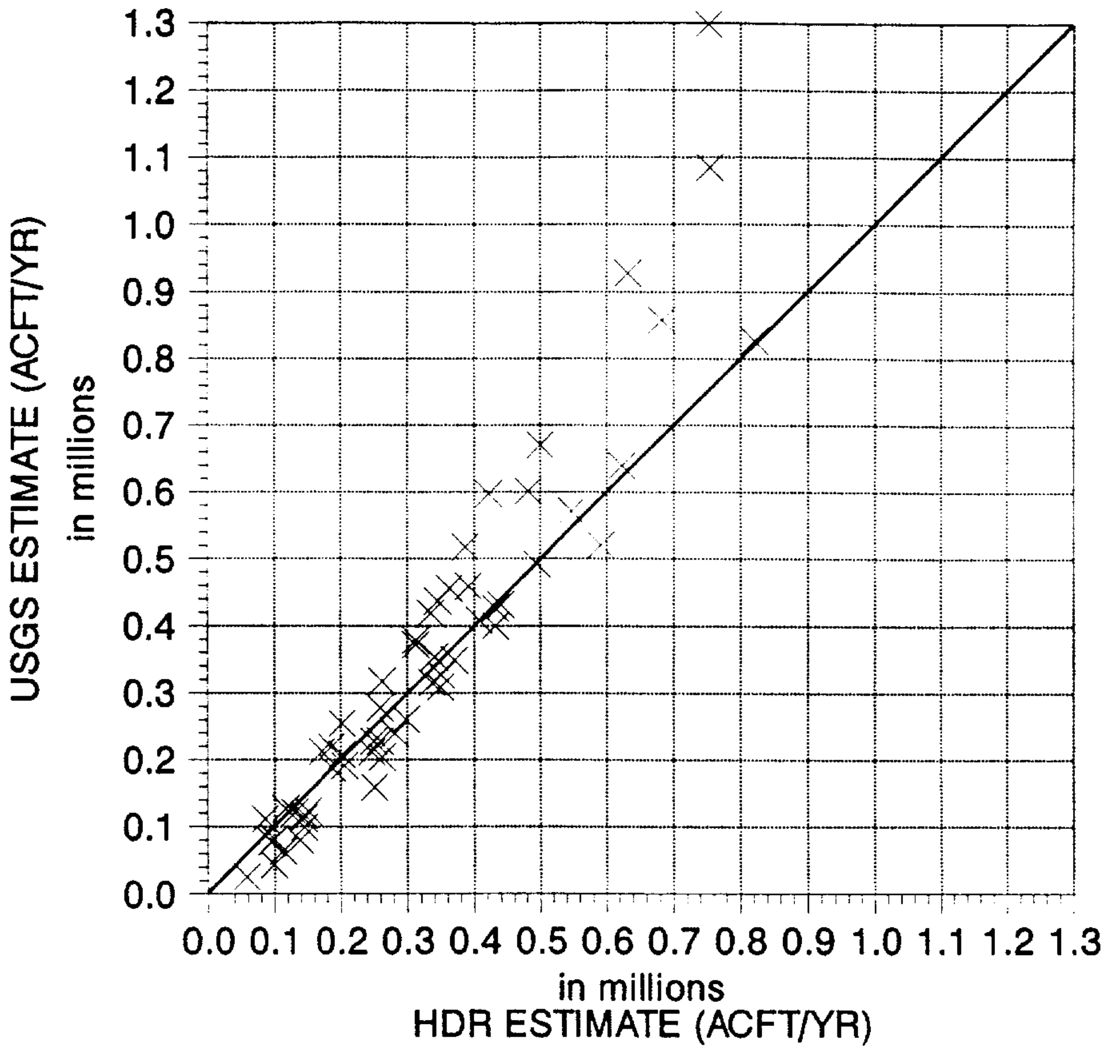
FIGURE 6.4-1



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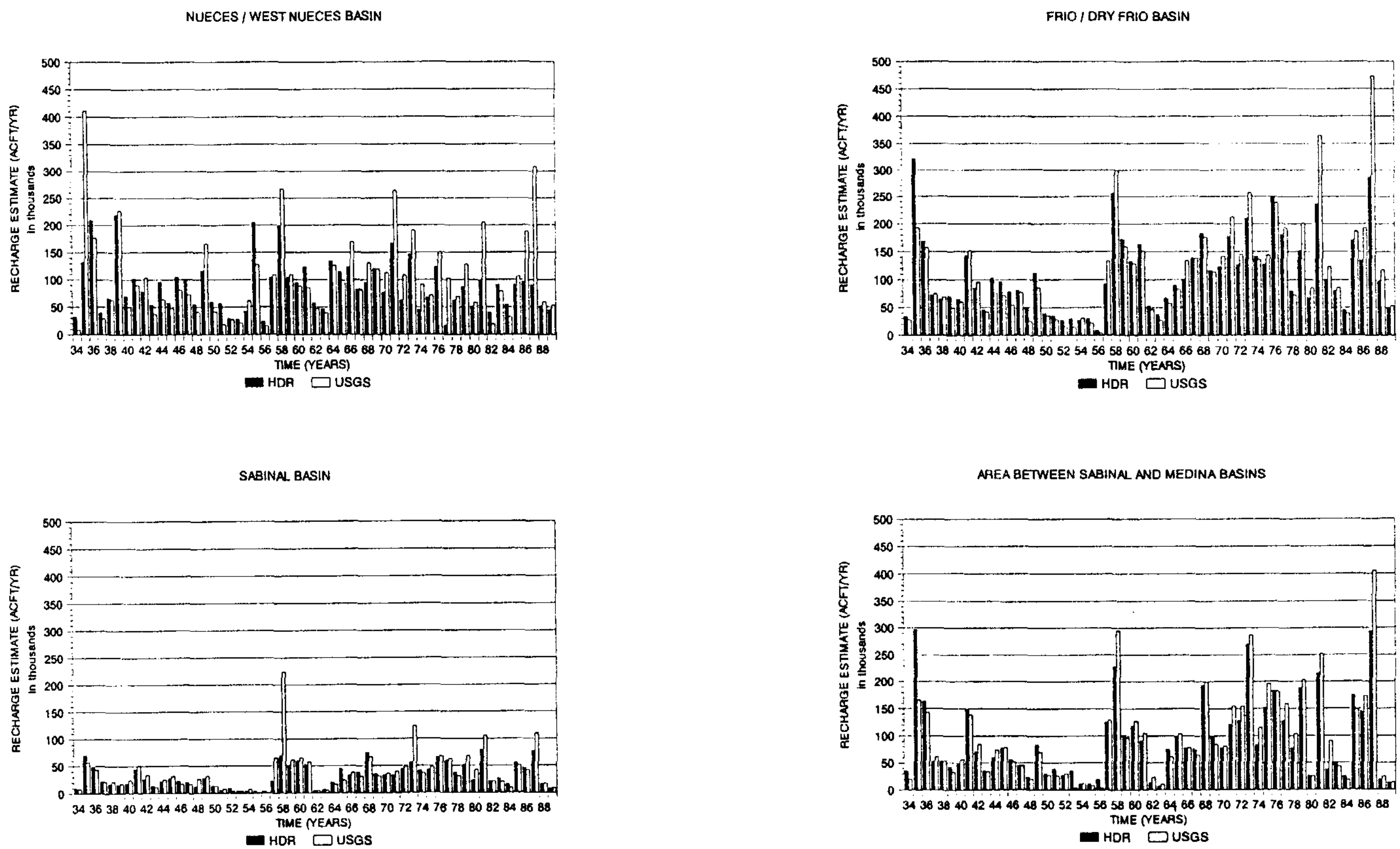
NUECES RIVER BASIN STUDY

COMPARISON OF ANNUAL RECHARGE VOLUMES FOR NUECES RIVER BASIN

FIGURE 6.4-2



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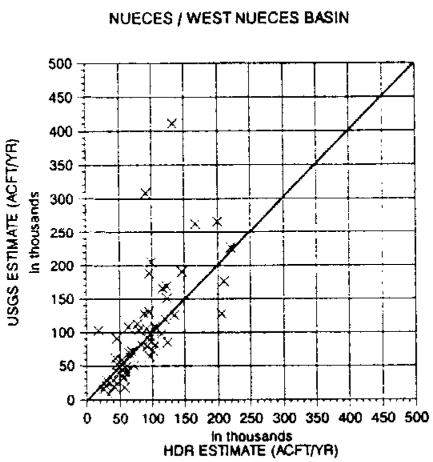
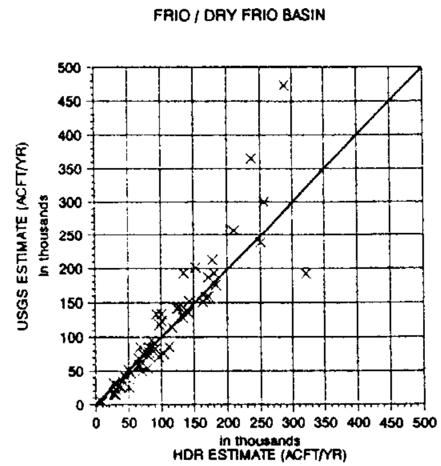
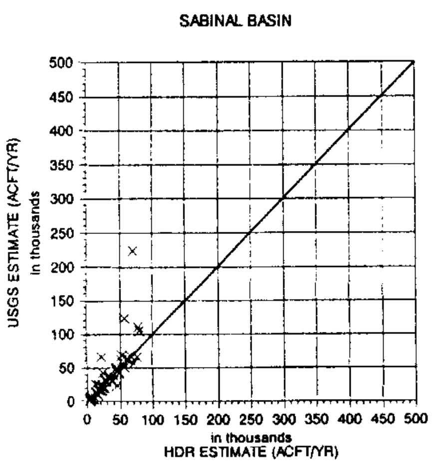
NUECES RIVER BASIN STUDY

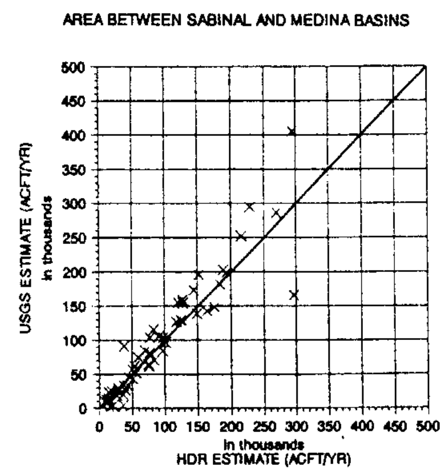
HISTORICAL COMPARISONS OF RECHARGE ESTIMATES FOR FOUR RECHARGE BASINS

FIGURE 6.4-3









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NUECES RIVER BASIN STUDY

VOLUMETRIC COMPARISONS OF RECHARGE ESTIMATES FOR FOUR RECHARGE BASINS

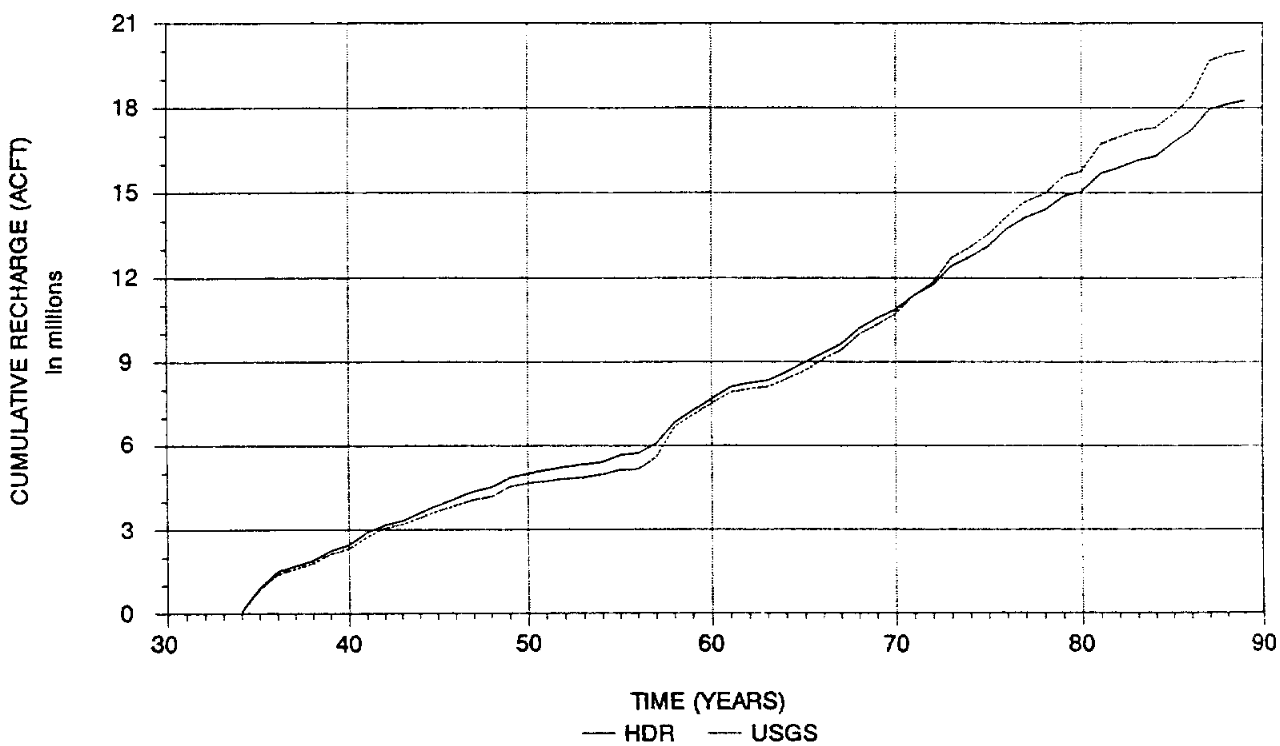
FIGURE 6.4-4

Table 6.4-2 shows that, at the lower flow values, the USGS recharge estimates average 21,135 acre-feet per year (or about 17 percent) lower than the corresponding HDR estimates. The opposite occurs during high flow years, with the USGS recharge estimates averaging 111,577 acre-feet per year (or about 19 percent) higher than HDR estimates. In reviewing the historical and volumetric comparisons of annual recharge (Refer to Figures 6.4-1 through 6.4-4), it appears that the largest volumetric differences in annual recharge occur in years with above average flow.

A second comparison of recharge estimates utilizing historical cumulative totals was made to determine whether any long-term trends are evident. The results of this comparison are presented in Figure 6.4-5. This comparison can generally be subdivided into four time periods:

Period 1 - 1934 through 1942 (9 years);
Period 2 - 1943 through 1956 (14 years);
Period 3 - 1957 through 1970 (14 years); and
Period 4 - 1971 through 1989 (19 years).

Periods 1 and 3, which include a combined 23-year period, generally show very good agreement. During these 23 years, USGS recharge estimates averaged 2.5 percent higher than HDR's estimates. A comparison of Period 2, which contains the 1950's drought, shows that the USGS estimate averaged 18.5 percent less than recharge as computed by HDR. A comparison of Period 4, however, shows the largest differences in recharge. During Period 4, which includes the most recent period, the USGS average annual recharge was 490,244 acre-feet per year, while HDR calculated recharge of only 388,366 acre-feet per year. This is an average difference of 101,878 acre-feet per year or 26.2 percent. Since the past



EDWARDS AQUIFER RECHARGE
NUECES RIVER BASIN

NUECES RIVER BASIN STUDY

COMPARISON OF CUMULATIVE EDWARDS AQUIFER RECHARGE FOR NUECES RIVER BASIN

HDR

HDR Engineering, Inc.

FIGURE 6.4-5

19 years have been wetter than normal, the USGS flows would tend to be high, as described in Section 6.1.

A review of the HDR and USGS procedures indicates that significant differences in recharge estimates are due to the manner in which recharge from infiltration (or, more precisely, deep percolation which reaches the water table) is estimated. By using the SCS method, which calculates monthly flows for the intervening area based on antecedent moisture conditions at an adjacent upstream gage, the HDR procedure may tend to overestimate recharge in months when the water table in the elevated portion of the Edwards Aquifer located in the upstream drainage area is being drawn down (as is the case in Period 2 during the drought). This is because the stored water which contributes to the baseflow is included in flows at the upstream gages. However, the long-term effects of this overestimation are, in part, offset in those months which include storm events contributing recharge to the water table above the upstream gages. In these months, the SCS method tends to underestimate recharge because the water contributing to infiltration or deep percolation does not contribute to flow at the upstream gage until some time later.

To account for the time lag involved with water stored in the elevated portion of the aquifer, the USGS has developed aquifer storage curves for each of the upstream watersheds. These curves are used to compute infiltration based on estimated changes in aquifer storage in the elevated portion of the aquifer as reflected in changes in baseflow at the upstream gages during storm events. This study does not include an investigation of the derivation of these curves and hence does not reach any conclusions as to whether their use is appropriate under various flow and aquifer conditions. If these curves were developed without the benefit of data from an extended wet period as has occurred in the past 20 years, they may need to be updated and possibly revised.

Other differences between the USGS and HDR procedures were investigated for the 1989 calendar year for the Nueces-W. Nueces recharge basin. In this year, the USGS estimated recharge at 52,578 acre-feet, while HDR estimated recharge at 45,222 acre-feet. This represents a difference of 7,356 acre-feet or 16.3 percent. Analyses performed by HDR indicate that drainage area differences accounted for 2,004 acre-feet per year or 27 percent of the total difference. The USGS computer model used for recharge calculation has apparently not been modified to account for revisions in drainage areas as published in 1984. Precipitation differences accounted for 999 acre-feet per year or 14 percent of the difference. The USGS precipitation weighting factors for the four rain gages utilized do not reflect appropriate weights based on their relative locations to the watershed. In our opinion, composite rainfall estimates developed using the Thiessen polygon method provide a more accurate estimate of areal precipitation. An additional 401 acre-feet per year or 5 percent of the difference in 1989 is explained by the fact that the USGS procedure does not account for water rights diversions which are included in the HDR estimates. The remaining 3,952 acre-feet or 54 percent of the 1989 difference is due to differences in the basic methodology for developing estimated flows and deep percolation in the intervening drainage area, as previously discussed.

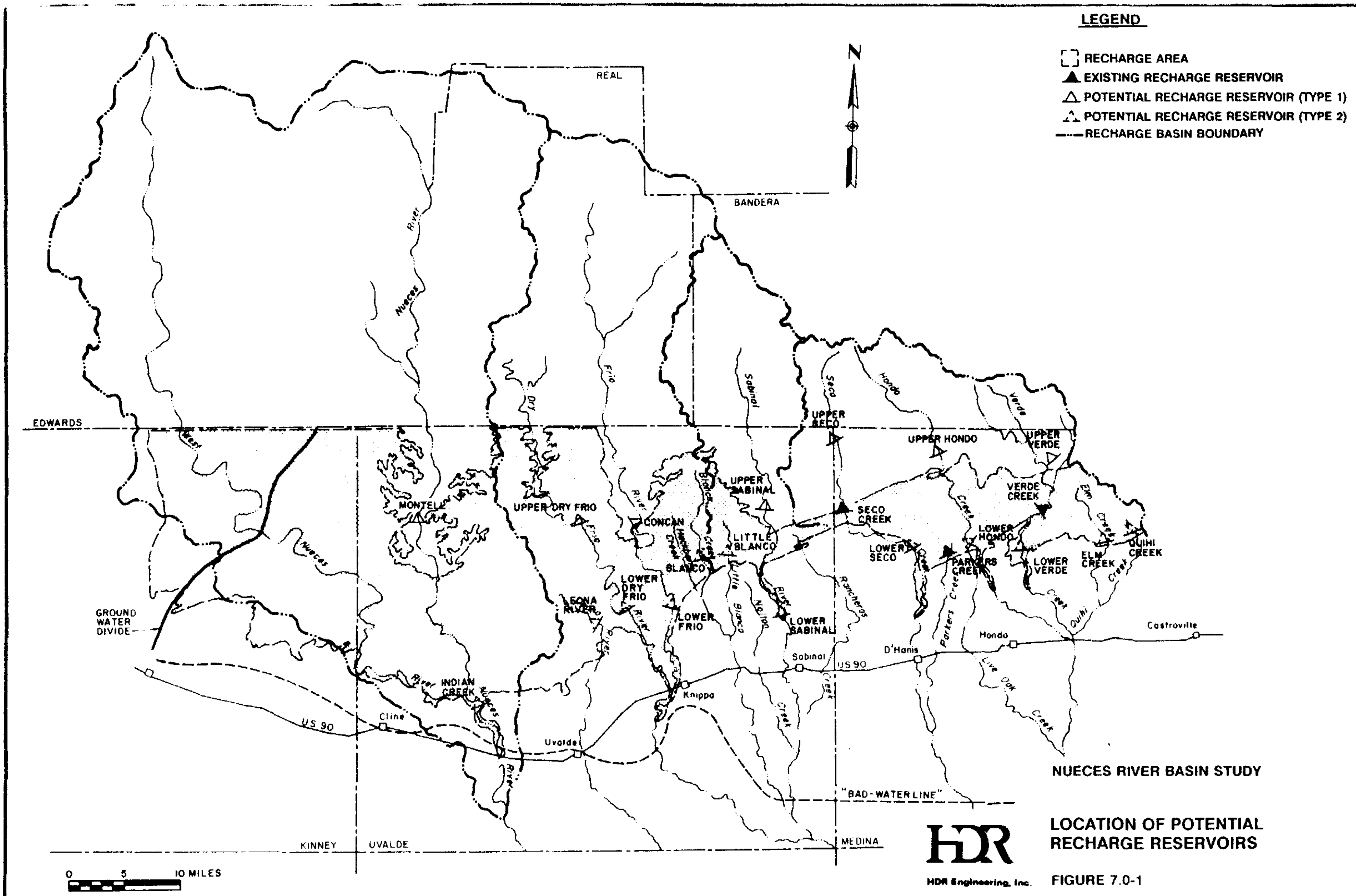
In summary, it is our opinion that the USGS method of calculating recharge produces reasonably accurate estimates in dry years, although their estimates may tend to underestimate recharge in these years. However, in wet years, the USGS method of calculating recharge significantly overestimates recharge.

7.0 RECHARGE RESERVOIRS

A total of 19 potential recharge reservoirs were evaluated to determine the additional volume of recharge they could provide. The location of each potential recharge reservoir site is shown in Figure 7.0-1. Six of these sites were identified in previous studies, while the remaining 13 sites were located during the course of this study. These reservoirs are moderate to large size structures complete with spillways. The structures were sited and sized without consideration for economic, geologic, environmental, or human factors. The express purpose of the structures selected for analysis was the determination of the theoretical maximum additional recharge attainable. Development of these structures will likely require compromises in size, location, mitigation of wildlife habitat, and other factors that may reduce the actual additional recharge attainable from the theoretical amounts reported in this study.

The two types of recharge reservoirs which were modelled in the performance of this study are shown in Figure 7.0-2. Type 1 structures are located upstream of the recharge zone and are operated to capture and store inflows for subsequent release at the maximum recharge rate of the downstream channel. Type 2 structures are located within the recharge zone and capture inflows for direct recharge. Water impounded by the Type 2 structures recharges directly through the bottom of the reservoir, as leakage, and the entire volume is drained within a period of less than one month. The Type 2, Indian Creek site located on the Nueces River, however, may take more than a year to drain. Release rates, storage capacities, surface areas, and drainage areas for each recharge reservoir used in the model are listed in Table 7.0-1.

Release rates for the Type 1 structures were based on measured streamflow losses across the recharge zone as reported by the USGS (Ref. 68) in 1983. Average loss rates



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LOCATION OF POTENTIAL RECHARGE RESERVOIRS

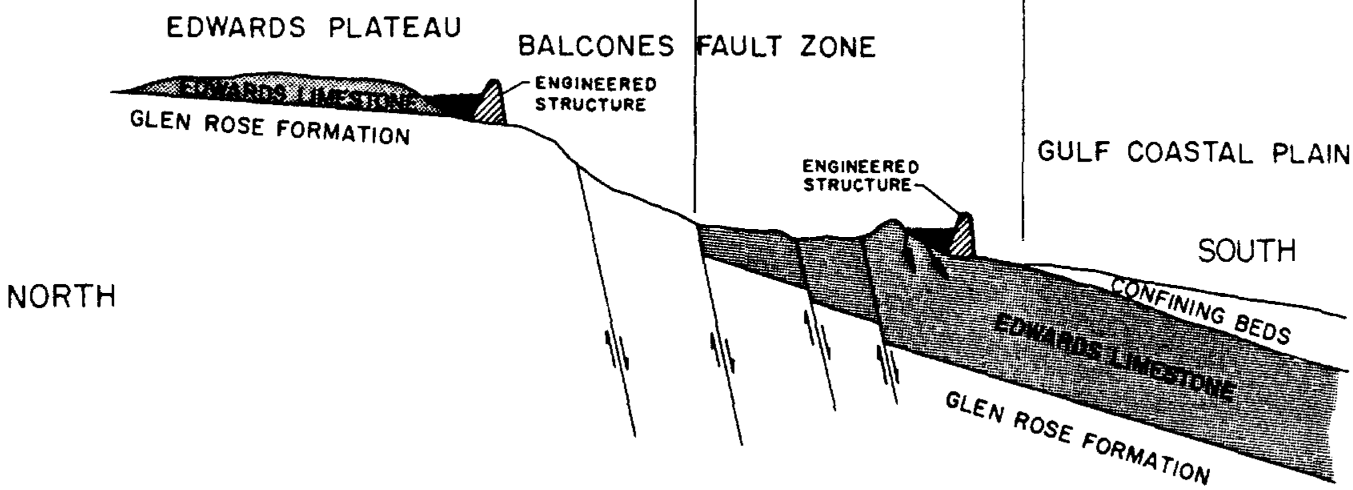
FIGURE 7.0-1

TYPE 1
CATCHMENT AREA

DURING MANY STORMS, RUNOFF FROM THE CATCHMENT AREA IS OF SUCH MAGNITUDE THAT MUCH OF IT FLOWS ACROSS THE RECHARGE AREA WITHOUT PERCOLATING TO THE AQUIFER. ANY TYPE OF ENGINEERED STRUCTURE THAT HOLDS OR RETARDS RUNOFF ON THE PLATEAUS SERVES TO PREVENT EXCESSIVE RUNOFF FROM FLOWING BEYOND THE RECHARGE AREA, AND THUS INCREASES RECHARGE TO THE AQUIFER.

TYPE 2
RECHARGE AREA

ENGINEERED STRUCTURES THAT HOLD OR RETARD RUNOFF IN THE RECHARGE AREA ARE THE MOST BENEFICIAL FOR RECHARGE ENHANCEMENT.



SOURCES: USGS AND EUWD

NUECES RIVER BASIN STUDY

TYPES OF RECHARGE PROJECTS

HDR

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FIGURE 7.0-2

Table 7.0-1
Maximum Storage, Surface Area, Drainage Area, and Release Rates for Recharge Structures

Reservoirs	Maximum Storage (Ac-Ft)	Maximum Surface Area (Acres)	Drainage Area* (Square Miles)	Average Release/Leakage Rate** (Ac-Ft/Month)	(CFS)	Minimum*** Time to Drain (Days)
I. Type 1 Reservoirs						
Montell	252,300	6,200	737	11,700	197	647
Upper Dry Frio	60,000	1,800	126	18,400	309	98
Concan	149,000	3,800	389	11,900	200	376
Upper Sabinal	93,300	3,000	206	4,880	82	574
Upper Seco	23,000	1,050[1]	45.0	9,460	159	73
Upper Hondo	47,000	1,800[1]	95.6	9,400	158	150
Upper Verde	23,000	1,050[1]	55.0	3,150	53	219
Totals - Type 1	647,600	18,700	1,653.6	68,890	1,158	
II. Type 2 Reservoirs						
Indian Creek	165,000	7,660	1861	8,440	142	586
Lower Dry Frio	30,000	1,200	631	80,000	1,344	30
Lower Frio	50,000	1,760				
Leona	2,930	250[2]	36	2,930	49	30
Blanco	6,580	550[2]	32	6,580	111	30
Lower Sabinal	35,000	1,440	241	35,000	588	30
Little Blanco	2,930	250[2]	18	2,930	49	30
Lower Seco	28,000	1,600	168	28,000	471	30
Lower Hondo	28,000	1,260[3]	149	28,000	471	30
Lower Verde	24,000	1,150[3]	105	24,000	403	30
Elm Creek	6,940	580[2]	47	8,510	143	30
Quihi Creek	1,570	150[2]				
Totals - Type 2	380,950	17,850	3,288	224,390	3,771	

*Drainage areas listed are those used in the model at the nearest control point. Actual drainage areas will need to be determined when, and if, more detailed siting studies are undertaken.

**Release rates for Type 1 structures are based on losses as measured by USGS in 1983. On streams with several sets of measurements, the minimum loss rate was used. The average release rate for Type 2 structures was based on the rate as measured at the Parker Creek site but not more than the rate calculated by draining a full reservoir over 30 days. For the Indian Creek and Montell sites a diversion rate of 8,440 ac-ft per month into the Dry Frio River or into the aquifer through an injection well was used.

***Minimum time to drain assumes no inflow occurs while reservoir is draining.

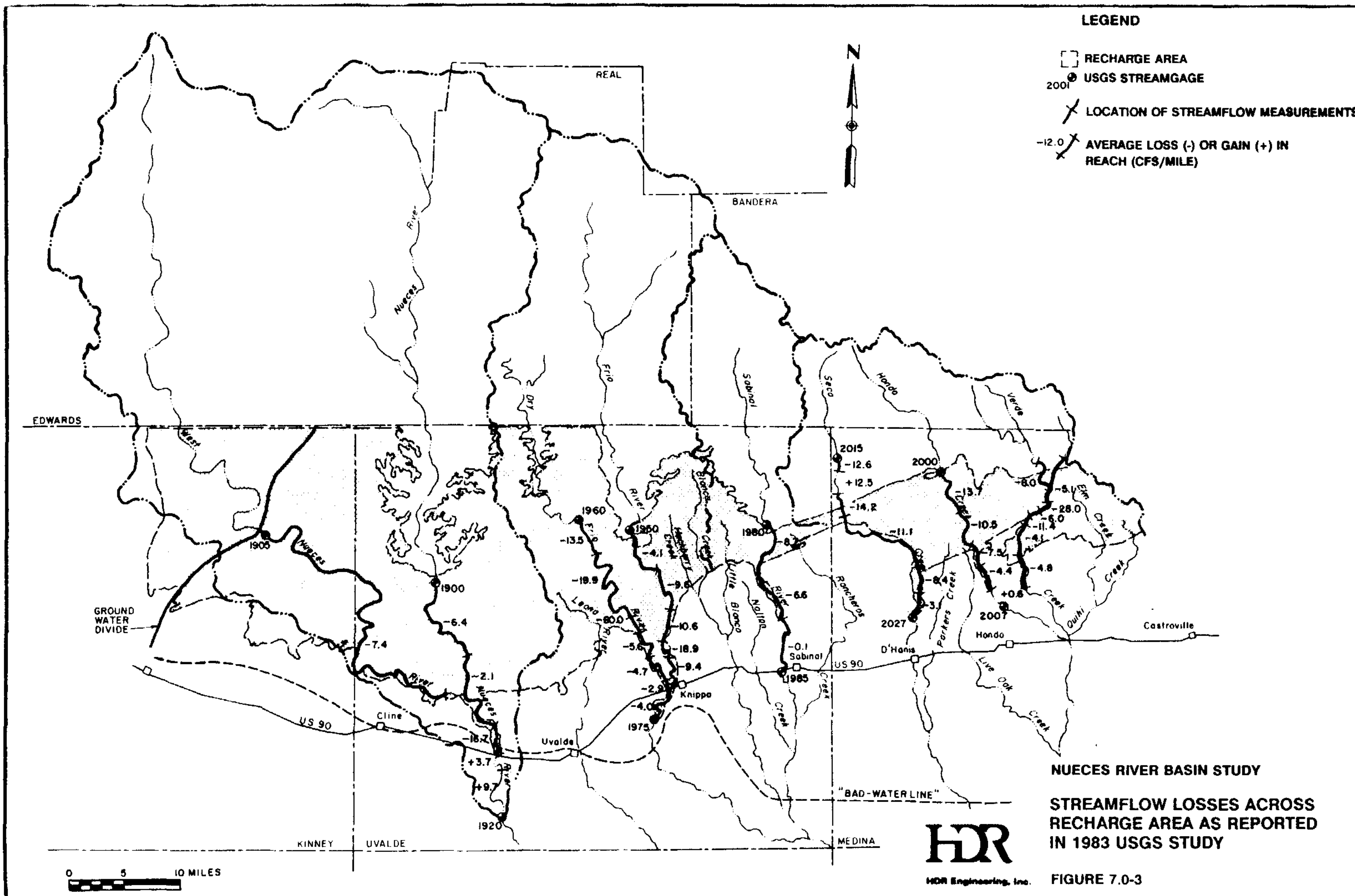
[1] Estimated on the basis of the area-capacity relationship for the Upper Sabinal Reservoir.
[2] Estimated on the basis of the area-capacity relationship for the Parker Creek Reservoir.
[3] Estimated on the basis of the area-capacity relationship for the Lower Sabinal Reservoir.

in cubic feet per second (cfs) per mile calculated by the USGS are shown in Figure 7.0-3 for each stream reach. These loss rates were assumed to be "threshold" rates such that upstream streamflow must exceed the threshold for some portion of the flow to cross the recharge zone. The loss rate reported by the USGS for each reach was applied on a monthly basis to determine the release or threshold rates shown in Table 7.0-1 for the Type 1 structures. Minor adjustments to the threshold rates for Seco and Verde Creek were made to reflect the presence of existing recharge structures.

In the Nueces River Basin model, the monthly contents of the Type 1 recharge reservoirs were simulated as described in Chapter 9 including the calculation of net evaporation losses. Releases of the monthly threshold rate and/or direct diversions were simulated during every month in which sufficient storage and inflow were available to do so. Once reservoir storage was depleted, inflows up to the monthly threshold were passed through the structure to recharge naturally.

Monthly recharge with Type 1 structures in place was calculated as the sum of direct diversions from the reservoir, releases less than or equal to the threshold rate, and "natural" recharge occurring across the recharge zone. This "natural" recharge was computed in much the same manner as described in Chapter 6 with adjustments for water rights diversions and changes in the upstream flow from baseline natural conditions.

When releases were required from Type 1 reservoirs to mitigate downstream water rights shortages, the actual release included not only the amount of the shortage adjusted for delivery to the point of shortage, but also the threshold rate which was assumed lost to recharge. Releases for downstream water rights were limited in all cases to monthly inflows. The order in which the various Type 1 reservoirs would be called upon to pass inflows to mitigate shortages at each downstream control point is specified in the input to the model



NUECES RIVER BASIN STUDY

STREAMFLOW LOSSES ACROSS RECHARGE AREA AS REPORTED IN 1983 USGS STUDY

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FIGURE 7.0-3

based on the percentage of a 20,000 acre-foot release which would arrive at the downstream location considering applicable threshold rates and delivery factors. For example, releases for shortages at Lake Corpus Christi with the Type 1 structures in place were made sequentially from the following sites: Upper Sabinal, Upper Verde, Upper Hondo, Montell, Upper Seco, Concan, and Upper Dry Frio.

The Type 2 structures are large structures which were located in the model at the downstream edge of the recharge zone to determine the maximum amount of water available for recharge. The leakage (or recharge) rates for the Type 2 structures were based on the actual measured leakage rate of Parker Creek reservoir which has been operated by the EUWD since 1974. A multi-site program of smaller structures on the recharge zone may be substituted for a Type 2 structure and still accomplish the same recharge, provided that the cumulative storage capacity and recharge rate of the multi-site program is equal to that of the Type 2 structure. In the case of the Indian Creek site with its slow recharge rate, artificial recharge by injection wells, diversion to the Dry Frio River, or a substitute multi-site program may be required to attain the computed recharge.

Modelling of the Type 2 recharge reservoirs was somewhat less complicated than modelling the Type 1 reservoirs because the applicable direct infiltration or leakage rates were such that the reservoirs would drain in less than one month. Hence, contents simulation and net evaporation calculations were unnecessary except at the Indian Creek site which was modelled as a Type 1 structure to account for evaporation losses. Monthly recharge with Type 2 structures in place was calculated as the sum of "natural" recharge, as described in Chapter 6 with adjustments for water rights diversions and changes in the upstream flow from natural conditions, and inflows up to the specified capacity of the reservoir. Inflows in excess of the storage capacity were spilled. Passage of inflows sufficient to mitigate downstream water rights shortages was modelled as described for the Type 1 structures without the additional consideration of a threshold rate. As delivery factors from the various Type 2 structures to each downstream control point were essentially equal, water rights release sequencing was specified to proceed from east to west in the model.

8.0 RESERVOIR ELEVATION-AREA-CAPACITY DATA

Data for reservoir elevation-area-capacity relationships were obtained from various sources for each of the reservoirs modeled. A listing of each reservoir, including the year and corresponding source from which the relationship was obtained, is shown in Table 8.0-1. Elevation-area-capacity relationships representative of conditions in 1948, 1959, 1972, and 1987 were used for Lake Corpus Christi. The 1987 relationship as originally calculated by the USGS was revised based on apparent errors in the USGS methodology. The results of these revisions are contained in Appendix J in Volume III. An elevation-area-capacity table dated June 1, 1983 provided by the City of Corpus Christi was used for Choke Canyon Reservoir.

Elevation-area-capacity relationships for Lake Corpus Christi and Choke Canyon Reservoir for 1990 and 2040 sediment conditions were calculated using the U.S. Bureau of Reclamation's "Empirical Area-Reduction Method Sediment Deposition Computation (Ref. 4 & 48)." A sedimentation rate of 1,256 ac-ft per year was used for Lake Corpus Christi which was calculated based on the average rate from 1934 to 1987. A sedimentation rate of 227 ac-ft per year was used for Choke Canyon Reservoir which is the rate as estimated by the U.S. Bureau of Reclamation (Ref. 49). Area-capacity relationships for several of the Type 1 recharge reservoirs (i.e., Upper Seco, Upper Hondo and Upper Verde) were assumed to be the same as the area-capacity relationship for the Upper Sabinal site. Since evaporation was not calculated at the Type 2 structures, it was not necessary to establish elevation-area-capacity relationships (except for Indian Creek). All elevation-area-capacity tables assembled during this study are contained in Appendix J in Volume III.

Tab).0-1
Summary of Elevation-Area-Capacity Data Sources

Reservoir	Year(s)	Conservation Pool Capacity (Ac-Ft)	Source of Elevation-Area-Capacity Data
Lake Corpus Christi	1948-1953	39,387	1948 SCS Sediment Survey (Ref. 19)
	1954-1958	37,500	1956 Survey (Ref. 41)
	1959-1965	302,160	1956 Survey (Ref. 41)
	1966-1979	272,352	1972 McCaughan & Etheridge Sediment Survey (Ref. 14)
	1980-1989	241,241	1987 USGS Sediment Survey Modified by HDR
	1990	237,473	1987 USGS (Modified) Relationship Adjusted for 3 years of Sedimentation*
	2040	174,673	1987 USGS (Modified) Relationship Adjusted for 53 years of Sedimentation*
Choke Canyon Reservoir	1982-1989	691,130	Initial USBR Survey (Ref. 49)
	1990	689,314	Initial USBR Relationship Adjusted for 8 years of Sedimentation**
	2040	677,964	Initial USBR Relationship Adjusted for 58 years of Sedimentation**
Type 1 Reservoirs			
Montell	1990	252,300	1964 USCE Report (Ref. 53)
Upper Dry Frio	1990	60,000	1985 Report (Ref. 7)
Concan	1990	149,000	1985 Report (Ref. 7)
Upper Sabinal	1990	93,300	1964 COE Report (Ref. 53)
Upper Seco	1990	23,000	Used Upper Sabinal Area-Capacity Relationship
Upper Hondo	1990	47,000	Used Upper Sabinal Area-Capacity Relationship
Upper Verde	1990	23,000	Used Upper Sabinal Area-Capacity Relationship
Type 2 Reservoirs***			
Indian Creek	1990	165,000	1982 Report (Ref. 10)

*Sedimentation rate of 1,256 ac-ft per year was used for Lake Corpus Christi which was calculated based on the rate which has occurred from 1934 to 1987. Sediment was distributed using the U.S. Bureau of Reclamation's "Empirical Area-Reduction Method Sediment Deposition Computation."

**Sedimentation rate of 227 ac-ft per year was used for Choke Canyon Reservoir which is the rate as estimated by the U.S. Bureau of Reclamation (Ref. 50). Sediment was distributed using the U.S. Bureau of Reclamation's "Empirical Area-Reduction Method Sediment Deposition Computation."

***Calculating E-A-C data for other Type 2 structures was not necessary for modeling purposes. However, E-A-C data for several of these sites as well as the existing Parker Creek Reservoir are included in Appendix J in Volume III.

9.0 COMPUTER MODEL DEVELOPMENT

Development of a computer model of the Nueces River Basin capable of calculating historical Edwards Aquifer recharge, assessing the potential effects of recharge enhancement dams, evaluating the present and future firm yield of the CC/LCC System, and quantifying fresh water inflows to the Nueces Estuary was a significant task undertaken in this study. The structure and components of the model were based on the physical characteristics and hydrologic phenomena which occur in the basin. Control points were generally established at streamflow gaging stations and other locations immediately upstream and downstream of the Edwards Aquifer recharge zone.

The logical computer code for the basin model is in the FORTRAN programming language, which is compatible with Texas Water Development Board models currently in use, such as SIMYLD-II (Ref. 46). The program has been compiled, debugged, and executed using the Microsoft FORTRAN, Version 5.0 compiler and a Dell 316LT laptop computer. The program code is sufficiently generic that it can be compiled and/or executed on mainframe, micro, and some personal computers. Comments and variable definitions are interspersed throughout the program code to facilitate understanding of computational logic and sequencing.

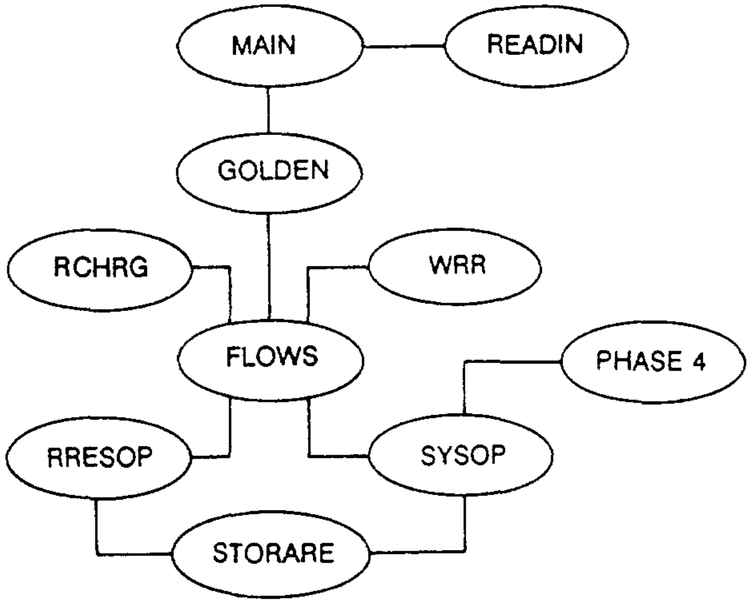
The program code for the Nueces River Basin model is written in subroutines which are program segments intended to simulate a specific process or perform a related sequence of calculations. These subroutines were written and compiled in three phases based on necessary model capabilities. The first phase involved the subroutines necessary for verification of the streamflow naturalization and historical recharge calculation analyses initially conducted independent of the model. In the second phase, subroutines needed to evaluate recharge enhancement projects, operate the CC/LCC System, and calculate firm yield were added. Finally, subroutines and various program modifications were incorporated to facilitate evaluation of recharge enhancement projects subject to downstream diversion or storage and diversion water rights.

The nine most significant subroutines are shown in Figure 9.0-1 along with connecting lines indicating their relationships within the Nueces River Basin model. Figure 9.0-1 also includes a brief definition of the function of each subroutine and indicates the model development phase during which it was implemented.

9.1 Verification

The first phase in the development of the Nueces River Basin model involved programming the basic streamflow simulation and recharge calculation algorithms to verify that the model could reproduce gaged streamflow and historical recharge from the input database. As indicated in Figure 9.0-1, the subroutines implemented during this phase are called MAIN, READIN, FLOWS, and RCHRG. These subroutines respectively perform the functions of input/output file management, data input, streamflow simulation, and recharge calculation.

The input data sets used in the verification phase included natural streamflow, historical diversions, monthly demand factors, and downstream delivery factors unique to each control point or major reach. Various control parameters were included in the input data to describe the physical locations of the control points relative to one another and the Edwards Aquifer recharge zone and to assign control point type (i.e., gaged stream, ungaged stream, system reservoir, or recharge reservoir). In subsequent phases of model



SUBROUTINE	PHASE	FUNCTION
MAIN	1	Input/Output File Management
READIN	1	Control Parameters and Data Input
GOLDEN	2	Solution Algorithm for Firm Yield
FLOWS	1	Streamflow Simulation
WRR	3	Water Rights Release Determination
RCHRG	1	Recharge Calculation
RRESOP	2	Recharge Reservoir Operation Simulation
SYSOP	2	Reservoir System Operation Simulation
PHASE4	2	System Operation Policy Application
STORARE	2	Area Calculation from Storage

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KEY MODEL SUBROUTINES

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FIGURE 9.0-1

development, additional databases were added, including diversion rights, reservoir elevation-area-capacity relationships, and net evaporation rates as well as control parameters to define system reservoir operation policy and recharge reservoir performance characteristics.

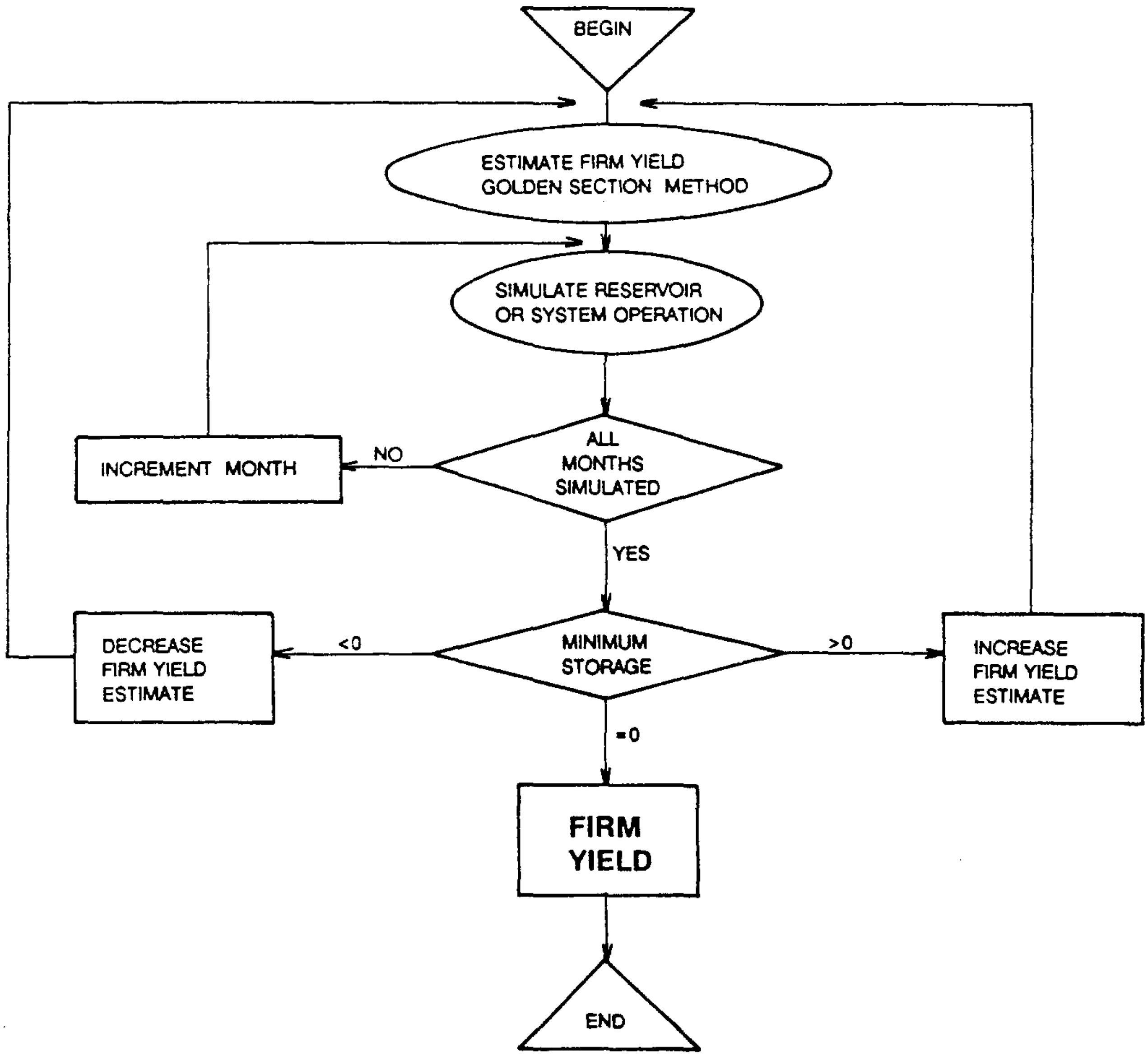
Monthly streamflow simulation in the model proceeds in an upstream to downstream fashion beginning in the headwaters of the Nueces River, proceeding downstream to the Frio River confluence, simulating the Frio River including the Sabinal River and Hondo, Seco, and Verde Creeks, and, finally, the remainder of the Nueces River downstream to the Nueces estuary. Recharge calculations are performed at each gaged and ungaged control point located at the downstream edge of the Edwards aquifer recharge zone in the manner described in Chapter 6. The natural streamflows at each control point were adjusted for historical diversions to obtain a modified flow which should, for verification, be equal to the historical gaged streamflows. The model programming was verified by comparing the modified streamflows calculated for each gaged control point with historical gaged streamflows and by comparing calculated recharge with that previously determined by HDR. Agreement was virtually exact with some very minor discrepancies arising from the limited use of integer variables in the model.

9.2 Recharge Projects and System Firm Yield

In the second phase of model development, subroutines were added to the Nueces River Basin model to facilitate simulation of existing reservoirs and potential recharge reservoir projects in order to estimate the firm yield of the CC/LCC System and quantify recharge enhancement of the Edwards aquifer. The significant subroutines added in this phase are indicated in Figure 9.0-1 and include GOLDEN, RRESOP, SYSOP, PHASE4, and STORARE. The respective functions of these subroutines are to solve for firm yield by successive approximation, simulate recharge reservoir operations, simulate CC/LCC System reservoir operations, determine monthly water supply releases from the CC/LCC System, and calculate surface area from storage contents to estimate monthly net evaporation losses from the reservoirs. Historical diversions at each control point were removed from the database and replaced with authorized diversion rights for each type of use. The model user may vary the percentage of total authorized diversion rights utilized above each control point.

The firm yield solution algorithm selected for incorporation in the Nueces River Basin model is called the Golden-Section Method (Ref. 8). It is an optimization method developed to efficiently solve for the maximum or minimum value of a function which is unimodal (i.e., has only one maximum or minimum) over a given uncertainty interval. The uncertainty interval is reduced to approximately 61.8 percent of its previous value, with each successive iteration requiring only one functional evaluation for each iteration after the first. In the model, the desired solution or firm yield is the maximum annual diversion rate subject to which the minimum allowable system storage occurs in one and only one month during the historical period simulated. The general computation procedure used in the model for determination of the firm yield of the CC/LCC System is summarized in Figure 9.2-1.

The reservoir operation simulation subroutines, RRESOP and SYSOP, written for recharge and system reservoirs, respectively, are based on the principle of continuity as formulated in the following equation:



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NUECES RIVER BASIN STUDY

FIRM YIELD
COMPUTATION PROCEDURE

FIGURE 9.2-1

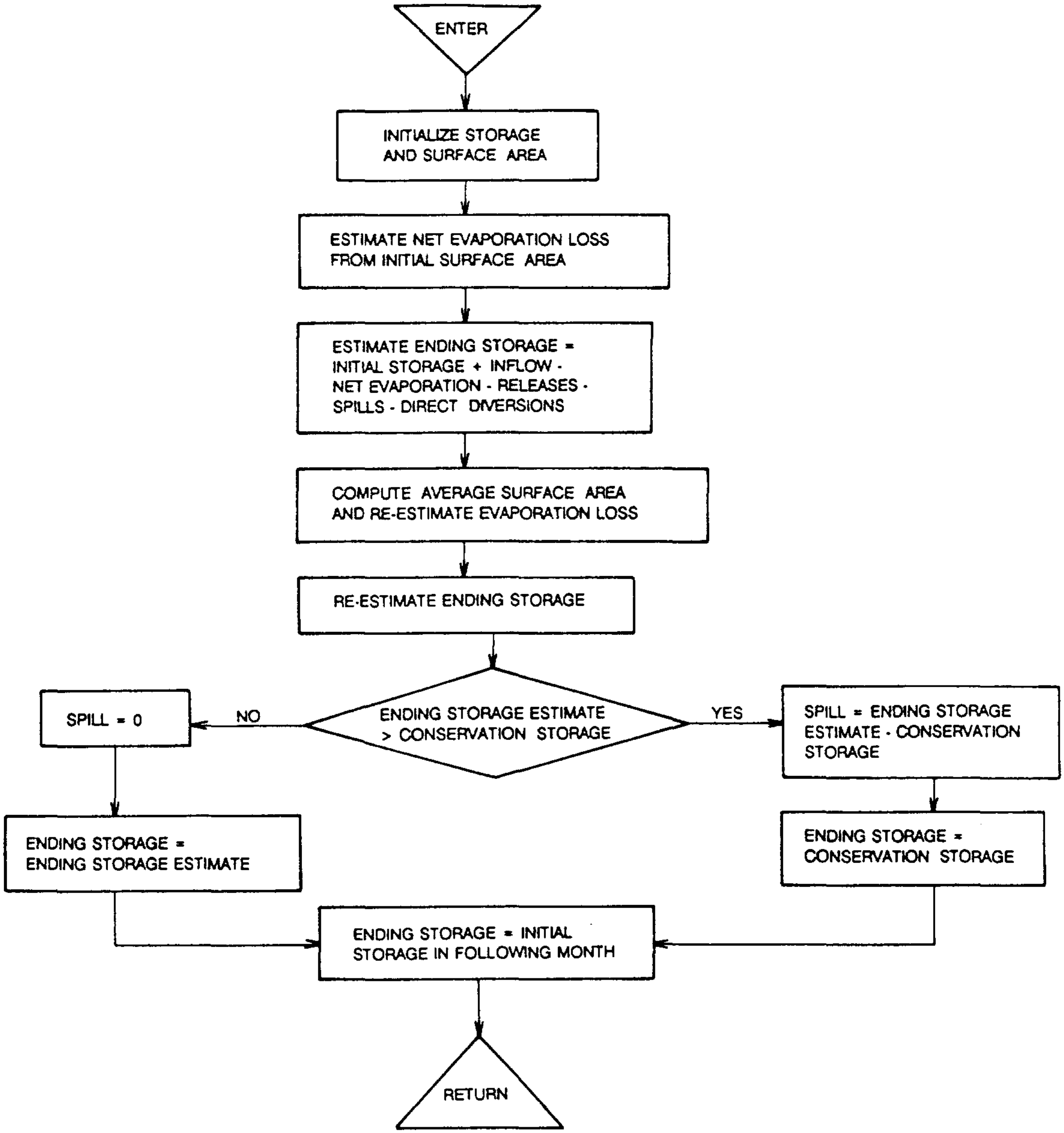
$$Z_t = Z_{t-1} + I_t - E_t - S_t - D_t$$

where:

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

Figure 9.2-2 presents a general flowchart summary illustrating the computational steps involved in monthly reservoir contents simulation. Monthly inflows are simply the natural inflow to the reservoir control point adjusted for all upstream water rights diversions and reservoir operations. Net evaporation losses are calculated by applying the historical rate to the average free water surface area based on reservoir contents in each month. The subroutine STORARE is a coded linear interpolation algorithm used to calculate reservoir surface area from contents based on input coincident values of surface area and storage volume for each reservoir. Due to the relatively brief residence time for waters impounded by Type 2 recharge structures, storage contents were not tracked from month to month and net evaporation losses were assumed insignificant.

Simulation of spills and/or releases from both recharge and system reservoirs was handled explicitly in the programming of the model. As indicated in Figure 9.2-2, spills occur in any month in which the estimated ending storage exceeds the designated conservation capacity of the reservoir. Releases, however, may be required for aquifer recharge or delivery of surface water supplies. Operation of Type 1 recharge reservoirs located immediately upstream of the Edwards Aquifer recharge zone includes the



NUECES RIVER BASIN STUDY

RESERVOIR CONTENTS SIMULATION PROCEDURE

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FIGURE 9.2-2

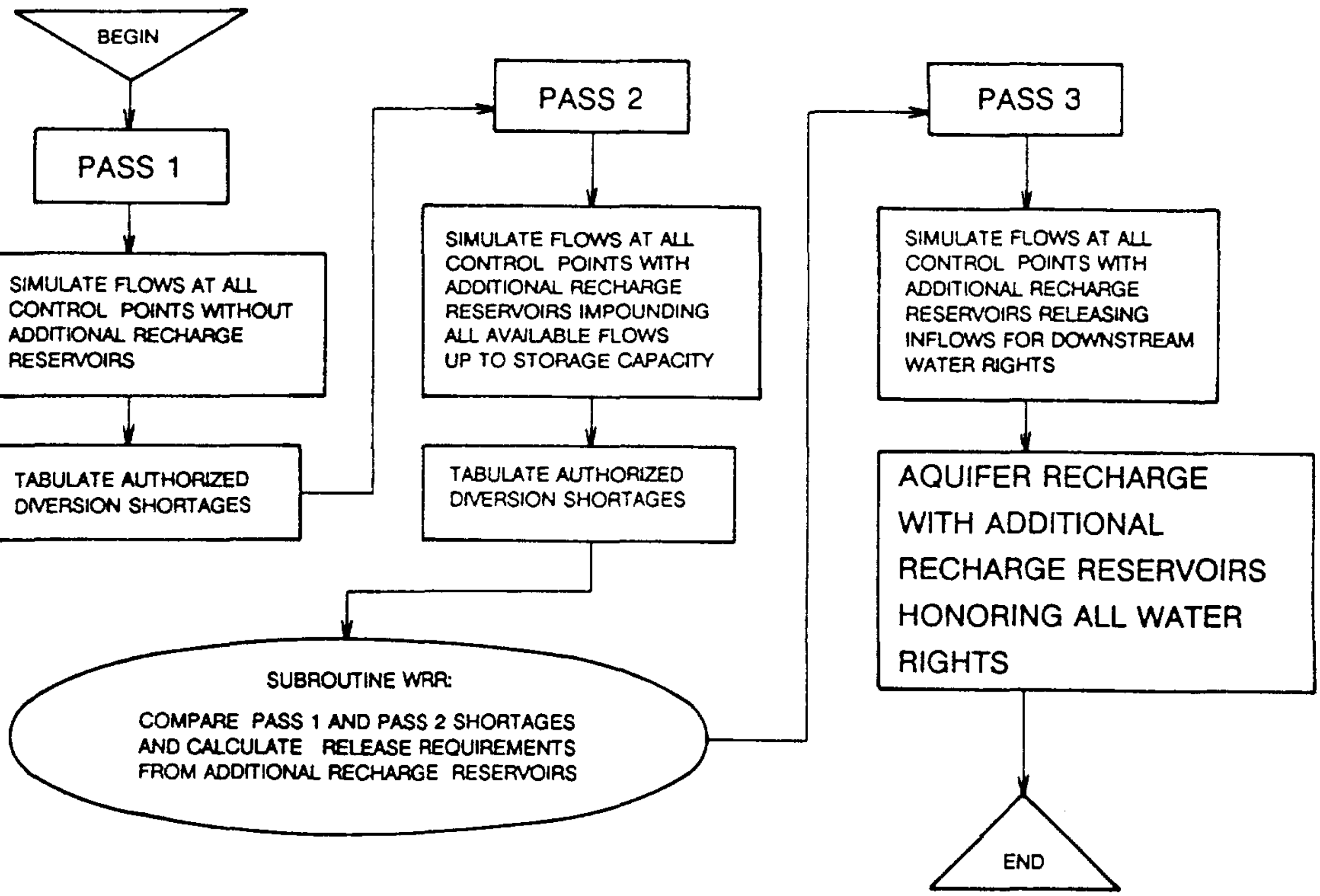
continuous release of stored water at the user-specified threshold rate which approximates the maximum natural infiltration capacity of the downstream reach crossing the recharge zone. Direct diversions from both the Type 1 and Type 2 sites on the Nueces River for recharge enhancement in the adjacent Dry Frio Basin or by direct injection to the Edwards were also simulated due to the limited natural recharge capacity of the Nueces River.

Monthly releases from Choke Canyon Reservoir and Lake Corpus Christi are calculated in the model by the subroutine called PHASE4. This subroutine executes the logic of the Phase IV policy from the Operations Plan for the Lake Corpus Christi - Choke Canyon Reservoir System which is applicable once Choke Canyon Reservoir has filled, water user demand or firm yield has exceeded 200,000 acre-feet per year, and developed long-term supply is less than 300,000 acre-feet per year. The option for the user to select the desired minimum water surface elevation or target elevation for Lake Corpus Christi has also been included in the model. Monthly release rates are calculated from the annual firm yield estimate using the municipal monthly demand factors determined for Reach 4 of the Nueces River Basin and adjusted by the amount of the intervening delivery losses upstream of Calallen Dam. Direct diversions from Lake Corpus Christi for the Alice Water Authority, Beeville Water Supply District, and the City of Mathis which are governed by contractual agreement with the City of Corpus Christi were assumed to be a portion of the firm yield of the CC/LCC System. Water rights held by the Nueces County WCID#3 which are senior to those of the City of Corpus Christi and are diverted from the pool created by Calallen Dam were accounted for by arithmetic reduction of the yield of the CC/LCC System computed at the Calallen Dam.

9.3 Water Rights

Programming the Nueces River Basin model to operate potential recharge reservoir projects while respecting downstream diversion and storage rights proved to be a complex task. Even without additional recharge reservoirs, the quantities of water authorized for diversion at various locations throughout the basin are sometimes unavailable due to insufficient streamflow. Hence, passage of inflows from the recharge reservoirs was assumed necessary only to the extent needed to limit downstream shortages to that which would have occurred historically. Protection of storage rights in the CC/LCC System was accomplished by limiting impoundment of monthly inflows in the recharge reservoirs to waters that could not have been captured and stored in the system reservoirs. The annual diversion rate assumed for the CC/LCC System when operating the recharge reservoirs subject to downstream water rights was fixed at the firm yield. In a manner consistent with the current Texas water law, no releases were required from carryover storage impounded in the additional recharge reservoirs during the preceding months.

Computation of the monthly inflow volumes to various potential recharge reservoirs which would have to be passed to assure water availability for authorized downstream diversions is accomplished in the model using the three pass process summarized in Figure 9.3-1. For each month in the historical database, flows are simulated and shortages are tabulated for all control points without additional recharge structures in place (Pass 1) and with additional recharge structures impounding all flows up to the specified storage capacity (Pass 2). The incremental authorized diversion shortages and system storage reductions affecting each control point are evaluated by the subroutine WRR indicated in Figure 9.0-1. This subroutine calculates the required passage of inflows at each additional recharge



NUECES RIVER BASIN STUDY

DOWNSTREAM WATER RIGHTS SIMULATION PROCEDURE

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FIGURE 9.3-1

reservoir to sustain historical water availability at each downstream control point. As is the case with water supply releases from the CC/LCC System, releases from the recharge reservoirs necessary to meet downstream shortages were adjusted by an amount sufficient to offset intervening channel losses. The user may designate preferred release sources by specifying the sequence in which the recharge reservoir inflows are assigned to mitigate downstream shortages, thereby minimizing delivery losses. In the third and final pass, flows are simulated for all control points with specified additional recharge structures in place and the enhanced Edwards Aquifer recharge quantities are calculated.

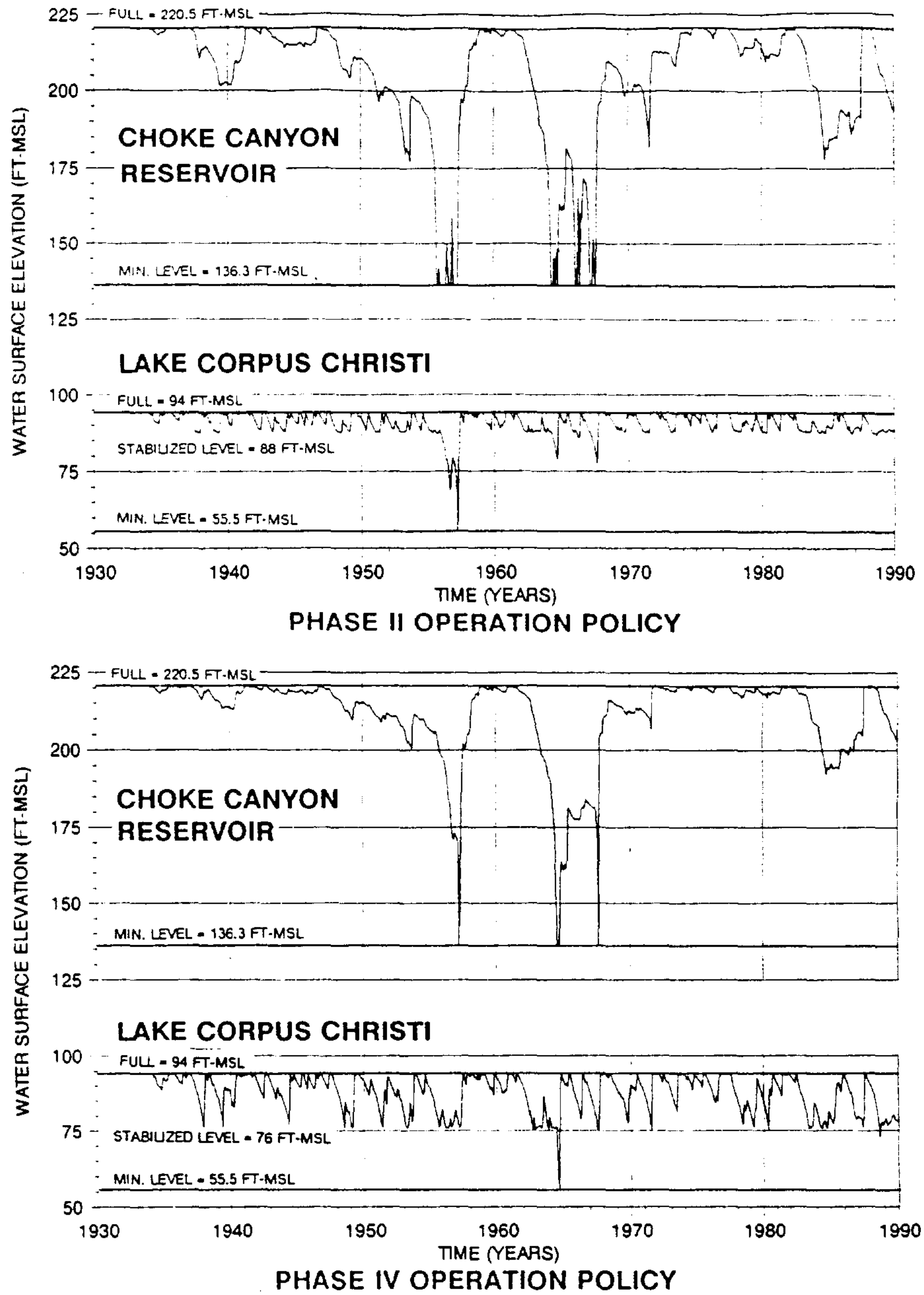
10.0 FIRM YIELD OF CHOKE CANYON RESERVOIR AND LAKE CORPUS CHRISTI SYSTEM WITHOUT ADDITIONAL RECHARGE STRUCTURES

Reservoir operation studies were performed on the CC/LCC System for both 1990 and 2040 reservoir sediment conditions to determine the firm yield of the system. The firm yield of a reservoir system is defined as the quantity of water which can be reliably diverted year after year from the reservoir system without a shortage. The period of record for this study is the 1934 through 1989 period, which included significant droughts in the 1950's, 1960's, and 1980's. The firm yield of a reservoir system will vary depending on sediment accumulation, operating rules, and, in the case of CC/LCC System, the location where water is actually diverted. Studies were performed for both 1990 and 2040 reservoir sediment conditions as well as for two sets of system operating rules (i.e., Phases II and IV of the City of Corpus Christi's reservoir system operations plan). Estimates of system firm yield reported in this study include the losses associated with delivery of water from Lake Corpus Christi to the Calallen diversion facility. Previous estimates of system firm yield by the U. S. Bureau of Reclamation (USBR) and TWDB have been based on direct diversion of water from Lake Corpus Christi.

Under the present reservoir operation policy (i.e., Phase II), 2,000 ac-ft are released each month from Choke Canyon Reservoir until the level in Lake Corpus Christi drops to 88 feet-MSL, which is 6 feet below conservation level. At this point, monthly releases from Choke Canyon are increased based on water supply requirements at Lake Corpus Christi sufficient to maintain an operating level of 88 feet-MSL. When the elevation of Choke Canyon Reservoir drops below elevation 155 feet-MSL, releases are reduced and remaining storage in Lake Corpus Christi is depleted. Under the Phase IV operation policy, 2,000 ac-ft are released each month from Choke Canyon Reservoir until the level in Lake Corpus Christi drops to 76 feet-MSL, which is 18 feet below conservation level. Figure 10.0-1 shows lake level fluctuations for 1990 sediment conditions for both reservoirs when operated at firm yield demands in accordance with Phase II and IV policies.

Firm yield analyses were performed considering two cases of water use by upstream water rights. Case 1 included existing upstream water rights diverting at 1988 reported use levels. Case 2 included existing upstream water rights diverting at full permitted authorization. Phase IV policy was analyzed first, considering both Case 1 and Case 2 conditions of upstream use. For Case 1 conditions, the firm yield of the CC/LCC System was determined to be 224,400 ac-ft per year for 1990 sediment conditions and 204,100 ac-ft per year for 2040 sediment conditions. Under Case 2 conditions, the firm yield of the system was reduced by 2.0 percent to 220,000 ac-ft per year for 1990 sediment conditions and by 3.2 percent to 197,500 ac-ft per year for 2040 sediment conditions. The effect of increased usage by existing upstream rights was to reduce the 1990 firm yield by 4,400 ac-ft per year and the 2040 firm yield by 6,600 ac-ft per year.

Firm yield analyses were next performed for the existing Phase II policy with upstream water rights diverting at full permitted authorization (i.e., Case 2 conditions). For 1990 sediment conditions, the yield was determined to be 187,800 ac-ft per year, which is 32,200 ac-ft per year or 14.6 percent less than the comparable yield using the Phase IV policy. For 2040 sediment conditions, the system yield was determined to be 169,700 ac-ft



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NUECES RIVER BASIN STUDY

CC/LCC SYSTEM 1990 FIRM YIELD WATER SURFACE ELEVATION TRACES

FIGURE 10.0-1

per year, which is 27,800 ac-ft per year or 14.1 percent less than the comparable yield using the Phase IV policy.

Lake level fluctuations for the entire 56-year period analyzed are shown in Figure 10.0-1 for both operation policies and show the differences in the timing of the critical drought. Under the Phase IV policy, the critical drought occurred from 1961 through 1964, however, with the Phase II policy in place, the critical drought occurred during the 1947 through 1957 period.

Permanent operating rules defining the water requirements for the Nueces Estuary have not been adopted by the Texas Water Commission (TWC). These rules are anticipated to be finalized sometime in 1991. A worst case scenario of providing at least 151,000 ac-ft per year to the estuary of return flows, spills, or releases from Lake Corpus Christi was analyzed without regard to the release abeyance provisions in the interim TWC order issued August 10, 1990. The results of these analyses are summarized in Table 10.0-1, which shows that the yield would be reduced by about 25 percent under the Phase IV policy for both 1990 and 2040 sediment conditions if the full 151,000 ac-ft were released each year without regard to the release abeyance provisions in the interim order.

The year 2010 firm yield of the CC/LCC System is approximately 184,100 ac-ft per year under Phase II policy, with full diversions by upstream rights. This yield is about 64,900 ac-ft per year or 26.1 percent less than the 2010 firm yield of 249,000 ac-ft per year as estimated by the Bureau of Reclamation (USBR). The original USBR yield of 252,000 ac-ft per year has recently been revised to 249,000 ac-ft per year based on refined yield studies by the USBR. Although a detailed analysis of factors contributing to the difference between the USBR's yields and those calculated in this report has not been performed, one major difference is that the USBR calculates yield at the lakes and does not include channel losses affecting water released from both Choke Canyon Reservoir and Lake Corpus Christi downstream to the Calallen Diversion Dam. This study calculates system yield based on water delivered to Calallen. Another significant difference between this study and the USBR's yield estimate is the conservation capacity of Lake Corpus Christi. Results of a recent sediment survey (See Appendix J, Volume III) indicate that, by the year 2010, Lake Corpus Christi will have a capacity of about 212,353 ac-ft or 47,647 ac-ft less than the year 2010 capacity used by the USBR in their studies.

Table 10.0-1
Firm Yield of Choke Canyon Reservoir and Lake Corpus Christi System with No Additional Recharge Structures

	System Firm Yield	
	1990 Sediment (Ac-Ft/Year)	2040 Sediment (Ac-Ft/Year)
I. Without Full Release of 151,000 Ac-Ft to Estuary*		
A) Phase IV Policy		
Case 1) Upstream Water Rights Diverting at 1988 Use Levels	224,400	204,100
Case 2) Upstream Water Rights Diverting at Full Authorization	220,000	197,500
B) Phase II Policy		
Case 2) Upstream Water Rights Diverting at Full Authorization	187,800	169,700
II. With Full Release of 151,000 Ac-Ft to Estuary**		
A) Phase IV Policy		
Case 1) Upstream Water Rights Diverting at 1988 Use Levels	171,700	152,700
Case 2) Upstream Water Rights Diverting at Full Authorization	166,300	147,300
B) Phase II Policy		
Case 2) Upstream Water Rights Diverting at Full Authorization	122,400	107,100

*Assumes that only 47% of water diverted is returned to the estuary. For the six yields shown, this would vary from a minimum of 79,800 ac-ft per year to a maximum of 105,500 ac-ft per year of return flows.

**Assumes 47% of water diverted contributes to return flows with balance of 151,000 ac-ft per year coming first from spills, if available, and any remainder coming from releases.

11.0 ADDITIONAL RECHARGE POTENTIAL

Reservoir operation studies were performed for Type 1 and Type 2 recharge structures to determine a theoretical, but reasonable, upper limit of recharge potential. It should be noted that when the analyses were performed for the Type 1 structures, the Type 2 structures were not present in the model operation. Likewise, the Type 2 structures were analyzed without the Type 1 structures in place. Operational analyses with both Type 1 and Type 2 structures included in tandem were not performed because review of flow data indicated that the additional recharge would likely not be sufficient to justify the construction of both types of projects. The five Type 2 structures located on tributary streams (i.e., Leona, Blanco, Little Blanco, Elm Creek and Quihi Creek sites) could be implemented independent of the Type 1 (or other Type 2) structures. For the purposes of this study, however, they were included in the model with the Type 2 structures and not with the Type 1 structures.

The theoretical recharge to the Edwards Aquifer was first calculated honoring all existing water rights (except for several small rights located downstream of Lake Corpus Christi). A second set of analyses was performed in which all water rights were honored except those of the City of Corpus Christi in the Choke Canyon/Lake Corpus Christi (CC/LCC) System and the several small rights located downstream of Lake Corpus Christi. Water rights of the City of Robstown (i.e., Nueces County WCID #3) at the Calallen Diversion Dam were among those rights honored in all analyses. The second set of analyses was performed to determine the theoretical maximum amount of recharge potential and the effects of that maximum recharge on the yield of the CC/LCC System.

Figure 2.2-1 in Chapter 2 of this report shows the locations of significant water rights in the basin, including those of Zavala-Dimmit County WID #1 and rights in the Crystal City-Carrizo Springs area. To insure protection of these (and other smaller) water rights, it will be necessary to install large capacity outlet works in each of the recharge structures to allow flows to be passed at a sufficient rate to arrive downstream. Flows would only need to be passed at those times when the recharge structures would cause an additional shortage to downstream rights. This generally represents how the watermaster would require the recharge structures to be operated and is the way existing water rights were satisfied in the model.

11.1 Additional Long-Term Recharge (1934-1989)

The results of the recharge calculations with the Type 1 structures in place are presented in Table 11.1-1. The Type 1 structures with a combined storage of 647,600 ac-ft provide an average gain of 85,261 ac-ft per year of recharge for the 56-year period honoring all water rights. This represents a 26.3 percent increase in historical recharge in the Nueces Basin. When the water rights of the CC/LCC System are not honored, a net average gain of 113,083 ac-ft per year of recharge can be attained. This represents a 34.9 percent increase in historical recharge in the Nueces Basin.

Table 11.1-2 summarizes the results for the Type 2 structures. With a combined capacity of 380,950 ac-ft (which is 59 percent of the total storage of the Type 1 structures), the Type 2 structures provide an average gain of 61,086 ac-ft per year of recharge if all water rights are honored. This is a 18.9 percent increase over historical recharge in the

Table 11.1-1
Maximum Storage Capacity and Additional Recharge Potential of Type 1 Recharge Structures

Recharge Area	Reservoirs	Maximum Storage (Ac-Ft)	Historical* Average Annual Recharge (Ac-Ft/Yr)	Additional Recharge with New Structures: Honoring All Water Rights (Ac-Ft/Yr)	Additional Recharge with New Structures: Honoring All Water Rights Except CC/LCC System (Ac-Ft/Yr)
1) Nueces-West Nueces			88,018	41,309	57,510
	Montell	252,300			
2) Frio-Dry Frio			109,136	16,306	19,758
	Upper Dry Frio	60,000			
	Concan	149,000			
3) Sabinal			32,228	12,226	16,794
	Upper Sabinal	93,300			
4) Area between Sabinal and Medina			94,647	15,420	19,021
	Upper Seco	23,000			
	Upper Hondo	47,000			
	Upper Verde	23,000			
Additional Recharge				85,261	113,083
Total Recharge			324,029	409,290	437,112
Percent Increase in Historical Recharge*				26.3%	34.9%

*Historical recharge is adjusted for three existing recharge projects and existing water rights.

Table 11.1-2
Maximum Storage Capacity and Additional Recharge Potential of Type 2 Recharge Structures

Recharge Area	Reservoirs	Maximum Storage (Ac-Ft)	Historical* Average Annual Recharge (Ac-Ft/Yr)	Additional Recharge with New Structures: Honoring All Water Rights (Ac-Ft/Yr)	Additional Recharge with New Structures: Honoring All Water Rights Except CC/LCC System (Ac-Ft/Yr)
1) Nueces-West Nueces			88,018	37,090	55,609
	Indian Creek	165,000			
2) Frio-Dry Frio			109,136	10,828	21,131
	Lower Dry Frio	30,000			
	Lower Frio	50,000			
	Leona	2,930			
	Blanco	6,580			
3) Sabinal			32,228	6,844	17,956
	Lower Sabinal	35,000			
	Little Blanco	2,930			
4) Area between Sabinal and Medina			94,647	6,324	18,188
	Lower Seco	28,000			
	Lower Hondo	28,000			
	Lower Verde	24,000			
	Elm Creek	6,940			
	Quihi Creek	1,570			
Additional Recharge				61,086	112,884
Total Recharge			324,029	385,115	436,913
Percent Increase in Historical Recharge*				18.9%	34.8%

*Historical recharge is adjusted for three existing recharge projects and existing water rights.

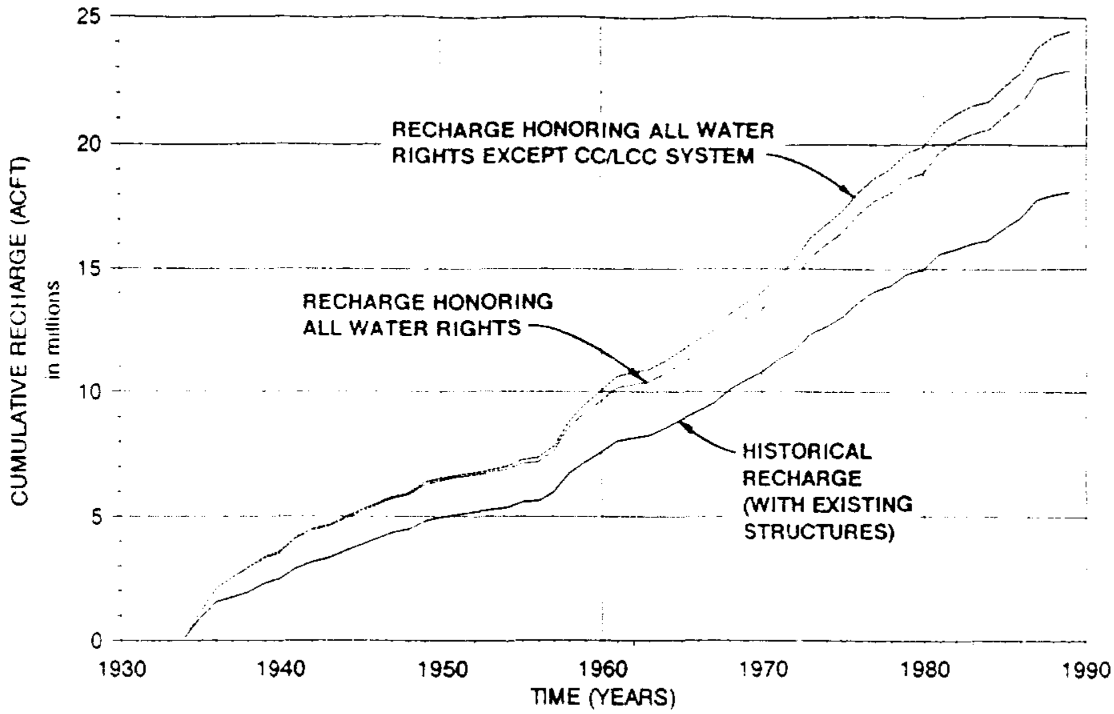
Nueces Basin. When the water rights of the CC/LCC System are not honored, a net average gain of 112,884 ac-ft per year of recharge can be attained. This represents a 34.8 percent increase in historical recharge. Figure 11.1-1 compares the cumulative recharge for the two types of structures for the 56-year study period.

11.2 Additional Drought Recharge (1947-1956)

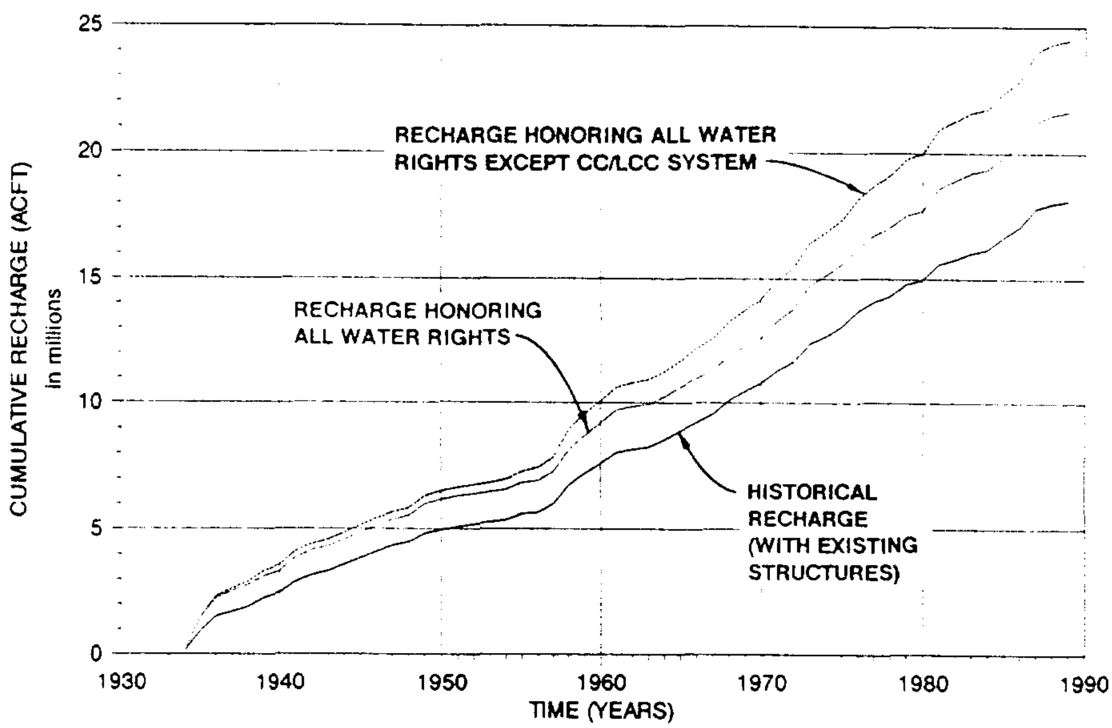
Figure 11.2-1 compares the historical annual recharge with the annual recharge with additional recharge structures for the 10-year drought period from 1947 to 1956. The additional recharge with the Type 1 structures averages 19,062 ac-ft per year when all water rights are honored and averages 29,673 ac-ft per year if the water rights of the CC/LCC System are not honored. This represents a 12.2 percent and 19.1 percent increase, respectively. For Type 2 structures, recharge for this same 10-year period could be increased by an average of 24,073 ac-ft per year if all water rights are honored and 44,801 ac-ft per year if the water rights of the CC/LCC System are not honored. This represents a 15.5 percent and 28.8 percent increase, respectively.

11.3 Significant Recharge Structures

It is interesting to note that about half of the increase in recharge for the Type 1 structures comes from the Montell site located on the Nueces River. This is the largest recharge project evaluated and has a maximum storage of 252,300 acre feet, which represents 39 percent of the total storage of the Type 1 recharge reservoirs. For the Type 2 recharge reservoirs, the largest increase in recharge is provided by the Indian Creek site,



TYPE 1 RECHARGE STRUCTURES



TYPE 2 RECHARGE STRUCTURES

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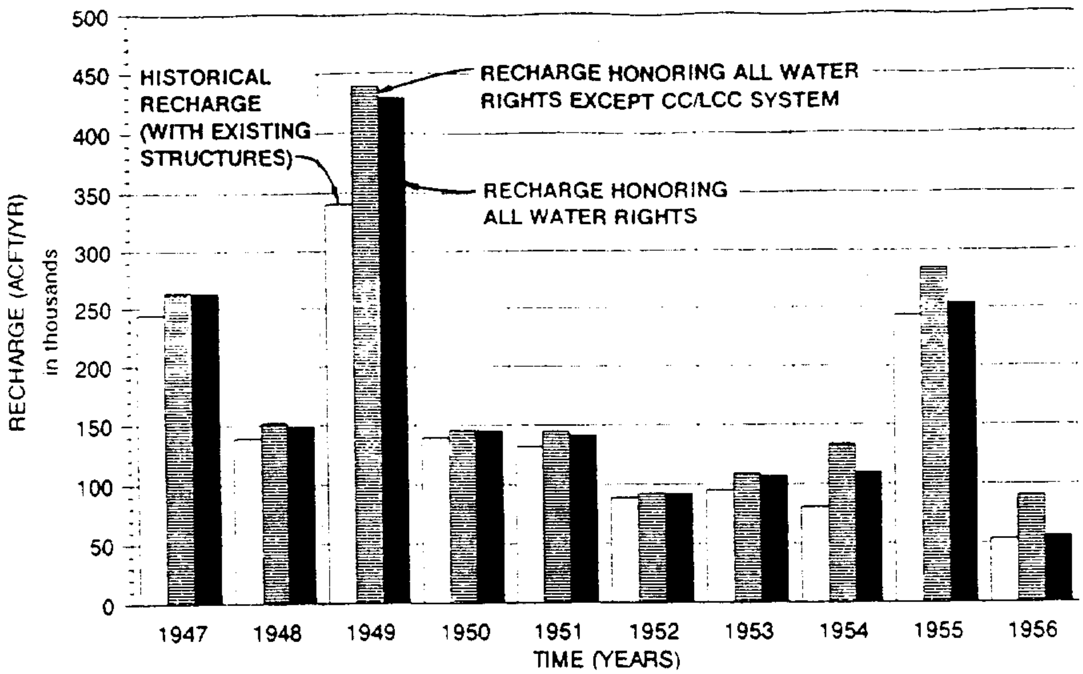
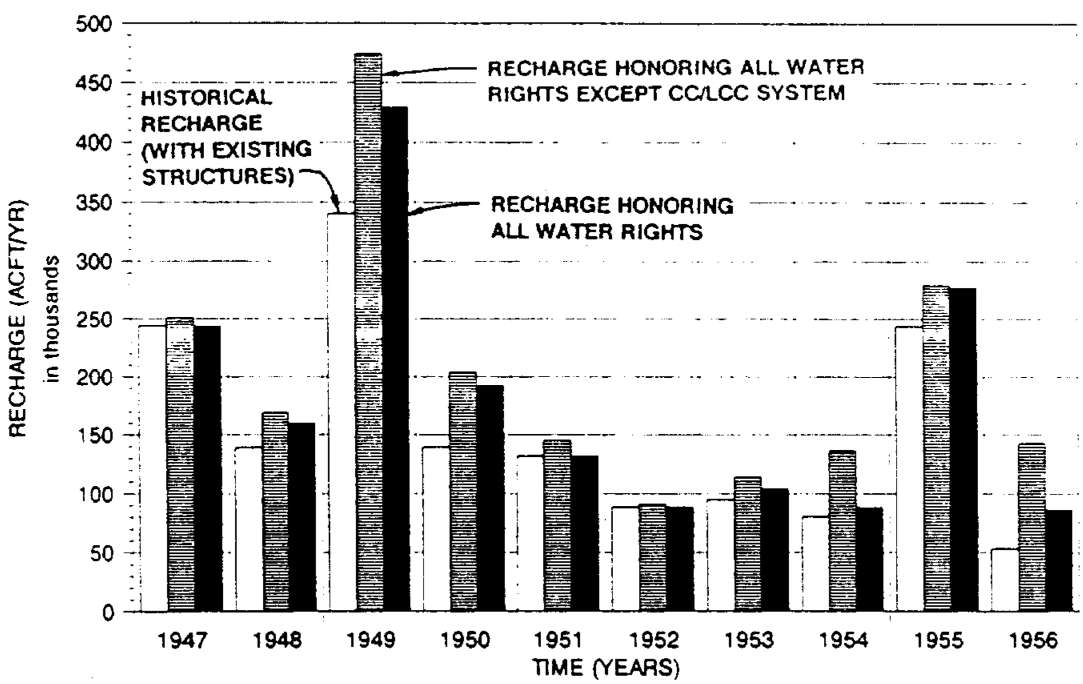
COMPARISONS OF CUMULATIVE EDWARDS AQUIFER RECHARGE WITH ADDITIONAL RECHARGE STRUCTURES

FIGURE 11.1-1



TYPE 1 RECHARGE STRUCTURES



TYPE 2 RECHARGE STRUCTURES

NUECES RIVER BASIN STUDY

COMPARISONS OF EDWARDS AQUIFER RECHARGE DURING DROUGHT WITH ADDITIONAL RECHARGE STRUCTURES

FIGURE 11.1-2

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which is also located on the Nueces River. This site has a maximum capacity of 165,000 acre-feet, which represents 43 percent of the total storage of the Type 2 structures and provides between 49 percent and 61 percent of the additional recharge, depending on which water rights are honored. For both the Montell and Indian Creek sites, recharge rates which exceed the natural recharge rate of the Nueces River channel as measured by the USGS were used in the model. This was done in order to use the full storage potential of these sites. It was assumed that aquifer injection wells or diversion to the Dry Frio River would be used to achieve the recharge rates necessary to fully use the water stored in these sites. Further detailed analyses will be necessary for these two sites to determine if recharge in this portion of the aquifer, which is west of the Knippa Gap, will benefit eastern portions of the aquifer or simply enhance spring flows at Leona Springs at Uvalde.

11.4 Recharge Limitations

The recharge figures presented herein generally represent a theoretical upper limit of increases in annual recharge if all recharge projects are fully developed. Although it is not likely that all projects will be fully developed, future appropriations of water in watersheds with fully developed projects will be limited. It is likely that further study will show that the actual recharge attainable from these recharge structures will be less than presented herein when considering the economic, environmental, or structural factors involved. In addition, the storage capacities of some sites may be limited by geologic or man-made features.

12.0 IMPACTS OF ADDITIONAL RECHARGE ON CC/LCC SYSTEM AND NUECES ESTUARY

12.1 Impact on Firm Yield of CC/LCC System

Reservoir operation studies were performed on the CC/LCC System for 1990 sediment conditions to determine the impacts of the two types of recharge structures on reservoir inflows, system yield, average lake levels, and inflows to the Nueces Estuary. The senior rights of the Choke Canyon/Lake Corpus Christi System were not honored. Phase IV operation policy for the CC/LCC System was used and upstream water rights were diverted at their full authorization subject to water availability.

Type 1 recharge structures were the first group analyzed. These are the seven reservoirs located upstream of the recharge zone which would catch water and then gradually release it at a rate that allows maximum recharge efficiency. Reservoir operation studies of the CC/LCC System with all seven Type 1 structures in place show that inflows to the CC/LCC System would be reduced on the average 37,800 ac-ft per year or 5.0 percent, and the 1990 system yield would decrease by 3,900 ac-ft per year to 216,100 ac-ft per year. This is a decrease of 1.8 percent of the 1990 yield without additional recharge structures. A comparison of average lake levels with and without the Type 1 recharge reservoirs in place indicates that the average level of Lake Corpus Christi will be reduced by 0.06 feet. At Choke Canyon Reservoir, the average reduction is 0.52 feet.

Type 2 reservoirs were the second group of recharge structures analyzed. These are the twelve reservoirs located within the recharge zone which, after filling, immediately recharge the aquifer. CC/LCC System yield analyses with Type 2 structures in place showed that inflows to CC/LCC System would be reduced on the average by 40,700 ac-ft per year or 5.4 percent, and the 1990 system yield would decrease 5,800 ac-ft per year to 214,200 ac-ft per year. This is a decrease of 2.6 percent of the 1990 yield without additional recharge structures. A comparison of average lake levels with and without the Type 2 recharge reservoirs in place indicates that the average level of Lake Corpus Christi will be reduced by 0.03 feet. At Choke Canyon Reservoir, the average reduction is 0.41 feet. A summary of the firm yield analyses of the CC/LCC System with and without additional recharge structures is provided in Table 12.1-1.

Table 12.1-1
Firm Yield of Choke Canyon Reservoir and Lake Corpus Christi System with Additional Recharge Structures

	1990 System Firm Yield* (Ac-Ft/Year)	% Decrease from Baseline
Baseline - No Additional Recharge Structures	220,000	---
Case 1) With Seven Type 1 Recharge Structures	216,100	1.7
Case 2) With Twelve Type 2 Recharge Structures	214,200	2.4

*Firm yield for Phase IV policy as calculated at Calallen Dam without regard to meeting 151,000 ac-ft release for estuary. All runs assume upstream water rights are diverting at full authorization subject to water availability.

12.2 Impact on Ability of CC/LCC System to Meet Required Estuary Inflows

Additional analyses were performed to determine the impact the recharge structures would have on the ability of the CC/LCC System to meet the 151,000 ac-ft requirement for inflows to the Nueces Estuary. The results of these analyses indicated that, under Phase IV operation policy, spills from Lake Corpus Christi were affected within the 151,000 ac-ft criteria in only six out of the 56 years analyzed. The reduced spill volume, which would have to be made up from additional reservoir releases, averaged 175 ac-ft per year for Type 1 structures and 206 ac-ft per year for Type 2 structures. Although these analyses showed that the recharge projects will not significantly impact the existing 151,000 ac-ft estuary requirement, additional analyses should be performed when final operating rules are established by the TWC.

12.3 Impacts on Inflows to Nueces Estuary

According to studies of the Nueces Estuary performed by the Texas Water Development Board, approximately 87 percent of historical fresh water inflows were contributed by water which originated upstream of Lake Corpus Christi. To determine the impacts of the recharge structures on inflows to the estuary, a comparison of average annual spills at Lake Corpus Christi (with full use of the system yield) was made for the 56-year study period. As shown in Table 12.3-1, spills at Lake Corpus Christi under 1990 sediment conditions and Phase IV operations averaged 288,000 ac-ft per year without any additional recharge structures. With all seven Type 1 structures in place, annual spills were reduced by 15,800 ac-ft per year or 5.5 percent on the average. The year in which the largest impact on the total spill volume occurred was 1935, when spills were reduced by 137,500 ac-ft or 6.0 percent. With all twelve Type 2 structures in place (and no Type 1 structures), annual spills were reduced by 15,200 ac-ft per year or 5.3 percent on the average. The year in which the largest impact on the total spill volume occurred was 1935, when spills were reduced by 136,800 ac-ft or 6.0 percent.

A comparison of the number of months with spills at Lake Corpus Christi was made with and without the recharge structures in place. For 1990 sediment conditions, Phase IV operation policy, and a firm yield demand of 220,000 ac-ft per year being diverted from the system, Lake Corpus Christi spills in 117 of the total 672 months analysed or 17.4 percent of the months. When the same analysis is performed with either the Type 1 or Type 2 recharge structures in place, Lake Corpus Christi spills in 112 or 113 of the total 672 months or approximately 16.7 percent of the months. This represents approximately a 4 percent reduction in the number of spill months.

Table 12.3-1
Reduced Inflow to Nueces Estuary with Additional Recharge Structures

	1990 System Spills (Ac-Ft/Year)	Decrease from Baseline (Ac-Ft/Yr)	% Decrease from Baseline
Baseline - No Additional Recharge Structures	288,000	----	----
Case 1) With Seven Type 1 Recharge Structures	272,200	15,800	5.5
Case 2) With Twelve Type 2 Recharge Structures	272,800	15,200	5.3

13.0 COMPARISON OF CC/LCC SYSTEM YIELD WITH PROJECTED WATER DEMANDS

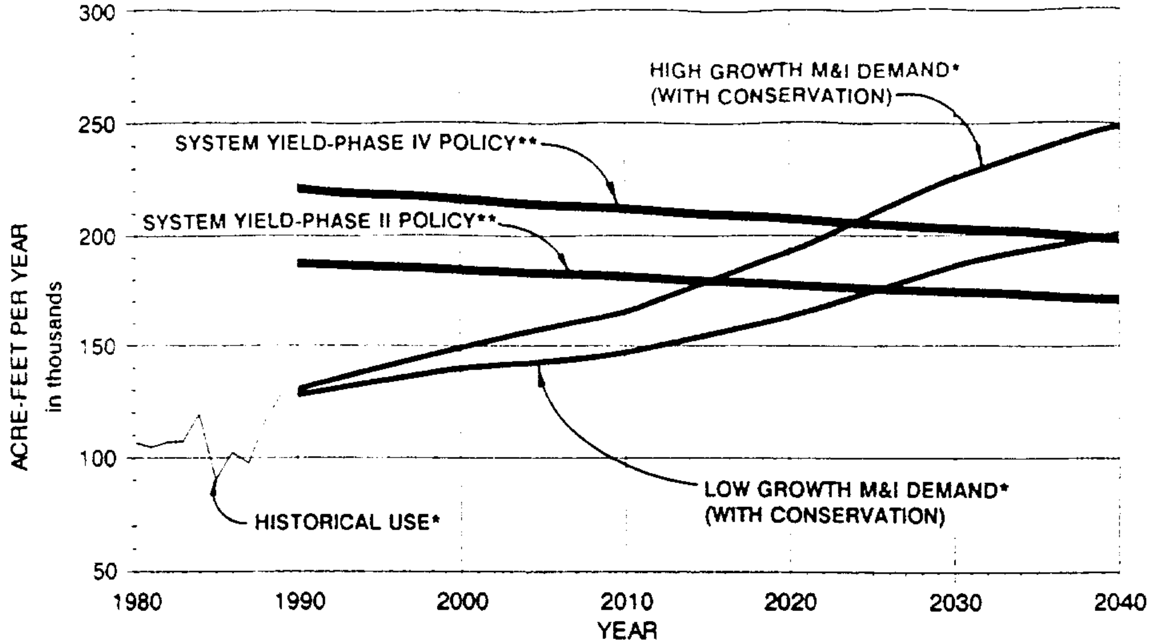
In the 12-county Choke Canyon/Lake Corpus Christi service area, population in 1980 was 502,058 and combined municipal and industrial (i.e., manufacturing) water use from ground and surface water sources was 146,615 ac-ft. The twelve counties in this service area include the four coastal counties of Aransas, San Patricio, Nueces, and Kleberg and the eight inland counties of Atascosa, Bee, Refugio, Live Oak, McMullen, Duval, Jim Wells, and Brooks. According to estimates prepared by the Texas Water Development Board, population in these counties is projected to increase to between 615,583 and 633,509 by 2000; to between 755,184 and 837,112 by 2020; and to between 913,637 and 1,051,681 by 2040. Projected water requirements (with conservation), considering only municipal and industrial needs, range between 174,000 and 183,000 acre-feet per year for the year 2000. Projected water requirements for 2020 range between 196,000 and 226,000 acre-feet per year and, for 2040, range between 235,000 and 283,000 acre-feet per year. Projections of population and water use are included in Appendix A in Volume III.

Presently, not all municipal and industrial (M&I) water users in the 12-county service area are supplied from the CC/LCC System. The latest water use data from the TWDB indicates that in 1985 about 34,000 ac-ft of demand in the 12-county area was met by water sources other than the CC/LCC System. Approximately 74 percent of this demand, or 25,000 ac-ft, was met from ground water sources. Although it is impossible to accurately predict when, and if, other entities will be supplied by the CC/LCC System, two scenarios have been prepared for the purpose of estimating the potential impact on system demands. These two scenarios include a best case (with respect to minimizing system demand) and a probable case. The best case scenario assumes that 34,000 ac-ft of the 12-county area demand will continue to be supplied from ground and surface water sources other than the CC/LCC System throughout the 1990 to 2040 period. The probable case scenario assumes that use of the 34,000 ac-ft will gradually decline as reliance on ground water sources is reduced so that, by the year 2020, only 17,000 ac-ft per year of demand will be met from sources other than the CC/LCC System. Table 13.0-1 shows the projected M&I demands for the CC/LCC System for both scenarios for the 1990 through 2040 period for both low and high growth rates.

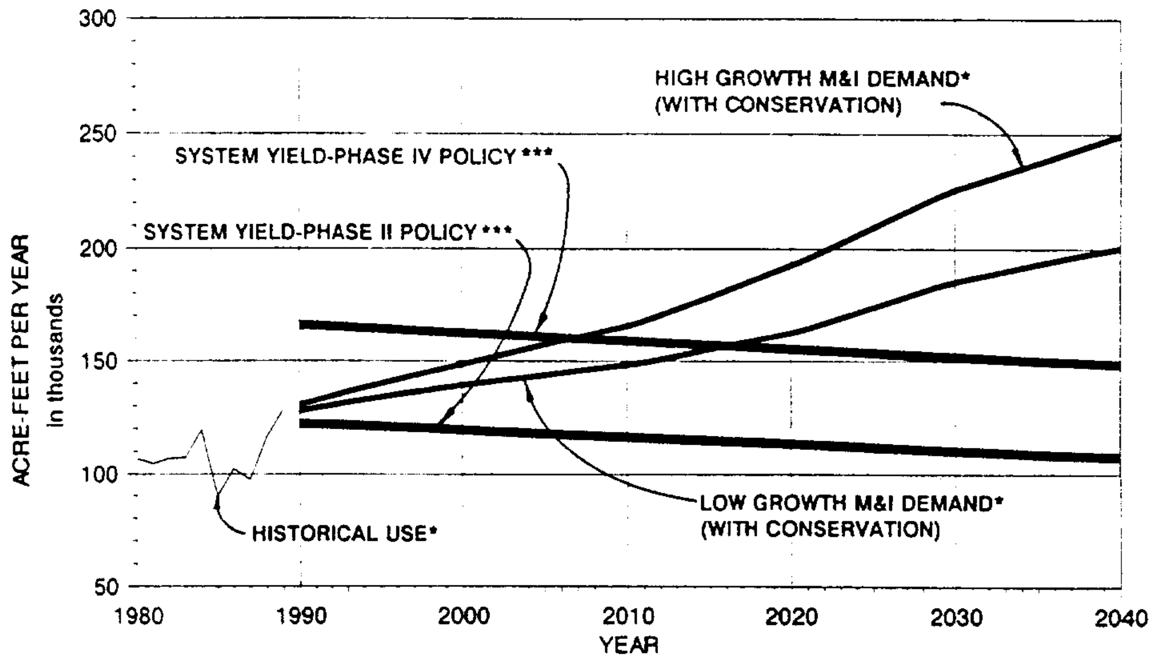
Comparisons of projected water demands with system yield estimates are presented in Figure 13.0-1 for the best case demand scenario and in Figure 13.0-2 for the probable case demand scenario. The upper graph on Figure 13.0-1 shows that for the best case scenario, if no additional recharge structures are constructed, the yield of the system (without considering releases to the estuary) will meet the service area needs until sometime between the years 2014 and 2025 under the existing Phase II operation policy and until between 2024 and 2039 under Phase IV operation policy. Phase II operation policy is the City of Corpus Christi's present system operation policy. Under this policy, the level of Lake Corpus Christi is generally stabilized at elevation 88 feet msl. Under the City's Phase IV operation policy, the level of Lake Corpus Christi is not stabilized until the lake level drops to elevation 76 feet msl. The bottom graph on Figure 13.0-1 shows that if an absolute requirement for 151,000 ac-ft per year of estuary inflows is met, without suspending releases during drought conditions, then the yield of the system is presently not adequate to meet

Table 13.0-1 Projected M&I Demands for CC/LCC System				
Year	Total 12-County M&I Demand Ac-Ft/Yr	Demand Met From Other Sources Ac-Ft/Yr	Demand on CC/LCC System Ac-Ft/Yr	Percent of 12-County M&I Demand on CC/LCC System
I. Best Case Scenario				
Low Growth				
1990	162,446	34,000	128,446	79
2000	174,082	34,000	140,082	80
2010	181,458	34,000	147,458	81
2020	196,355	34,000	162,355	83
2030	219,705	34,000	185,705	85
2040	234,710	34,000	200,710	86
High Growth				
1990	164,194	34,000	130,194	79
2000	183,459	34,000	149,459	81
2010	199,092	34,000	165,092	83
2020	226,110	34,000	192,110	85
2030	259,817	34,000	225,817	87
2040	282,794	34,000	248,794	88
II. Probable Case Scenario				
Low Growth				
1990	162,446	31,500	130,946	81
2000	174,082	26,500	147,582	85
2010	181,458	21,500	159,958	88
2020	196,355	17,000	179,355	91
2030	219,705	17,000	202,705	92
2040	234,710	17,000	217,710	93
High Growth				
1990	164,194	31,500	132,694	81
2000	183,459	26,500	156,959	86
2010	199,092	21,500	177,592	89
2020	226,110	17,000	209,110	92
2030	259,817	17,000	242,817	93
2040	282,794	17,000	265,794	94

demands under Phase II operation policy. The firm yield under Phase IV operation policy will meet the service area needs until sometime between 2008 and 2016. Under the best case demand scenario, between 3,200 and 141,700 ac-ft per year of additional water will be needed by the year 2040, depending on the growth rate, system operation policy, and the



CC/LCC SYSTEM DEMANDS AND FIRM YIELD WITHOUT FULL RELEASE FOR ESTUARY**



CC/LCC SYSTEM DEMANDS AND FIRM YIELD WITH FULL RELEASE FOR ESTUARY***

*M&I Demands are for best case conditions which assume that 34,000 ac-ft per year of M&I demand for the 12-county area will be met from sources other than the CC/LCC System. Historical use from July 1984 through February 1985 (and for a period of time thereafter) was limited by severe drought conservation measures.

**Assumes that only spills and wastewater return flows contribute to estuary inflows. No releases are made to the estuary.

***Assumes that releases are made as needed to provide 151,000 ac-ft per year to the estuary after crediting spills and wastewater return flows. No drought contingency relief provision is included for estuary releases.

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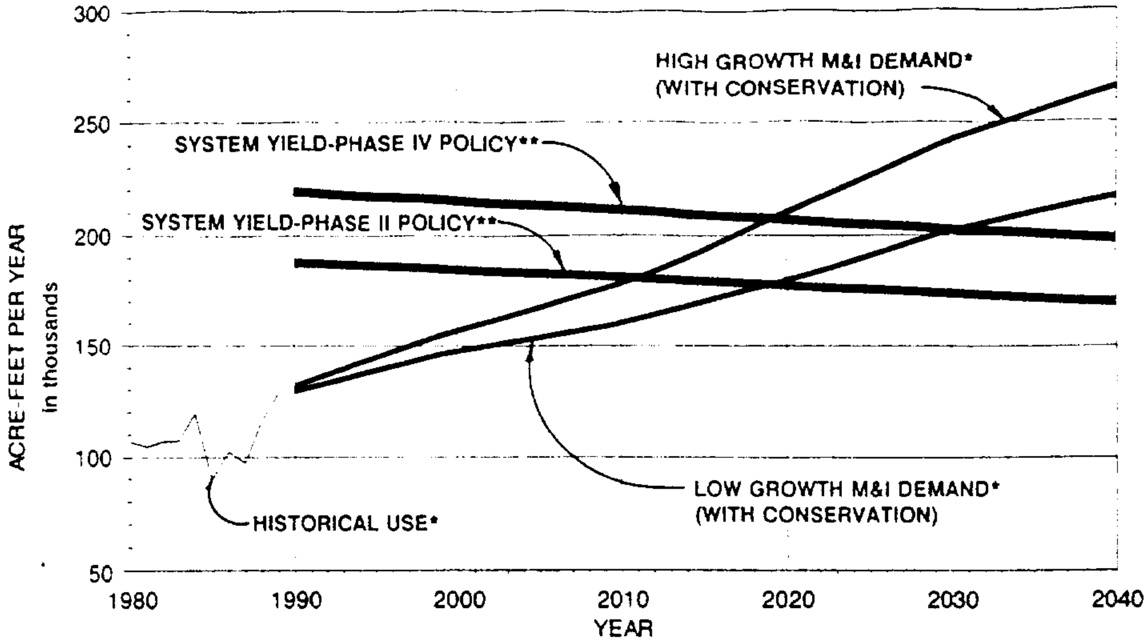
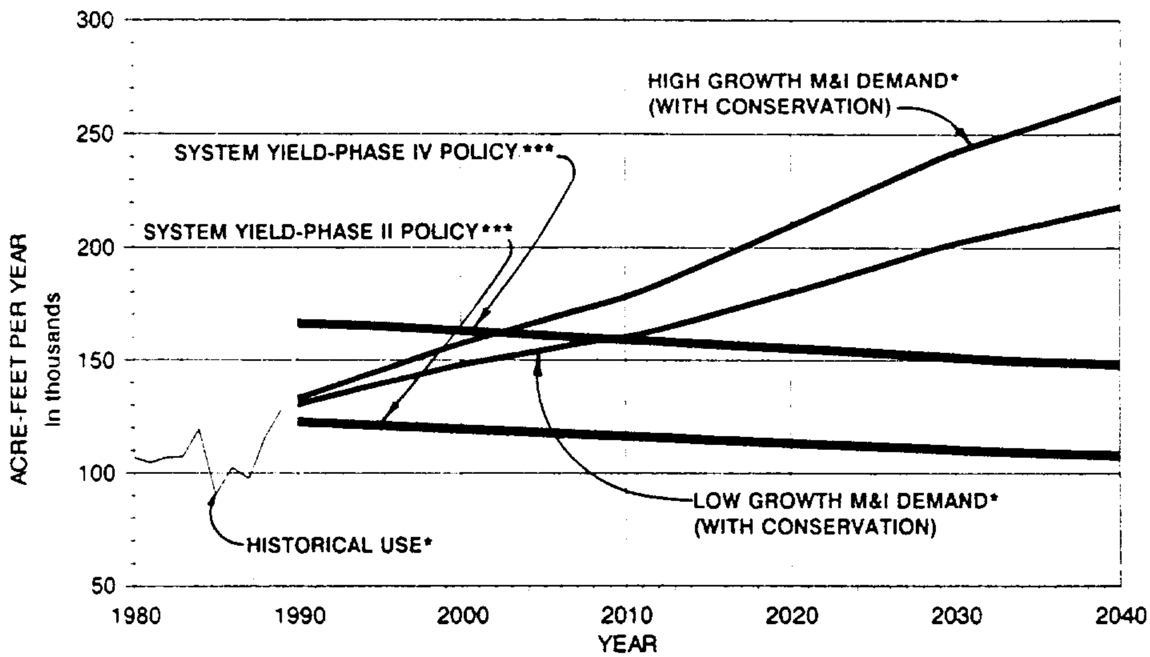
NUECES RIVER BASIN STUDY

COMPARISONS OF BEST CASE CC/LCC SYSTEM DEMANDS WITH SYSTEM FIRM YIELD

FIGURE 13.0-1



CC/LCC SYSTEM DEMANDS AND FIRM YIELD WITHOUT FULL RELEASE FOR ESTUARY**



CC/LCC SYSTEM DEMANDS AND FIRM YIELD WITH FULL RELEASE FOR ESTUARY***

*M&I Demands are for probable case conditions which assume that by the year 2020, 17,000 ac-ft per year of M&I demand for the 12-county area will be met from sources other than the CC/LCC System. Historical use from July 1984 through February 1985 (and for a period of time thereafter) was limited by severe drought conservation measures.

**Assumes that only spills and wastewater return flows contribute to estuary inflows. No releases are made to the estuary.

***Assumes that releases are made as needed to provide 151,000 ac-ft per year to the estuary after crediting spills and wastewater return flows. No drought contingency relief provision is included for estuary releases.

NUECES RIVER BASIN STUDY

COMPARISONS OF PROBABLE CASE CC/LCC SYSTEM DEMANDS WITH SYSTEM FIRM YIELD

HDR Engineering, Inc.

FIGURE 13.0-2

final impact of permanent operating rules for estuary releases on system yield.

The upper graph on Figure 13.0-2 shows that for the probable case demand scenario, the yield of the system (without considering releases to the estuary) will meet the service area needs until sometime between the years 2010 and 2018 under Phase II operation policy and until between 2020 and 2030 under Phase IV operation policy. The bottom graph on Figure 13.0-2 shows that if an absolute requirement for 151,000 ac-ft per year of estuary inflows is met, then the yield of the system is presently not adequate to meet demands under Phase II operation policy. The firm yield under Phase IV operation policy will meet the service area needs until sometime between 2002 and 2009. Under the probable case scenario, between 20,200 and 158,700 ac-ft per year of additional water will be needed by the year 2040, depending on the growth rate, system operation policy, and final impact of permanent operating rules for estuary releases on system yield.

In order to meet the projected water demands of the CC/LCC service area, additional water supplies will be needed. The timing of the development of the additional supplies will vary depending on growth rates, the number of new customers, the final TWC estuary release requirements, system operation policy, and whether or not additional recharge structures are constructed. Additional water supply alternatives available to the 12-county service area include the following:

* Construction of a pipeline from Choke Canyon Reservoir to either Lake Corpus Christi or the O.N. Stevens Water Treatment Plant at Calallen to avoid natural channel losses which are significant under existing operating conditions;

* Construction of a pipeline from Lake Corpus Christi to the O.N. Stevens Water Treatment Plant to avoid natural channel losses (this pipeline could also serve as a portion of the pipeline to Choke Canyon);

* Construction of a diversion dam, pump station, and pipeline from a point on the Nueces River (either near Simmons or below Three Rivers) to pump flows into Choke Canyon Reservoir at those times when Lake Corpus Christi is above a specified level and Choke Canyon is below conservation level;

* Construction of a pump station and pipeline from near Lake Texana to either a new treatment plant located in the eastern portion of the service area or to the O.N. Stevens Water Treatment Plant; or

* Construction of a diversion dam, pump station, off-channel balancing reservoir, and pipeline from the Guadalupe River (and/or San Antonio River) to either a new treatment plant located in the eastern portion of the service area or to the O.N. Stevens Water Treatment Plant. (This project could serve as the first phase of the pipeline to Lake Texana.)

14.0 CONCLUSIONS

Significant study findings and conclusions are as follows:

* Historical recharge to the Nueces River Basin portion of the Edwards Aquifer can be increased by an average of about 85,300 ac-ft per year if all seven Type 1 recharge structures are constructed and all water rights are honored. This represents an increase of about 26.3 percent in the historical average recharge to the Nueces River Basin portion of the Edwards Aquifer from surface water sources. Recharge during the 10-year drought period from 1947 through 1956 could be increased by about 19,100 ac-ft per year or 12.3 percent of the historical average during this 10-year period.

* Recharge with all twelve Type 2 recharge structures in place can be increased on the average by about 61,100 ac-ft per year or 18.9 percent if all water rights are honored. For the 1947-1956 drought period, recharge could be increased by about 24,100 ac-ft per year or 15.5 percent.

* The recharge estimates in this report represent a theoretical maximum and are subject to significant reductions due to likely economic, environmental, structural, and political limitations on more detailed review.

* With no additional recharge structures in place, the firm yield of the CC/LCC System under Phase IV operating policy is 220,000 ac-ft per year for 1990 conditions and 197,500 ac-ft per year for 2040 conditions. These yields are based on existing water rights diverting at full authorization and do not consider the full release of 151,000 ac-ft per year to the Nueces Estuary. If system releases needed to insure 151,000 ac-ft of annual estuarine inflows are made, without abeyance provisions for drought conditions, then the 1990 firm yield is 166,300 ac-ft per year and the 2040 firm yield is 147,300 ac-ft per year.

* With no additional recharge structures in place, the firm yield of the CC/LCC System under Phase II operating policy is 187,800 ac-ft per year for 1990 conditions and 169,700 ac-ft per year for 2040 conditions. These yields are based on existing water rights diverting at full authorization and do not consider the full release of 151,000 ac-ft per year to the Nueces Estuary. If system releases needed to insure 151,000 ac-ft of annual estuarine inflows are made, without abeyance provisions for drought conditions, then the 1990 firm yield is 122,400 ac-ft per year and the 2040 firm yield is 107,100 ac-ft per year.

* The 1990 firm yield of the CC/LCC System would be reduced by up to 3,900 ac-ft per year with the implementation of all seven Type 1 recharge structures, if these structures were operated without honoring the water rights of the CC/LCC System.

* The 1990 firm yield of the CC/LCC System would be reduced by up to 5,800 ac-ft per year with the implementation of all twelve Type 2 structures, if these structures were operated without honoring the water rights of the CC/LCC System.

* The firm yield of the CC/LCC System is not adequate to meet the system demands over the next 50 years.

* The City of Corpus Christi will need to develop an additional water supply to supplement the yield of the CC/LCC System within the next several decades depending on growth rates, the number of new customers, reservoir operation policy, construction of additional recharge projects, and the impact of the final TWC operating rules with respect to releases to the Nueces Estuary.

* If fully implemented, the Type 1 recharge structures will reduce inflows to the Nueces Estuary by an average of about 15,800 ac-ft per year. The construction of all Type 2 recharge structures will reduce inflows by about 15,200 ac-ft per year. These figures represent between 5.3 percent and 5.5 percent of the average annual spill volume at Lake Corpus without recharge projects. The average number of spill events will be reduced by about 4 percent with either type of recharge structures.

* If all seven Type 1 recharge structures are implemented, average inflows to the CC/LCC System will be reduced by 37,800 ac-ft per year or 5.0 percent. Average reservoir water levels at Choke Canyon Reservoir would be reduced by 0.52 feet and at Lake Corpus Christi by 0.06 feet.

* If all twelve Type 2 recharge structures are implemented, average inflows to the CC/LCC system will be reduced by 40,700 ac-ft per year or 5.4 percent. Average reservoir water levels at Choke Canyon Reservoir would be reduced by 0.41 feet and at Lake Corpus Christi by 0.03 feet.

* Methods used by the USGS to develop annual estimates of recharge to the Edwards Aquifer significantly over-estimate recharge in wet years.

15.0 RECOMMENDATIONS

15.1 Further Evaluation of Recharge Projects

The findings of this study indicate that recharge to the Edwards Aquifer can be substantially enhanced by the construction of additional recharge structures. In order to determine whether these projects are truly feasible and to quantify potential benefits to well yields and springflows, the following additional studies are recommended:

1) Benefit/cost analyses of individual recharge projects should be performed considering costs and potential environmental impacts;

2) The Texas Water Development Board model of the Edwards Aquifer should be updated to operate on a monthly (rather than annual) time step. The model should then be used to evaluate the various recharge options to determine benefits to well yields and springflows;

3) Depending on favorable results from Items and 1 and 2, the TWDB model and the recharge portion of the model developed in this study should be combined into one model to further evaluate whether additional benefits could be obtained by adopting a delayed release policy for the Type 1 reservoirs. Under this type of policy, reservoir releases could be tied to aquifer levels and contribute recharge during drought periods when it is needed the most; and

4) Depending on results from Items 1, 2 and 3, detailed hydrologic, geologic, structural, environmental and costs analyses should be performed for each watershed above the recharge zone considering various combinations of recharge reservoir locations and capacities.

15.2 Other Recommendations

Other recommendations based on the findings and conclusions of this study are as follows:

1) The interim TWC order should be evaluated to determine impacts on firm yield of CC/LCC System and inflows to the Nueces Estuary;

2) A water supply alternatives study should be undertaken by the City of Corpus Christi to determine the most feasible and economical alternatives to meet the long-term needs of the CC/LCC service area;

3) Water delivery loss studies between Choke Canyon Reservoir, Lake Corpus Christi, and Calallen Dam should be undertaken to determine the volume of water lost at various delivery rates;

4) A new recharge model of the Edwards Aquifer should be developed which combines appropriate elements of the USGS and HDR recharge procedures;

5) Within the next 10 years, a re-evaluation of potential long-term trends in runoff characteristics within the Nueces River Basin should be performed; and

6) Additional streamflow gaging stations should be installed at the following locations:

   * Upstream of Parker Recharge Reservoir with daily reservoir outflows calculated using existing water level recorder;

   * Upstream of Verde Recharge Reservoir with daily reservoir outflows calculated using existing water level recorder;

   * At the upstream and downstream limits of the recharge zone on Verde Creek;

   * At the downstream limit of the recharge zone on Elm Creek and Blanco Creeks; and

   * USGS Calallen gage should be changed from a partial record gage to a full-time daily flow gage.

7) Additional daily precipitation stations should be established on a long-term basis within the following basins:

   * Within the Parker Creek, Verde Creek, Elm Creek and Blanco Creek watersheds; and

   * Within the watersheds of the Tilden and Cotulla gages.

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