TEXAS BOARD OF WATER ENGINEERS

BULLETIN 6201

RECHARGE, DISCHARGE, AND CHANGES IN GROUND-WATER STORAGE IN THE EDWARDS AND ASSOCIATED LIMESTONES SAN ANTONIO AREA, TEXAS A PROGRESS REPORT ON STUDIES, 1955-59

Prepared in cooperation with the Geological Survey
United States Department of the Interior
and the
San Antonio City Water Board
Edwards Underground Water District
San Antonio City Public Service Board
Bexar Metropolitan Water District

January 1962

TEXAS BOARD OF WATER ENGINEERS

BULLETIN 6201

RECHARGE, DISCHARGE, AND CHANGES IN GROUND-WATER STORAGE IN THE EDWARDS AND ASSOCIATED LIMESTONES, SAN ANTONIO AREA, TEXAS

A PROGRESS REPORT ON STUDIES, 1955-59

By

Sergio Garza, Hydraulic Engineer
United States Geological Survey

Prepared in cooperation with the Geological Survey
United States Department of the Interior
and the
San Antonio City Water Board
Edwards Underground Water District
San Antonio City Public Service Board
Bexar Metropolitan Water District

January 1962

ADDENDUM: ACKNOWLEDGEMENT OF SPECIFIC COOPERATORS

It is pointed out to the reader that cooperators participating in this report along with the Texas Board of Water Engineers and the U. S. Geological Survey include:

San Antonio City Water Board

Edwards Underground Water District

San Antonio City Public Service Board

Bexar Metropolitan Water District

Due to an unfortunate oversight, the Cooperator acknowledgements appearing on illustrations and elsewhere herein mention the city of San Antonio, but do not indicate the participation of the specific above-listed cooperators.

TABLE OF CONTENTS

TABLE OF CONTENTS (Cont'd.)

TABLES

ILLUSTRATIONS

Figures

TABLE OF CONTENTS (Cont'd.)

Page

TABLE OF CONTENTS (Cont'd.)

Plates

RECHARGE, DISCHARGE, AND CHANGES IN GROUND-WATER STORAGE IN THE EDWARDS AND ASSOCIATED LIMESTONES, SAN ANTONIO AREA, TEXAS

A PROGRESS REPORT ON STUDIES, 1955-59

ABSTRACT

The San Antonio area, as the term is used in this report, includes parts of Kinney, Uvalde, Medina, Bexar, Comal, and Hays Counties, Texas. It lies within two physiographic provinces, the Edwards Plateau on the north and northwest and the Gulf Coastal Plain on the south and southeast, the two provinces being separated by the Balcones fault zone. The principal aquifer in the area is the Edwards and associated limestones, whose hydraulic boundaries coincide with the boundaries of the San Antonio area.

Springflow from the water-table part of the aquifer in the Edwards Plateau forms the base flow of the southward-flowing streams which drain the plateau; most of the base flow and a part of the flood flow is lost at the fault zone on the outcrop of the Edwards and associated limestones. Recharge to the aquifer in the fault zone is chiefly by seepage from the streams that cross the outcrop of the Edwards and associated limestones, but partly by direct infiltration of precipitation on the outcrop. During the period 1934-59, the average annual recharge was estimated to be 500,000 acre-feet.

Since 1934 most of the discharge from the Edwards and associated limestones has been from springs except during the period 1954-57, when the discharge from wells exceeded the discharge from springs. In 1959, the discharge from springs was about 387,000 acre-feet, 90 percent of which was in Comal and Hays Counties; discharge from wells totaled about 234,200 acre-feet, about 82 percent of which was in Bexar County. The average annual discharge from both wells and springs for the period 1934-59 was about 507,000 acre-feet.

Water levels in wells in the Edwards and associated limestones were the lowest of record in 1956 and early 1957. As a result of the heavy rains in 1957 and 1958, water levels rose nearly to the levels of 1947, when the drought began.

The movement of water in a large part of the Edwards and associated limestones is characteristically nonuniform and generally unsteady during most of the year. In general, nearly steady flow occurs only during the winter, when recharge and discharge are at a minimum. Changes in storage are determined more accurately by comparing periods of nearly steady flow.

The estimated accretion of ground water to the aquifer during 1957-58 was nearly 2 million acre-feet, whereas the decrease in ground-water storage during the drought period 1947-57 was slightly more than 2 million acre-feet.

The water from the Edwards and associated limestones, although hard, is almost uniformly a calcium bicarbonate water of good quality. In the southern part of the San Antonio area, the water contains hydrogen sulfide gas; still farther south, the water becomes saline. The mineralization of water from some wells in the transitional zone between water of good quality and water of poor quality decreases as the artesian pressure increases.

Where water circulates freely in the Edwards and associated limestones, temperature and mineralization show little change in relation to depth; where circulation is restricted, however, both temperature and mineralization increase with depth.

RECHARGE, DISCHARGE, AND CHANGES IN GROUND-WATER STORAGE IN THE EDWARDS AND ASSOCIATED LIMESTONES, SAN ANTONIO AREA, TEXAS

A PROGRESS REPORT ON STUDIES, 1955-59

INTRODUCTION

Location and Extent of Area

The term "San Antonio area" is used in this report to include parts of Kinney, Uvalde, Medina, Bexar, Comal, and Hays Counties, Texas, within and adjacent to the Balcones fault zone. (See Figure 1.) The area forms a strip about 180 miles long and about 5 to 40 miles wide. The main ground-water reservoir (aquifer) in the area is the Edwards and associated limestones, whose hydraulic boundaries coincide with the boundaries of the San Antonio area. The aquifer supplies water to the city of San Antonio, center of activity in the area, and to the irrigation, military, and industrial establishments of practically all the area. It also sustains the flow of several large springs, including Comal Springs one of the largest in the southwestern part of the United States.

Purpose and Scope

Geologic and hydrologic investigations of the Edwards and associated limestones in the San Antonio area have been carried on for many years by the U. S. Geological Survey in cooperation with the Texas Board of Water Engineers and the city of San Antonio. Most of the general geology of the area has been described, and the currently continuing quantitative studies are chiefly hydrologic. This report is one of several progress reports which have been prepared periodically to summarize the results of the investigations. Its chief purpose is to supplement and bring up-to-date through 1959 the data published in previous reports. It gives estimates of recharge to and discharge from the aquifer, records of precipitation and streamflow, and water-level data. The relation of aquifer head to the movement of water is discussed, and the balances between recharge and discharge as related to aquifer head are used to make estimates of the changes in storage in the aquifer. The report also brings up-to-date the results of studies of the quality of water in the zone of transition between water of good quality and water of poor quality in the Edwards and associated limestones.

This report was prepared under the administrative direction of P. E. LaMoreaux, chief of the Ground Water Branch of the Geological Survey, and under the immediate supervision of R. W. Sundstrom, district engineer in charge of ground-water investigations in Texas.

Previous Work and Acknowledgments

Previous geologic and hydrologic investigations in the San Antonio area have been made as either countywide or areal studies. Most of the results of these studies have been published either by the Texas Board of Water Engineers or by the U. S. Geological Survey. (See References.)

Appreciation is expressed to the many persons who contributed information which aided in the preparation of this report. Special thanks are due Mr. R. A. Thompson, Manager of the City Water Board of San Antonio, and Mr. Ben M. Petitt, Jr., also of the City Water Board, who made helpful suggestions concerning the project. The author is grateful to the drillers, farmers, ranchers, and representatives of industrial concerns who gave freely of their time and information.

Topography and Drainage

The San Antonio area of this report lies within two physiographic provinces, the Edwards Plateau on the north and northwest and the Gulf Coastal Plain on the south and southeast, the two provinces being separated by the Balcones fault zone. The topography of the San Antonio area is related to the composition of the rocks and the geologic structure associated with the physiographic provinces. The Edwards Plateau has been cut by streams into a steep and rugged terrain, underlain chiefly by limestone beds which dip very gently toward the southeast. The gently rolling Gulf Coastal Plain is underlain by beds of clay, marl, limestone, and sand dipping gently toward the southeast though at greater rates than the beds underlying the plateau.

Most of the San Antonio area is drained by southeastward-flowing streams of the Nueces and Guadalupe River basins (Figure 1). Springflow from the Edwards and associated limestones in the Edwards Plateau forms the base flow of the streams. In turn, most of this base flow and a part of the flood flow infiltrates into the Balcones fault zone on the outcrop of the Edwards and associated limestones. South of the outcrop of the Edwards and associated limestones, most of the streams are dry or flow intermittently. The Guadalupe River, however, which contributes little or no water to the Edwards, is a perennial stream.

Climate

A warm, temperate, and generally subhumid climate prevails in the San Antonio area. Temperatures during the winter generally are well above freezing; maximum summer temperatures usually are above 90°F but rarely above 100°F. The last killing frosts in the spring are usually in late February or early March, and the first killing frosts in the fall are generally in November. The growing season is long, ranging from 248 days in Uvalde County to 279 days in Bexar County.

The average annual precipitation in the San Antonio area increases generally from west to east (Table 1). Precipitation may vary considerably from year to year, but the distribution within a year generally is fairly uniform. During the

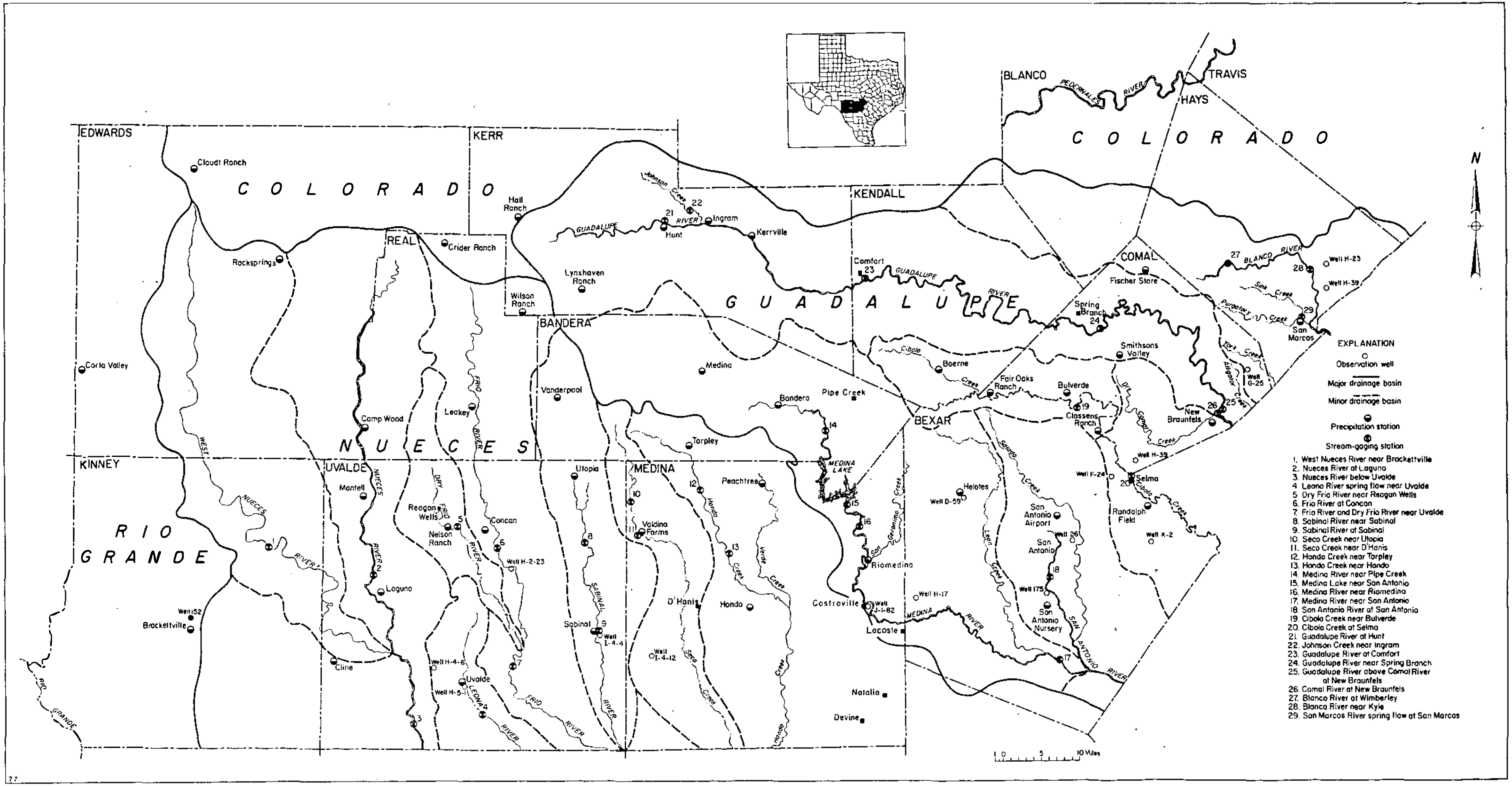


FIGURE 1.-Map of San Antonio and adjacent areas showing observation wells, drainage basins, precipitation stations, and stream-gaging stations

Table 1.--Average annual precipitation at selected stations in the San Antonio area

Station	Length of record (years)	Annual average* (inches)
San Marcos	62	33.19
New Braunfels	69	31.11
Fischer's Store	67	29.40
Boerne	68	32.35
San Antonio	86	27.61
Riomedina	37	26.38
Hondo	59	28.54
Sabinal	44	25.61
Uvalde	61	24.26
Brackettville	73	20.61

*Average of complete years only.

wet years of 1957 and 1958, the heaviest rainfall was in April, May, June, September, and October. Occasionally rainfall during the winter is widespread, but most of the rain falls as isolated thundershowers.

The monthly precipitation at selected stations of the U. S. Weather Bureau in the San Antonio area is shown in Figure 2. The location of these and other stations is shown in Figure 1. The heavy rains of 1957 and 1958 apparently broke the drought that had prevailed during the previous several years. Precipitation during 1959 generally was above average.

GENERAL GEOLOGY

The geology of the San Antonio area has been described in considerable detail in reports on the individual counties in the area (see References) and has been summarized in a report by Petitt and George (1956). The description of the geology in this report is therefore limited to a brief discussion of the geologic units forming the major and minor aquifers and their general hydrologic properties.

The geologic units, in order of their importance as aquifers, are the Edwards and associated limestones, the Glen Rose limestone, the Leona formation, the Travis Peak formation, the Austin chalk, rocks of the Taylor and Navarro groups, the Carrizo sand, and undifferentiated sands of the Wilcox group.

The Edwards and associated limestones, which consists of the Georgetown, Edwards, and Comanche Peak limestones of Cretaceous age, forms the main groundwater reservoir in the San Antonio area. It underlies or forms the surface of the Edwards Plateau north and northwest of San Antonio. In fresh exposures, most of the Edwards is a dense, hard limestone, but, on weathering, the rock is extensively honeycombed and cavernous. Thus, where the Edwards and associated limestones is exposed, conditions are favorable for direct infiltration of rainwater. The exact thickness of the Edwards and associated limestones at all places is not known, but it probably averages at least 500 feet. Wells that penetrate fractures or cavernous zones obtain large yields, but other wells may yield little or no water.

The Glen Rose limestone of Early Cretaceous age crops out north of the Balcones fault zone, where the overlying Edwards and associated limestones has been removed by erosion. In general, the Glen Rose yields small to moderate amounts of water of fair to poor quality for domestic and stock use. In the Camp Stanley area in northern Bexar County, some wells tapping the Glen Rose were acidized in the summer of 1958. The yields of the wells increased, but whether the increase resulted from recharge due to the heavy rains in September 1958 or from the acidization of the wells is not known definitely. The acidizing probably did increase the yield of the wells inasmuch as the yields were not increased in 1957 or early 1958 when rainfall was above normal.

The Leona formation of Pleistocene age consists of alluvium and terrace deposits in the valleys of the major streams of the San Antonio area. The Leona formation is important as an aquifer only in the Leona River valley southeast of the city of Uvalde, where some wells yield enough water for irrigation. In this area the Edwards and associated limestones and the gravels of the Leona formation are hydraulically connected, and production from the Leona is limited by the recharge the Leona recieves from the underlying Edwards and associated limestones.

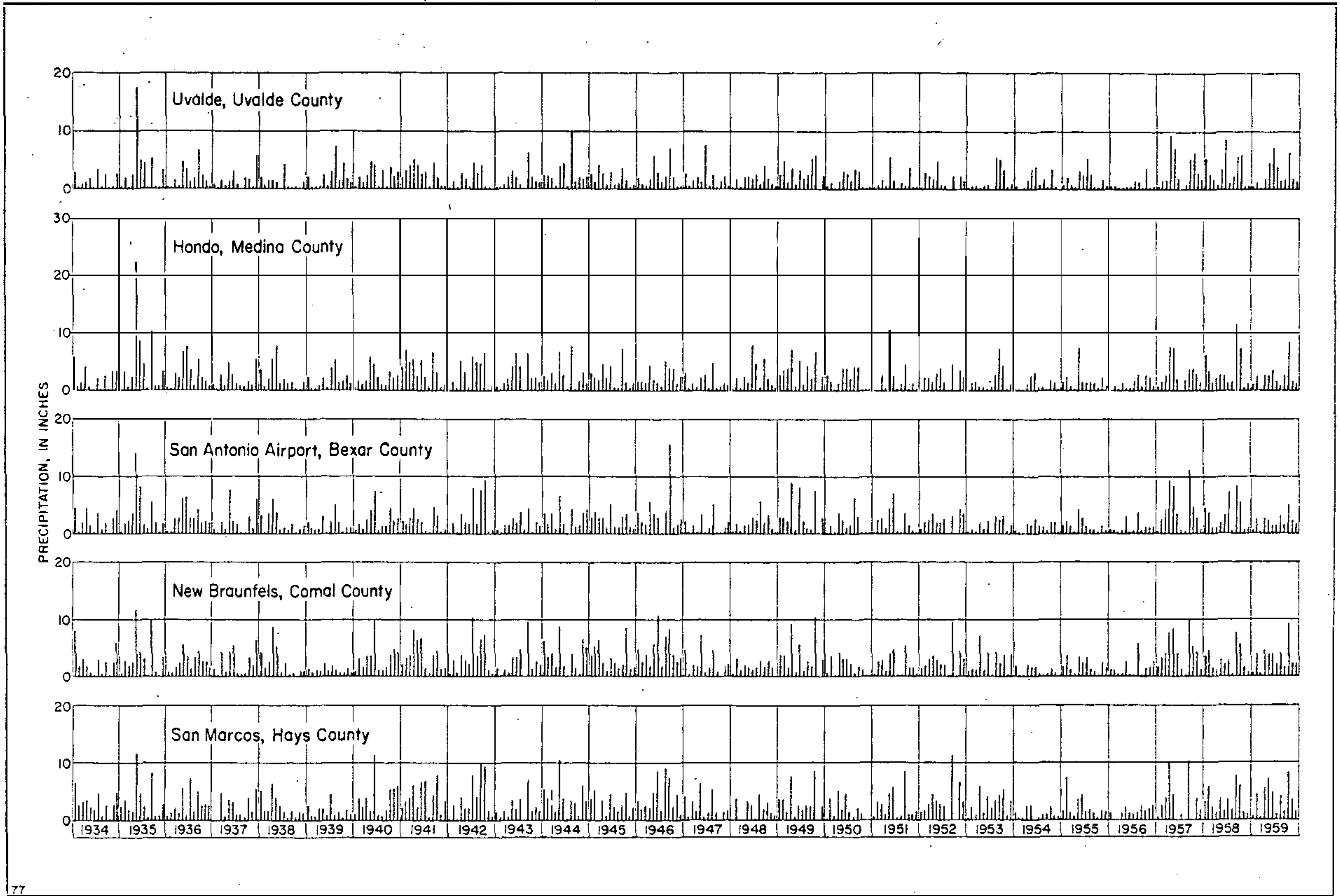


FIGURE 2.- Precipitation at selected stations in the San Antonio area
(From records of U.S. Weather Bureau)

The yields of wells that draw from the other formations generally are small, and the quality of the water from some of the formations is unsatisfactory in most of the San Antonio area. In Comal and Kendall Counties, the Cow Creek limestone member of the Travis Peak formation of Early Cretaceous age yields moderate quantities of water to wells; in the Cibolo Creek drainage area the Cow Creek may transmit a significant volume of water to the Edwards and associated limestones by underflow. In general, the Austin chalk of Late Cretaceous age yields only small quantities of water to wells, and in most places the water contains hydrogen sulfide gas in objectionable quantities. Near Uvalde and other localized areas, the Austin chalk yields moderate quantities of water similar in chemical quality to the water in the Edwards and associated limestones, suggesting a hydraulic connection between the formations. The Anacacho limestone of Taylor age and the Escondido formation of the Navarro group yield small quantities of water for domestic and stock uses west of Bexar County.

The Carrizo sand of Eocene age supplies water to the city of Devine in Medina County and to a few irrigation wells in the extreme southern part of Bexar County. The undifferentiated sands of the Wilcox group have not been fully tested, but in wells used for domestic supply the water is generally of fair to poor quality.

HYDROLOGY

The principal aquifer in the San Antonio area is the Edwards and associated limestones; it supplies most of the water for municipal, industrial, irrigation, and domestic purposes.

Under natural conditions and over a long period, recharge to the Edwards and associated limestones must balance the discharge. During short periods, however, when the recharge-discharge relationship is not in balance, the storage in the reservoir increases or decreases, and determinations of the changes in storage are based on the amount of recharge to and discharge from the aquifer. Recharge to the Edwards and associated limestones is estimated from streamflow and rainfall records; discharge from the aquifer through springs and wells is inventoried. Changes in storage are correlated with the artesian head in the aquifer, as obtained from recording gages in representative wells, and a curve is obtained which shows the changes in storage for each foot of change in artesian head through the range of observed fluctuations.

Because of the wide variation in the rate of movement of the water in the Edwards and associated limestones, a method has been devised for the determination of change-in-storage curves for three of the four segments of the aquifer. The flow of ground water in the Edwards and associated limestones is nonuniform--that is, the rate of movement changes from place to place--and generally is unsteady--that is, the rate of movement changes from time to time at a particular place. When both pumpage and recharge are small, the flow is nearly steady, but because changes in storage are constantly occurring, as shown by the continually fluctuating water levels in wells, true steady flow is never attained. However, the periods of nearly steady flow as used in this report, are relatively free from the effects of rapid changes in the rate of recharge and discharge that produce unsteady flow; consequently, the changes in storage and artesian head can be related during these periods almost as well as if the flow were steady.

Hydrologic observations in the Edwards and associated limestones in the San Antonio area have been made intermittently since 1929. The records cover a wide range of climate; the data in this report were obtained during part of a severe drought and also during part of an extremely wet period.

Recharge

A large part of the recharge to the Edwards and associated limestones in the San Antonio area is derived by seepage from streams that cross the outcrop of the aquifer in the Balcones fault zone. Petitt and George (1956, page 22) determined the recharge to the Edwards and associated limestones in the San Antonio area from seepage studies made at different stages of the streams and from discharge measurements made at established gaging stations on the major streams (Figure 1). The monthly mean discharge at the gaging stations during the period 1958-59 is shown in Table 2; records for the period 1934-57 have been published by the Texas Board of Water Engineers (1958), and those for 1957-58 have been published by the U. S. Geological Survey (1960).

The estimates of recharge to the Edwards and associated limestones for the period 1934-53 by Petitt and George (1956, pages 21-41) have now been revised slightly and extended to January 1960 (Table 3). The revisions were considered advisable for two reasons: (1) the inadvertent omission, in the early estimates, of 314 square miles of drainage area that furnishes recharge to the reservoir, and (2) refinements made possible by records from several new gaging stations since 1955.

The additional area consists of the following:

(1) Forty-eight square miles of the Blanco River basin and 46 square miles of the upper Leona River basin which have been included with the Frio-Dry Frio recharge basin. Recharge to the aquifer from these areas was prorated on the basis of flood-flow records for the Frio-Dry Frio River basin.

(2) Thirty-three square miles in the Little Blanco Creek and Nolton Creek area and 23 square miles in the Ranchero Creek area, both of which are included with the Sabinal River basin.

(3) Eighty-five square miles of drainage area in the area of recharge between the Sabinal River and Medina River basins.

(4) Seventy-nine square miles in the area of recharge between the Medina River and Cibolo Creek drainage basins.

The establishment of several new gaging stations since 1955 has permitted a refinement of the recharge estimates in some of the basins. The West Nueces River gage at Brackettville, which was re-established in 1956, accounts for all flow contributed by the West Nueces River to the recharge area in the Nueces River basin. Previously, flow from the West Nueces had been prorated according to flood flow past the Nueces River gage at Laguna.

A gage on the Blanco River near Kyle, below the outcrop of the Edwards and associated limestones, was established in June 1956. Recharge in the Blanco River basin is the difference between inflow above the outcrop of the Edwards and associated limestones and outflow at the gage near Kyle. The inflow includes the discharge at the gage near Wimberley and the prorated runoff on the area between the gages based on the unit runoff at the gage near Wimberley. The outflow is the discharge at the gage near Kyle.

Table 2.--Monthly mean discharge, in cubic feet per second, at stream-gaging stations in the San Antonio area, October 1958-December 1959

Station	1958 Oct.	1958 Nov.	1958 Dec.	1959 Jan.	1959 Feb.	1959 Mar.	1959 Apr.	1959 May	1959 June	1959 July	1959 Aug.	1959 Sept.	1959 Oct.	1959 Nov.	1959 Dec.
West Nueces River near Brackettville	88	76	9	0	0	0	0	30	253	182	31	5	38	0	0
Nueces River at Laguna	502	422	255	169	147	125	105	129	434	387	196	203	461	167	139
Nueces River below Uvalde	406	380	196	120	78	56	41	58	615	378	153	318	833	170	115
Leona River springflow near Uvalde	0	0	0	0	2	4	6	8	11	15	18	16	26	29	33
Dry Frio River near Reagan Wells	166	127	52	34	26	19	20	33	76	57	25	58	166	37	28
Frio River at Concan	403	391	197	133	102	84	84	87	387	238	125	98	253	133	106
Frio River below Dry Frio River near Uvalde	89	81	0	0	0	0	0	0	305	3	0	1	112	0	0
Sabinal River near Sabinal	299	321	130	74	50	35	45	33	220	150	62	36	123	82	65
Sabinal River at Sabinal	191	219	62	18	5	3	2	0	197	64	5	2	52	10	4
Seco Creek near Utopia	89	77	25	11	6	5	23	10	15	19	7	3	26	16	12
Seco Creek near D'Hanis	82	59	10	0	0	0	5	0	4	0	0	0	8	0	0
Hondo Creek near Tarpley	140	134	46	23	15	10	51	28	39	33	12	6	66	34	22
Hondo Creek near Hondo	89	87	15	2	0	0	19	0	11	0	0	0	48	0	0
Medina River near Pipe Creek	503	478	220	143	115	86	162	113	214	127	53	37	359	110	94
Medina River near Riomedina	523	582	120	50	65	33	23	23	95	71	22	23	35	27	43
Medina River near San Antonio	734	759	248	142	170	103	112	94	119	129	62	54	247	81	88
San Antonio River at San Antonio	57	90	79	68	73	62	60	55	22	17	17	16	62	40	50
Cibolo Creek near Bulverde	40	38	0	0	0	0	0	0	35	0	0	0	0	0	0
Cibolo Creek at Selma	15	18	0	0	0	0	0	0	2	0	0	0	0	0	0
Johnson Creek near Ingram	35	30	28	22	19	16	24	21	33	16	14	10	300	20	*
Guadalupe River at Comfort	181	243	200	165	147	110	190	132	403	149	76	56	1,090	124	115
Guadalupe River near Spring Branch	377	486	303	231	229	177	308	220	619	247	120	84	1,397	206	214
Guadalupe River above Comal River at New Braunfels	608	741	454	367	384	346	422	308	663	335	181	121	1,496	328	326
Comal River at New Braunfels	332	335	338	335	339	335	340	324	300	301	290	287	324	310	316
Blanco River at Wimberley	160	238	111	82	122	107	219	120	115	61	60	43	376	77	99
Blanco River near Kyle	167	262	116	77	111	97	204	120	96	50	50	33	347	76	93
San Marcos River springflow at San Marcos	181	217	202	176	175	163	167	176	162	154	142	135	163	160	151

*Discontinued Nov. 1959

Table 3.--Estimated recharge, in thousands of acre-feet, to the Edwards and associated limestones in the San Antonio area

Year	Nueces and W. Nueces River basins	Frio and Dry Frio River basins	Sabinal River basin	Medina River basin	Cibolo and Dry Comal Creek basins	Guadalupe River basin	Blanco River basin and adjacent area	Area between Sabinal and Medina River basins	Area between Cibolo Creek and Medina River basins	Total
1934	8.6	27.9	7.5	46.5	28.4	0.0	19.8	19.9	21.0	179.6
1935	411.3	192.3	56.6	71.1	182.7	.0	39.8	166.2	138.2	1,258.0
1936	176.5	157.4	43.5	91.6	146.1	.0	42.7	142.9	108.9	909.6
1937	28.8	75.7	21.5	80.5	63.9	.0	21.2	61.3	47.8	400.7
1938	63.5	69.3	20.9	65.5	76.8	.0	36.4	54.1	46.2	432.7
1939	227.0	49.5	17.0	42.4	9.6	.0	1.1	33.1	9.3	399.0
1940	50.4	60.3	23.8	38.8	30.8	.0	18.8	56.6	29.3	308.8
1941	89.9	151.8	50.6	54.1	191.2	.0	57.8	139.0	116.3	850.7
1942	103.5	95.1	34.0	51.7	93.6	.0	28.6	84.4	66.9	557.8
1943	36.5	42.3	11.1	41.5	58.3	.0	20.1	33.8	29.5	273.1
1944	64.1	76.0	24.8	50.5	152.5	.0	46.2	74.3	72.5	560.9
1945	47.3	71.1	30.8	54.8	129.9	.0	35.7	78.6	79.6	527.8
1946	80.9	54.2	16.5	51.4	155.3	.0	40.7	52.0	105.1	556.1
1947	72.4	77.7	16.7	44.0	79.5	.0	31.6	45.2	55.5	422.6
1948	41.1	25.6	26.0	14.8	19.9	.0	13.2	20.2	17.5	178.3
1949	166.0	86.1	31.5	33.0	55.9	.0	23.5	70.3	41.8	508.1
1950	41.5	35.5	13.3	23.6	24.6	.0	17.4	27.0	17.3	200.2
1951	18.3	28.4	7.3	21.1	12.5	.0	10.6	26.4	15.3	139.9
1952	27.9	15.7	3.2	25.4	102.3	.0	20.7	30.2	50.1	275.5
1953	21.4	15.1	3.2	36.2	42.3	.0	24.9	4.4	20.1	167.6
1954	61.3	31.6	7.1	25.3	8.8	.0	10.7	11.9	4.2	160.9
1955	128.0	22.1	.6	16.5	3.3	.0	9.5	7.7	4.3	192.0
1956	15.6	4.2	1.6	6.3	2.2	.0	8.2	3.6	2.0	43.7
1957	108.6	133.6	65.4	55.6	397.9	.0	76.4	129.5	175.6	1,143
1958	266.7	300.0	223.8	95.5	268.7	.0	70.7	294.9	190.9	1,711
1959	109.6	158.9	61.6	94.7	77.9	.0	33.6	96.7	57.4	690.4
Total	2,467	2,057	819.9	1,232	2,415	.0	769.9	1,764	1,523	13,050
Average	94.9	79.1	31.5	47.4	92.9	.0	29.6	67.9	58.6	501.8

The earlier estimates of recharge from the Frio and Dry Frio Rivers (Petitt and George, 1956, page 32) were based on the assumption that all flows less than 600 cfs (cubic feet per second) that passed the upper gages entered the reservoir, inferring that 600 cfs might be the maximum rate of recharge. However, records show that in 1958 losses from the Frio-Dry Frio River basin were as great as 939 cfs on March 7, indicating a greater recharge potential.

The total recharge for the period 1934-53, as revised, is approximately 7 percent greater than the estimated recharge previously published. Although this increase may seem insignificant when applied over a short term, it is appreciable when applied over the period of record.

During the period 1934-59, the annual recharge to the Edwards and associated limestones in the San Antonio area (Table 3) was estimated to range from about 44,000 acre-feet in 1956 to slightly more than 1,700,000 acre-feet in 1958, and averaged about 500,000 acre-feet.

Discharge

Ground water is discharged from the Edwards and associated limestones through springs and wells. Figure 3 shows that prior to 1954 most of the discharge was from springs, although the discharge from wells showed an annual increase. In 1954, the discharge from wells exceeded the discharge from springs, and by 1956, the last year of the long drought, approximately 80 percent of the total discharge was from wells. In 1957, when precipitation was above normal, the discharge from wells approximately equaled the flow from springs, but in 1958 and 1959, when precipitation continued above normal, the discharge from wells was only about 35 percent of the total discharge.

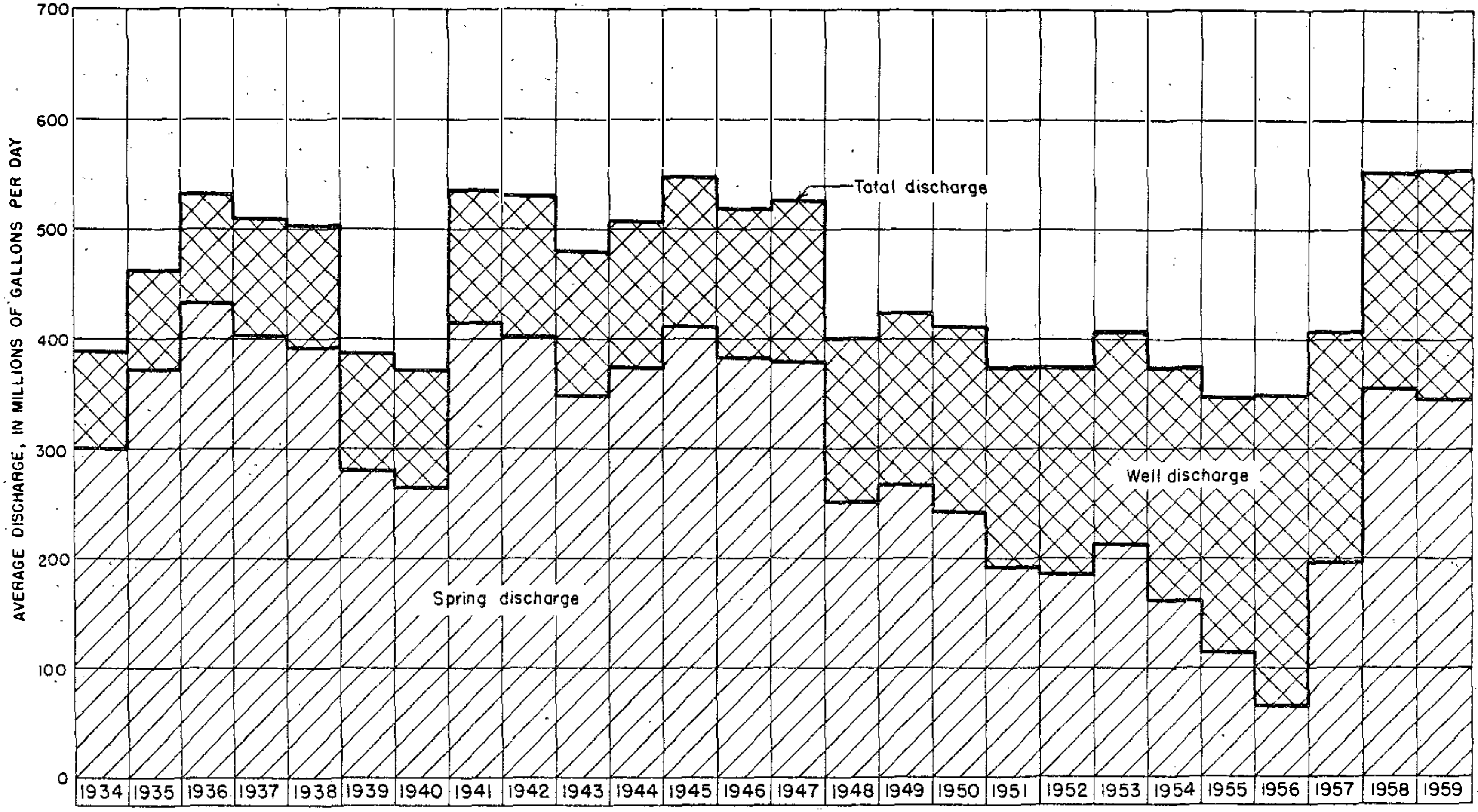
The total discharge of ground water is shown, by counties, in Figure 4 and Table 4. A large part of the discharge is in Bexar, Comal, and Hays Counties. In Comal and Hays Counties all but a small part of the discharge is from Comal and San Marcos Springs, whereas in the remaining counties most of the water is discharged from wells. The discharge in eastern Kinney, Uvalde, and Medina Counties has increased since 1954 due, principally, to the increasing use of ground water for irrigation in Uvalde and Medina Counties.

Discharge from Springs

The large springs in the San Antonio area are along faults that provide openings for the discharge of water from the Edwards and associated limestones. The principal springs are the Leona River Springs near Uvalde, San Antonio and San Pedro Springs at San Antonio, Comal Springs at New Braunfels, and San Marcos Springs at San Marcos (Figure 1).

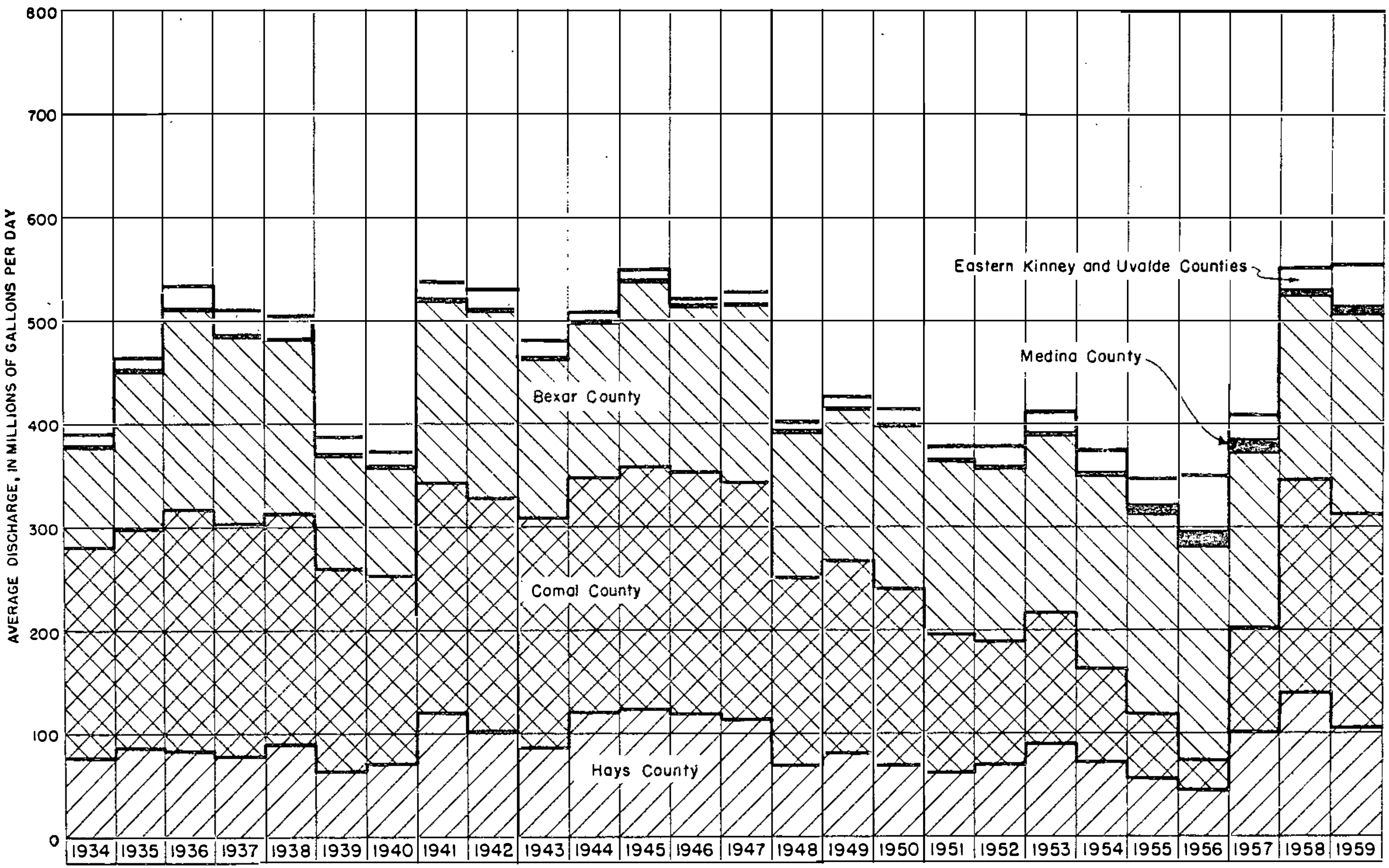
The average annual discharge of the major springs from 1955 to 1959 is shown in Figure 5. During the period 1955-57 all the springs, except San Marcos Springs ceased flowing during at least a part of the period. The Leona River Springs and San Pedro and San Antonio Springs began to flow again in the latter part of 1958 and early 1959 after several years of little or no flow.

The Leona River Springs consist of four groups of springs issuing from the Leona formation along the Leona River near Uvalde (Figure 1). The springflow is maintained by discharge from the underlying Edwards and associated limestones,



77

FIGURE 3.-Discharge from springs and wells in the Edwards and associated limestones in the San Antonio area



77

FIGURE 4.—Total discharge, by counties, from the Edwards and associated limestones in the San Antonio area

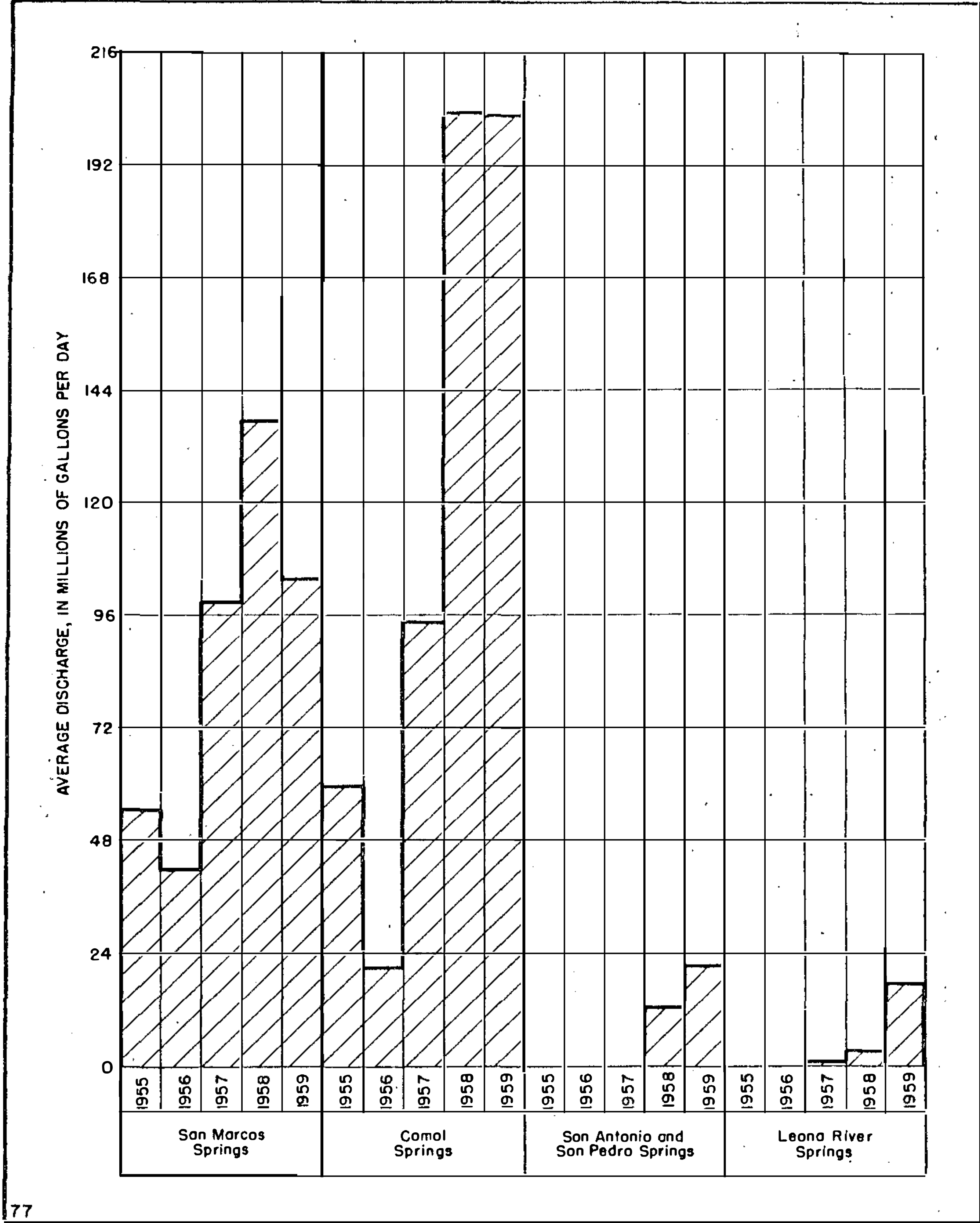


FIGURE 5.—Discharge from major springs in the San Antonio area

Table 4.--Total discharge, by counties, from the Edwards and associated limestones in the San Antonio area, 1934-59, in millions of gallons per day

Year	Eastern Kinney County	Uvalde County	Medina County	Bexar County	Comal County	Hays County	TOTAL Million gallons per day	TOTAL Thousand acre-feet per year
1934	0.2	11.1	1.2	97.6	204.5	76.4	391.0	437.9
1935	.2	10.7	1.3	153.4	211.8	86.5	463.9	518.6
1936	.2	23.6	1.3	192.1	233.7	83.2	534.1	598.2
1937	.2	25.1	1.3	180.2	225.4	77.8	510.0	571.2
1938	.2	21.9	1.3	167.7	223.5	83.4	498.0	557.8
1939	.2	16.1	1.4	109.4	195.8	63.5	386.4	432.8
1940	.2	14.2	1.4	104.2	182.0	70.0	372.0	416.6
1941	.2	15.8	1.4	176.3	223.2	119.9	536.8	601.2
1942	.2	19.9	1.5	181.4	227.8	100.2	531.0	594.7
1943	.2	17.0	1.5	153.6	222.4	86.8	481.5	539.3
1944	.2	9.1	1.5	149.0	226.0	120.8	506.6	567.4
1945	.2	10.9	1.5	178.4	234.9	123.0	548.9	614.8
1946	.2	5.4	1.5	160.8	233.8	119.6	521.3	583.9
1947	.2	12.1	1.8	172.6	229.3	113.9	529.9	593.5
1948	.2	8.0	1.7	142.1	181.3	69.0	402.3	450.6
1949	.2	11.6	1.8	147.6	187.0	80.2	428.4	479.8
1950	.2	15.7	2.0	158.3	170.6	69.9	416.7	466.7
1951	.2	14.9	2.0	166.8	134.4	61.7	380.0	425.6
1952	.2	20.1	2.8	167.0	118.9	70.4	379.4	424.9
1953	.2	24.4	3.6	172.9	126.5	90.5	418.1	468.3
1954	.2	23.6	5.6	186.4	90.2	72.8	378.8	424.3
1955	.2	25.1	9.9	192.1	62.6	57.2	349.1	388.8
1956	.2	53.0	15.8	205.0	30.0	45.0	349.0	392.0
1957	.2	25.7	10.6	169.1	101.1	100.9	407.6	456.5
1958	.2	21.1	5.9	178.2	206.9	139.2	551.5	617.7
1959	.2	40.1	7.4	194.2	206.9	105.8	554.6	621.2

the water moving upward along faults and thence into the Leona formation. A part of the water from the Edwards flows into the Leona River through the springs, the flow of which is measured at stream-gaging station 4 below Uvalde (Figure 1), and a part moves under the river southeastward in the Leona formation. The underflow in the Leona formation below the gaging station was estimated from the prevailing hydraulic gradient of the water table, the permeability of the sediments, and the cross-sectional area. On this basis the underflow was more than 800 acre-feet in 1957, nearly 3,600 acre-feet in 1958, and about 7,200 acre-feet in 1959. The flow of the springs above the gaging station began in February 1959, whereas that below the gage began in the latter part of 1958. The discharge of the Leona River Springs (Figure 5) includes the underflow in the Leona formation.

Comal Springs ceased flowing for the first time of record on June 13, 1956, and started to flow again on November 3, 1956; however, the average discharge during 1958 and 1959 was greater than the long-term average of 295 cfs. The flow of San Marcos Springs reached a record low of 46 cfs on August 15, 1956; a record high of 292 cfs was measured on May 9, 1958.

Discharge from Wells

A large part of the discharge of water from wells that draw from the Edwards and associated limestones is in Bexar County, whereas the discharge from such wells in Comal and Hays Counties is usually less than 10 percent of the total discharge from the two counties. The withdrawal of water from wells was greatest in 1956, principally because 1956 was the last full year of the drought that extended from 1947 into 1957.

Most of the water pumped from wells in the San Antonio area is used to supply the cities and military establishments. More than 70 percent of the water withdrawn for municipal supply is used by the city of San Antonio.

The withdrawal of water from wells in Bexar County from 1955 to 1959 is shown in Figure 6. The amount of water used annually for irrigation in Bexar County and elsewhere in the San Antonio area varies according to the distribution as well as the amount of precipitation. For example, the use of ground water for irrigation in Bexar County in 1956, when precipitation totaled only 14.3 inches, was 50.6 mgd (million gallons per day); in 1958, when precipitation was 39.7 inches, pumpage of ground water for irrigation amounted to only 22.7 mgd. Most of the irrigation in Bexar County is in the western and southwestern parts of the county, but a small area is under irrigation within the eastern limits of the city of San Antonio along Salado Creek. More than 15,000 acres, mostly of vegetable and feed crops, was irrigated with water from wells in Bexar County during 1959. The use of water for industry and air conditioning and for commercial purposes has remained relatively constant since 1955.

In Uvalde and Medina Counties most of the water is used for irrigation. In Uvalde County nearly 14,000 acres of feed crops and garden vegetables was irrigated in 1959, and in Medina County about 3,600 acres was irrigated. The principal irrigated area in Uvalde County is in the vicinity of the city of Uvalde, although scattered areas in the eastern part of the county also have been developed. A large part of the irrigated acreage in Medina County is in the eastern part between Castroville and the Bexar County line; scattered areas throughout the rest of Medina County also are irrigated.

The cities of Uvalde and Sabinal in Uvalde County, and Hondo, Castroville, D'Hanis, and Lacoste in Medina County depend upon water from the Edwards and

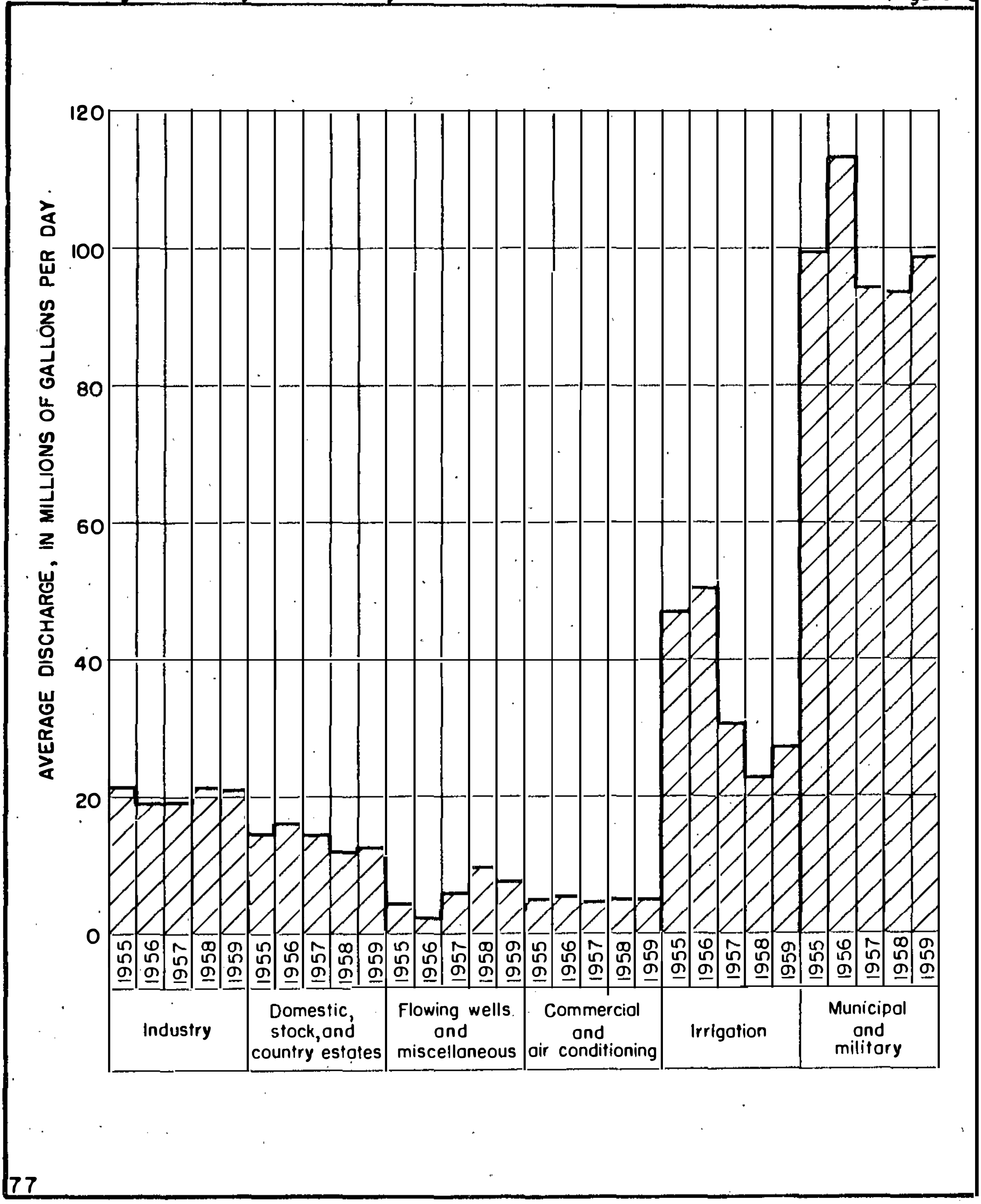


FIGURE 6.– Use of water from wells in the Edwards and associated limestones in Bexar County

associated limestones. The cities of Devine and Natalia, in the southeastern part of Medina County, obtain water from wells that draw from the Carrizo sand and sands of the Wilcox group.

The withdrawals of water in eastern Kinney County are small and are primarily for domestic and stock needs.

Fluctuation of Water Levels

Water levels in about 150 observation wells that draw from the Edwards and associated limestones in the San Antonio area are measured periodically. During 1959, 75 wells were measured bimonthly and 54 were measured monthly; recording gages were in operation on 22 other wells.

In most of these wells the water levels fluctuate seasonally in response to changes in ground-water withdrawals; the annual fluctuations reflect the shifting imbalance between recharge to and discharge from the aquifer. In general, water levels fluctuate more rapidly during periods of recharge than during periods of discharge, the magnitude of the fluctuation depending on the proximity of the well to the centers of pumping or recharge.

The fluctuations of water levels in representative wells that draw from the Edwards and associated limestones in the San Antonio area are shown on Figures 7 and 8. From 1947 to 1956 the trend of the water levels was downward, reflecting the drought throughout the area and the accompanying increase in ground-water withdrawals. Water levels rose somewhat during 1952 and 1953 after heavy rains in parts of the area; however, the recharge was insufficient to stop the general downward trend. In most of the wells, water levels declined to record lows in 1956, although in eastern Kinney County and Uvalde County water levels were lowest in 1957. They rose rapidly as a result of the above-normal rainfall during 1957-59, nearly reaching the levels of 1947. Figure 9 shows a close correlation of water-level fluctuations in Bexar County well 26, discharge of Comal Springs, and precipitation at Boerne. The fluctuations in the flow of Comal Springs reflect chiefly the changes in pumping rates in the area of heavy pumping in Bexar County.

Figures 7 and 8 show that water-level fluctuations throughout the San Antonio area follow similar trends, differing in degree near the large springs and in areas remote from centers of large ground-water withdrawal. For example, fluctuations of the water level in well 152 in eastern Kinney County are relatively uniform in comparison with those in most of the other wells, the range between the highest and lowest water levels being only about 10 feet. In fact, nearly all changes of water level in this well are related to changes in the discharge of Las Moras Springs. The water levels in Bexar County wells K-2 and 175 (Figure 7), which are in the zone that yields water of poor quality, fluctuate similarly to those in well F-24, which is also in Bexar County but in the zone of fresh water. The similarity of fluctuation indicates close hydraulic connection between the zones of fresh water and water of poor quality.

Movement of Water

The approximate altitudes of the water table and the piezometric surface in the Edwards and associated limestones in August 1956 and March 1958 are shown in

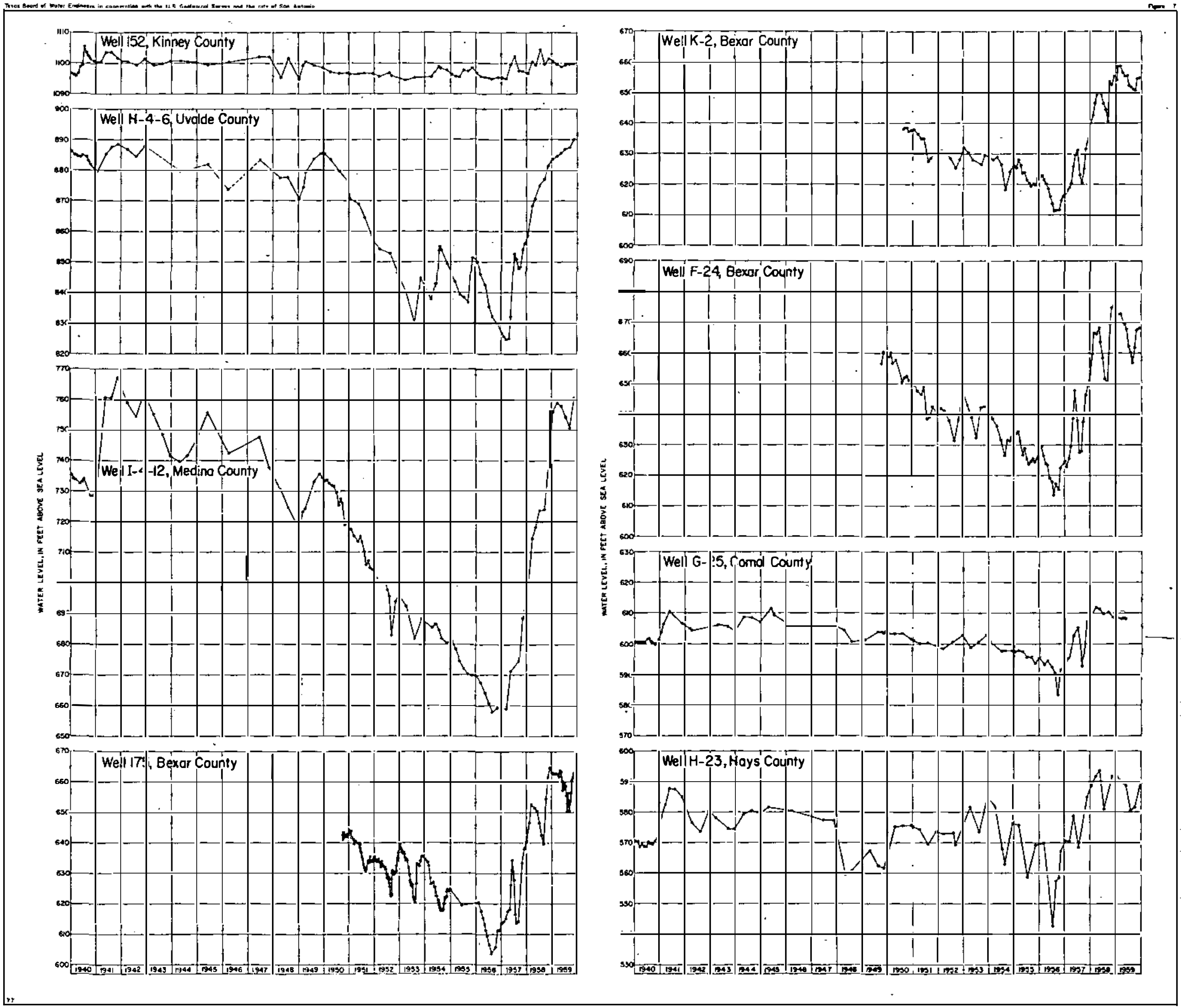


FIGURE 7- Hydrographs of representative wells in the Edwards and associated limestones in the San Antonio area

77

FIGURE 8.-Hydrographs of representative wells in the Edwards and associated limestones in the San Antonio area

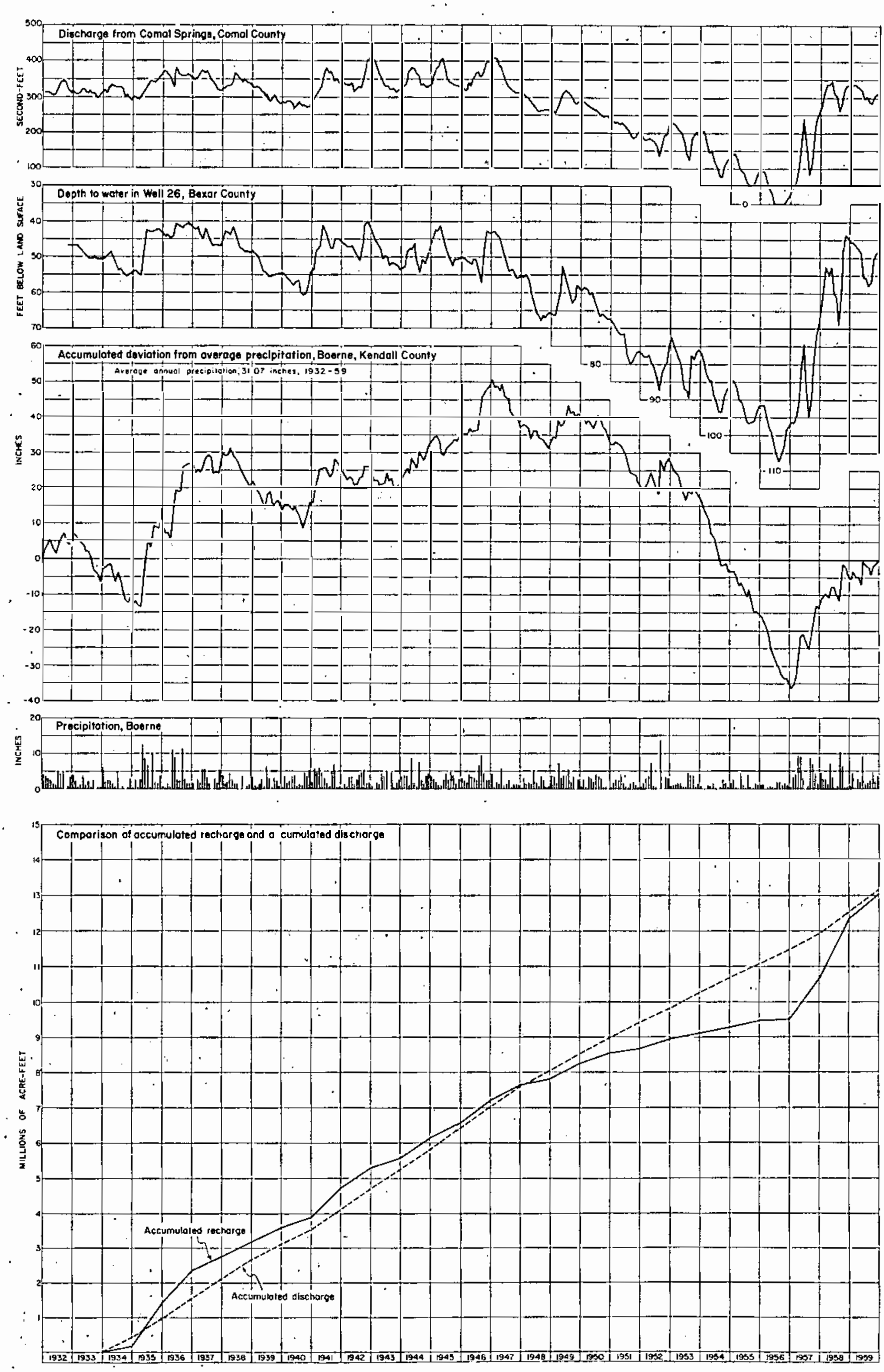


FIGURE 9.- Discharge from Comal Springs, water level in Bexar County well 26, precipitation at Boerne, and comparison of accumulated recharge and accumulated discharge in the Edwards and associated limestones in the San Antonio area

Plates 1 and 2. The Edwards and associated limestones is not homogeneous; therefore, the water table and the piezometric surface cannot be mapped in great detail with the control available. The maps show, however, the general direction of movement of ground water in the San Antonio area.

Plates 1 and 2 show ground-water divides in the vicinity of Brackettville in Kinney County and in the northeastern part of Hays County. These divides are arbitrarily considered as the boundaries of the Edwards and associated limestones in the San Antonio area, because it is believed that changes in hydrostatic head beyond these boundaries have no significant effect on the water levels in the San Antonio area.

In the area of outcrop of the Edwards and associated limestones, water-table conditions prevail and the hydraulic gradients are steep, the water moving generally southward or southeastward toward the artesian part of the aquifer (Plates 1 and 2). In the artesian zone, however, the hydraulic gradients are relatively low and ground water moves eastward and northeastward, roughly parallel with the main system of faults. This relatively low hydraulic gradient indicates that movement is through large openings, whereas the steep gradients indicate movement through smaller openings in which losses in hydrostatic head are large.

According to Petitt and George (1956, page 58), the piezometric surface fluctuates uniformly throughout the artesian part of the aquifer, and the fluctuations of the piezometric surface along lines normal to the main zone of faulting do not materially affect the hydraulic gradients. However, fluctuations of water levels along lines that roughly parallel the zone of faulting affect the hydraulic gradient. Figure 10, which is based on simultaneous water-level measurements made in pairs of observation wells, shows that in general the hydraulic gradient increases as the piezometric surface rises. A local exception to this relationship has been observed at Uvalde, where correlation of the water levels in wells H-4-6 and H-5-1 shows that above about 850 feet in well H-5-1 the hydraulic gradient decreases as the artesian pressure increases. The decrease in hydraulic gradient may be attributed to the discharge of water from the Edwards and associated limestones into the overlying formations (Austin chalk and Leona formation). According to Welder and Reeves (1960, page 52), hydraulic connections between the formations probably exist in many places in the faulted area in the vicinity of the city of Uvalde. Below an altitude of about 845 feet in well H-5-1, water moves eastward in the Edwards and associated limestones; above 845 feet, however, water also moves upward into the overlying formations and thence laterally, where it is discharged through Leona Springs. If most of the upward movement is in the vicinity of well H-4-6, then this area, in effect, becomes a point of discharge for the Edwards and associated limestones. Thus, a cone of pressure relief occurs in the area of discharge and the hydraulic gradient between wells H-4-6 and H-5-1 decreases. The group of springs near Uvalde begin to flow at a water-level altitude of 845 feet in well H-5-1; the discharge from this group makes up the largest flow of the Leona River Springs.

The rate of movement of ground water in the Edwards and associated limestones varies widely throughout the San Antonio area because the aquifer contains openings of greatly varying size, ranging from minute cracks to caverns. As stated on page 9, the flow of ground water in the aquifer is characteristically nonuniform and generally unsteady. The unsteady flow is indicated by an increase in the hydraulic gradient as the artesian head increases, which means that the velocity of flow increases as the artesian heas rises. Under natural conditions a decrease in artesian head does not cause a rapid decrease in the velocity of flow because the decline in artesian head is gradual. Although it is recognized that any fluctuation in artesian head results in unsteady flow, when the changes in

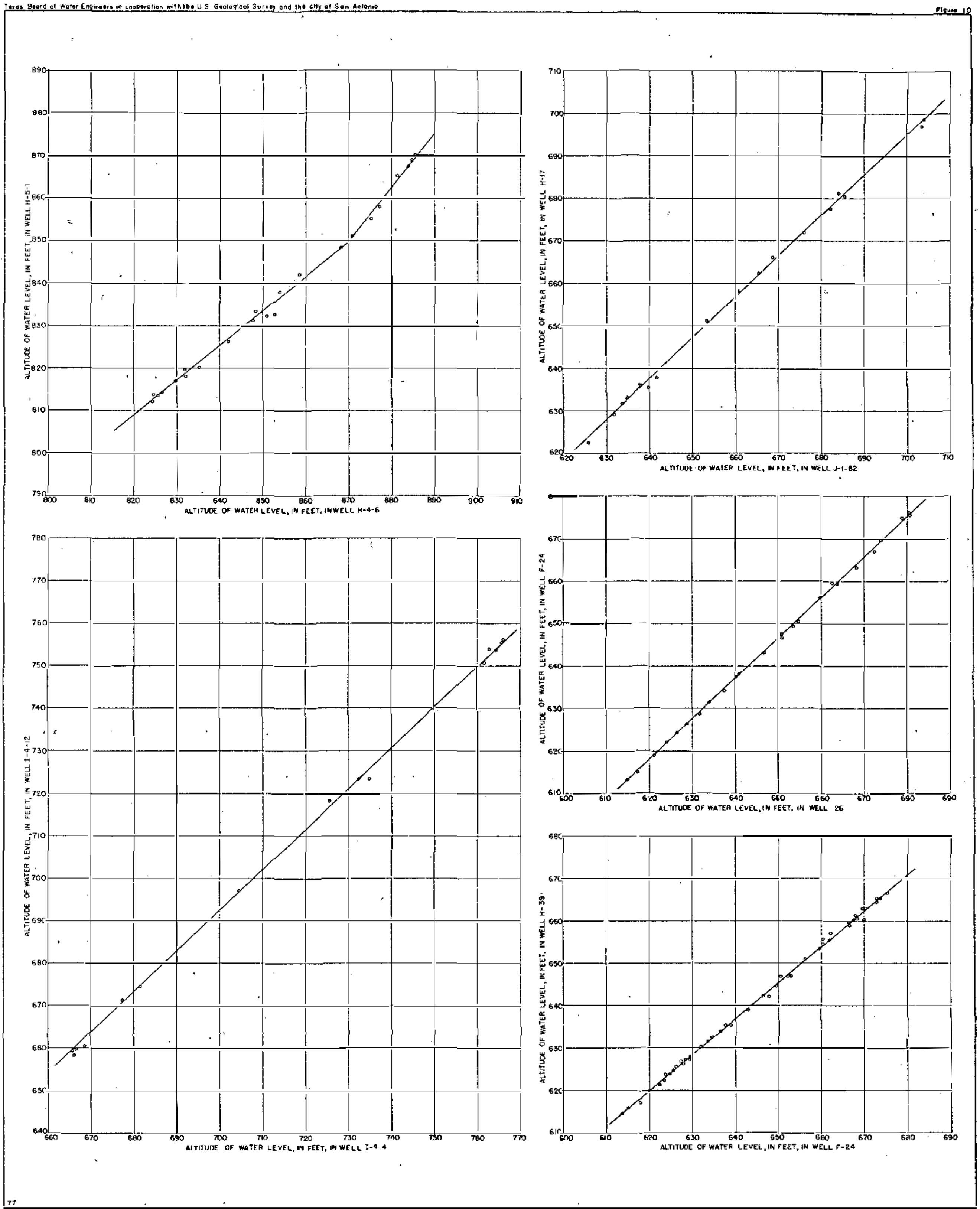


FIGURE 10.– Correlation of water levels in selected wells in the Edwards and associated limestones in the San Antonio area

head are small and gradual, the velocity of flow may be considered to be nearly steady. Generally unsteady-flow conditions predominate throughout a large part of the aquifer during most of the year. Actually, nearly steady-flow conditions may be approached only during the winter, when natural recharge to and artificial discharge from the aquifer are small.

Because of the variations in velocity during periods of unsteady flow, the relation between flow and artesian head is complex, and any correlation between changes in storage and aquifer head during these periods is not possible because the actual mass movement of the water lags the change in artesian head. This can be shown at San Pedro Springs, where it has been observed that the increase in springflow caused by a rapidly rising head lags the increasing head observed in nearby observation wells.

When the forces that cause unsteady flow reach a minimum, equilibrium conditions are approached and artesian head and aquifer stage become nearly synonymous. These conditions admittedly do not represent true steady flow involving no change in storage, but rather they represent a gradually changing flow, which in this report is referred to as nearly steady flow.

In summary, the larger changes in storage in the Edwards and associated limestones occur during periods of unsteady flow, but the changes in storage cannot be correlated with aquifer head except during periods when the flow is nearly steady.

Changes in Storage

The Edwards and associated limestones is an areally extensive ground-water reservoir, and the use of fluctuations of water levels in one well to indicate the changes in storage in the entire area may lead to errors of considerable magnitude. Therefore, the reservoir has been divided into four segments, which are, from west to east, (1) eastern Kinney and Uvalde Counties, (2) Medina County, (3) Bexar County, and (4) Comal and Hays Counties.

In order to determine reasonably accurately the change in storage in each segment of the reservoir, the following data are needed:

(1) The quantity of natural recharge, which is estimated from records of losses from streams that cross the outcrop of the Edwards and associated limestones and the infiltration of precipitation that falls on the surface.

(2) The quantity of discharge, both natural (from springs) and artificial (from wells).

(3) The underflow into and out of each segment.

(4) Continuous water-level records of representative wells.

Figure 11 shows schematically the ground-water cycle in the segments of the Edwards and associated limestones defined above. It shows the elements of recharge, discharge, and underflow that provide a balance in each segment. The change in storage for the entire aquifer, therefore, is the sum of the differences between the recharge and discharge in the segments.

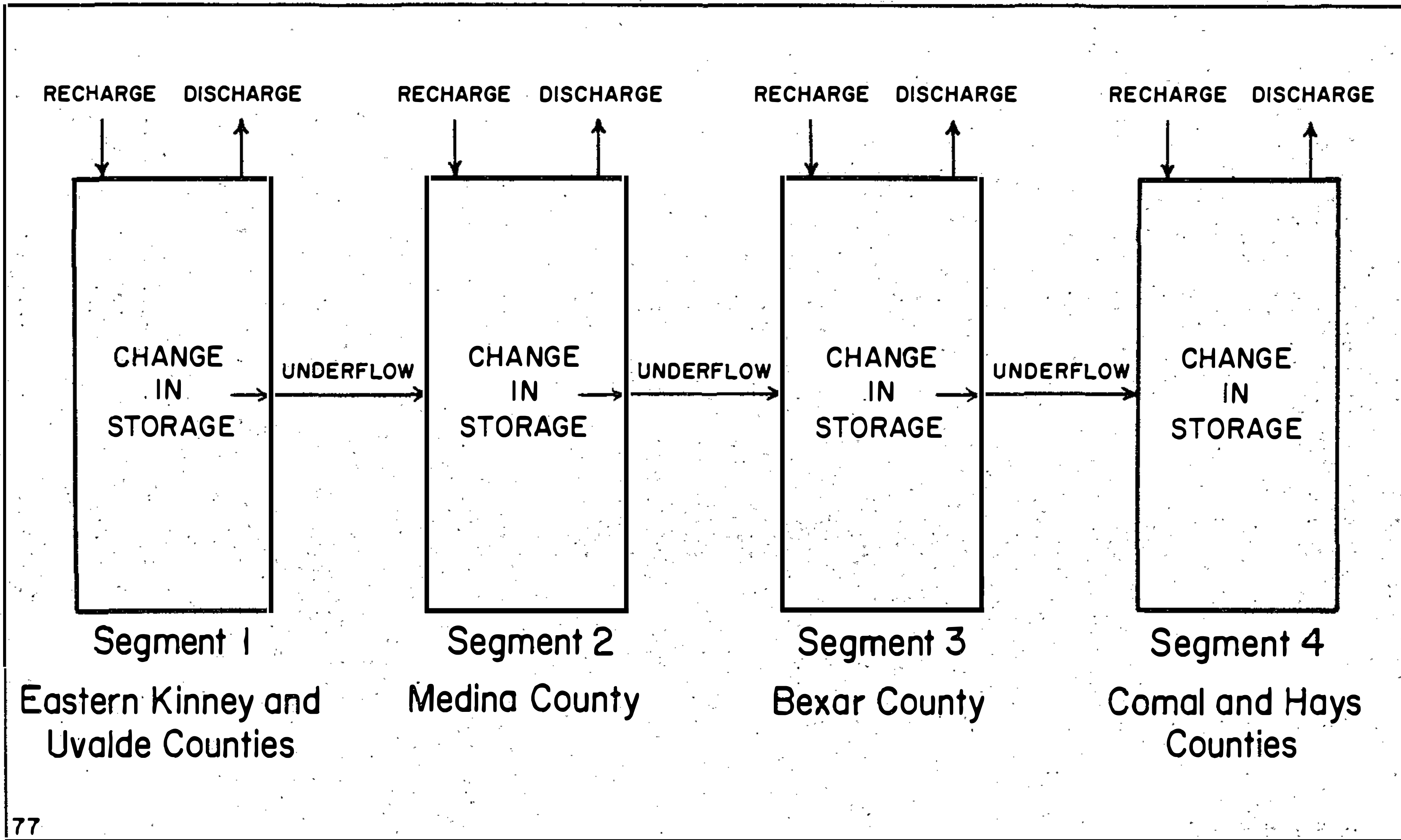


FIGURE 11.– Ground-water cycle in the segments comprising the Edwards and associated limestones in the San Antonio area

The underflow from any segment is equal to the difference between the recharge, including any underflow into the segment, and the discharge for periods during which the net change in storage is negligible. Artesian heads during periods of nearly steady flow represent approximately true aquifer stages. However, during periods of unsteady flow the artesian head does not represent the true aquifer stage, and unchanged artesian heads do not necessarily reflect a negligible change in storage (same aquifer stage). An approximation of unchanging aquifer stages may be made during unsteady flow by relating identical artesian heads during rising trends or falling trends, thus bracketing a condition in which the change in storage would be small or negligible. Therefore, underflow may be approximated during both steady and unsteady flow. The underflow for periods representing different stages of the aquifer may be correlated with the artesian head during nearly steady flow; it may be correlated with the hydraulic gradient during unsteady flow. The resultant correlation would thus define the underflow completely through the range of artesian heads observed.

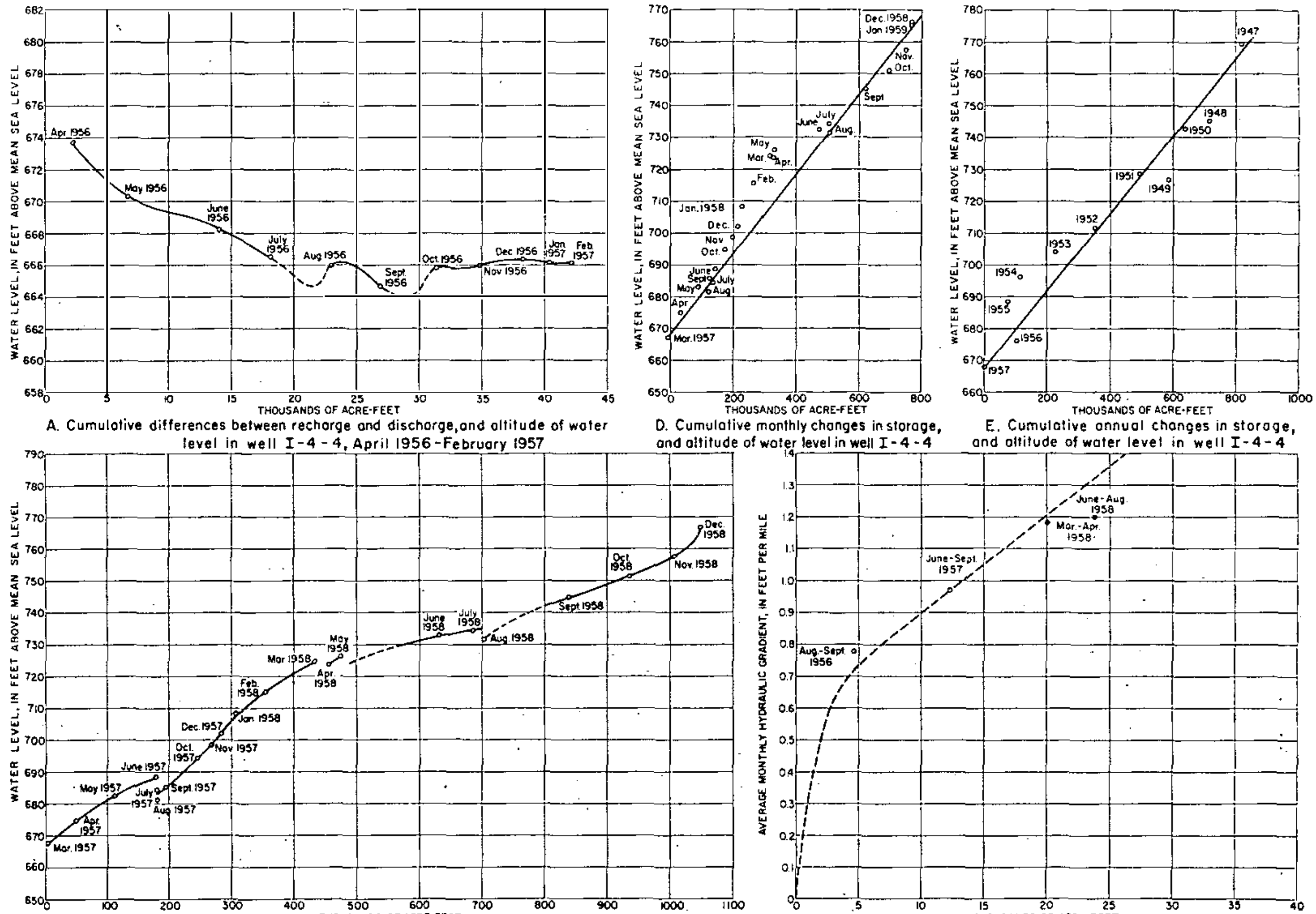
The change in storage in any segment is the difference between the recharge and the discharge (including the underflow) in that segment. The cumulative changes in storage for any period may be correlated with the artesian head at the end of that period. Because changes in storage cannot be related to artesian head during unsteady flow, points representing changes in storage for periods of nearly steady flow define the change-in-storage curve. Points that fall above or below the curve represent periods of unsteady flow.

The underflow and the change in storage for each foot of change in water level in each segment are described briefly in the following pages.

Segment 1

Recharge of ground water to Segment 1 (Kinney and Uvalde Counties) consists of stream losses from the Nueces, Frio-Dry Frio, and Sabinal River basins; discharge consists of pumpage from wells in eastern Kinney and Uvalde Counties, the flow of the Leona River Springs, and the underflow into Segment 2. The changes in water level were determined by a recording gage in well I-4-4 at the extreme lower edge of Segment 1 in Uvalde County. The cumulative differences between monthly recharge to and discharge (not including the underflow to Segment 2) from the segment and the altitude of the water levels in well I-4-4 at the end of each month from April 1956 to December 1958 are shown in Figures 12-A and 12-B. Figure 12-A represents the fluctuations during a falling stage: Figure 12-B represents fluctuations during a rising stage. The breaks in the curve on Figure 12-B represent short periods of water-level decline during a generally rising trend of water levels. During the periods August-September 1956, June-September 1957, March-April 1958, and July-August 1958, the changes in storage were negligible. The monthly average underflow for these periods and the corresponding average hydraulic gradient between wells I-4-4 and I-4-12 were plotted on Figure 12-C to determine the underflow curve. Table 5 shows the monthly underflow, cumulative underflow, cumulative difference between recharge and discharge, and cumulative changes in storage. The monthly underflow was determined from the hydraulic gradient between wells I-4-4 and I-4-12 at the end of each month and the curve in Figure 12-C. The cumulative changes in storage and the corresponding hydrostatic head in well I-4-4 are shown in Figure 12-D. The points that fall above or below the curve represent periods during which unsteady-flow conditions prevailed.

The method for determining annual changes in storage is similar to that for determining monthly changes in storage. Although water-level fluctuations in well



A. Cumulative differences between recharge and discharge, and altitude of water level in well I-4-4, April 1956-February 1957

D. Cumulative monthly changes in storage, and altitude of water level in well I-4-4

E. Cumulative annual changes in storage, and altitude of water level in well I-4-4

B. Cumulative differences between recharge and discharge, and altitude of water level in well I-4-4, March 1957-December 1958

C. Average monthly underflow and average monthly hydraulic gradient between wells I-4-4 and I-4-12

77

FIGURE 12.-Relation of recharge, discharge, underflow, and changes in storage in Segment I of the Edwards and associated limestones in the San Antonio area

Table 5.--Underflow to Segment 2, and cumulative underflow, cumulative differences of recharge and discharge, and cumulative changes in storage, in thousands of acre-feet, in the Edwards and associated limestones of Segment 1, March 1957-January 1959

Month	Underflow to Segment 2	Cumulative underflow	Cumulative differences of recharge and discharge	Cumulative changes in storage
Mar. 1957	-8.5	-8.5	+3.1	-5.4
Apr.	-8.5	-17.0	+48.6	+31.6
May	-6.8	-23.8	+112.7	+88.9
June	-11.7	-35.5	+178.4	+142.9
July	-11.7	-47.2	+181.5	+134.3
Aug.	-11.3	-58.5	+180.3	+121.8
Sept.	-11.1	-69.6	+193.5	+123.9
Oct.	+2.0	-67.6	+243.6	+176.0
Nov.	0	-67.6	+265.2	+197.6
Dec.	-2.0	-69.6	+282.4	+212.8
Jan. 1958	-11.7	-79.3	+306.7	+227.4
Feb.	-15.0	-94.3	+357.2	+262.9
Mar.	-16.5	-110.8	+431.5	+320.7
Apr.	-16.5	-127.3	+454.3	+327.0
May	-16.5	-143.8	+473.8	+330.0
June	-16.5	-160.3	+630.6	+470.3
July	-19.8	-180.1	+684.8	+504.7
Aug.	-19.8	-199.9	+702.6	+502.7
Sept.	-16.5	-216.4	+838.3	+621.9
Oct.	-23.0	-239.4	+936.8	+697.4
Nov.	-19.8	-259.2	+1,007.1	+749.9
Dec.	-22.3	-281.5	+1,049.0	+767.5
Jan. 1959	-21.7	-303.2	+1,065.4	+762.2

I-4-4 were not available for the entire period of record (1947-57), extrapolation of the water levels was made from well I-4-12, Medina County, and the information from Figure 10. The annual changes in storage and the corresponding water level in well I-4-4 from 1947 to 1957 are shown in Figure 12-E. The curve in Figure 12-E is remarkably similar to the curve in Figure 12-D, indicating that the curves may be used to determine changes in storage in the Edwards and associated limestones in Segment 1 with a reasonable degree of accuracy.

Segment 2

Recharge to Segment 2 (Medina County) consists of underflow from Segment 1, infiltration of precipitation and streamflow in the area between the Sabinal and Medina Rivers, and half the recharge from Medina Lake. The maps showing the general direction of movement of water (Plates 1 and 2) indicate that a part of the recharge from Medina Lake moves south and southwest into Medina County, and a part moves southeast into Bexar County. Discharge from Segment 2 consists of pumpage from wells and the underflow into Segment 3.

The underflow from Segment 2 was determined for the periods November-December 1956, June-October 1957, April-May 1958, and November-December 1958, when the water levels were on a rising trend. The relation between the underflow and the corresponding hydraulic gradient between wells J-1-82 near the eastern edge of Medina County and H-17 in Bexar County is shown in Figure 13-A. The cumulative differences between recharge and discharge, cumulative underflow, and cumulative changes in storage from January 1957 to January 1959 in Segment 2 are shown in Table 6. Because of the proximity of Segment 2 to areas of large ground-water withdrawals, the conditions of relatively steady flow occur less frequently than in Segment 1. As a result, the curve representing monthly changes in storage in Segment 2 (Figure 13-B) is more difficult to define. The data show, however, that relatively steady flow occurred in the early part of 1957 and 1959. The points that do not fall on the curve represent unsteady flow, when either recharge or pumpage predominated.

Records of water levels in well J-1-82 are not available for the period prior to 1950; however, correlation of the water levels in well H-17 in Bexar County and Figure 10 permits a rough extension of the data for well J-1-82 back to 1934. These data indicate a steadily declining artesian head from 1947 to 1956, inclusive. Figure 13-C shows the relation between annual changes in storage and the altitude of the water level in well J-1-82 for the period 1947-56.

Because the water levels in wells J-1-82 and H-17 are readily affected by the pumping in Segment 3, conditions of relatively steady flow probably occur mainly during December and January of each year when natural recharge and pumpage from wells generally are at a minimum. Although the monthly and annual curves agree closely (Figure 13-C), the annual curve shows a larger storage change, probably because the change in artesian head during the period 1947-56 slightly exceeded the change during 1957-58.

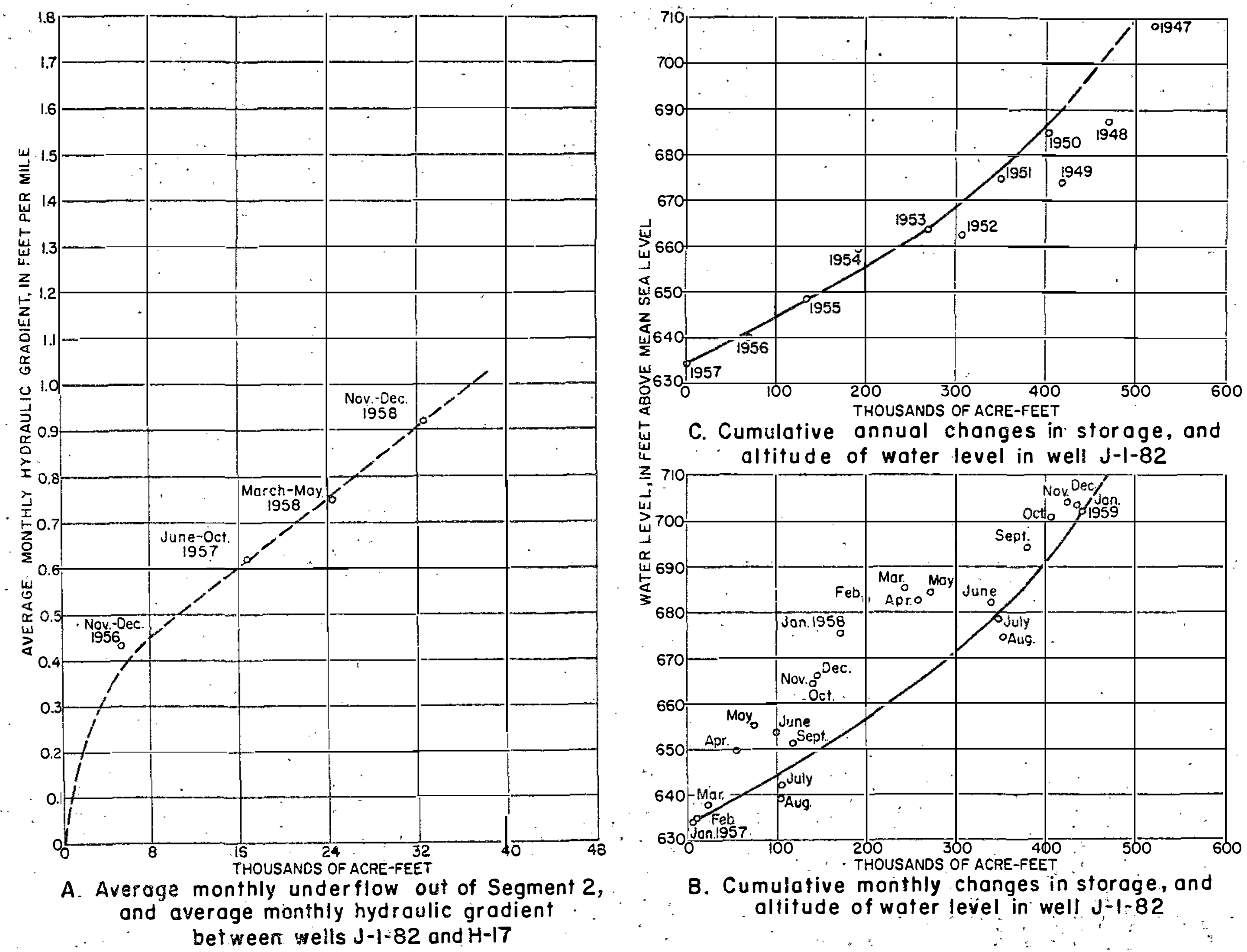
Segment 3

Recharge to Segment 3 (Bexar County) consists of underflow from Segment 2, infiltration of precipitation and streamflow in the area between Medina River and Cibolo Creek, half the recharge from Medina Lake, and half the recharge from

Table 6.--Underflow to Segment 3, and cumulative underflow, cumulative differences of recharge and discharge, and cumulative changes in storage, in thousands of acre-feet, in the Edwards and associated limestones in Segment 2, January 1957-January 1959

Month	Underflow to Segment 3	Cumulative underflow	Cumulative differences of recharge* and discharge	Cumulative changes in storage
Jan. 1957	4.0	-4.0	8.3	4.3
Feb.	4.0	8.0	16.5	8.5
Mar.	4.0	12.0	33.7	21.7
Apr.	4.0	16.0	70.5	54.5
May	2.5	18.5	92.9	74.4
June	6.6	25.1	124.2	99.1
July	10.4	35.5	140.2	104.2
Aug.	14.8	50.3	153.8	103.5
Sept.	14.8	65.1	183.1	118.0
Oct.	10.4	75.5	204.7	129.2
Nov.	6.6	82.1	223.2	141.1
Dec.	10.4	92.5	238.3	145.8
Jan. 1958	6.6	99.1	272.3	173.2
Feb.	19.4	118.5	319.5	201.0
Mar.	10.4	128.9	371.9	243.0
Apr.	19.4	148.3	405.9	257.6
May	19.4	167.7	439.2	271.5
June	19.4	187.1	525.5	338.4
July	28.1	215.2	563.7	347.5
Aug.	23.8	239.0	592.8	353.8
Sept.	28.1	267.1	646.8	379.8
Oct.	32.5	299.6	706.6	407.0
Nov.	28.1	327.7	753.3	425.6
Dec.	28.1	355.8	791.2	435.4
Jan. 1959	28.1	383.9	824.2	440.3

*Recharge includes underflow from Segment 1.



A. Average monthly underflow out of Segment 2, and average monthly hydraulic gradient between wells J-1-82 and H-17

C. Cumulative annual changes in storage, and altitude of water level in well J-1-82

B. Cumulative monthly changes in storage, and altitude of water level in well J-1-82

FIGURE 13.-Relation of underflow and changes in storage in Segment 2 of the Edwards and associated limestones in the San Antonio area

Cibolo Creek. Discharge from Segment 3 consists of pumpage from wells, springflow from San Antonio and San Pedro Springs, and underflow into Segment 4.

The fluctuations of water level in well F-24 at the northeast edge of Segment 3, as shown in Figure 7, are based on monthly measurements. The fluctuations of water level between measurements were interpolated from the records of water levels in wells 26 (Bexar County) and H-39 (Comal County), which are equipped with recording gages. The records show that from 1957 to 1959 the water levels rose rapidly except during the summers of 1957 and 1958, when they declined sharply owing to heavy pumping, and during November-December 1958, when they were nearly constant. Therefore, the average monthly underflow, which was determined for the periods May-October 1957 and November-December 1958, and the corresponding hydraulic gradient between wells F-24 and H-39 are shown in Figure 14-A. The accuracy of the curve cannot be determined with the available data; nevertheless, the underflow, cumulative underflow, cumulative differences between recharge and discharge, and cumulative changes in storage were computed as shown in Table 7. The monthly changes in storage for the period January 1957-December 1958 and the corresponding altitudes of water levels in well F-24 are shown in Figure 14-B. Accurate definition of the curve was not possible because water levels in Segment 3 were affected by either heavy recharge or pumpage almost continuously during the period.

The fluctuations of water levels in well F-24 were extrapolated back to 1934 according to the correlation of water levels between wells F-24 and 26 shown in Figure 10. On this basis the annual change in storage from 1945 to 1957 was determined, and is shown in Figure 14-C. The annual changes in storage computed for the period 1954-56 fell below the curve because recharge was small and discharge from wells was large. The change-in-storage curves shown in Figure 14-B and 14-C are similar; however, the curves, at best, are only approximations because of the effects of the large ground-water withdrawals in Bexar County during most of the year.

Segment 4

Recharge to Segment 4 (Comal and Hays Counties) consists of underflow from Segment 3, half the recharge from Cibolo Creek, seepage of streamflow from Dry Comal Creek, and infiltration of precipitation and streamflow from the Blanco River basin. Discharge from the segment is through wells in Comal and Hays Counties and by springflow from Comal Springs and San Marcos Springs.

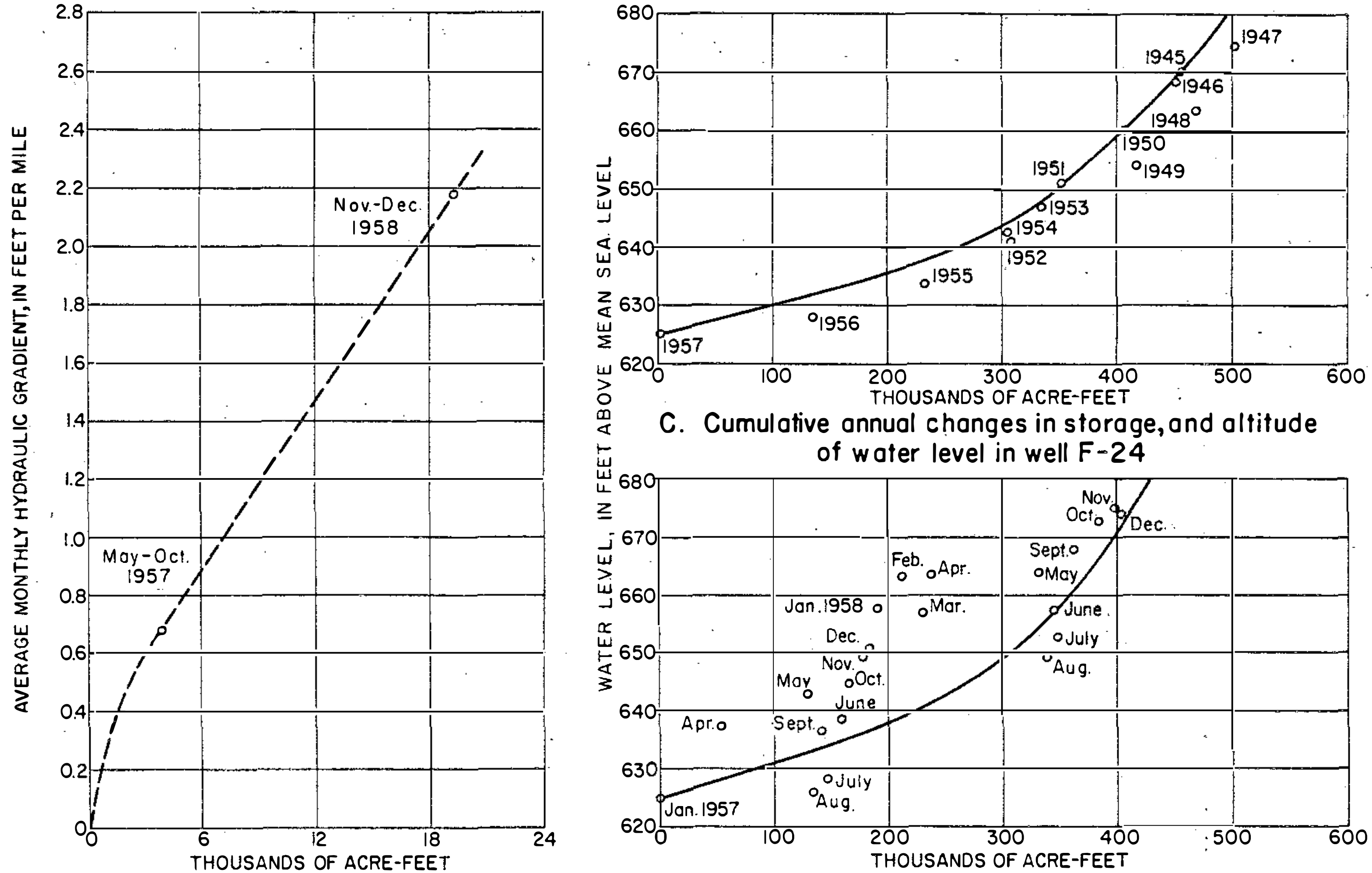
The discharge from Hueco Springs in Comal County was not included in the discharge from the Edwards and associated limestones. According to George (1952, pages 50-51), Hueco Springs may be supplied by a ground-water reservoir that is separate from that supplying Comal Springs. According to available records, Hueco Springs had no flow from February 1954 to February 1957. Since 1957, individual discharge measurements have ranged from 13.8 to 102 cfs, the latter being the highest measured discharge since 1924.

A curve showing the changes in storage in Segment 4 could not be obtained owing to insufficient water-level data. Although the water levels in wells in Comal County fluctuate similarly to those in the other segments, the fluctuations in Hays County do not correlate closely with those for the rest of the San Antonio area. The net change in storage, or the difference between recharge and discharge, in Segment 4 for the period 1957-58 was an increase of about 200,000

Table 7.--Underflow to Segment 4, and cumulative underflow, cumulative differences of recharge and discharge, and cumulative changes in storage, in thousands of acre-feet, in the Edwards and associated limestones in Segment 3, January 1957-December 1958

Month	Underflow to Segment 4	Cumulative underflow	Cumulative differences of recharge* and discharge	Cumulative changes in storage
Jan. 1957	0.4	0.4	-10.0	-10.4
Feb.	.5	.9	-19.6	-20.5
Mar.	.7	1.6	-18.4	-20.0
Apr.	1.3	2.9	+57.5	+54.6
May	4.7	7.6	+136.8	+129.2
June	7.6	15.2	+176.1	+160.9
July	2.0	17.2	+164.0	+146.8
Aug.	.8	18.0	+152.4	+134.4
Sept.	1.5	19.5	+163.0	+143.5
Oct.	5.3	24.8	+191.1	+166.3
Nov.	8.6	33.4	+211.0	+177.6
Dec.	10.1	43.5	+226.8	+183.3
Jan. 1958	11.8	55.3	+246.8	+191.5
Feb.	13.4	68.7	+280.4	+211.7
Mar.	16.7	85.4	+313.6	+228.2
Apr.	16.2	101.6	+338.8	+237.2
May	16.9	118.5	+449.4	+330.9
June	14.5	133.0	+478.7	+345.7
July	13.7	146.7	+495.3	+348.6
Aug.	11.1	157.8	+498.2	+340.4
Sept.	11.4	169.2	+531.0	+361.8
Oct.	17.0	186.2	+571.2	+385.0
Nov.	19.3	205.5	+603.7	+398.2
Dec.	18.9	224.4	+626.7	+402.3

*Recharge includes underflow from Segment 2.



A. Average monthly underflow out of Segment 3, and average monthly hydraulic gradient between wells H-39 and F-24

B. Cumulative monthly changes in storage, and altitude of water level in well F-24

C. Cumulative annual changes in storage, and altitude of water level in well F-24

77

FIGURE 14.—Relation of underflow and changes in storage in Segment 3 of the Edwards and associated limestones in the San Antonio area

acre-feet, whereas the change in storage during the period 1947-56 was a decrease of approximately 225,000 acre-feet.

Summary

Changes in storage in small segments of the aquifer, as determined from water levels in representative wells in each segment, are probably more accurate than changes in storage in the entire aquifer, as determined from water levels in a single well. Moreover, the changes in storage are determined more accurately by comparing those periods when the changes in artesian head are small--that is, when the ground-water flow is nearly steady. Periods of nearly steady flow generally occur during December and January, when pumpage and recharge are relatively small.

The changes in storage for each segment of the Edwards and associated limestones and totals for the period 1947-58 are shown in the following table.

Segment	Key well	Period 1947-56		Period 1957-58	
		Water-level change (altitude in feet)	Storage decrease (acre-feet)	Water-level change (altitude in feet)	Storage increase (acre-feet)
1	I-4-4	768 - 668	820,000	668 - 768	800,000
2	J-1-82	710 - 634	500,000	634 - 705	450,000
3	F-24	680 - 625	500,000	625 - 675	415,000
4	--	--	225,000	--	200,000
Total			2,045,000		1,865,000

The table shows that the decrease in storage during the period 1947-56, when precipitation generally was below normal, was nearly balanced by the accretion of ground water during the 2-year period 1957-58. This is shown also in a comparison of the accumulated recharge and discharge in Figure 9. In 1947 the accumulated recharge slightly exceeded the discharge, but from 1947 to 1956 the discharge exceeded recharge at an annually increasing rate, and by the end of 1956 the difference amounted to about 2,000,000 acre-feet. From 1957 through 1958, however, the recharge was very heavy, and by the end of 1958 the accumulated discharge exceeded the accumulated recharge by only about 180,000 acre-feet.

QUALITY OF WATER

The quality of the water in the Edwards and associated limestones in the San Antonio area varies considerably within short distances, but in general the dissolved-solids content of the water increases toward the south and southeast. The water is almost uniformly a calcium bicarbonate water of good quality, except that it is hard, generally more than 200 ppm (parts per million). Chemical analyses of water from wells and springs in the various formations in the San Antonio area are given in the report by Petitt and George (1956, volume 2, part 3, pages IV-1 to IV-38) and in the reports on individual counties. (See References.)

Plate 3 shows the dissolved solids, sulfate, and chloride content of water from wells in the Edwards and associated limestones in the zone of transition between water of good and water of poor quality. The plate shows also the approximate boundary between water containing less than 1,000 ppm and water containing more than 1,000 ppm of dissolved solids. In several wells the dissolved-solids content was estimated from the specific conductance of the water. Water from some wells north of the line and all the wells south of the line contain hydrogen sulfide gas.

A study of analyses of samples taken periodically since 1955 shows that the dissolved-solids content of the water in parts of the aquifer changes in response to changes in the artesian head. This is shown in Figure 15, where the specific conductance of samples from several wells is plotted against the altitude of the water level in well 26 at the times the samples were collected. The points are connected in the chronological order of sampling. Wells J-40 and J-87 are in the zone of water of good quality; the other wells are south and southeast of the line, where water is of poor quality. Wells G-8 and J-75 are close to the line, and wells M-44 and J-90 are at a considerable distance south of the line. The data indicate that in the zone of poor-quality water the dissolved-solids content of water from wells that are close to the line generally decreases as the artesian pressure in the aquifer increases, whereas wells that are in the zone of good-quality water or that are in the zone of poor quality distant from the line show little or no net change. Thus, a change in artesian head, such as the change during 1955-59, probably causes a slight shift of the line in accordance with the change in pressure. The relatively small shift of the line probably accounts for the principal changes occurring in wells that are closest to the line in the zone of poor quality.

The relation of the dissolved-solids content, depth of well, and temperature is shown in Figure 16. Water containing less than 500 ppm dissolved solids shows little change in temperature even though the wells range in depth from about 100 to 2,500 feet. The thermal gradient of the water having less than 1,000 ppm dissolved solids is less than 0.5°F per 100 feet of depth, as compared to a thermal gradient of about 2.5°F per 100 feet of water containing more than 1,000 ppm dissolved solids. The low thermal gradient of the water of good quality may be attributed to free and relatively rapid circulation, whereas the water of poor quality probably does not circulate freely. Where the circulation is restricted, the temperature and mineralization of the water increase.

Texas Board of Water Engineers in cooperation with the U.S. Geological Survey and the city of San Antonio

Figure 15

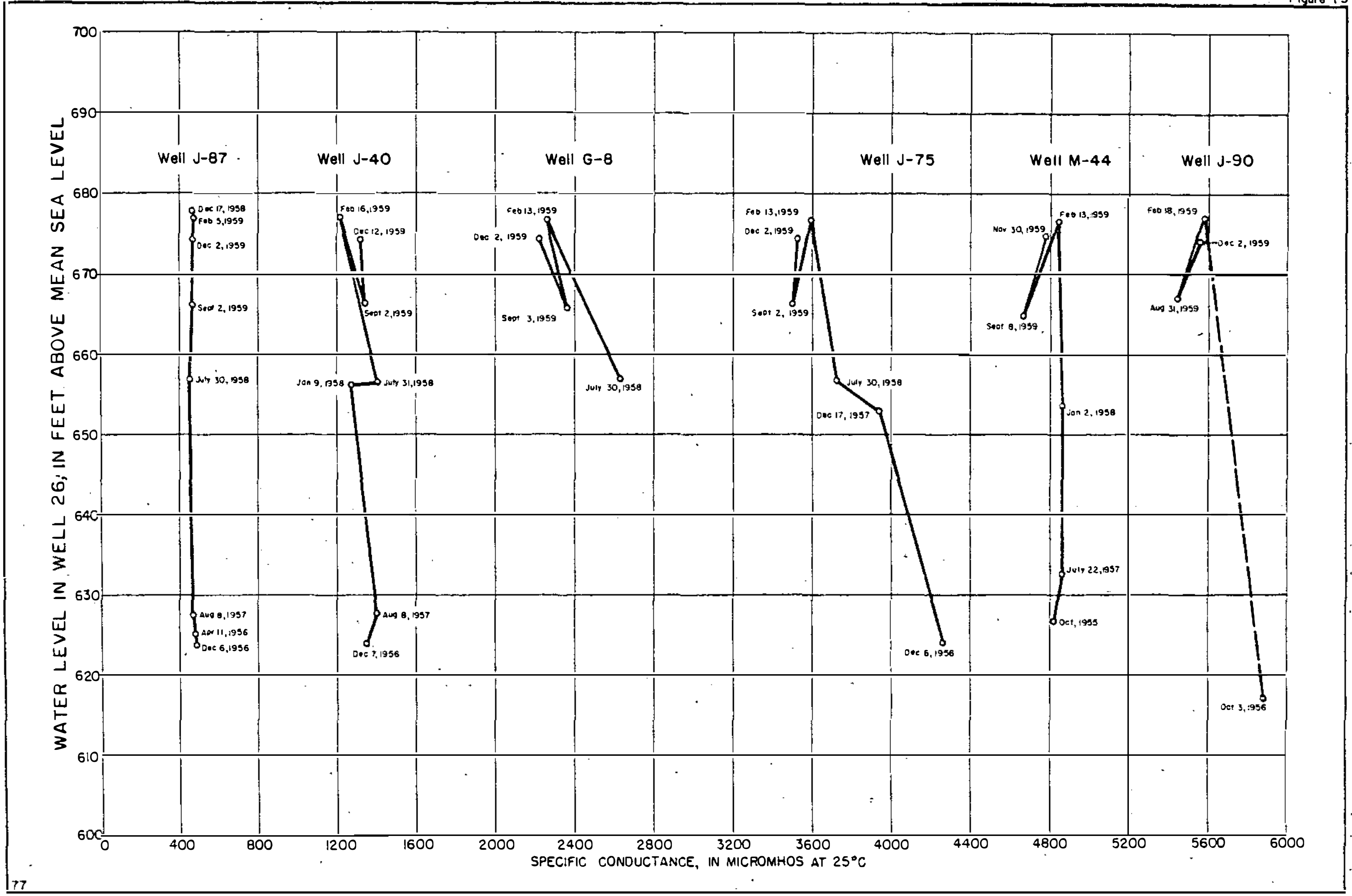
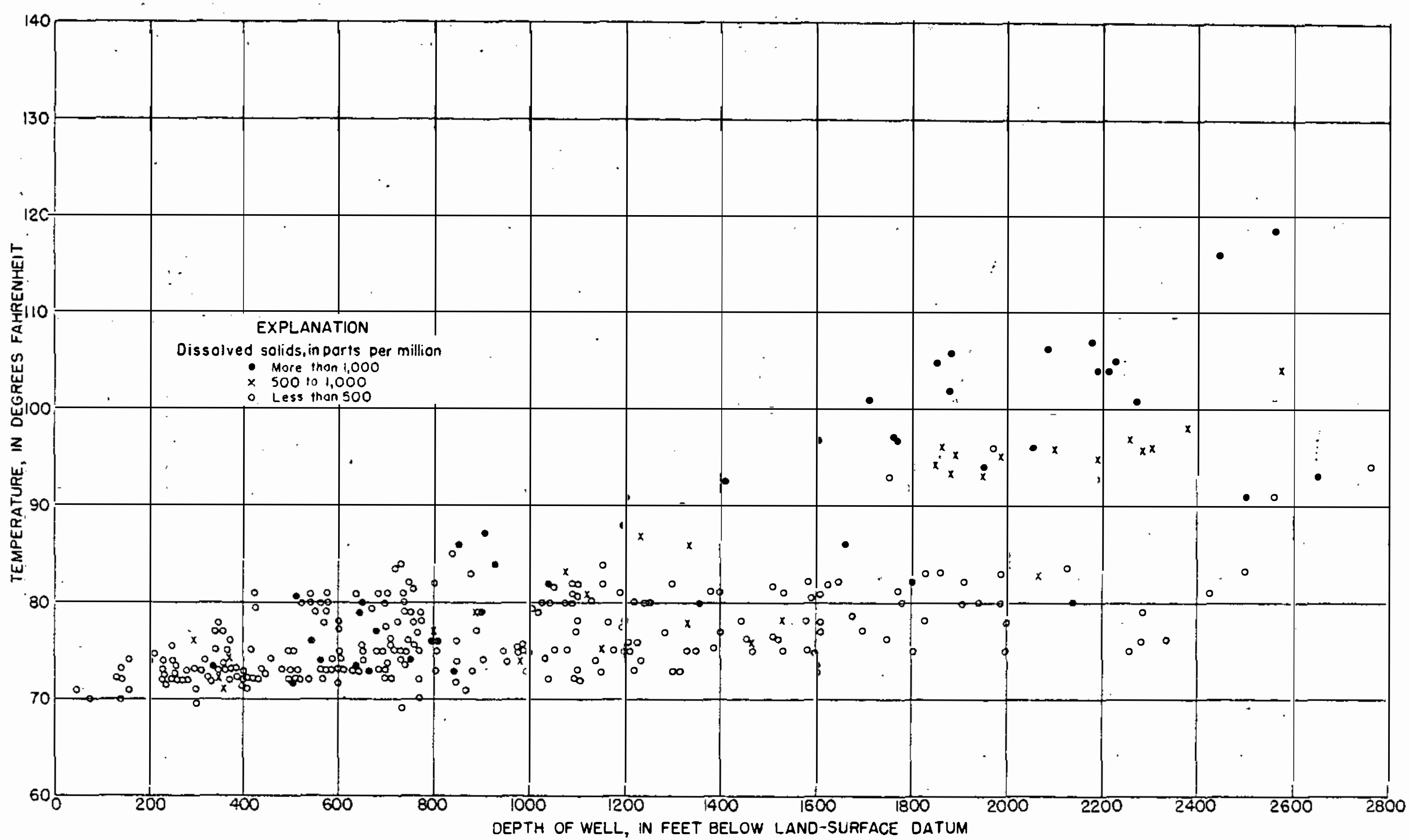


FIGURE 15.—Relation of specific conductance of water from selected wells in the Edwards and associated limestones in Bexar County and altitude of water level in well 26



77

FIGURE 16.– Temperature, depth, and quality of water in the Edwards and associated limestones in the San Antonio area

REFERENCES

Arnow, Ted, 1959, Ground-water geology of Bexar County, Texas: Texas Board Water Engineers Bull. 5911.

Burgreen, David, 1960, Development of flow in tank draining: Am. Soc. Civil Engineers Proc., Hydraulics Div., Jour., v. 86, no. HY3, p. 13-28, March.

DeCook, K. J., and Doyel, W. W., 1955, Records of wells in Hays County, Texas: Texas Board Water Engineers Bull. 5501.

George, W. O., 1952, Geology and ground-water resources of Comal County, Texas, with sections on Surface-water runoff, by S. D. Breeding, and Chemical character of the water, by W. W. Hastings: U. S. Geol. Survey Water-Supply Paper 1138 [1953].

Hem, J. D., 1959, Study and interpretation of the chemical characteristics of natural water: U. S. Geol. Survey Water-Supply Paper 1473.

Holt, C. L. R., Jr., 1959, Geology and ground-water resources of Medina County, Texas: U. S. Geol. Survey Water-Supply Paper 1422.

Lang, J. W., 1954, Ground-water resources of the San Antonio area, Texas: Texas Board Water Engineers Bull. 5412.

Livingston, Penn, 1947, Ground-water resources of Bexar County, Texas: Texas Board Water Engineers mimeo. rept.

________1947, Relationship of ground water to the discharge of the Leona River in Uvalde and Zavala Counties, Texas: Texas Board Water Engineers mimeo. rept.

Livingston, Penn, Sayre, A. N., and White, W. N., 1936, Water resources of the Edwards limestone in the San Antonio area, Texas: U. S. Geol. Survey Water-Supply Paper 773-B.

Lowry, R. L., 1955, Recharge to the Edwards ground-water reservoir: Consulting Eng. Rept. to San Antonio City Water Board.

Meinzer, O. E., ed., 1949, Hydrology, v. 9 of Physics of the earth: New York, Dover Publications, Inc., 702 p.

Petitt, B. M., Jr., and George, W. O., 1956, Ground-water resources of the San Antonio area, Texas: Texas Board Water Engineers Bull. 5608.

Rouse, Hunter, 1950, Elementary mechanics of fluids: New York, John Wiley & Sons, Inc., 365 p.

Sayre, A. N., 1936, Geology and ground-water resources of Uvalde and Medina Counties, Texas: U. S. Geol. Survey Water-Supply Paper 678.

Sayre, A. N., and Bennett, R. R., 1942, Recharge, movement, and discharge in the Edwards limestone reservoir, Texas: Am. Geophys. Union Trans., pt. 1, p. 19-27, August.

Texas Board of Water Engineers and U. S. Geological Survey, 1958, Compilation of surface-water records in Texas through September 1957: Texas Board Water Engineers Bull. 5807-A.

________1959, Summary of peak flood flow measurements and other measurements of stream discharge in Texas at points other than gaging stations: Texas Board Water Engineers Bull. 5807-C.

________1960, Channel gain and loss investigations, 1918-1958: Texas Board Water Engineers Bull. 5807-D.

U. S. Geological Survey, 1960, Surface water supply of the United States, 1958, pt. 8, Western Gulf of Mexico basins: U. S. Geol. Survey Water-Supply Paper 1562.

Welder, Frank, and Reeves, R. D., 1960, Geology and ground-water resources of Uvalde County, Texas: Texas Board Water Engineers open-file rept.

APPROXIMATE ALTITUDE OF WATER LEVELS IN WELLS IN THE EDWARDS AND ASSOCIATED LIMESTONES IN THE SAN ANTONIO AREA, AUGUST 1956

APPROXIMATE ALTITUDE OF WATER LEVELS IN WELLS IN THE EDWARDS AND ASSOCIATED LIMESTONES IN THE SAN ANTONIO AREA, MARCH 1958

QUALITY OF WATER IN THE ZONE OF TRANSITION BETWEEN WATER OF GOOD AND WATER OF POOR CHEMICAL QUALITY IN THE EDWARDS AND ASSOCIATED LIMESTONES IN THE SAN ANTONIO AREA