BULLETIN 5608

VOLUME I

GROUND-WATER RESOURCES OF THE SAN ANTONIO AREA, TEXAS

A PROGRESS REPORT ON CURRENT STUDIES

By

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and
W. O. George, Geologist

Prepared in cooperation with the Geological Survey,
United States Department of the Interior
and the
City of San Antonio

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ABSTRACT

The Edwards and associated limestones constitute the principal ground-water reservoir in the San Antonio area of Texas. The reservoir extends along the Balcones fault zone as a hydrologic unit in parts of Kinney, Uvalde, Medina, Bexar, Comal, and Hays Counties. North of the Balcones fault zone, the rocks of the Edwards Plateau store substantial amounts of water that slowly drain out to form the base flow of the perennial streams that have cut their channels into or through the aquifer.

Recharge to the reservoir in the fault zone is partly by direct infiltration of precipitation on the outcrop of the Edwards and associated limestones, but to a greater extent by seepage from the streams that cross the outcrop in the Balcones fault zone. During the period 1934-53, the estimated annual recharge to the reservoir has ranged from 129,300 to 1,168,200 acre-feet and has averaged 426,300 acre-feet.

Most of the discharge from the reservoir in the San Antonio area has been by springs; however, the quantity of water discharged by wells increased throughout the period 1934-53. The largest increase in discharge by wells has been since 1947, the start of the prolonged drought of recent years. Crops have been irrigated since the founding of the earliest missions in the area, but the amount of water used for irrigation increased greatly during the drought. The amount of water withdrawn for municipal supply has increased as the population and per-capita consumption have increased in San Antonio and other cities in the area. During the period 1934-53 the annual discharge from the reservoir ranged from 395,800 to 615,100 acre-feet and averaged 515,800 acre-feet.

Most of the recharge to the reservoir is in the western part of the area, and the water moves eastward. The springs serve as natural spillways for the reservoir. The two largest, Comal and San Marcos Springs, are in the eastern part of the area. The recharge to the aquifer exceeded the discharge in only three years between 1934 and 1953. A comparison of the difference between recharge and discharge with the water level in an index well indicates that a decline of 1 foot represents a withdrawal of about 55,000 acre-feet from storage.

The difference between the recharge to the reservoir and the discharge from it is indicated by the fluctuations of water levels. Although the water levels have fluctuated rather widely, the trend after 1947 was downward, indicating the water was being withdrawn from storage at an increasing rate.

Many wells are capable of yielding more than 3,000 gallons a minute from the Edwards and associated limestones. However, the lack of homogeniety in the Edwards makes it impossible to predict the yield of a well; wells within a few hundred feet of each other may have widely different yields.

As the water levels have declined, the flow of the springs has declined. Correlations of water levels and spring flows have been made to define the relation that water levels in different areas have to the flow of the springs.

The temperature of the water from the Edwards and associated limestones remains relatively constant to a depth of about 600 feet; between 600 and 1,200 feet, however, it increases at a rate of about half a degree per 100 feet; from 1,200 to 2,500 feet, it increases more rapidly, from approximately 81°F to 117°F, or nearly 3°F per 100 feet.

The water from the Edwards and associated limestones is almost uniformly a calcium bicarbonate water of good quality although somewhat hard. In the southern part of the area the water is charged with hydrogen sulfide, and farther downdip it becomes highly mineralized.

INTRODUCTION

Location and Extent of Area

The San Antonio area, as used in this report, includes the parts of Kinney, Uvalde, Medina, Bexar, Comal, and Hays Counties that lie within and adjacent to the Balcones fault zone. The area forms a curved strip about 200 miles long that ranges in width from about 5 miles to about 40 miles. The boundaries of the area coincide with the boundaries of the underground reservoir that supplies ground water to the city of San Antonio. The reservoir is in the Edwards and associated limestones of Cretaceous age.

Purpose and Scope

The extensive development of ground water in the San Antonio area, occuring simultaneously with a prolonged drought, at the time of this report (1954), had resulted in a material decline in the artesian pressure in the Edwards and associated limestones, which are the major source of water in the area. The persistent decline of water levels in the reservoir brought about the need for a detailed investigation to determine whether water was being withdrawn from the ground-water reservoir in the Edwards and associated limestones at a rate in excess of the normal rate of recharge.

In 1949, the San Antonio Water Board requested the help of the Texas Board of Water Engineers and the United States Geological Survey in making a comprehensive study of the ground-water resources of the San Antonio area with emphasis on the aquifer formed by the Edwards and associated limestones. Several reports have been published covering parts of the area and several others are in preparation. This report is one of a series of progress reports on the ground-water resources of the entire area. (See list of references.) It includes geological studies (Volume I), records of wells and springs (Volume II, part 1), drillers' logs of wells (volume II, part 2), records of water levels in wells, chemical analyses of water, records of selected stream flow and reservoir contents, discharge measurements to determine seepage gains and losses, and records of precipitation (Volume II, part 3). All available data for the estimation of the perennial yield of the Edwards and associated limestones in the San Antonio area are presented. These data include the thickness, depth, and areal extent of the water-bearing formations, estimates of the recharge, discharge, and movement of water in the Edwards and associated limestones in the Balcones fault zone, the relation of water levels to spring flow, and the chemical character of the ground water.

This report was prepared under the administrative direction of A. N. Sayre, chief of the Ground Water Branch of the U. S. Geological Survey, and under the supervision of R. W. Sundstrom, district engineer in charge of the ground-water investigations in Texas.

Previous Investigations

The U. S. Geological Survey and the Texas Board of Water Engineers have collected water-resources data in the San Antonio area for many years. Most of this information has been published in reports of the two agencies. These publications and others pertinent to the area are listed at the end of this report. The data in them have been fully utilized in the preparation of this report.

Acknowledgments

In the compilation of this report, the notes and records of many persons have been used freely. Appreciation is expressed for the interest and assistance of R. A. Thompson, General Manager of the City Water Board of San Antonio, V. H. Braunig, General Manager of the City Public Service Board, and of W. F. Guyton and R. L. Lowry, consultants for the City Water Board. The data furnished by well drillers, geologists, and engineers have been helpful.

TOPOGRAPHY

Physical Features

The San Antonio area lies within two physiographic provinces: the Edwards Plateau and the Coastal Plain. The provinces are separated by the Balcones escarpment, which extends southwestward from Williamson County to San Antonio and thence westward.

The Edwards Plateau, which lies north and northwest of the Balcones escarpment, is underlain, in ascending order, by pre-Travis Peak rocks and the Travis Peak formation, Glen Rose limestone, Walnut clay, Edwards and associated limestones, and remnants of the Washita and younger groups. Streams that rise in the plateau have cut steep valleys and canyons below the upland surface, forming areas of pronounced relief. Much of the plateau has been cut into buttes and narrow ridges, and in many places the Edwards limestone that caps the highest hills is all that remains of the original plateau.

The Coastal Plain lies south and southeast of the Balcones escarpment and consists of a gently rolling plain and moderately hilly country. The Coastal Plain, from the surface down, is underlain by clays, marls, limestones, and sands of Eocene, Paleocene, and Cretaceous age.

Drainage

Most of the area of study lies within the Nueces and Guadalupe River basins (fig. 1). The Nueces River drains the western part of Uvalde County, and its principal tributaries in the area are the West Nueces River which drains the northeastern part of Kinney County, the Frio and Dry Frio Rivers which drain the middle part of Uvalde County, the Sabinal River which drains the eastern part of Uvalde and extreme western part of Medina County, and Seco and Hondo Creeks which drain all but the northeastern corner of Medina County. The Guadalupe River drains most of Comal County. The Medina and San Antonio Rivers drain the northeastern corner of Medina and nearly all of Bexar County. The extreme northern and eastern parts of Bexar County and a part of Comal County are drained by Cibolo Creek. The Blanco River drains the southern part of Hays County and a small part of Comal County. The San Antonio area is drained primarily by perennial streams that rise in the plateau and flow south and southeastward until they reach the southern margin of the plateau, where the water disappears into the Edwards limestone. With the exception of the Guadalupe River, all the streams are dry or flow intermittently after crossing the outcrop of the Edwards limestone.

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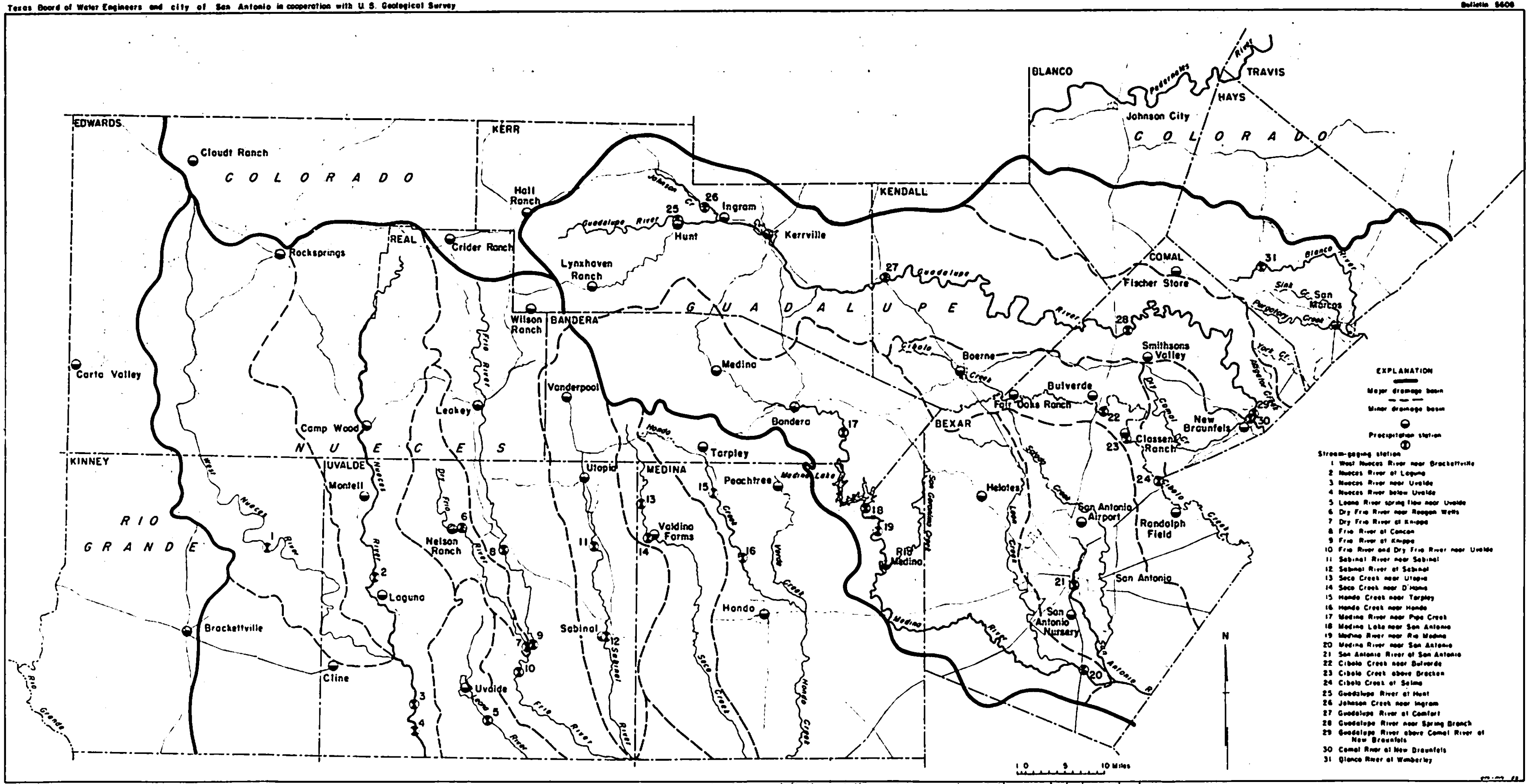

FIGURE 1.- Map of San Antonio and adjacent area showing precipitation stations, stream-gaging stations, and drainage basins.

CLIMATE

Temperature

The San Antonio area has a warm temperate climate. The summers are hot, the daily maximum temperature being above 90° most of the time. Temperatures exceeding 100°F are rare, however, and, because of the Gulf breeze that commonly rises in the evening, the temperature drops rapidly after sunset and the nights are comfortable. The winters are mild, the temperatures generally being well above freezing. Southeast winds prevail throughout the year, but north winds are common during the winter.

The climatic data in the following table show a long growing season, although late killing frosts occasionally occur in the spring.

Table 1.- Climatic data for the San Antonio area.

County and station	Length of record (yrs.)	Temperature				Average dates of killing frosts			
		Jan. normal (°F)	July normal (°F)	Maximum (°F)	Minimum (°F)	Length of record (yrs.)	Last in spring	First in fall	Average growing season (days)
Bexar, San Antonio	68	50.6	84.2	107	0	62	Feb. 24	Nov. 30	279
Medina, Hondo	44	52.9	84.7	112	10	42	Mar. 10	Nov. 23	258
Kinney, Brackettville	35	50.8	84.3	109	9	44	Feb. 26	Nov. 27	274
Uvalde, Sabinal	39	53.6	84.0	111	9	36	Mar. 9	Nov. 12	248
Comal, New Braunfels	63	51.5	83.7	109	2	55	Mar. 2	Nov. 26	269
Hays, San Marcos	50	50.6	83.6	111	1	46	Mar. 11	Nov. 23	257

Precipitation

The San Antonio area lies between a semiarid zone to the west and a zone of heavy coastal precipitation to the east. The average annual rainfall in the area generally is sufficient for normal production of most crops. Precipitation is fairly well distributed throughout the year but is heaviest during April, May, and September. Show in measurable quantity falls only once every 3 or 4 years.

The U. S. Weather Bureau has many precipitation stations in the San Antonio area, and the U. S. Geological Survey has established several supplementary stations as a part of this investigation (fig. 1). Many of the stations have only intermittent records or records too short to indicate significant trends. Stations for which records exceeding 25 years are available are shown in table 2.

The tables (vol. II, pt. 3) and graphs showing the monthly precipitation (figs. 2, 3, and 4) indicate that, in general, if any station has an appreciable amount of rainfall during the month, most of the other stations also have some rain. Although the monthly and annual totals at the several stations are proportional, the rain falls principally in isolated thundershowers and only occasionally in widespread general rains. The average annual rainfall decreases generally from east to west, as shown in the following table.

Table 2.- Average annual precipitation at selected stations in the San Antonio area.

Station	Length of record (years)	Annual average* (inches)
San Marcos	57	33.24
New Braunfels	64	30.88
Fischer's Store	62	29.32
Boerne	63	32.35
San Antonio	81	27.52
Riomedina	32	25.97
Hondo	54	28.55
Sabinal	39	25.29
Brackettville	68	20.08

*Average of complete years only.

GEOLOGY

For purposes of this report, discussion of the geology is limited to the hydrologic properties of the formations and to those structural features that control or influence the movement of water. All the formations underlying the area have some bearing on the ground-water problems; those that are permeable may serve as conduits, and those that are relatively impermeable may restrict the movement of water or confine it to produce artesian conditions. Wide or extensive outcrops of impermeable rocks such as clay or shale tend to increase runoff, whereas outcrops of more permeable rocks such as fractured or honeycombed limestone permit infiltration to the underlying ground-water reservoir and, consequently, decrease direct runoff.

Plate 1 is a geologic map showing the areal distribution of the rocks forming the principal aquifer--the Edwards and associated limestones, and of younger and older rocks. Fault traces and contours on the top of the Georgetown limestone show the main structural features of the area. Geologic cross sections are shown on plates 2 and 3.

The geologic formations are listed in table 3 in their natural sequence, from youngest to oldest, but in the following discussion the rocks are described in the order of their importance as aquifers.

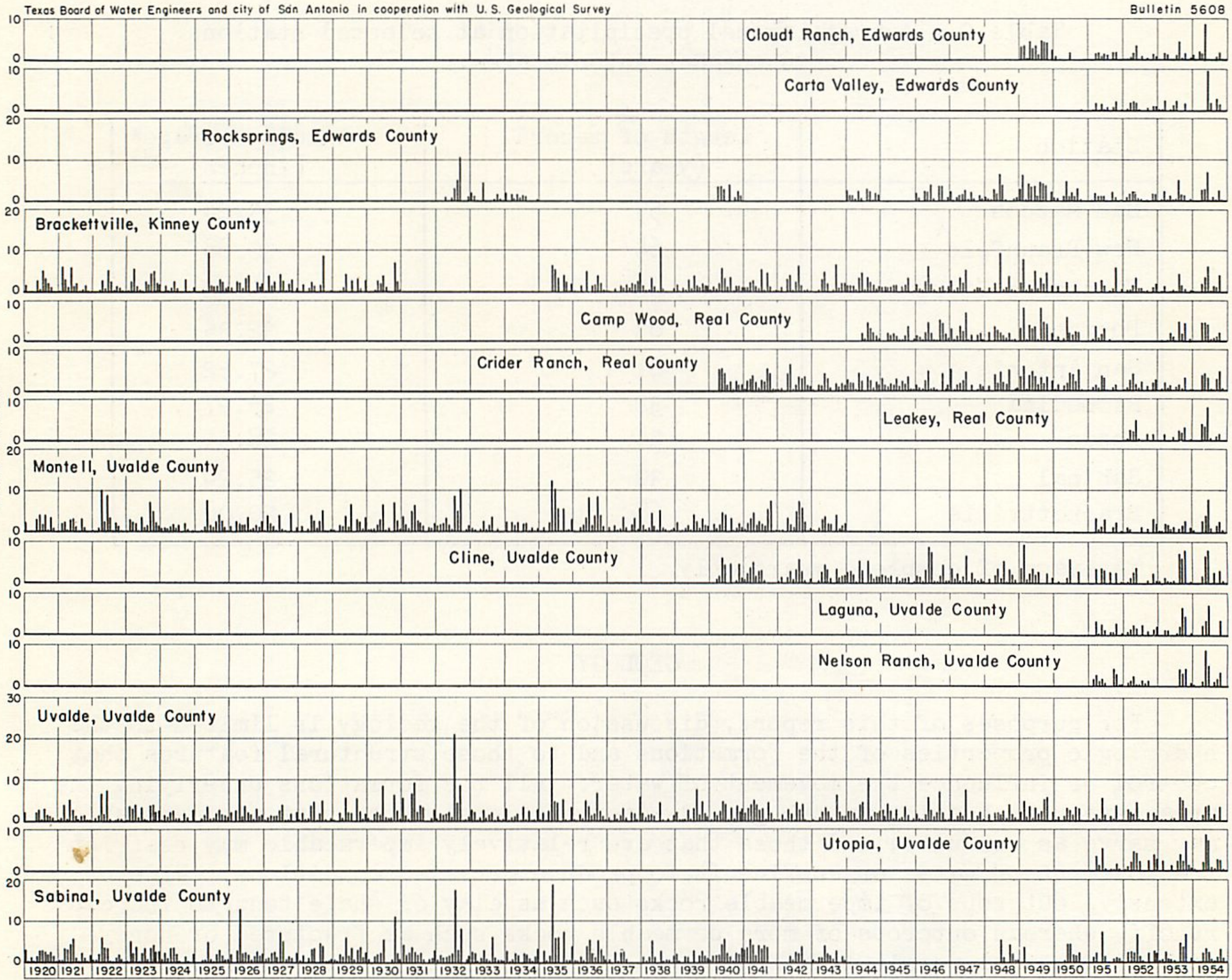

FIGURE 2.-Graphs of precipitation, by months, in Edwards, Kinney, Real, and Uvalde Counties, Tex., 1920-54.

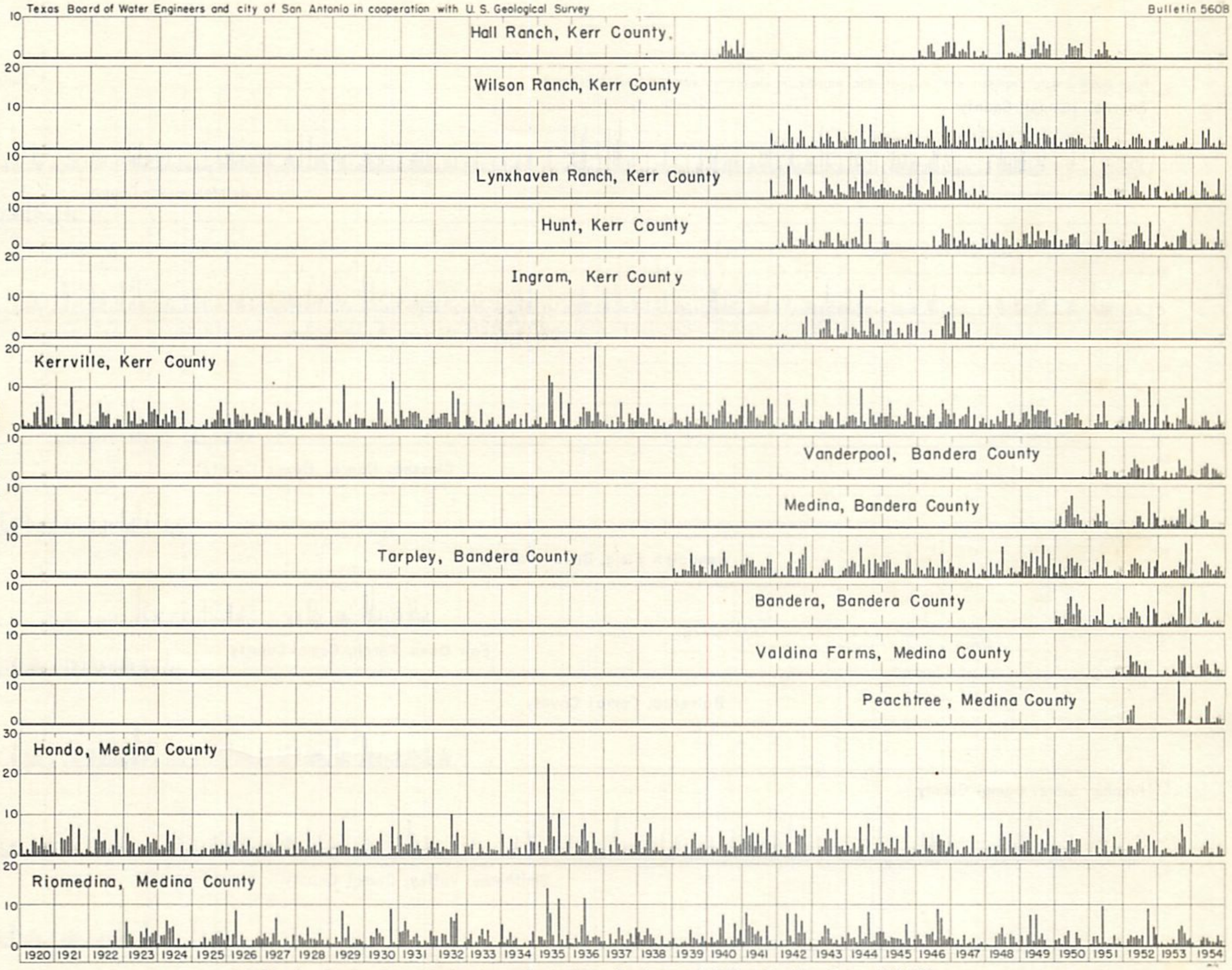

FIGURE 3.- Graphs of precipitation, by months, in Kerr, Bandera, and Medina Counties, Tex., 1920-54.

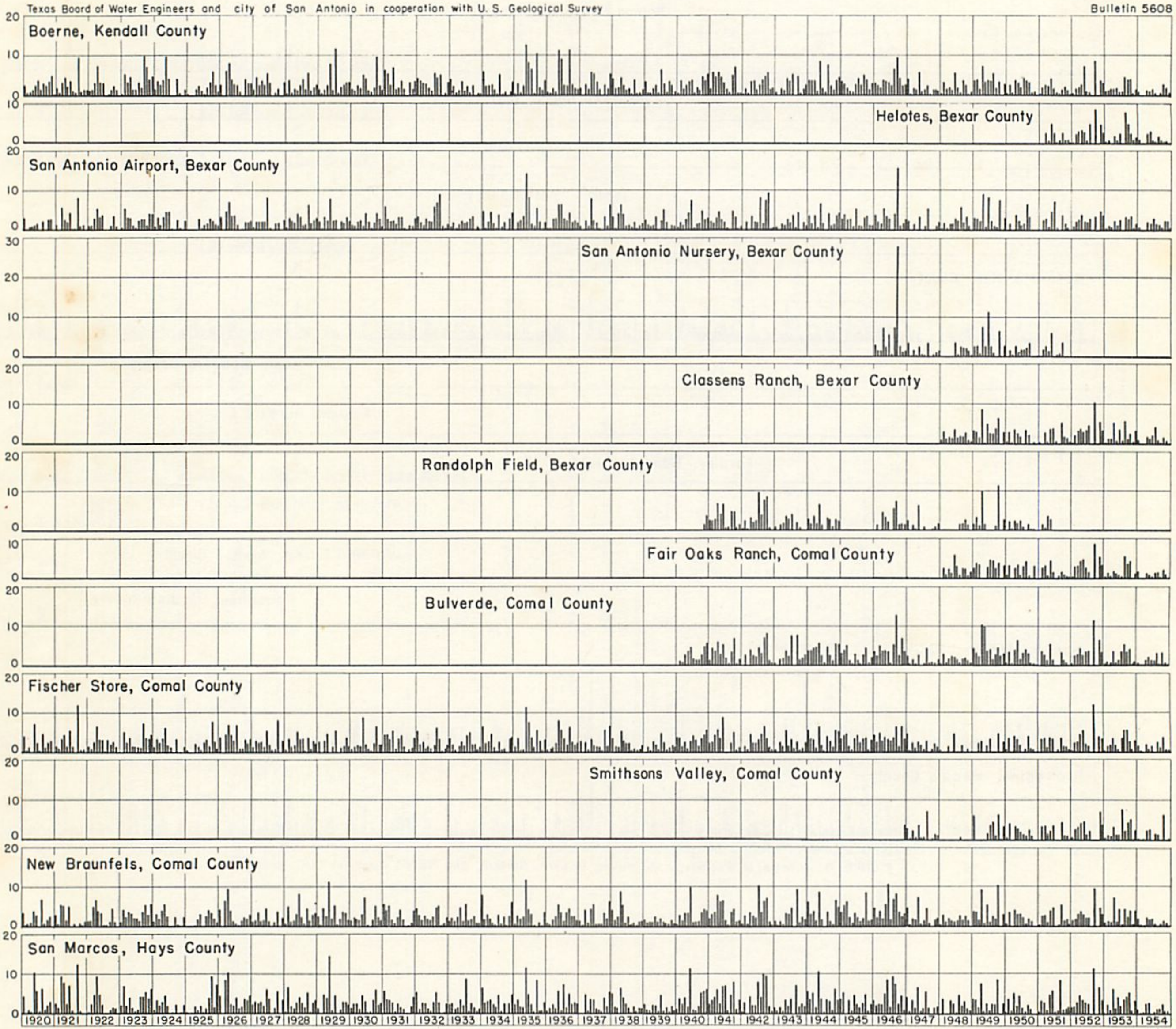

FIGURE 4.- Graphs of precipitation, by months, in Kendall, Bexar, Comal and Hays Counties, Tex., 1920-54.

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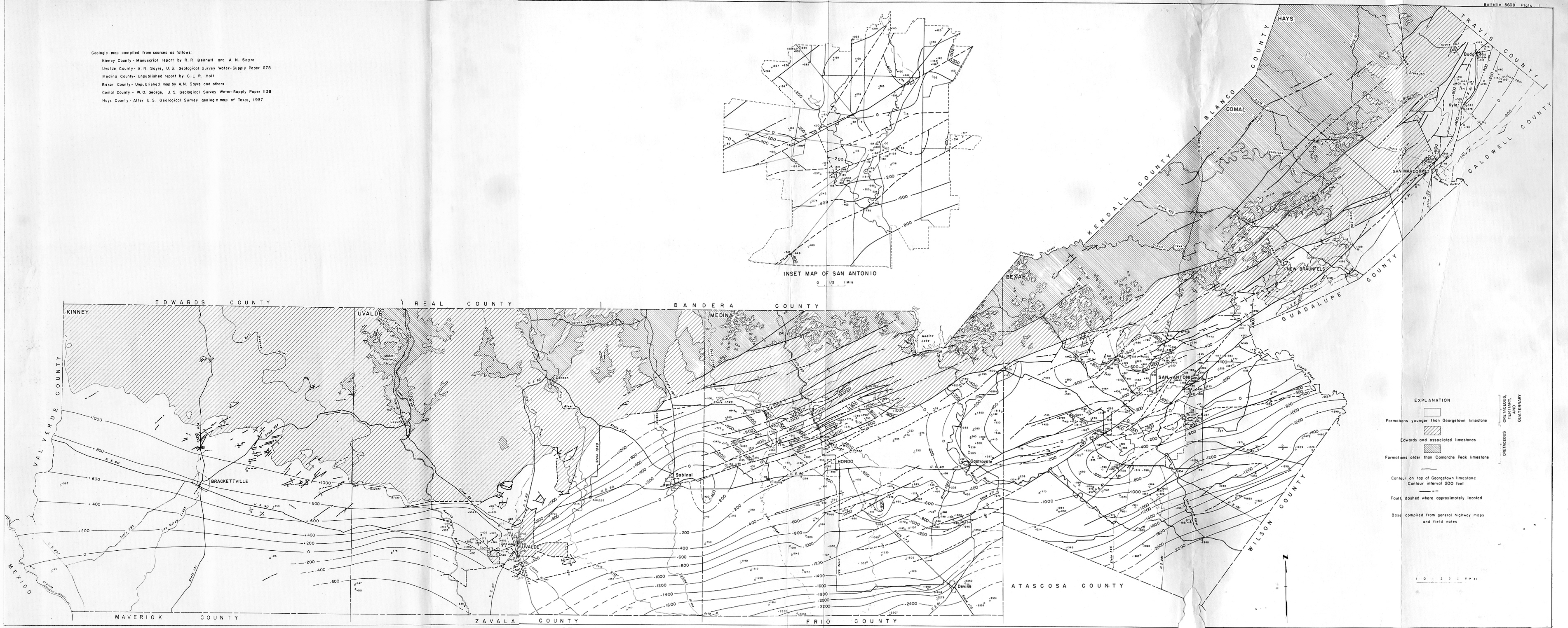

Geologic map compiled from sources as follows:

- Kinney County - Manuscript report by R. R. Bennett and A. N. Sayre
- Uvalde County - A. N. Sayre, U. S. Geological Survey Water-Supply Paper 678
- Medina County - Unpublished report by C. L. R. Holt
- Bexar County - Unpublished map by A.N. Sayre and others
- Comal County - W. O. George, U. S. Geological Survey Water-Supply Paper 1138
- Hays County - After U. S. Geological Survey geologic map of Texas, 1937

GEOLOGIC MAP OF SAN ANTONIO AREA, TEXAS

NORTH-SOUTH GEOLOGIC CROSS SECTIONS IN MEDINA, BEXAR, AND COMAL COUNTIES, TEX.

EAST-WEST GEOLOGIC CROSS SECTION OF SAN ANTONIO AREA, TEXAS

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Table 3.- Geologic formations of the San Antonio area, Texas

System	Group or age	Formation	Thickness (feet)			Character of rocks	Remarks
			Kinney County a/	Bexar County b/	Hays County c/		
Quaternary	Recent		0-20 (?)	0-20	0-15 (?)	Clay, silt, sand, and gravel.	Furnishes potable water in some valleys. Supply generally not dependable.
	Pleistocene	Leona formation	0-30	0-90	0-30 (?)	Silt, sand, and gravel.	Supplies water to irrigation wells in southern Uvalde County.
Tertiary	Pliocene (?)	Uvalde gravel	0-75	0-20	0-10±	Flint, gravel, caliche, and sand.	Furnishes potable water in parts of southwestern Kinney County. Generally too thin elsewhere.
	Claiborne group	Carrizo sand	Absent	200	Absent	Mostly sand; some clay.	Supplies water for irrigation and public supplies south of the area.
	Wilcox group	Undifferentiated	Absent	650±	Absent	Fine salt and pepper sand, clay, and lignite	Small yield to domestic wells, mostly of poor quality.
	Midway group	Undifferentiated	Absent	650±	Absent	Mostly clay.	Yields no water.
Cretaceous	Navarro group	Undifferentiated	Featheredge exposed in southern part of county	300±	300±	Mostly clay.	Includes the Escondido formation, which yields some water from sandy facies in western Medina County.
	Taylor age	Undifferentiated	400-500	150-600	300±	Marl and limestone	Taylor marl east of Bexar County grades into Anacacho limestone west of Bexar County. Anacacho yields small supplies to wells.
	Austin age	Austin chalk	400-600	125-400	200±	Limestone and chalk	Moderate to large supplies of water in outcrop, generally of poor quality.
	Eagle Ford age	Eagle Ford shale	150-350±	25-90	25±	Shale, lignite, and sandstone	Small supplies of water west of Bexar County.
	Washita group	Buda limestone	80-110	40-120	30-60	Limestone	Generally unproductive. Some large yields reported locally in Bexar County.
		Grayson shale	40-155	50-100±	35	Clay and fossil aggregates	Not water bearing. Locally known as Del Rio clay.
		Georgetown limestone	50-550	20-50	30-40	Hard limestone	Yields water in large quantities in Bexar County and westward. Included as Edwards limestone by most drillers.

Table 3.- Geologic formations of the San Antonio area--Continued

System	Group or age	Formation	Thickness (feet)			Character of rocks	Remarks
			Kinney County [a]	Bexar County [b]	Hays County [c]		
Cretaceous	Fredericksburg group	Edwards limestone	550	500±	500±	Hard limestone	Principal water-bearing formation in the area.
		Comanche Peak limestone	60-70	40±	30-40	Limestone	Thickness includes Walnut clay in Kinney County. Not distinguished from Edwards limestone in wells.
		Walnut clay	-	1-20	10±	Limestone and marl	Does not yield water.
	Trinity group	Glen Rose limestone	1,000-2,000	1,000-1,200	800±	Limestone and shale	Generally tight, yielding small quantities of water with high sulfate content. Locally cavernous, yielding moderate quantities of good quality.
		Travis Peak formation	(?)	100-400±	200±	Limestone, marl, sandstone, and conglomerate	Yields water of fair to poor quality in small to moderate amounts.
	Sligo age	Sligo formation	140 (?)	[d] 60-700	(?)	Limestone and black shale	Possibly yields some water to wells, especially in eastern part of area. Often reported as Trinity by drillers. Does not crop out in Texas.
	Hosston age	Hosston formation	140	60-240	(?)	Sandstone, shale and limestone	Water-bearing properties not tested but believed to be relatively poor.

[a] Bennett, R. R., and Sayre, A. N., Unpublished manuscript.

[b] Lang, Joe W., 1954, p. 8.

[c] From field notes by K. J. DeCook.

[d] Imlay, Ralph W., 1945.

Water-Bearing Formations

Edwards and associated limestones.- The Comanche Peak, Edwards, and Georgetown limestones have a greater capacity, both as a conduit and as a reservoir, than all other formations in the San Antonio area. The Edwards and associated limestones supply most of the water for municipal, industrial, irrigation, and domestic use in the San Antonio area. The aquifer also supplies the largest springs in Texas.

The Edwards limestone is the surface rock in parts of a dozen or more counties lying north and northwest of San Antonio. This area is known as the Edwards Plateau. On a part of the plateau, the Edwards is covered by younger rocks, but, where it is exposed, conditions are favorable for direct infiltration of rainwater.

Along the southern edge of the plateau, streams have cut through the Edwards limestone, exposing the underlying Glen Rose limestone, and in places the Walnut clay. The streams are fed by springs which issue from the basal part of the nearly flat lying Edwards, causing the ground-water reservoir underlying the Edwards Plateau to be partly drained. The streams flow southward on beds of the Glen Rose limestone until they cross a fault zone in which the Edwards limestone reappears at the surface. Most of the water then infiltrates into the Edwards limestone again and enters the main ground-water reservoir.

The Edwards limestone, as seen at the surface, is weathered generally to form a honeycomb rock. In places it forms a relatively flat surface having a reddish soil containing rounded residual pebbles or cobbles of flint. Sinkholes are common in such areas. In its unaltered state, most of the Edwards is a dense, hard limestone, and in places the texture is that of lithographic stone. Soft beds reported by drillers are generally those beds that have been dissolved by underground water and are now only a spongelike rock called honeycomb limestone. Irregularly distributed caverns are found in the outcrop and are indicated downdip in drillers' logs by such notes as "cavity, 2 feet." Interconnected solutional cavities of all shapes and sizes form more or less linear channels, which generally follow fractures that are associated with and parallel to faults. Beds containing large numbers of fossils appear to be more porous or more susceptible to solution than others. Some water is encountered in the upper 100 feet of the formation in nearly every well; however, in some wells large yields have been obtained from the upper part of the formation. In general, however, wells that penetrate only the upper part of the Edwards limestone have smaller yields than those that penetrate the entire thickness of the formation.

The average thickness of the Edwards limestone is probably about 350 feet, but because of the difficulty in determining its upper and lower limits, the exact thickness cannot be determined in all parts of the area. The average thickness reported by drillers is about 500 feet, but this often includes the Georgetown and Comanche Peak limestones.

The Comanche Peak limestone underlies the Edwards limestone. The Comanche Peak is a hard limestone but is less brittle than the Edwards. Although the limestone is recognizable in outcrop, it is not easily distinguished by drillers, and it is included generally as part of the Edwards. It ranges in thickness from 30 to 70 feet.

The Georgetown limestone lies unconformably upon the Edwards limestone. In much of the San Antonio area the Georgetown-Edwards contact shows no evidence of the unconformity; however, the Kiamichi formation, which intervenes between the Edwards and Georgetown in some other areas, is absent throughout the San Antonio area, and in some places the upper part of the Edwards and possibly the lower part of the Georgetown are missing.

From Medina County eastward, the unconformity between the Edwards and Georgetown limestones may be located in outcrops by faunal differences and by lithic changes at the contact. Nodules of flint or chert, which here are characteristic of the Edwards, are not found in the Georgetown. West of Medina County the contact is difficult to locate. Flint is found higher in the section and, although there are some characteristic fossils in the Georgetown, the contact with the Edwards is not sharply defined.

In outcrops east of Uvalde County, the Georgetown limestone seems to have been only slightly affected by solutional processes and the beds rarely appear honeycombed. From Bexar County westward, the Georgetown yields water to some wells, but most of the water comes from cavities in the Edwards limestone. In drillers' logs, the Comanche Peak, Edwards, and Georgetown limestones are often grouped as one unit and called Edwards.

Glen Rose limestone.- The Glen Rose limestone, separated from the Comanche Peak limestone above by the Walnut clay, crops out in the northern part of the Balcones fault zone and in wide valleys north of the fault zone, where the overlying rocks have been removed by erosion. The Glen Rose as a whole is a poor aquifer. Yields generally are small and most of the water is of poor quality. The water occurs in thick beds of limestone and dolomite separated by beds of clay or marl. Drill cuttings from some wells contain particles of gypsum (hydrous calcium sulfate), which is more soluble than limestone. The solution of gypsum increases the permeability of the formation and at the same time increases the sulfate content of the water. Gypsum has been found mostly in beds near the middle of the Glen Rose; however, this part of the formation yields relatively small quantities of water.

Two large caves in Kendall County and large seepage losses in the bed of Cibolo Creek where it crosses the Glen Rose suggest that in some places the lower member of the Glen Rose is capable of transmitting large volumes of water. In apparent contradiction, however, many wells that have penetrated the entire thickness of the lower member of the Glen Rose limestone generally have not obtained large yields. Although most of the wells have been drilled for domestic and stock use and consequently have not been tested for maximum yield, very few of those wells so tested have produced more than 50 gallons per minute (gpm). One or two wells at Camp Bullis, in northern Bexar County, have yields of about 350 gpm. In Comal County, water levels in the deeper wells are lower generally than those in shallow wells. This suggests a possibility of free movement of water out of the Glen Rose into the Edwards and associated limestones at places where faulting has brought the two units together.

Seepage measurements along that part of the Guadalupe River which flows over the lower member of the Glen Rose limestone indicate that a large part of the flow is lost from the river near Spring Branch in Comal County and is returned to the river by springs a few miles downstream.

Similar, although smaller, losses and gains occur in those portions of the Medina, Frio, Sabinal, Hondo, and Nueces Rivers that flow over the outcrop of the Glen Rose. Seepage measurements indicate that most of the water lost from these streams by way of faults and cavernous passages is returned before the streams pass onto the Edwards limestone.

Leona formation.- The Leona formation, of Pleistocene age, crops out in the valleys of all the larger streams along the Balcones fault zone and is found to a lesser extent along the smaller tributaries. The formation is composed of clay, silt, sand, and gravel laid down by the rivers in the form of terrace deposits. Gravel generally is present in the lower part of the formation. The Leona also contains much caliche, which is a calcium carbonate residue formed by the evaporation of ground and surface waters.

In the valley of the Leona River, south of Uvalde and north of Batesville, the Leona formation is several miles wide and has a maximum thickness of 70 feet. The average thickness of the formation, where present, in the San Antonio area is about 30 feet.

Although the Leona formation is spread over a fairly large area in Bexar County, in San Antonio along the San Antonio River the formation is thin, and wells yield only a few gallons a minute. Near Batesville in Zavala County some wells in the Leona produce enough water to irrigate 200 to 300 acres, but, because of the limited storage capacity of the formation, the wells are not dependable during droughts.

The surface of the Leona formation is nearly flat in most places, and rainfall infiltrates easily into the sandy soil. Some of this water, however, is lost by evapotranspiration. In places, especially along the Nueces River, the broad flats support a fairly dense growth of mesquite and other water-loving plants. The Leona provides temporary storage for the water that is not lost by evapotranspiration. Where the Leona lies directly on the Edwards limestone, a considerable volume of Water may move from it into the Edwards and associated limestones.

Travis Peak formation.- The Travis Peak formation, which underlies the Glen Rose limestone and is the oldest formation of the Trinity group, crops out in western Travis County, where it has been divided into three members: the Hensell sand member at the top, the Cow Creek limestone member in the middle, and the Sycamore sand member of Hill (1901) at the base. The Travis Peak changes in character along the strike. In Comal County, the Hensell sand member is represented by marl beds that are relatively impervious; the Cow Creek limestone member is cavernous in some places and generally yields more water than the Glen Rose limestone. The Sycamore sand member has not been recognized in wells.

It is quite possible that the Cow Creek limestone member is one of the conduits that carries water from the Cibolo Creek drainage basin. Although the volume of water transmitted through the Cow Creek to the Edwards limestone reservoir may be significant in Comal and Kendall Counties, where the Cow Creek is at or near the land surface, it is probable that much smaller quantities of water are transmitted through it west of Bexar County, because there the Cow Creek is more deeply buried. About 40 feet of relatively impervious greenish-gray to black shale and limestone underlie the Cow Creek limestone member. The correlation of these beds is questionable.

KRH- note

Austin chalk.- The Austin chalk, also of Cretaceous age (table 3), is at or near the surface in much of the artesian area of the Edwards and associated limestones. In general, the Austin chalk is a poor aquifer, yielding only small quantities of water to wells. Moreover, in most places, the water contains hydrogen sulfide gas and minerals in objectionable quantities.

Throughout the area the Grayson shale, Buda limestone, and Eagle Ford shale lie between the Austin and the Edwards and associated limestones. Water in the Edwards and associated limestones is under artesian pressure where overlain by the Grayson, Buda, and Eagle Ford, thus proving that the three formations are relatively impervious. Their combined thickness ranges from about 100 to 300 feet in most of the artesian area. However, water under artesian pressure in the Edwards and associated limestones breaks through the cover, presumably along faults, as is indicated by the spring at Brackettville and the former springs at Brackenridge Park in San Antonio. Locally near San Antonio, wells in the Austin chalk yield water similar in chemical quality to the water obtained from the Edwards and associated limestones, and water levels rise and fall with those of wells in the Edwards and associated limestones, indicating a direct connection between the formations.

Hosston and Sligo formations.- The Hosston formation and the overlying Sligo formation are exposed at the surface in Mexico but do not crop out in Texas. The formations are well known to oil geologists in south Texas but are seldom recognized in water wells.

Test holes drilled by the Guadalupe-Blanco River Authority to explore a dam site on the Guadalupe River in Kendall County penetrated the Sligo formation and a part of the Hosston formation. The Sligo at this locality is light- to dark-gray limestone with shale partings; the Hosston is mostly gray to red siltstone but contains about 15 feet of sandstone. The sandstone probably has been called the Trinity in the drillers' logs of some water wells. The Hosston is not likely to yield much water nor is it a probable contributor to the Edwards and associated limestones.

Rocks of Taylor age and the Navarro group.- In southern Bexar County, the Austin chalk is buried under nearly 1,500 feet of relatively impermeable non-water-bearing clay and shale that are of Taylor age or belong to the Navarro group. West of Bexar County, the Taylor marl grades into the Anacacho limestone, and the Escondido formation of the Navarro group becomes sandy in western Medina County. The Anacacho and Escondido yield small amounts of water for domestic and stock use.

Structure

Faults.- The Balcones fault zone consists of a series of more or less parallel faults extending from Williamson County southwestward to Bexar County and thence westward. West of Uvalde County, the forces that caused the faulting were weaker, and the fault zone grades into a monocline that dips rather steeply southward. Most of the faults are of the normal or tension type with the downthrow to the south or east, depending on the strike. They range in length from a few hundred feet to about 50 miles. Displacement is greatest generally near the middle of the fault trace, and the maximum displacement of any single fault is about 700 feet. In Comal County, the combined displacement of all the faults is about 1,500 feet. The amount of displacement is greater than the slope of the surface, so that in general each faulted block exposes successively younger rocks in a southward or eastward direction. Some of the smaller faults are probably surficial, resulting from the collapse of the roofs of solutional caverns. On the other hand, caves and caverns also are associated with the major, deep-seated faults. The rocks in the vicinity of the faults were jointed in the process of faulting, and both the joints and the faults were enlarged by solution to form caverns.

In most places where the displacement of the Edwards and associated limestones does not exceed the thickness of the aquifer, water appears to flow across the fault planes from one part of the aquifer to another without much retardation. In a few places, however, the differential movement along the fault plane left finely ground rock (gouge), which is nearly impervious. Where the displacement is greater than the thickness of the Edwards and associated limestones and the overlying relatively impervious beds have been brought into contact with the aquifer, the downdip movement of water may be impeded or cut off. However, considerable volumes of water from the Edwards and associated limestones can and do move upward along fault planes through the Grayson shale, the Eagle Ford shale, and a part of the Austin chalk. This is shown by the flow of water from the Edwards and associated limestones in springs issuing from the Austin chalk at Brackettville and (formerly) at San Antonio in Brackenridge Park.

Folding.- Large-scale folding is not common in an area such as the Balcones fault zone where deformation is the result of tensional forces. However, Sellards (1919, p. 83) described and named the Culebra structure in Bexar County, which extends westward for a short distance into Medina County (Holt, 1954). The structure seems to have no effect on the movement of ground water.

In the northwestern part of Guadalupe County, near Cibolo Creek, the pattern of outcrops suggests some sort of uplift. Is is significant that water of good quality is not found in this area, and it is possible that an uplift causes the water in the Edwards and associated limestones to be diverted northward into the area of water-table conditions in Comal County.

Igneous rocks

Intrusions of basic igneous rocks in the Balcones fault zone have been described by Lonsdale (1927). The intrusions are generally in the form of plugs, many of which form rounded hills of black rock. Many such hills can be seen in Uvalde County, and a few in Travis County. Elsewhere along the Balcones fault zone, only small traces of igneous rocks are found at the surface. Nearly all the outcrops are composed of basalt or other basic rocks.

Under favorable circumstances, intrusives may branch out to form sills or dikes. Sills are relatively thin sheets of intrusive rocks that are parallel to the bedding planes of the intruded sedimentary rock. At Knippa in Uvalde County, a well was drilled through a sill about 70 feet thick in the Edwards limestone, and a good supply of water was obtained in the Edwards and associated limestones below the sill.

Dikes also are relatively thin, but they are in the form of sheets that cut across the bedding planes of the intruded sedimentary rocks. An extensive dike could form a ground-water dam that would change the direction of movement of ground water. Southwest of Bandera in Bandera County, the presence of a dike with a definite linear outcrop suggests the possibility that other smaller outcrops of igneous rocks might mark the presence of bodies that are interconnected beneath the surface in the form of dikes.

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The igneous rocks in the Balcones fault zone probably cause local diversion of ground water, but they probably do not seriously change the general direction of movement. Igneous rocks are not significant as aquifers in the Balcones fault zone.

HYDROLOGY

Recharge, or the amount of water that flows into an aquifer, must equal the discharge over a long period under a natural regimen. In the San Antonio area, discharge is both natural and artificial--from springs and from wells. In times of drought the volume of water in storage declines; during floods the aquifer is replenished. The length of time that water can be withdrawn at a given rate without replenishment depends upon the volume of water stored in the reservoir.

The principal water-bearing formation in the San Antonio area is the Edwards limestone. However, because in some places it is impossible to distinguish the Edwards from the overlying Georgetown limestone and the underlying Comanche Peak limestone, both of which are water bearing, the three formations are referred to as the Edwards and associated limestones. That term is used to designate the aquifer.

Because of the irregularity of the solution channels, joints, and other fractures in the Edwards and associated limestones, the porosity varies tremendously, both horizontally and vertically. Estimates of the capacity of the reservoir to yield water may be based on records of inflow and outflow. Changes of water levels in wells indicate whether the reservoir is filling or draining. When recharge is greater than discharge, water levels rise and the flow of springs increases; when discharge is greater than recharge, water levels lower and the spring flow decreases. The spring flow can be measured; the pumpage is determined by inventory. The recharge is estimated from records of losses from streams that cross the outcrop, rainfall records, and water-level measurements.

The program of hydrologic observations in the San Antonio area has been in progress since 1929 and was greatly intensified after 1949. Although the records are not as complete as might be desired, they cover a wide range of climatic conditions including a severe drought. In order to estimate the average annual yield of the reservoir, it has been necessary to extrapolate and to estimate by proportion for areas where adequate data were not available and for periods when observations were not made.

Recharge

The ground-water reservoir in the fault zone is recharged in part by direct infiltration of precipitation on the outcrop but to a great extent by seepage from streams that cross the outcrop of the aquifer along the Balcones fault zone. The recharge to the reservoir is closely related to the runoff in the streams. With the exception of the Guadalupe River, all the streams that rise in the Edwards Plateau lose most of their flow to the reservoir.

The ground-water reservoir of the Edwards Plateau is not directly connected with the reservoir system in the fault zone except in a few places. However, the two are hydraulically connected because the streamflow from the plateau furnishes continuous recharge to the reservoir in the fault zone.

The U. S. Geological Survey and the Texas Board of Water Engineers have maintained gaging stations for many years on the major streams (fig. 1). For the present phase of the investigation additional gages were established both above and below the recharge areas on almost all the streams of any consequence. The monthly mean discharges of the streams are shown in figures 5, 6, 7, and 8. In addition to the discharge measurements at the established gaging stations, seepage studies have been made at different stages of the streams to determine the stretches where the streams lose water and the amounts lost (vol. II, pt. III). These data have been used to estimate the stream-stage-loss relationships in the determination of the recharge to the ground-water reservoir from the hydrographs of the individual streams.

Recharge from the Nueces River and tributaries.- Gaging stations have been maintained on the Nueces River at Laguna since October 1923, below Uvalde since April 1939, and near Uvalde from October 1927 to April 1939. From September 1939 through September 1950 a gage was maintained on the West Nueces River near Brackettville (fig. 1).

The regimen of the Nueces River has been discussed in considerable detail by Sayre (1936, p. 73-81); the following excerpts are from his report:

> The Nueces River enters Uvalde County near the northwest corner and flows for a distance of about 20 miles in a steep-walled, rather narrow flat-bottomed valley similar to the valleys of other streams in this part of the Edwards Plateau. It emerges from the steep-walled valley about 3 miles above the mouth of the West Nueces River. Thence downstream for a distance of about 7½ miles the river valley is bounded on the west by fairly high hills and on the east by a gently rolling plain that rises gradually from the river. About three-fourths of a mile above the Uvalde gaging station the width of the valley is reduced to a little more than a mile, and it is bounded on both sides by steep but moderately low valley walls. This constricted portion of the valley extends downstream for a distance of about 3 miles. Below this point the valley becomes gradually wider and the walls rise gently from the river.
>
> The West Nueces is the only large tributary to the Nueces in Uvalde County, and it seldom has a flow at its mouth. The numerous smaller tributary valleys are dry most of the time, but on occasions, usually months and sometimes years apart, during and immediately after exceptionally heavy rains, these streams contribute largely to the flow of the river.
>
> In Uvalde County bedrock is exposed in the bed of the river in some places, but in most places the bedrock is covered and the river bed and adjacent terraces are underlain by gravel. The gravel deposits in the section of the valley above the mouth of the West Nueces have a smaller areal extent and are apparently thinner than in the section between the mouth of the West Nueces and the Uvalde gaging station. In that section the maximum thickness is not known, but thicknesses of 52 and 75 feet are reported in wells H-4-26 and H-4-10.

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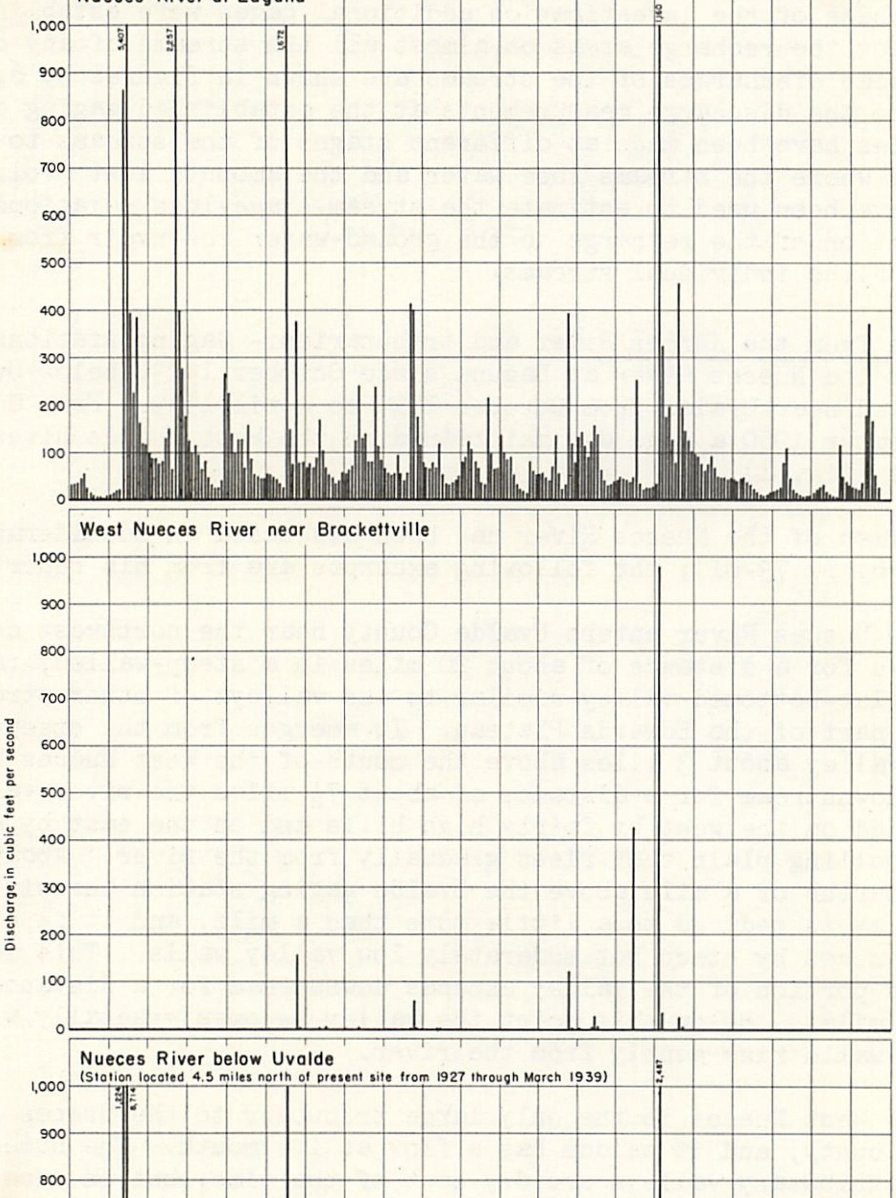

FIGURE 5.—Monthly mean discharge of Nueces River and West Nueces River in the San Antonio area, Tex., 1934-54.

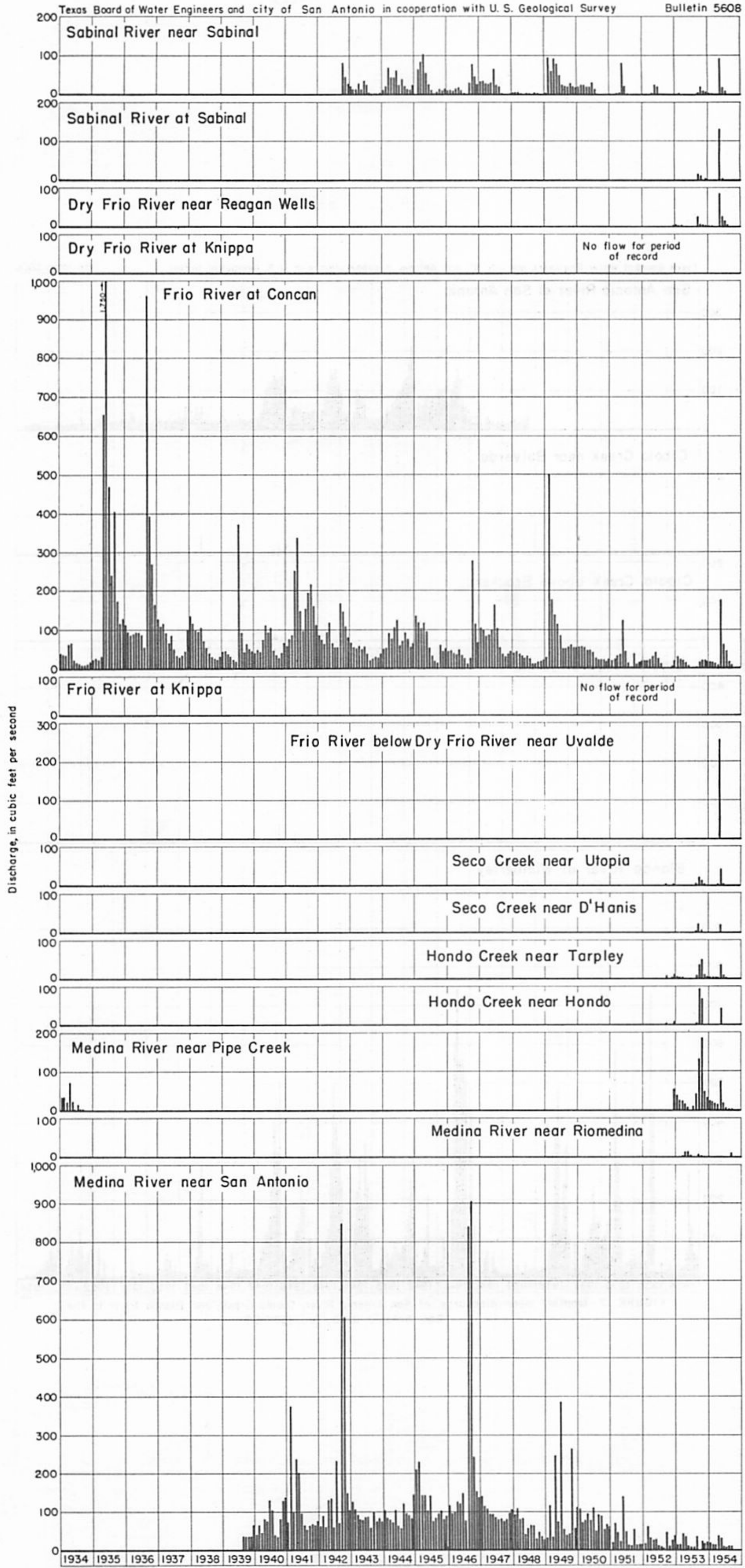

FIGURE 6.- Monthly mean discharge of Sabinal River, Dry Frio River, Frio River, Seco Creek, Hondo Creek, and Medina River in the San Antonio area, Tex., 1934-54.

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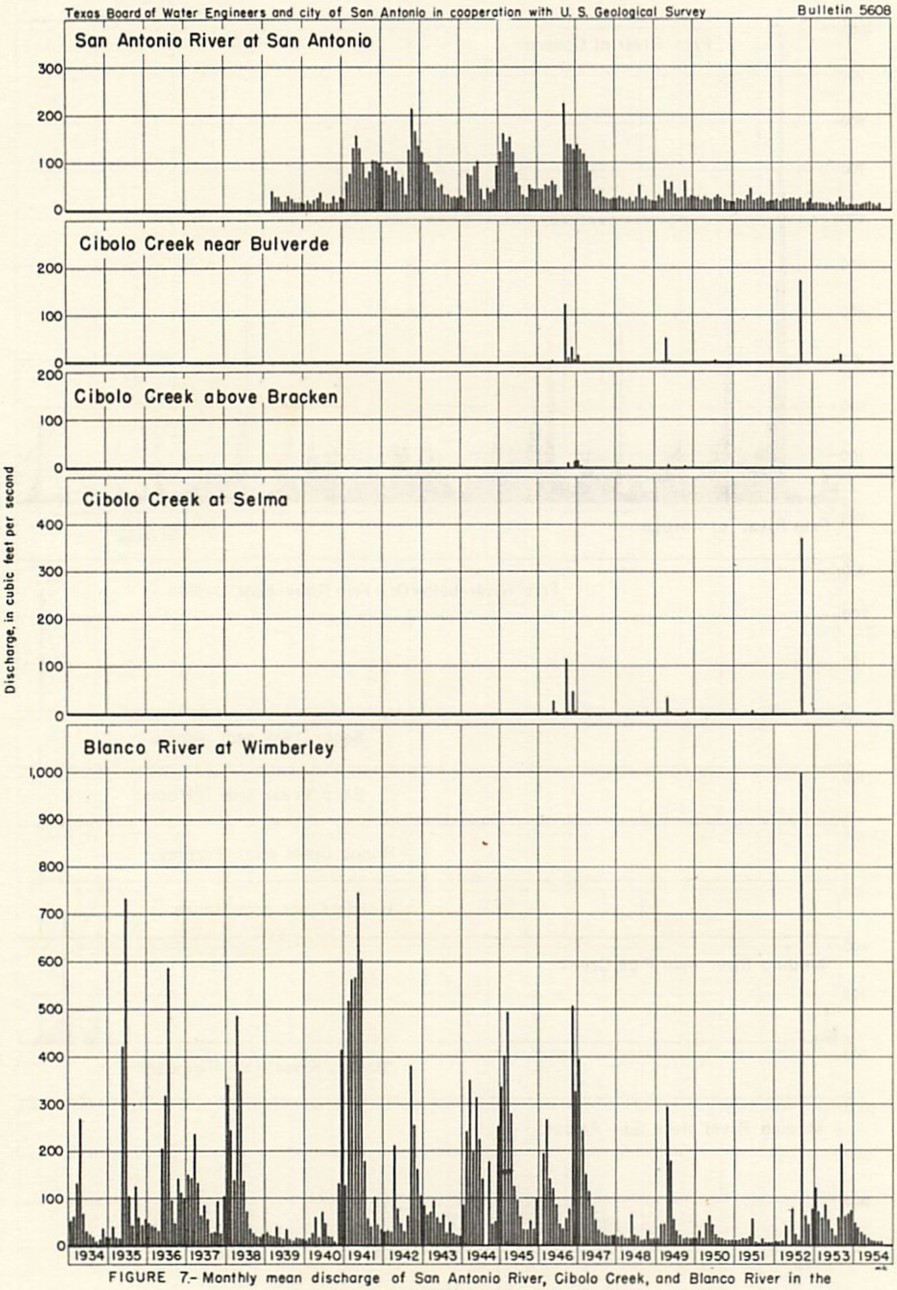


FIGURE 7.- Monthly mean discharge of San Antonio River, Cibolo Creek, and Blanco River in the San Antonio area, Tex., 1934-54.

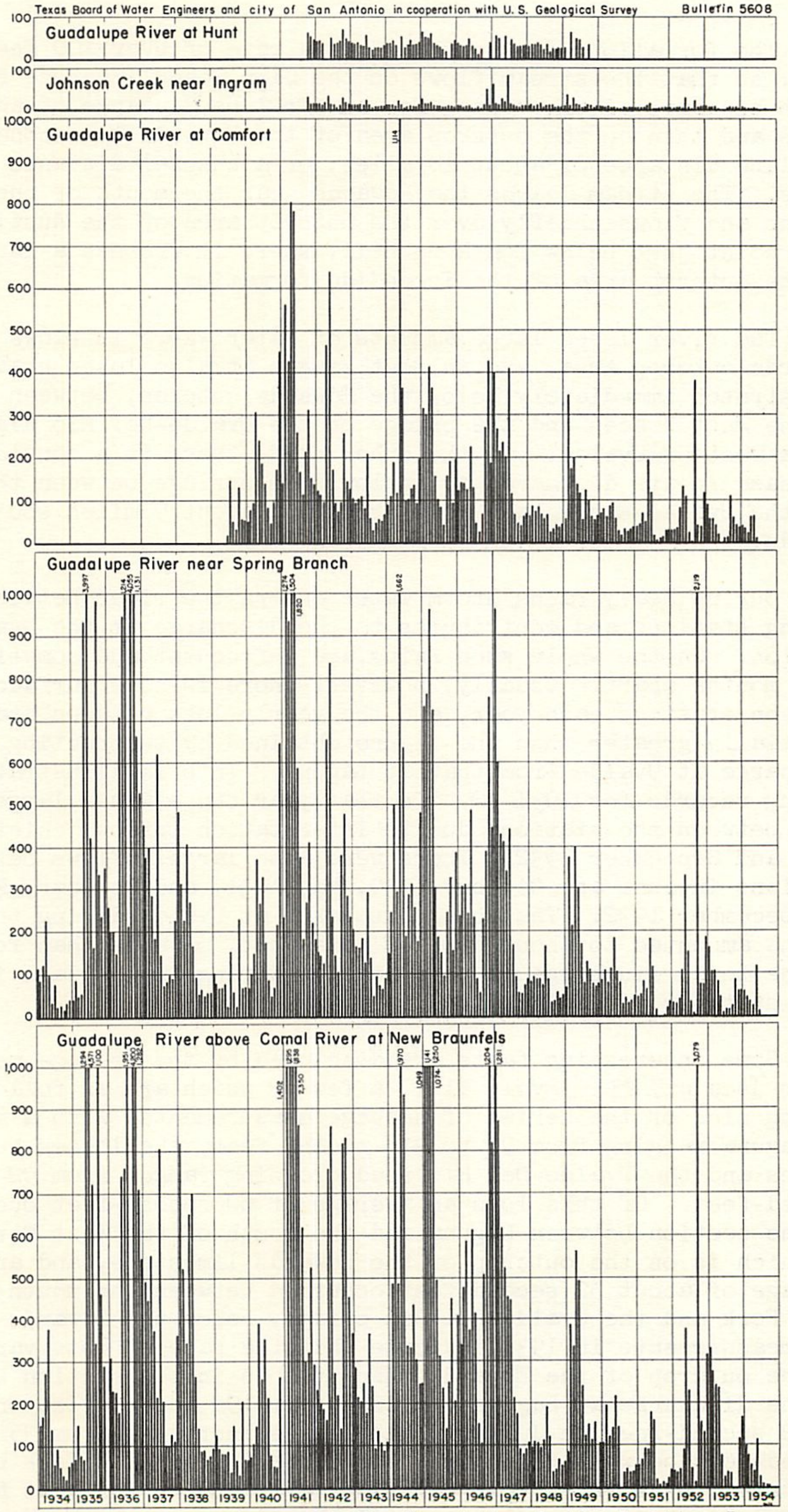


FIGURE 8.- Monthly mean discharge of Guadalupe River and Johnson Creek in the San Antonio area, Tex., 1934-54.

The formations dip southward at a rate of over 100 feet to the mile, so that the stream flows on the Glen Rose limestone from the north boundary of the county for an air-line distance of about 15 miles and then on the outcrop area of the Edwards limestone for an air-line distance of about 10 miles, or a channel distance of 13 miles. The stream leaves the Edwards near the mouth of the West Nueces and flows chiefly over the outcrop area of the Austin chalk to a point just below Tom Nunn Hill, where it crosses a large fault to the outcrop area of the Escondido formation.

The river loses large amounts of water where it flows over the Edwards outcrop area, and in most stages it also loses heavily in the stretch immediately below the Edwards outcrop, between the mouth of the West Nueces and the bridge on the Uvalde-Del Rio Highway, 7 miles west of Uvalde. On the other hand, there is a considerable increase in its discharge by inflow from springs between the bridge and the Uvalde-Eagle Pass road crossing, about 9 miles southwest of Uvalde.

During heavy rains storm water enters the river between the gaging stations and contributes to the discharge at the Uvalde station. On the whole such rains are infrequent and sometimes are many months apart. Usually, however, there is some surface inflow between stations each year, and the yearly loss between stations is materially greater than the figure obtained by subtracting the yearly discharge at Uvalde from that at Laguna. This is illustrated by the gaging records for 1931-32. In that year there was a large total gain between the stations due to interstation inflow, chiefly in July and September 1932. There were also large inflows between the stations in June and October 1930, May 1931, and October, November, and December 1932. The total discharge at Uvalde during these 8 months amounted to about 690,000 acre-feet, or more than four-fifths of the total discharge at that station during the 6 years in which both stations were maintained prior to 1934.

Some interesting facts are disclosed by the seepage measurements [see pt. III , vol. II], a few of which are as follows: During nine of the series of seepage measurements, with a discharge at Laguna ranging from 92 to 316 second feet, the losses between Laguna and the Uvalde-Del Rio road crossing ranged from 92 to 148 second-feet. Of this loss an average of 60 second-feet occurred in the section between Laguna and the mouth of the West Fork, most of which is on the outcrop of the Edwards limestone, and an average of about 52 second-feet occurred between the mouth of the West Fork and the Uvalde-Del Rio bridge, below the Edwards outcrop. The measurements in 1931 indicate that the rate of loss varies more on the outcrop of the Edwards than it does in the section below it. As the discharge at Laguna declines from 192 second-feet on June 4 to 92 second-feet on July 16, the losses increased from 35 to 67 second-feet between Laguna and the mouth of the West Fork but were maintained at a relatively constant rate between the West Fork and the Del Rio bridge, at least until the discharge at the West Fork had declined to about 36 second-feet.

All the seepage measurements show a substantial increase in the flow of the river between the Del Rio bridge and the Uvalde gaging station and a further increase between the Uvalde station and the crossing of the Eagle Pass road $5\frac{1}{2}$ miles below that station. The rate of pick-up in these sections was relatively constant for months after the stream ceased flowing above the Del Rio bridge in September 1931 but slowly declined during the fall, winter, and spring 1931-32.

The apparently complicated regimen of the river indicated by the records of stream measurements at the gaging stations and intermediate points can be explained as follows: On the outcrop of the Edwards limestone the river loses large quantities of water, which first is absorbed by percolation into the gravel and then is paid our gradually from the gravel into the limestone. During floods the stream leaves its normal channel, which in places is narrow, and spreads over the adjacent bottom lands. Thereby a larger quantity of water is absorbed by the gravel than at low or moderate stages, and a temporary water table is built up, which in places is at the level of the stream bed or above it. The water thus placed in storage by the floods, sometimes called "bank storage", is gradually depleted by downward percolation into the limestone and to some extent by evaporation or transpiration, and as the water table declines percolation from the stream increases, even though the flow of the stream is decreasing.

In April 1930 the flow at Laguna was about 30 second-feet and the stream lost water rapidly after it crossed the Comanche Peak-Edwards contact. The last flowing water was near United States Geological Survey bench mark 1045 (about 3 miles north of the confluence of Nueces and West Nueces River). At this point the bed of the stream is formed by gravel. A well drilled several years prior to 1930 on the east side of the river near this bench mark found no water until it had passed through the gravel and 100 feet into the Edwards. This indicates that the water from the river passed through the gravel and entered the limestone.

During a large proportion of the time the discharge at Laguna is less than the intake capacity of the Edwards, and as there is therefore no flow in the river no recharge occurs in the section below the mouth of the West Nueces. In times of high water, however, the losses in this section are very large. It is believed that this water must enter the gravel directly. The fact that large quantities of water enter the gravel is indicated by the records of water-level fluctuations in wells H-4-8 and H-4-28 which show that the water levels in these wells rose 27 and 18 feet, respectively, after floods in the spring of 1930. Well H-4-8, which was equipped with a water-stage recorder, showed a very rapid rise of 27 feet in a period of 3 weeks during and shortly after the flood of June 1930 and then declined rapidly at first and then more slowly, indicating that during the flood there was considerable loss from the river into the gravel and after the flood there was probably a gradual spreading movement both away from the river (eastward) and back toward the river. This spreading movement continued until equilibrium was reached, after which the water level remained nearly constant.

The volume of water that the gravel is capable of taking in or releasing is surprisingly large. If the gravel above the Uvalde gaging station covers an area of 5 square miles and has an average effective porosity of 25 percent it would alternately store and release 20,000 acre-feet if a thickness of 25 feet were alternately watered and unwatered.

It was formerly believed that this water entered the gravel and that a part of it was paid out slowly to the river during dry periods, a part was lost from the gravel by evaporation and by transpiration from deep-rooted trees and shrubs, and the remainder increased the storage in the gravel.

However, on the basis of data now available, the computed losses into the gravel in this stretch of the stream in excess of the return flow near the Uvalde station during each year of the period from 1927-28 to 1932-33 are so great that it does not seem possible to account for them by storage, evaporation, and transpiration, and the writer believes that some but not a large amount of this water is lost by percolation from the gravel into permeable beds of the Austin chalk and a part, possibly a large part, may be lost into the Edwards immediately below the mouth of the West Nueces by downward movement along fault planes.

It is believed that the ground water flow between the Del Rio bridge and the Eagle Pass road crossing is largely due to seepage from the gravel reservoir, although in the section below Tom Nunn Hill a part of the flow may be due to fault springs bringing water up from the Edwards. The water begins to rise a short distance above the Uvalde gaging station. The valley becomes narrower in this vicinity, thereby constricting the cross-sectional area of the gravel and producing the conditions requisite for bringing the underflow to the surface. In an earlier paper it was suggested that igneous intrusions had baked and hardened the clays overlying the Edwards and permitted the Edwards limestone water to rise in this vicinity along joint cracks. There is also a large fault south of Tom Nunn Hill which may allow water from the Edwards to reach the surface. On the other hand, when the artesian head in the Edwards reservoir is high, the water levels in nearby wells that penetrate to the Edwards reach altitudes that are above the river beds at the Uvalde station, but fluctuations in the flow to the river do not appear to synchronize with fluctuations in the artesian head in the Edwards. The inflow is greatest immediately after heavy floods and declines gradually with the lapse of time between floods, just as would be expected from a gravel reservoir that is filled comparatively rapidly during floods and yields water at its lower end at a rate that decreases as the water level in the reservoir declines. The head in the Edwards reservoir builds up and declines slowly and lags many months behind the fluctuations in the stream discharge.

In summary it may be pointed out that the average annual loss from the Nueces into the Edwards limestone above the mouth of West Nueces during the 6-year period was about 36,000 acre-feet. A much smaller amount was lost into the gravel below the mouth of the West Nueces. Some of this water may have entered the Edwards, some probably entered the Austin chalk, and some remained in the gravel. Of the water that remained in the gravel a part was lost by evaporation and transpiration and a part was returned to the stream.

As a part of the present investigation, the recharge from the Nueces and West Nueces Rivers has been computed for the period 1934-53. In April 1939, the lower gage was moved about 5 miles downstream from the original location. Because additional water is measured at the site of the present gage, the record at the original site was adjusted to that of the present site on the basis of seepage data.

In estimating the recharge from the Nueces River the following assumptions were necessary:

1. All the water passing out of the area above the Laguna gage is accounted for by the flow at that point.
2. All the water passing out of the area to the south is accounted for by the flow past the Uvalde gage.
3. The record for the gage on the West Nueces for the period September 1939 through September 1950 shows that only flood flows pass the gage and that the West Nueces contributes about as much flood water per unit of drainage area as does the upper Nueces River. Except for major floods, the flood flow may be estimated for the period of study for which no records are available by comparison with flow from the upper Nueces. Major flood flows may be estimated by comparison with the observed runoff on areas to the west and north of the Nueces drainage.
4. All the inflow from the area between the Laguna and Uvalde gages can be prorated on the basis of the flood flow passing the Laguna gage.

With these assumptions in mind, the following tabulation shows the estimated recharge to the ground-water reservoir of the San Antonio area from the Nueces Basin.

Table 4.- Estimated recharge to the ground-water reservoir from the Nueces Basin, in thousands of acre-feet.

Year	Total flow at Laguna	Flood flow West Nueces	Inflow Laguna to Uvalde	Total inflow above Uvalde	Total outflow at Uvalde	Recharge to ground-water reservoir
1934	17.8	0.4	1.0	19.2	10.6	8.6
1935	465.0	227.8	398.8	1,091.6	680.3	411.3
1936	233.4	31.5	161.1	426.0	249.5	176.5
1937	61.9	10.5	13.0	85.4	56.6	28.8
1938	72.4	27.1	17.3	116.8	53.3	63.5
1939	164.0	25.2	125.5	314.7	87.7	227.0
1940	52.8	.4	9.8	63.0	12.6	50.4
1941	86.6	.2	34.3	121.1	31.2	89.9
1942	96.1	3.9	45.0	145.0	41.5	103.5
1943	43.4	.1	5.3	48.8	12.3	36.5
1944	63.8	.0	14.1	77.9	13.8	64.1
1945	45.5	.0	8.7	54.2	6.9	47.3
1946	67.0	7.6	29.1	103.7	22.8	80.9
1947	65.9	2.5	19.1	87.5	15.1	72.4
1948	39.4	25.6	13.6	78.6	37.5	41.1
1949	183.4	58.2	116.5	358.1	192.1	166.0
1950	47.1	.0	4.2	51.3	9.8	41.5
1951	19.4	.2	.4	20.0	1.7	18.3
1952	21.9	2.5	6.7	31.1	3.2	27.9
1953	22.3	4.0	5.5	31.8	10.4	21.4
TOTAL	1,869.1	427.7	1,029.0	3,325.8	1,548.9	1,776.9
Average	93.5	21.4	51.4	166.3	77.5	88.8

Recharge from the Frio and Dry Frio Rivers.- Records of the flow of the Frio River at Concan are available for the period October 1923 to January 1953, but the gage on the Dry Frio near Reagan Wells has been in operation only since September 1952. Gages were established on the Frio and Dry Frio Rivers at Knippa in September 1952, discontinued in September 1953, and replaced by a gage below the confluence of the two streams. The record of discharge of the Dry Frio at Reagan Wells has been estended to cover the period of study by correlating the observed data with those of the Frio at Concan. Seepage runs show that all the base flow is lost from the streams and recharges the ground-water reservoir.

A seepage run on the Dry Frio in 1925 showed that the flow gradually increased from an estimated 0.05 cubic feet per second (cfs) 6 miles above Reagan Wells to 9.66 cfs 8 miles below Reagan Wells. The total flow was lost in the next 1½ miles on the outcrop of the Edwards limestone; however, the stream flowed only part of the way across the Edwards outcrop, and much additional water probably would be lost if the flow were sufficient to extend farther downstream.

Four seepage investigations have been made on the Frio River. The flows at the gaging station at the times of the investigations ranged from 40.5 cfs to 233 cfs. The seepage runs show that the river loses its total flow between the gage and the Uvalde-Sabinal road crossing 18½ miles below the gage.

The flood of 1954 offers one of the best measures of the capacity of the aquifer to absorb water where the streams cross the outcrop. During the storm of June 26-27, 1954, flow as great as 577 cfs passed the upper gages and none passed the lower gage. Therefore, it has been arbitrarily assumed that all flow less than 600 cfs that passes the upper gages enters the reservoir. The following tabulation shows the estimated recharge from these streams.

Table 5.- Estimated recharge to the ground-water reservoir from the Frio and Dry Frio Rivers, in thousands of acre feet.

Year	Frio	Dry Frio	Total
1934	21.7	5.8	27.5
1935	121.9	53.0	174.9
1936	105.2	41.9	147.1
1937	53.7	21.2	74.9
1938	49.8	18.2	68.6
1939	35.3	10.7	46.0
1940	44.8	13.4	58.2
1941	103.2	42.1	145.3
1942	67.2	25.6	92.8
1943	32.0	10.1	42.1
1944	54.5	19.7	74.2
1945	51.0	18.9	69.9
1946	38.5	13.2	51.7
1947	55.3	20.6	75.9
1948	20.3	5.1	25.4
1949	59.2	21.8	81.0
1950	27.2	8.1	35.3
1951	21.4	5.7	27.1
1952	12.8	2.7	15.5
1953	10.7	4.1	14.8
TOTAL	985.7	362.5	1,348.2
Average	49.3	18.1	67.4

Recharge from the Sabinal River.- Continuous discharge records from the Sabinal River just above the outcrop of the Edwards limestone have been available since September 1942. The lower gage, however, has been in operation only since September 1952, and the record covers only the recent drought. The records obtained simultaneously at the upper gage and at the gage on the Frio at Concan have been correlated to enable extension of the record for the upper gage on the Sabinal from 1934 to 1942.

A few seepage investigations have been made, all when flows at the upper gage were less than 50 cfs, to determine the losses on the Sabinal (see pt. III vol. II.) These investigations show that essentially all the flow up to 45 second-feet was lost to the Edwards limestone. However, measurements made at both stations during the storms of June 26 and 27, 1954 (table 6) indicate that the infiltration capacity of the reservoir in this basin is considerably greater than 45 cfs.

Table 6.- Flow in cubic feet per second at stations above and below the outcrop of the Edwards limestone.

Date	Sabinal near Sabinal	Sabinal at Sabinal	Difference	Difference adjusted for 1-day time lag between stations
June 25	2.5	0.9	1.6	-
26	223	1.4	221.6	160
27	113	63	50	90
28	36	23	13	32.1
29	24	3.9	20.1	20.1
30	20	3.9	16.1	-

All the storm runoff was from the area above the upper gages on both the Frio and the Dry Frio Rivers; therefore, it is assumed that all the storm runoff on the Sabinal also passed the upper gage. The records have been adjusted for a time lag of 1 day between stations, and on this basis it is assumed that from a flow of 223 cfs passing the upper gage, 160 cfs probably entered the Edwards limestone as the stream crossed the outcrop.

An inspection of the daily hydrographs of the discharge at the stations at and above Sabinal and the results of the seepage investigations show that almost all the base flow and a part of the flood flow enters the ground-water reservoir. Therefore, the base flows have been separated from the flood flows, and each flood has been analyzed. The estimated losses to the Edwards are shown in the following table.

Table 7.- Estimated recharge to the ground-water reservoir from the Sabinal River, in thousands of acre-feet.

1934	6.8	1944	22.5
1935	49.0	1945	27.3
1936	39.4	1946	14.9
1937	20.3	1947	15.7
1938	19.6	1948	24.2
1939	15.1	1949	28.4
1940	21.0	1950	9.6
1941	45.2	1951	6.4
1942	30.9	1952	2.8
1943	10.5	1953	2.8
TOTAL	412.4		
Average	20.6		

<u>Recharge from Medina River</u>.- Recharge conditions along the Medina River are different from those of the other streams because it is the only stream in the area where regulation and storage are provided by a dam. An extensive investigation of the leakage from the Medina Lake and Diversion Reservoir was made by Lowry (1955, p. 19-21), from which he concluded the following:

The Medina Dam creates a reservoir with a total capacity of 254,000 acre-feet, which affords a high percentage of control to all inflow from the drainage area of 587 square miles that lies above it. This reservoir began the storage of water in May, 1913. The records show that shortly thereafter flood inflow increased the storage to nearly 150,000 acre-feet by the end of that year. It spilled in April and May of 1914 and again in September and October 1919. Subsequent to that date it has been full only once in the 36 years that have elapsed since that time, and that was in 1936, immediately following the big flood year of 1935. Heavy withdrawals following the spill in 1936 depleted the storage by October 1940. Since that date the maximum storage of 150,000 acre-feet has been reached only once in 1941, and during the current drouth, the average storage has been rather inconsequential.

This reservoir, with the dam located nearly coincident with the Balcones Escarpment has been a notorious water loser from its inception. The Bexar, Medina, Atascosa Counties Water Control and Improvement District No. 1 has a permit from the Texas Board of Water Engineers to divert 300,000 acre-feet of water annually to irrigate 150,000 acres of land. The records show that only a small fraction of such acreage has ever been irrigated. This is evident when it is indicated that the average annual inflow to the reservoir is only slightly in excess of 100,000 acre-feet. Evaporation and losses to the ground-water reservoir annually accounts for a high percentage of the total inflow. When water was plentiful, large withdrawals were made, but in most years the available supply has been adequate to irrigate only a very small acreage, a mere fraction of the 150,000 acrea authorized.

During the study, it was found that there was an apparent relation between the water surface elevation in the reservoir and the resulting leakage. This relation was defined by two curves; one representing losses on a rising stage, and the other representing losses on a falling stage. The two curves are substantially different from one another. The actual capacity figures have been applied to these curves for the indicated loss.

The diversion structure, which is about 4 miles downstream from the main dam, is also a well-known water loser. Overlapping records in 1930 indicated the annual loss at this point to be 16,000 acre-feet. Records of runoff are not available by which an exact analysis could be made for the period since 1930, but on the assumption that conditions in this respect have not improved, the losses have been estimated.

According to Lowry (personal communication, 1955), the losses to the ground-water reservoir from Medina Lake have averaged 35,000 acre-feet annually for the period 1934-53, and the loss from the pool impounded by the Diversion Dam has averaged 11,800 acre-feet annually for the same period. The following tabulation gives the estimated recharge to the ground-water reservoir from the Medina River.

Table 8.- Estimated recharge to the ground-water reservoir from Medina Lake and Diversion Dam, in thousands of acre-feet.
(by R. L. Lowry)

Year	Medina Lake	Diversion Dam	Total
1934	30.5	16.0	46.5
1935	57.1	14.0	71.1
1936	77.1	14.5	91.6
1937	65.5	15.0	80.5
1938	50.0	15.5	65.5
1939	26.4	16.0	42.4
1940	22.8	16.0	38.8
1941	38.6	15.5	54.1
1942	36.2	15.5	51.7
1943	25.5	16.0	41.5
1944	34.0	16.5	50.5
1945	39.8	15.0	54.8
1946	34.9	16.5	51.4
1947	28.0	16.0	44.0
1948	11.8	3.0	14.8
1949	29.0	4.0	33.0
1950	18.8	4.8	23.6
1951	21.1	0	21.1
1952	25.4	0	25.4
1953	30.6	5.6	36.2
TOTAL	703.1	235.4	938.5
Average	35.1	11.8	46.9

Recharge from Cibolo and Dry Comal Creeks.- Gaging stations near Bulverde and at Selma on Cibolo Creek have been maintained since March 1946. The station above Bracken was in operation from March 1946 to September 1949. These records, for the most part, cover only the present drought and indicate only the losses during low flow.

Cibolo Creek shows much evidence of large losses to the ground-water reservoir and, according to George (1952, p. 56-59), losses from Cibolo Creek have been observed as far upstream as the mouth of Balcones Creek. Most of the runoff above the Bulverde gage enters caverns in the lower member of the Glen Rose limestone and thence passes laterally through underground channels into the Edwards limestone. Between the Bulverde station and the Bracken station, the bed of Cibolo Creek is in the upper member of the Glen Rose limestone and the losses are relatively small. Between the Bracken station and the bridge at Bracken, the bed of the creek is in the Edwards limestone, which is honeycombed and broken by many small faults. The losses are probably large in proportion to the amount of water that reaches this stretch of the stream.

Dry Comal Creek has a drainage area of 117 square miles above Comal Springs. Below Comal Springs the stream is called the Comal River. Records of the discharge of the Comal River at New Braunfels are available for the period 1928-54. Water seldom flows in the channel of Dry Comal Creek, and the discharge has been determined by subtracting the flow of Comal Springs from the discharge of Comal River. Records of the runoff from Cibolo Creek at Selma are available from March 1946 and have been estimated from 1934 to 1946 by correlation with the observed discharge of the Dry Comal.

A study has been made of the runoff per square mile in the drainage areas of streams both below and above the Balcones escarpment to compute the annual runoff that should occur in the Cibolo and Dry Comal Basins if there were no large losses to the ground-water reservoir. The difference between the computed and observed runoff is believed to be the part that infiltrates into the ground-water reservoir.

Table 9 shows the computed runoff from Dry Comal and Cibolo Creeks, the observed runoff, and the estimated recharge to the ground-water reservoir.

Table 9.- Estimated recharge to the ground-water reservoir from Cibolo and Dry Comal Creeks, in thousands of acre-feet

Year	Cibolo Creek			Dry Comal Creek			Total recharge
	Computed runoff	Observed runoff	Estimated recharge	Computed runoff	Observed runoff	Estimated recharge	
1934	18.2	2.3	15.9	14.6	2.1	12.5	28.4
1935	140.0	7.4	132.6	58.5	8.4	50.1	182.7
1936	126.0	4.7	121.3	29.3	4.5	24.8	146.1
1937	51.8	3.1	48.7	22.8	7.6	15.2	63.9
1938	51.8	6.0	45.8	33.9	2.9	31.0	76.8
1939	7.8	0.3	7.5	2.1	0.0	2.1	9.6
1940	25.8	1.4	24.4	12.5	6.1	6.4	30.8
1941	142.8	8.8	134.0	58.5	1.3	57.2	191.2
1942	67.2	5.9	61.3	44.5	12.2	32.3	93.6
1943	36.4	2.5	33.9	15.2	0.8	14.4	58.3
1944	112.0	8.8	103.2	52.7	3.4	49.3	152.5
1945	100.8	7.6	93.2	46.8	10.1	36.7	129.9
1946	119.0	11.7	107.3	64.4	16.4	48.0	155.3
1947	67.2	0.0	67.2	25.2	2.9	22.3	79.5
1948	14.0	0.0	14.0	5.9	0.0	5.9	19.9
1949	39.2	2.0	37.2	23.4	4.7	18.7	55.9
1950	18.2	0.0	18.2	7.4	1.0	6.4	24.6
1951	9.8	0.3	9.5	3.9	0.9	3.0	12.5
1952	84.0	22.0	62.0	70.2	29.9	40.3	102.3
1953	22.4	0.3	22.1	23.4	3.2	20.2	42.3
TOTAL	1,254.4	95.1	1,159.3	615.2	118.4	496.8	1,656.1
Average	62.7	4.7	58.0	30.8	5.9	24.8	82.8

Recharge from the Guadalupe River.- The Guadalupe River, in contrast to most of the other streams crossing the Balcones fault zone, apparently does not lose significant quantities of water to the Edwards limestone. Records of the discharge of the Guadalupe are available for the station at Hunt for the period October 1941 to September 1949, for the station at Comfort since May 1939, for the station near Spring Branch since June 1922, and for the station above the Comal River at New Braunfels since December 1927 (v. II, pt.III). Discharge records of one of the upper tributaries, Johnson Creek near Ingram, are available for the period September 1941 to September 1954.

The Guadalupe is normally a perennial stream, but at times during the current drought the river has been dry in the upper section and almost dry immediately above the mouth of the Comal River.

Investigations to determine seepage losses (vol. II, pt. III) have failed to disclose losses greater than those that might be expected from evapotranspiration. However, there are minor losses and gains in various reaches of the river. The daily hydrographs indicate that the base flows are more or less constant between the station at Comfort and the station at New Braunfels; however, the flood runoff per square mile from similar amounts of precipitation is much greater than that observed on other streams in the area. Records of the Guadalupe River between Spring Branch and New Braunfels indicate that stream losses and gains are insignificant. This is probably the result of (1) the stream channel cutting deeper into the Edwards than in the rest of the area, and (2) the water levels in wells in the Edwards standing at approximately the same altitude as the stream surface.

Recharge from the Blanco River and adjacent area.- Records of the discharge of the Blanco River at Wimberley, which is above the outcrop of the Edwards, are available for the period since June 1928. No continuous records of discharge are available below the outcrop. Discharge measurements to determine seepage losses or gains (vol. II, pt.III) indicate that, with discharge up to approximately 200 cfs at the gage, the loss in crossing the outcrop of the Edwards limestone is about 15 cfs. Therefore, the limit of infiltration in this section has been set at 15 cfs regardless of flow above 200 cfs at the gage. All flows up to 15 cfs are assumed to be recharge to the ground water reservoir. The estimated recharge to the reservoir from the Blanco River is shown in table 10.

Sink, Purgatory, York, and Alligator Creeks drain 94 square miles of Edwards outcrop which is assumed to have runoff characteristics similar to those of the Dry Comal Creek. The drainage area of these creeks is surrounded by those of the Blanco River above Wimberley, the Guadalupe River between Spring Branch and New Braunfels, and Plum Creek above Luling. The recharge to the reservoir has been computed to be equal to the drainage area times the difference between (1) the average runoff per square mile of the Guadalupe between Spring Branch and New Braunfels, the Blanco at Wimberley, and Plum Creek at Luling, and (2) the flood runoff per square mile measured on the Dry Comal. Table 10 shows the estimated recharge as computed.

Table 10.- Estimated recharge to the ground-water reservoir from the Blanco River, and from Sink, Purgatory, York and Alligator Creeks, in thousands of acre feet.

Year	Blanco River	Sink, Purgatory, York, and Alligator Creeks	Total
1934	9.8	10.0	19.8
1935	10.7	29.1	39.8
1936	11.0	31.7	42.7
1937	11.0	10.2	21.2
1938	10.1	26.3	36.4
1939	8.9	2.2	11.1
1940	9.7	9.1	18.8
1941	11.0	46.8	57.8
1942	11.0	17.6	28.6
1943	11.0	9.1	20.1
1944	11.0	35.2	46.2
1945	11.0	24.7	35.7
1946	11.0	29.7	40.7
1947	11.0	20.6	31.6
1948	9.7	3.5	13.2
1949	10.5	13.0	23.5
1950	10.1	7.3	17.4
1951	7.0	3.6	10.6
1952	9.4	11.3	20.7
1953	11.0	13.9	24.9
TOTAL	205.9	354.9	560.8
Average	10.3	17.7	28.0

Recharge from area between the Sabinal and Medina River basins.- The area between the Sabinal and Medina Rivers is drained by Seco, Hondo, and Verde Creeks. Gages have been established on Seco and Hondo Creeks, but the record covers only the last 2 years of the current drought. A mean value of runoff of the Sabinal and Medina Rivers is assumed to be representative of the runoff for the area. It is assumed also that the losses from the drainage system would be similar to those of the Sabinal. The recharge has been computed by multiplying the ratio of recharge to total runoff of the Sabinal by the estimated total runoff from this area. Table 11 shows the computed recharge to the ground-water reservoir.

Table 11.- Estimated recharge to the ground-water reservoir from the area between the Sabinal and Medina River basins, in thousands of acre-feet.

Year	Sabinal runoff (ac-ft/ sq mi)	Medina runoff (ac-ft/ sq mi)	Estimated intermediate area runoff (ac-ft/ sq mi)	Estimated total runoff in intermediate area (thousands of acre-feet)	Ratio of recharge from Sabinal to total flow (%)	Estimated recharge intermediate area, Sabinal to Medina
1934	37.2	52.2	44.7	18.6	89.2	16.6
1935	275.8	492.7	384.2	159.4	86.9	138.5
1936	211.3	417.9	314.6	130.6	91.2	119.1
1937	107.6	159.5	133.5	55.4	92.3	51.1
1938	102.0	129.7	115.8	48.1	93.8	45.1
1939	82.6	66.0	74.3	30.8	89.6	27.6
1940	115.6	139.9	127.7	53.0	89.0	47.2
1941	248.6	379.3	314.0	130.0	88.9	115.8
1942	166.3	205.7	186.0	77.2	91.0	70.3
1943	54.0	89.8	71.9	29.8	94.6	28.2
1944	121.7	209.1	165.4	68.6	90.3	61.9
1945	150.4	205.4	177.9	73.8	88.7	65.5
1946	81.1	151.9	116.5	48.3	89.6	43.3
1947	81.1	111.3	96.2	39.9	94.6	37.7
1948	12.6	74.0	43.3	18.0	93.4	16.8
1949	152.9	158.1	155.5	64.5	90.9	58.6
1950	48.4	64.1	56.2	23.3	96.7	22.5
1951	35.8	90.8	63.3	26.3	83.5	22.0
1952	15.9	126.5	71.2	29.5	85.4	25.2
1953	15.0	13.9	14.5	4.1	90.5	3.7
TOTAL	2,415.9	3,337.8	2,726.7	1,129.2	1,810.1	1,016.7
Average	120.8	116.7	126.3	56.5	90.5	50.8

<u>Recharge from the area between the Medina River and Cibolo Creek drainage basins</u>.- An area of 213 square miles between the Medina River and Cibolo Creek drainage basins lies above the outcrop of the Edwards north of San Antonio, and is drained by San Geronimo, Leon, and Salado Creeks, all of which cross the Edwards limestone before they join the Medina and San Antonio Rivers. The area above the Edwards outcrop consists of generally hilly country which normally would have a relatively high rate of runoff; however, very little water escapes from the area. In this respect, it is similar to the Cibolo drainage basin, and it is assumed that the runoff per square mile is approximately equal to that observed for Cibolo Creek at Selma. The runoff that should occur were it not for infiltration has been computed from the runoff rates above and below the Balcones escarpment. The recharge is estimated to be the difference between the computed total runoff and the assumed actual runoff based on the observed runoff on the Cibolo at Selma. Table 12 shows the estimated recharge to the ground-water reservoir.

Table 12.- Estimated recharge to the ground-water reservoir from the area between the Cibolo Creek and Medina River basins, in thousands of acre feet.

Year	Computed total runoff	Assumed actual runoff	Recharge
1934	17.0	1.7	15.3
1935	106.5	5.6	100.9
1936	83.1	3.6	79.5
1937	37.3	2.4	34.9
1938	38.3	4.6	33.7
1939	7.0	.2	6.8
1940	22.4	1.0	21.4
1941	91.6	6.7	84.9
1942	53.3	4.5	48.8
1943	23.4	1.9	21.5
1944	59.6	6.7	52.9
1945	63.9	5.8	58.1
1946	85.2	8.5	76.7
1947	40.5	.0	40.5
1948	12.8	.0	12.8
1949	32.0	1.5	30.5
1950	12.6	.0	12.6
1951	11.5	.2	11.3
1952	53.3	16.7	36.6
1953	14.9	.2	14.7
TOTAL	866.2	71.8	794.4
Average	43.3	4.2	39.7

Summary of recharge.- Recharge estimates have been made for the entire drainage area above the outcrop of the Edwards limestone in the San Antonio area. Those areas from which there is practically no runoff have been included either as part of the basins for which estimates of recharge have been made or as separate areas with assumed runoff characteristics similar to other basins. The absence of long-term records on all streams except the Nueces and Guadalupe Rivers made it necessary to extend the records of flow by correlation, in order to complete the estimates for the entire period of study. Several assumptions have been made which may or may not be valid. The error due to an invalid assumption may be amplified by using the figures derived from it as a basis for others.

The recharge estimates for the entire San Antonio area are shown in table 13.

Table 13.-Estimated recharge to the ground-water reservoir in the San Antonio area, in thousands of acre-feet.

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	27.5	6.8	46.5	28.4	0.0	19.8	16.6	15.3	169.5
1935	411.3	174.9	49.0	71.1	182.7	.0	39.8	138.5	100.9	1,168.2
1936	176.5	147.1	39.4	91.6	146.1	.0	42.7	119.1	79.5	842.0
1937	28.8	74.9	20.3	80.5	63.9	.0	21.2	51.1	34.9	375.6
1938	63.5	68.6	19.6	65.5	76.8	.0	36.4	45.1	33.7	409.2
1939	227.0	46.0	15.1	42.4	9.6	.0	11.1	27.6	6.8	385.6
1940	50.4	58.2	21.0	38.8	30.8	.0	18.8	47.2	21.4	286.6
1941	89.9	145.3	45.2	54.1	191.2	.0	57.8	115.8	84.9	784.2
1942	103.5	92.8	30.9	51.7	93.6	.0	28.6	70.3	48.8	520.2
1943	36.5	42.1	10.5	41.5	58.3	.0	20.1	28.2	21.5	258.7
1944	64.1	74.2	22.5	50.5	152.5	.0	46.2	61.9	52.9	524.8
1945	47.3	69.9	27.3	54.8	129.9	.0	35.7	65.5	58.1	488.5
1946	80.9	51.7	14.9	51.4	155.3	.0	40.7	43.3	76.7	514.9
1947	72.4	75.9	15.7	44.0	79.5	.0	31.6	37.7	40.5	397.3
1948	41.1	25.4	24.2	14.8	19.9	.0	13.2	16.8	12.8	168.2
1949	166.0	81.0	28.4	33.0	55.9	.0	23.5	58.6	30.5	476.9
1950	41.5	35.3	9.6	23.6	24.6	.0	17.4	22.5	12.6	187.1
1951	18.3	27.1	6.4	21.1	12.5	.0	10.6	22.0	11.3	129.3
1952	27.9	15.5	2.8	25.4	102.3	.0	20.7	25.2	36.6	256.4
1953	21.4	14.8	2.8	36.2	42.3	.0	24.9	3.7	14.7	160.8
TOTAL	1,776.9	1,348.2	412.4	938.5	1,656.1	.0	560.8	1,016.7	794.4	8,504.0
Average	88.8	67.4	20.6	46.9	82.8	.0	28.0	50.8	39.7	425.2

Discharge

Most of the ground-water discharge in the San Antonio area has been by springs; however, the withdrawal of water by wells has been increasing and in 1954 it exceeded the discharge by springs. (See fig. 9A.) Most of the discharge is in the eastern part of the area, whereas the recharge is distributed throughout the area. Some of the largest springs in the United States are in the Balcones fault zone between Del Rio and Austin (Meinzer, 1927). Several other large springs northwest of Del Rio, such as Goodenough Spring at Comstock and Devils River Springs, discharge water from the Edwards and associated limestones. Throughout the San Antonio area, the Edwards and associated limestones supply water to wells for domestic, stock, industrial, irrigation, military, and municipal uses.

Discharge by springs.- Most of the springs in the San Antonio area are along faults that permit water from the Edwards to escape into cracks and other channels and flow to the land surface. 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.

The U. S. Geological Survey and the Texas Board of Water Engineers have carried on a program of measurements of spring discharge in the Balcones fault zone for many years. Several measurements have been made on all the large springs between Del Rio and Austin, and continuous records covering many years are available for some of them. Table 14 shows the average, maximum, and minimum discharges of most of the principal springs.

Table 14.- Discharge of major springs between Del Rio and Austin, Tex.

Springs	Discharge, in cfs			Period of record	Remarks
	Average	Maximum	Minimum		
Las Moras Springs	28.6	60	2.8	1895-1953	140 misc. discharge measurements.
Leona River Springs	10.7	33	0	1939-1953	Daily records.
San Antonio Springs and San Pedro Springs	44	-	0	1934-1954	Estimated.
Comal Springs	295	420	72	1928-1954	Daily records.
San Marcos Springs	142	286	51	1894-1954	281 misc. discharge measurements.
Barton Springs	40.3	166	10.9	1894-1953	561 misc. discharge measurements.
TOTAL	560.6	965	136.7		

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

Bulletin 5608

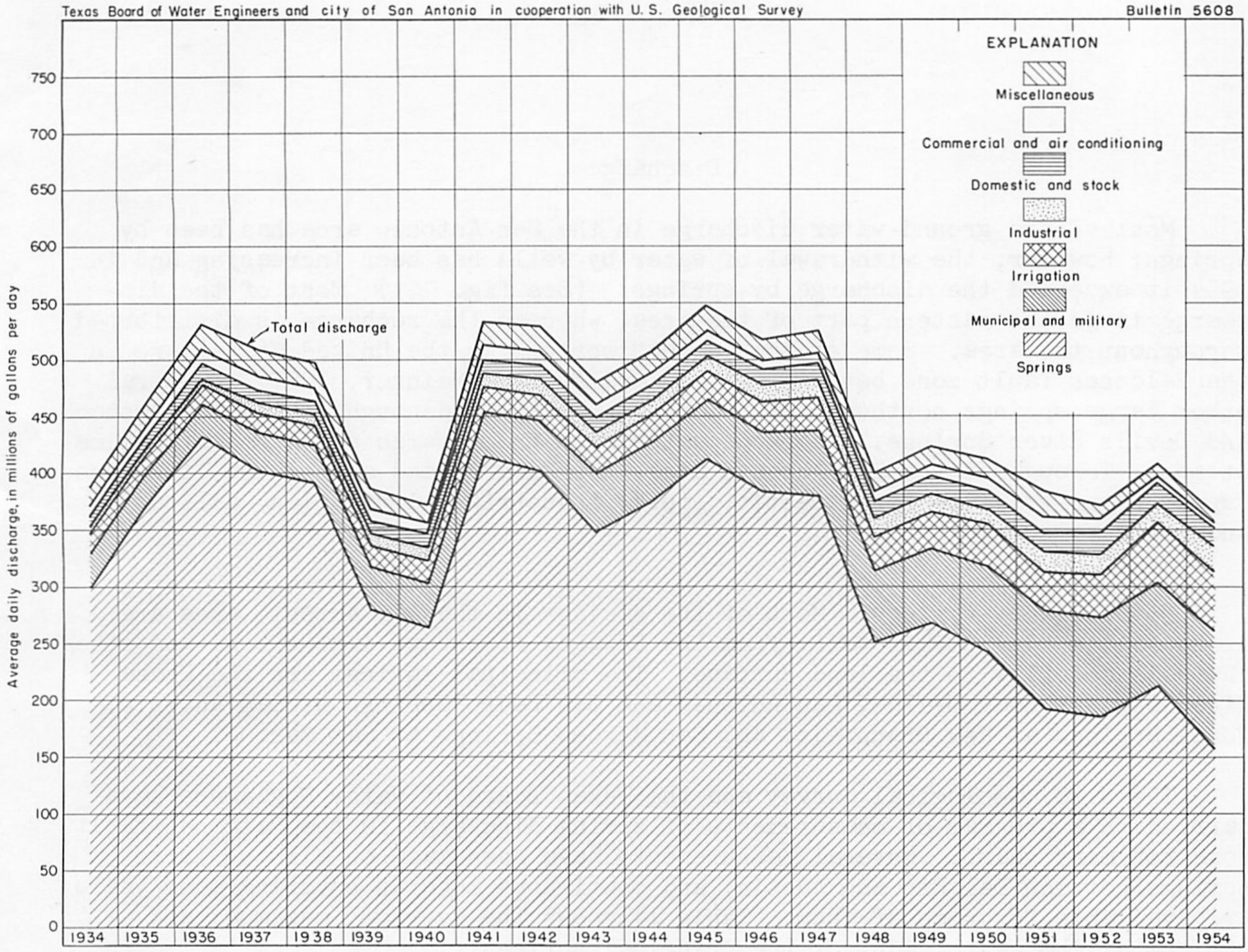


FIGURE 9 A.- Graph showing type of discharge or use of water from the Edwards and associated limestones in the San Antonio area, Texas, 1934-54.

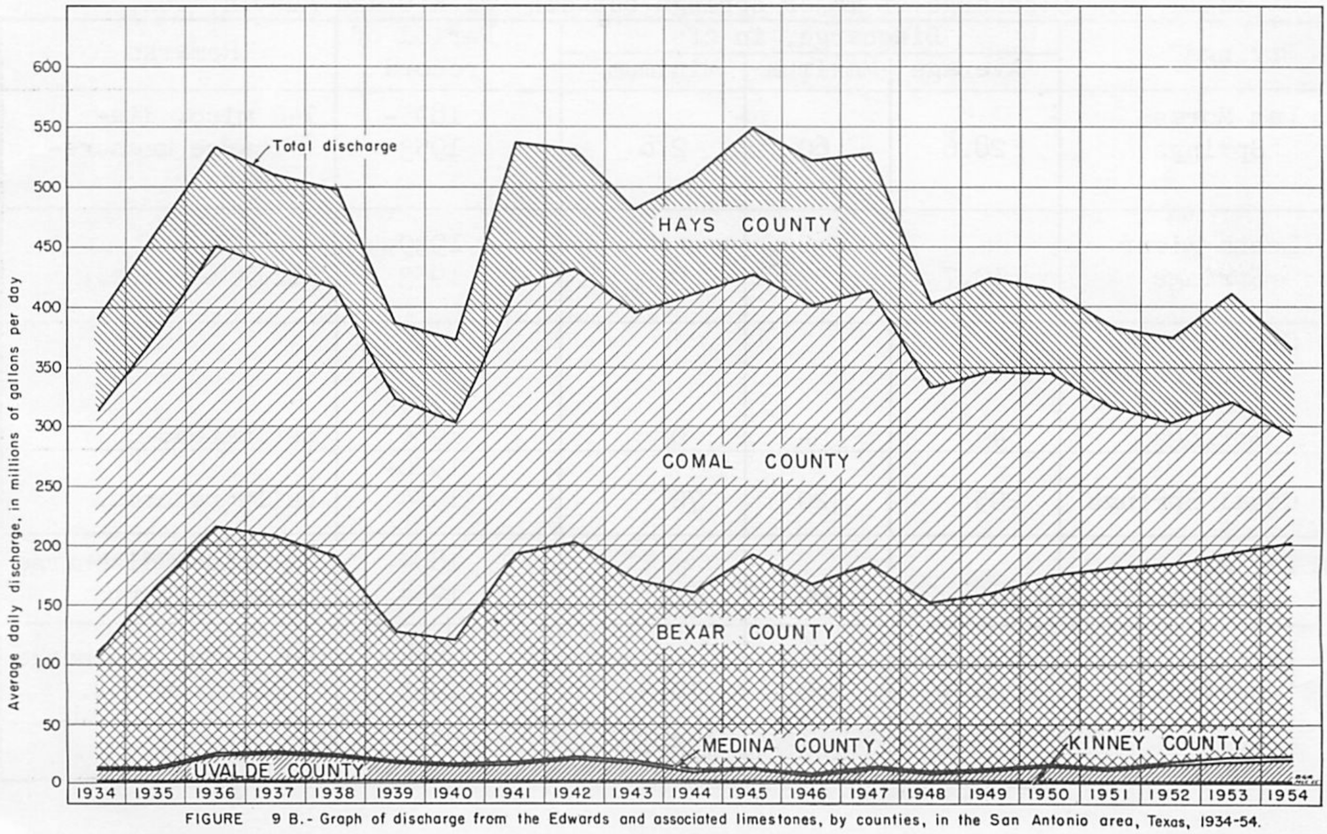


FIGURE 9 B.- Graph of discharge from the Edwards and associated limestones, by counties, in the San Antonio area, Texas, 1934-54.

Discharge from wells.- The withdrawal of water from wells has continued to increase since the first wells were drilled to the Edwards and associated limestones in about 1885. In 1907 more than 100 artesian wells were used in Bexar County. According to Lang (1954, p. 21), by the end of 1953 there were between 1,500 and 2,000 wells tapping the Edwards limestone in Bexar County, of which about 250 were large-capacity wells. Most of the water withdrawn from wells in the San Antonio area is used for municipal supply. The cities of San Antonio, Uvalde, Sabinal, Hondo, Castroville, New Braunfels, and San Marcos depend upon wells tapping the Edwards limestone. Many small independent water companies and the military installations adjacent to the city of San Antonio also withdraw water from the Edwards limestone.

The withdrawal of water from the Edwards and associated limestones for irrigation has been increasing because of the continued drought. East of San Antonio along Salado Creek and west and southwest of San Antonio, areas have been extensively developed for the irrigation of garden truck. The area around Uvalde also has been developed for irrigation of garden truck and field crops. The sustained drought has caused many ranchers to drill wells into the Edwards for supplementary irrigation of pastures and feed crops.

Practically all water used by the larger industries is supplied by private wells. Many of these wells formerly flowed and much water was wasted, but the decline in artesian head in recent years has caused most of them to cease flowing. Many industrial wells are so located and constructed that the installation of pumping equipment is not feasible. The reduction in discharge of flowing wells, due to the decline in artesian head, has partly offset the increased use by expanding industries.

The water used for air conditioning theaters, hotels, and office buildings is practically all supplied from privately owned wells. A large part of the water, after it was used for this purpose, was formerly emptied into the San Antonio River. In the past few years, however, recirculation of water has become common as a conservation practice, and much of the water is reused. It is estimated that about 4.3 mgd was used for air conditioning in 1954 as compared to 11.9 mgd in 1952.

Probably more wells are used for domestic and stock supplies than for all other purposes combined. The total quantity of water discharged by the wells, however, represents only a small part of the water discharged from the reservoir. In 1954 approximately 17.1 mgd was withdrawn from the Edwards and associated limestones throughout the area for domestic and farm use.

Livingston, Sayre, and White (1936, p. 91) noted that much water from flowing wells was wasted. Most of this water was from wells south and southwest of San Antonio which are allowed to flow all the time. Some of these wells are used for irrigation during a part of the time, but much of the discharge is emptied into the nearest stream. Most of these wells yield "sulfur water", but a few yield fresh water. Among the "strong" flowing wells in the vicinity of San Antonio are those along Salado Creek, which are allowed to flow into the creek to supply stock and some domestic needs on farms several miles downstream. Only a small part of the water is utilized during most of the year. The decline in artesian head has reduced the discharge from the wells in recent years.

San Antonio and San Pedro Springs have had no flow for the last few years. Both springs formerly discharged into the San Antonio River, and the flow was measured by a gage just south of the business district of San Antonio. Since the springs have ceased flowing, the flow of the river has been maintained by wells in Brackenridge Park, the water emptied into the river by industrial and commercial wells, and local flood runoff. The flow past the gage in 1954 ranged from 2.7 to 758 cfs and averaged 12.1 cfs.

Total discharge from the reservoir and its distribution.- Estimates of the annual discharge from the Edwards and associated limestones in the San Antonio area have been made for the period 1934 to 1954. Figures 9A and 9B show that most of the water has been discharged by springs in Bexar, Comal, and Hays Counties. Since 1951, however, the discharge from wells has approximately equaled the flow from springs.

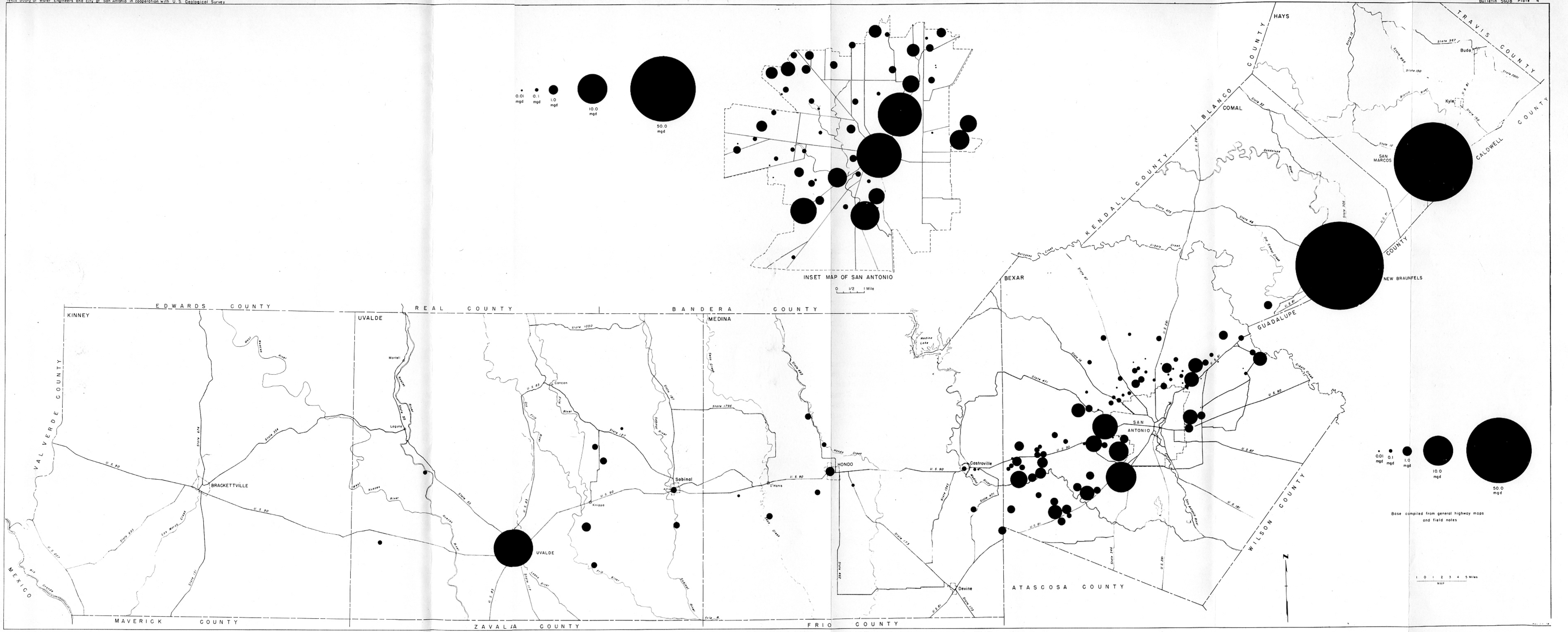
Accurate production figures are available from meter records of the San Antonio City Water Board and the military installations. The discharge of Comal Springs has been measured throughout the period of study. A record of daily discharge from Leona Springs is available from 1939. Less accurate figures based on periodic discharge measurements have been obtained from the remaining springs. Production figures for many industrial and air-conditioning wells have been estimated from discharge rates and operation schedules. The quantity of water used for irrigation has been estimated from the duty of water for crops and the acreage or from the amount of current used by electrically operated pumps. The amount of water discharged by some of the flowing wells has been estimated by correlation of water levels and measured discharges.

The distribution of water from all springs and wells discharging more than 5,000 gpd in 1954 is shown in plate 4. The illustration shows that most of the water is discharged from four areas in Comal, Hays, Uvalde, and Bexar Counties. In Comal and Hays Counties, all but a small part of the discharge is from Comal and San Marcos Springs. In Uvalde and Bexar Counties, the discharge is exclusively from wells. Most of the discharge occurs in the eastern part of the area, whereas the recharge is spread throughout the area.

Yields of Wells

The logs of a large number of wells drilled into the Edwards and associated limestones in the San Antonio area show that the aquifer is traversed by an intricate system of openings. These openings range from minute joints and other cracks to solution channels approaching large caverns in size. Wells in which only small openings are encountered usually yield only small amounts of water and have large drawdowns; those wells in which large openings and caves are encountered usually yield large amounts of water and have drawdowns that may be too small to measure.

The size of openings varies considerably from place to place and wells spaced only a few feet apart may differ greatly in yield. It generally is believed that the largest and most extensive systems of openings occur in the vicinity of faults.



MAP SHOWING DISTRIBUTION OF DISCHARGE FROM THE EDWARDS AND ASSOCIATED LIMESTONES IN THE SAN ANTONIO AREA, TEXAS, 1954.

Well capacities cannot be estimated by conventional methods because of the variations in size of openings that a well may encounter. If a well encounters openings sufficient in number and size to produce water, the yield will be limited primarily by the size of the well casing.

Many wells, especially domestic and stock wells, are capable of producing much more water than their pumps will discharge. The use for which the well is intended generally determines the pump capacity. Where a well will not supply the water needed without excessive drawdown, additional wells have been drilled.

It was recognized by Sayre and Bennett (1942, p. 27) that in general the Edwards is more productive in and near San Antonio than elsewhere.

> The number of faults increases from Kinney County toward San Antonio; thus the opportunity for widespread solutional openings increases toward the east. Furthermore, the quantity of water moving through the openings increases by accretion from recharge and hence the amount of solution increases toward the east. The fact that in Kinney County area the wells are generally less productive and the water levels fluctuate erratically, whereas in the vicinity of San Antonio most wells have large yields and the water levels fluctuate uniformly indicates that the development of solutional openings has been more widespread to the east.

Plate 5 shows the discharge, the drawdown at that rate of discharge, and the use of the water from wells in the San Antonio area. For most wells, the discharge represents the maximum yield of which there is a record. Plate 5 shows that most of the large-capacity wells are in the vicinity of Uvalde and San Antonio and others are scattered throughout the area.

Among the many large wells in the San Antonio area, the largest are well 164 in Bexar County, which had a natural flow of 16,800 gpm when measured in June 1942, and the San Antonio City Water Board's new well at the Market Street plant, which was pumped at nearly 15,000 gpm when completed in 1954. Bexar County wells 267, 274, J-21, and N-4 all have been reported to yield more than 6,000 gpm each. In contract to these high yields, Bexar County well 161, which is 40 feet from well 164, has never yielded much water, although 80 quarts of "nitro" was discharged in the well to enlarge the openings.

In recent years acid has been used to increase the yield of some wells. The action of the acid on the limestone tends to increase the size and extent of the cracks and other channels near the well. If this process is successful in connecting the well to larger openings, the yield may be increased appreciably. Many wells in the San Antonio area have been improved by this method.

Livingston, Sayre, and White (1936, p. 73) summarize the lack of homogeneity of the Edwards as follows:

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

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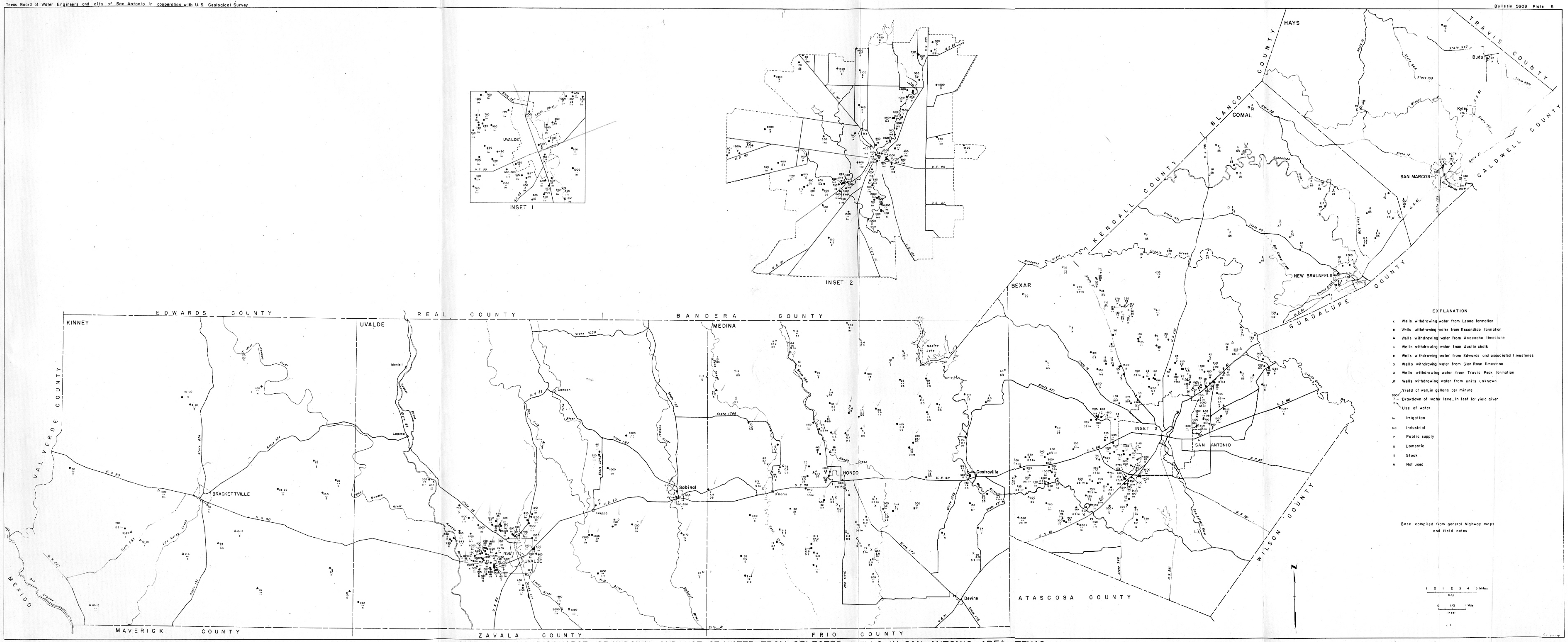


EXPLANATION

- x Wells withdrawing water from Leona formation
- ■ Wells withdrawing water from Escondido formation
- ▲ Wells withdrawing water from Anacacho limestone
- △ Wells withdrawing water from Austin chalk
- ● Wells withdrawing water from Edwards and associated limestones
- ○ Wells withdrawing water from Glen Rose limestone
- □ Wells withdrawing water from Travis Peak formation
- ø Wells withdrawing water from units unknown

800 Yield of well, in gallons per minute
7 Drawdown of water level, in feet for yield given
D Use of water

- Irr Irrigation
- Ind Industrial
- P Public supply
- D Domestic
- S Stock
- N Not used

Base compiled from general highway maps
and field notes

MAP SHOWING DISCHARGE, DRAWDOWN, AND USE OF WATER FROM SELECTED WELLS IN SAN ANTONIO AREA, TEXAS

Even in the district in and around San Antonio, where the largest number of successful wells have been drilled, it not infrequently happens that closely spaced wells have widely different yields. For example, in downtown San Antonio of four flowing wells of about equal depth put down within a distance of a few hundred feet, three had a flow of only a few gallons a minute, but the fourth had a flow of more than a thousand gallons a minute.

Fluctuations of Water Levels

The water levels in the Edwards limestone reservoir fluctuate within fairly wide limits, depending upon the rate of recharge to the reservoir and to a lesser extent on changes in discharge. The rate of recharge varies with the distribution, amount, and intensity of the rainfall. During periods of below-normal rainfall, the water levels gradually decline, but they recover rapidly after heavy rains. Hydrographs of representative wells in the Edwards and associated limestones throughout the area are shown in figures 10 to 16.

Water levels rose rapidly after the heavy general rains of May - July 1935, May - September 1936, and July - September 1942. After each rain the water levels rose quickly and reached high levels, which were maintained for periods up to 2 months, before starting to decline gradually as water was discharged from the reservoir. Levels declined from 1936 to 1940 as water was discharged from the reservoir at a rate in excess of the rate of recharge, but the heavy rains of 1941 and 1942 caused the water levels to rise to their highest recorded levels. From 1942 through 1946 the rainfall was above normal generally, and the water levels remained relatively high. The trend from 1947 through 1954 has been downward, reflecting below normal rainfall throughout the area and increased withdrawals from the reservoir. Water levels recovered slightly after heavy rains in parts of the area in September 1952 and May - June 1954; however, the recharge was not enough to stop the overall trend downward.

Changes in the rate of withdrawal of large quantities of water cause minor fluctuations of water levels near the points of withdrawal. For example, when well 164 was tested at 16,800 gpm, the water level in a well 18 feet away was lowered about 29 feet and that in another well about 2,000 feet away declined less than a foot.

Changes in the rate of withdrawal in San Antonio cause a daily fluctuation in the water level in Bexar County well 26, ranging from about 0.3 foot in the winter to 4.5 feet in the summer. The water level also shows a weekly fluctuation in response to reductions of withdrawal during weekends.

Measurements of the depth to water in wells throughout the area have been made periodically. (See vol. II, p.III-1.) Since 1950 the number of wells regularly measured has been increased to afford a better coverage throughout the area of study. Currently, measurements are being made bimonthly in 124 observation wells, and monthly in 37 wells. Recording gages are in operation on 12 wells in the area to give a continuous record of the changes in artesian pressure.

Representative hydrographs of wells (figs. 10 - 16) show a fairly uniform trend in fluctuations. In general, water-table wells in the outcrop area fluctuate with the same frequency as artesian wells, but with much greater amplitude. Wells near springs show very little change in artesian pressure.

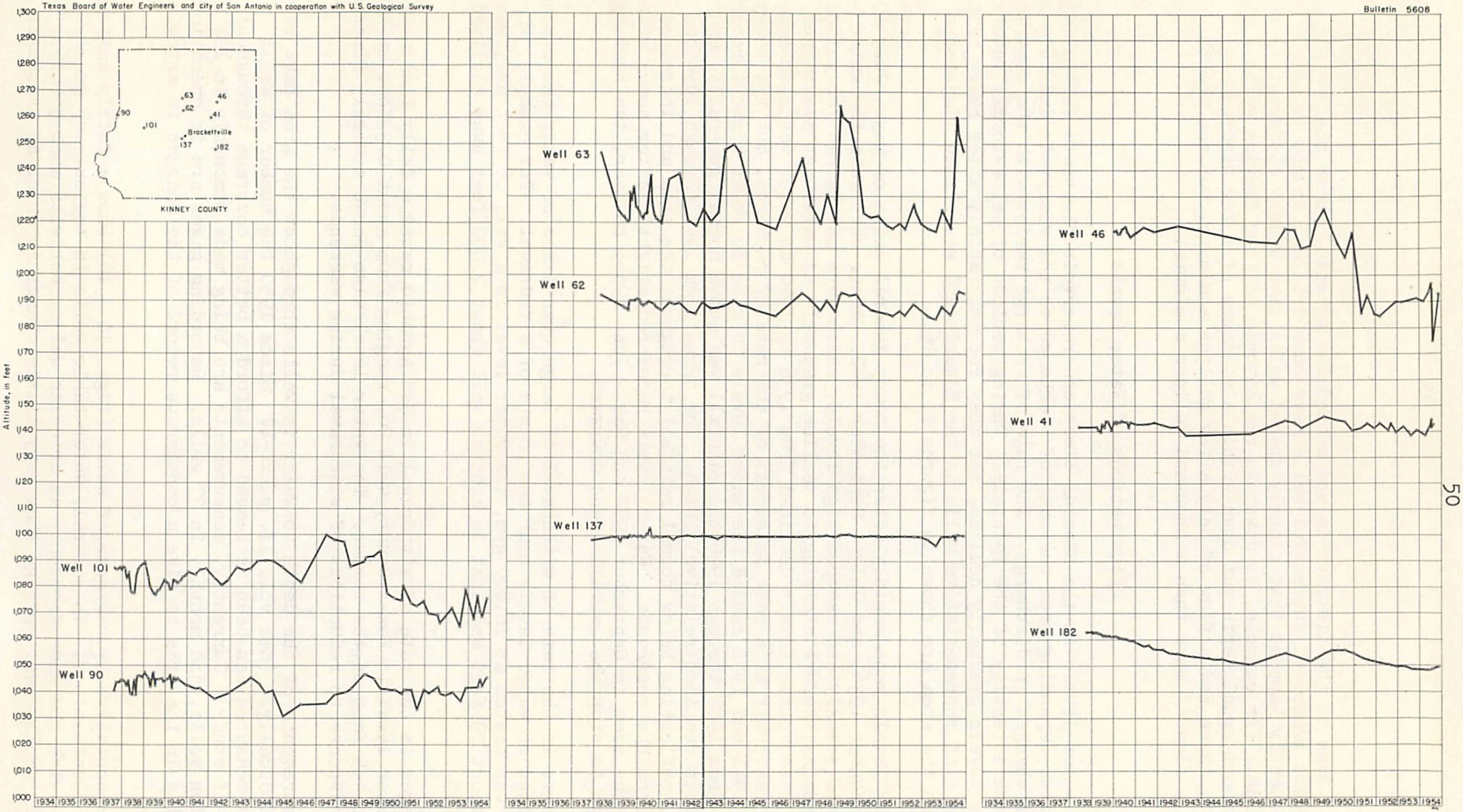


FIGURE 10.- Hydrographs of representative wells in the Edwards and associated limestones, Kinney County, Tex.

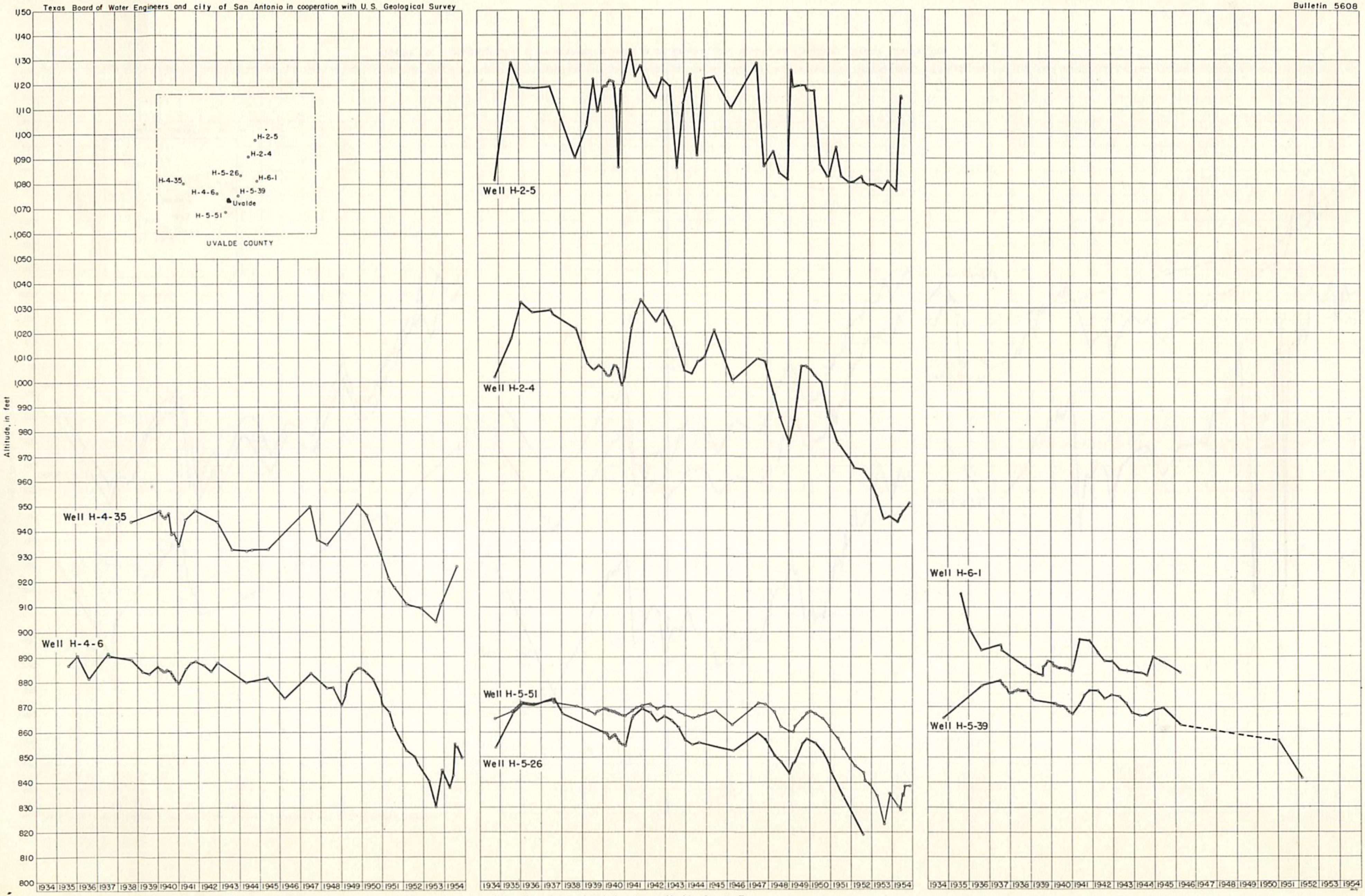


FIGURE 11.- Hydrographs of representative wells in the Edwards and associated limestones, Uvalde County, Tex.

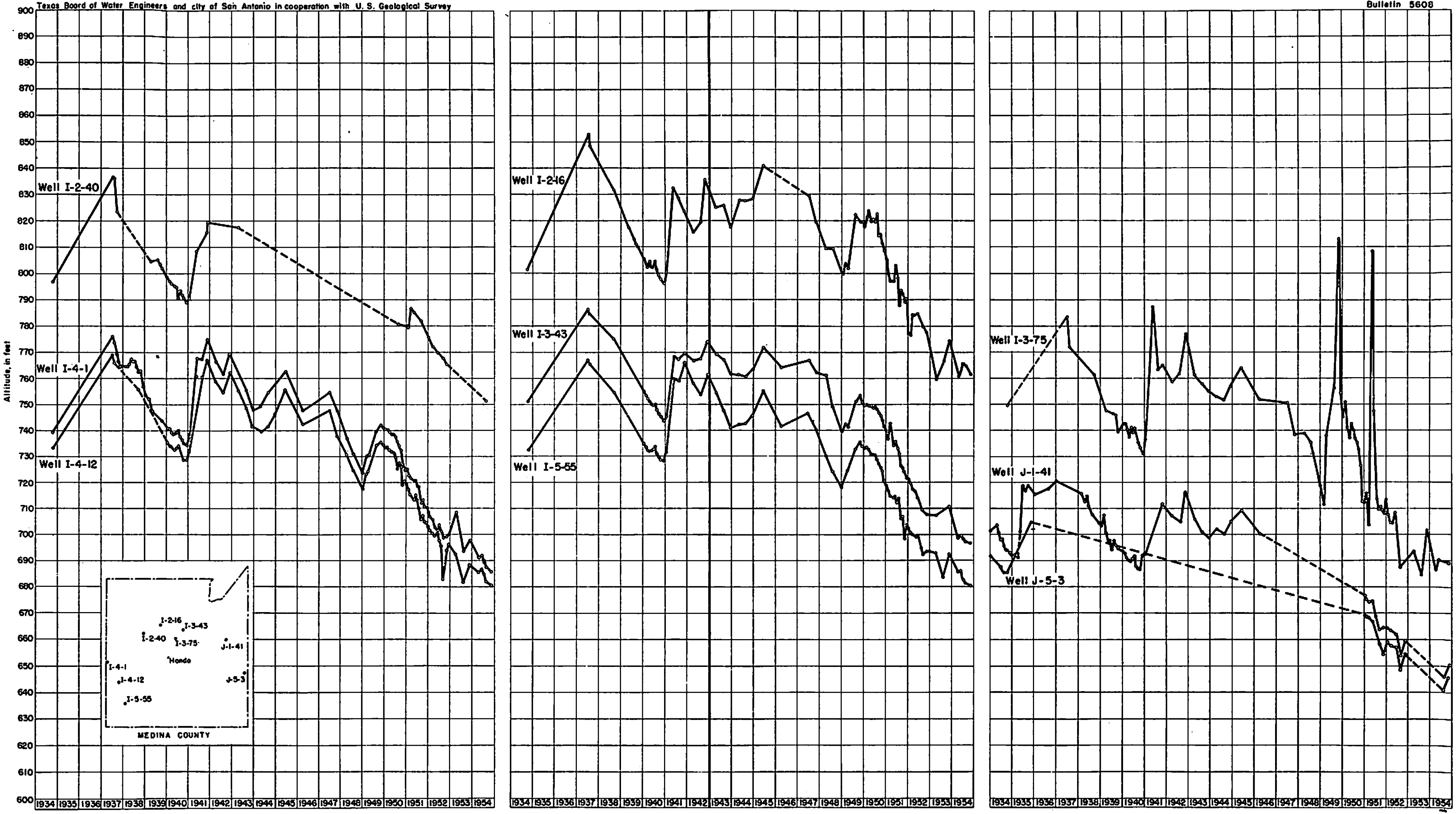


FIGURE 12 - Hydrographs of representative wells in the Edwards and associated limestones, Medina County, Tex.

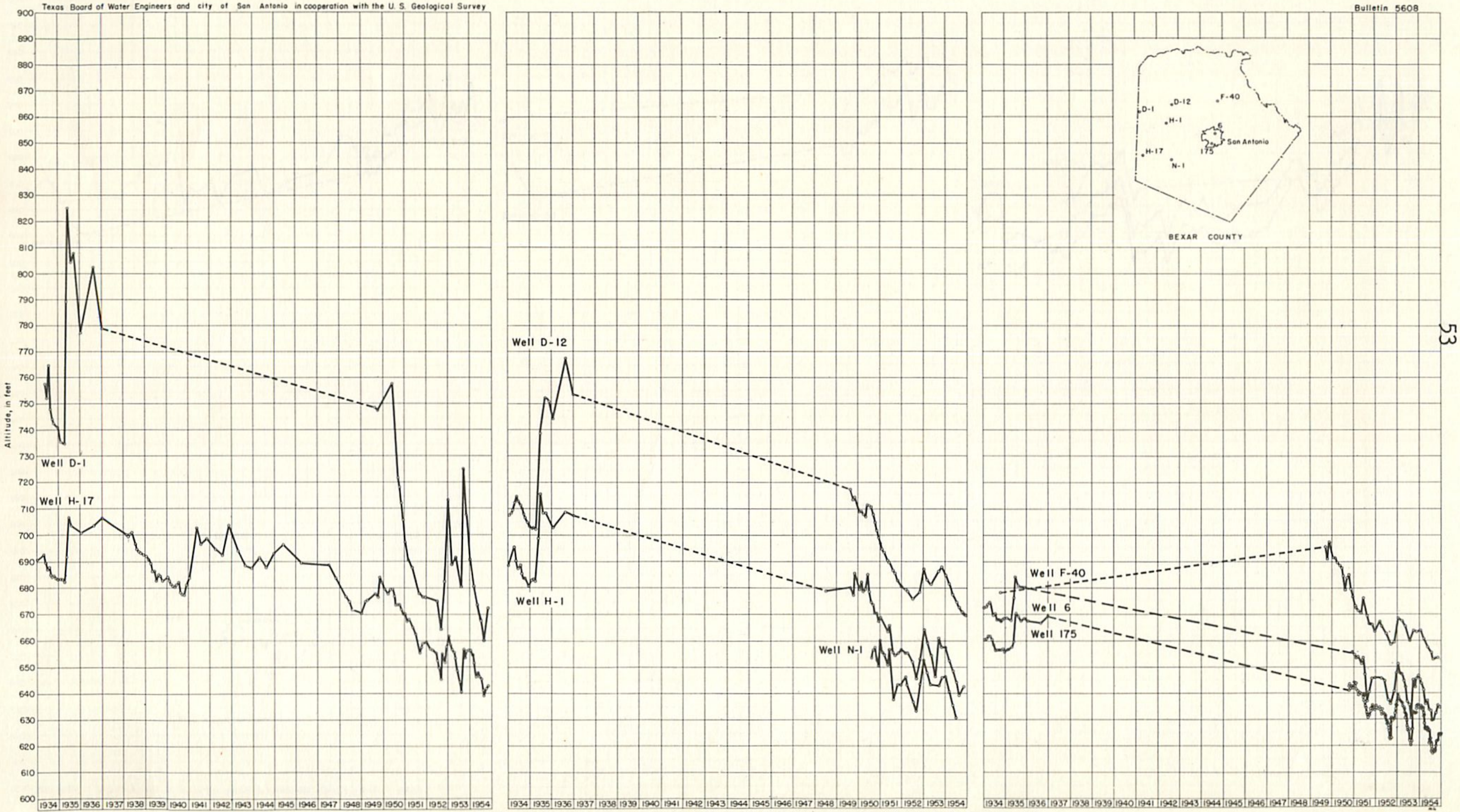


FIGURE 13 - Hydrographs of representative wells in the Edwards and associated limestones, Bexar County, Tex.

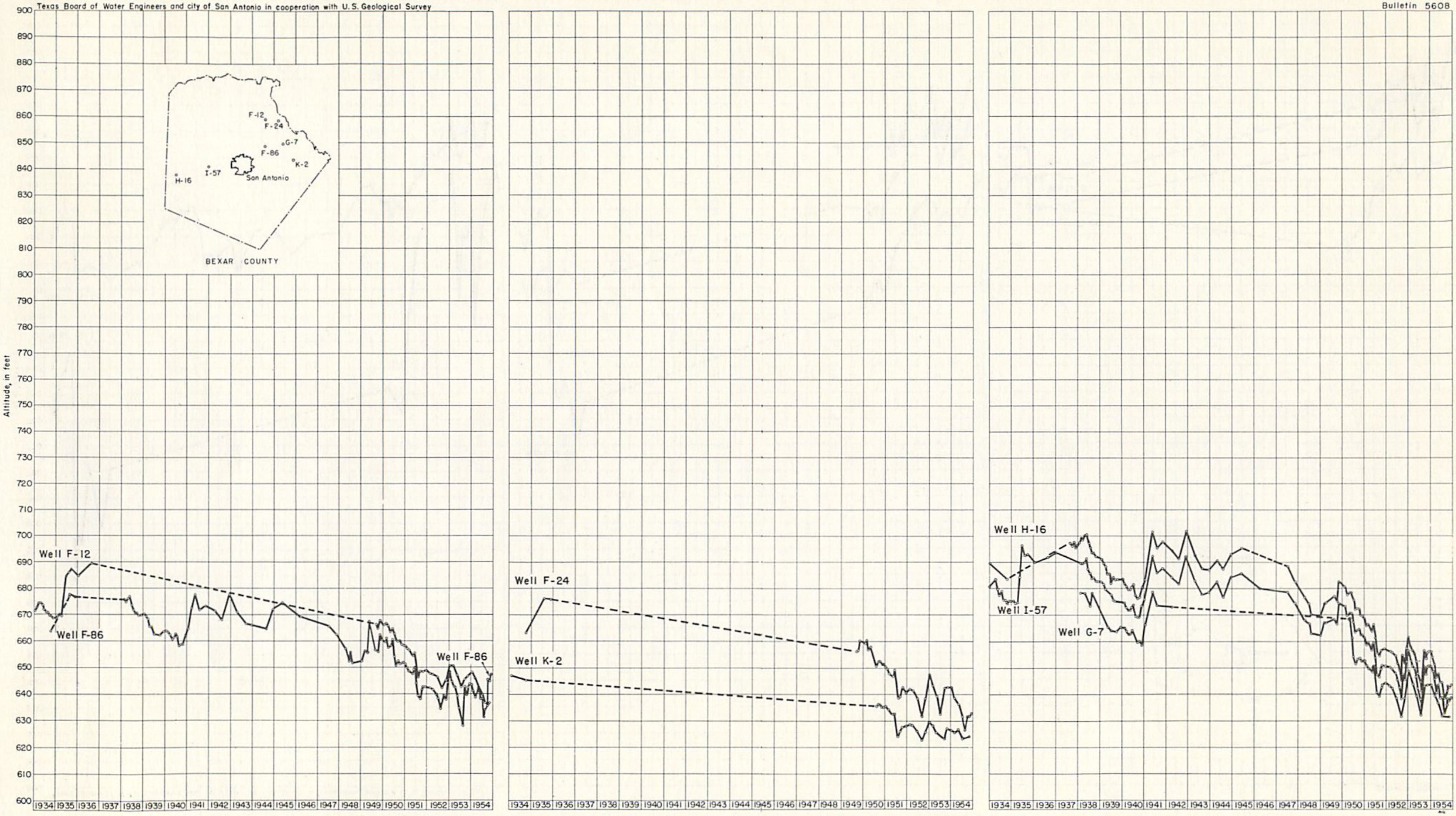


FIGURE 14 - Hydrographs of representative wells in the Edwards and associated limestones, Bexar County, Tex.

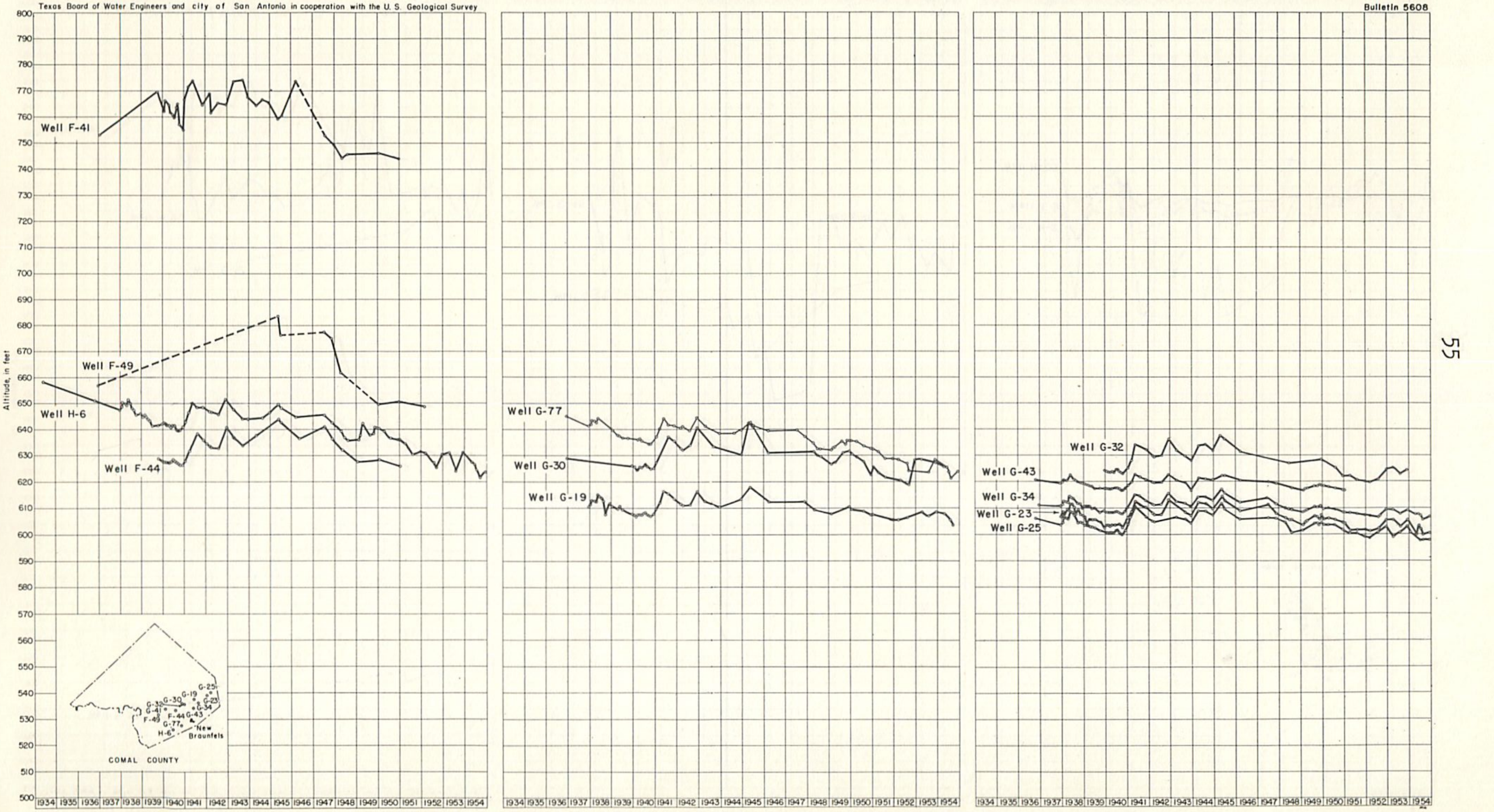


FIGURE 15.- Hydrographs of representative wells in the Edwards and associated limestones, Comal County, Tex.

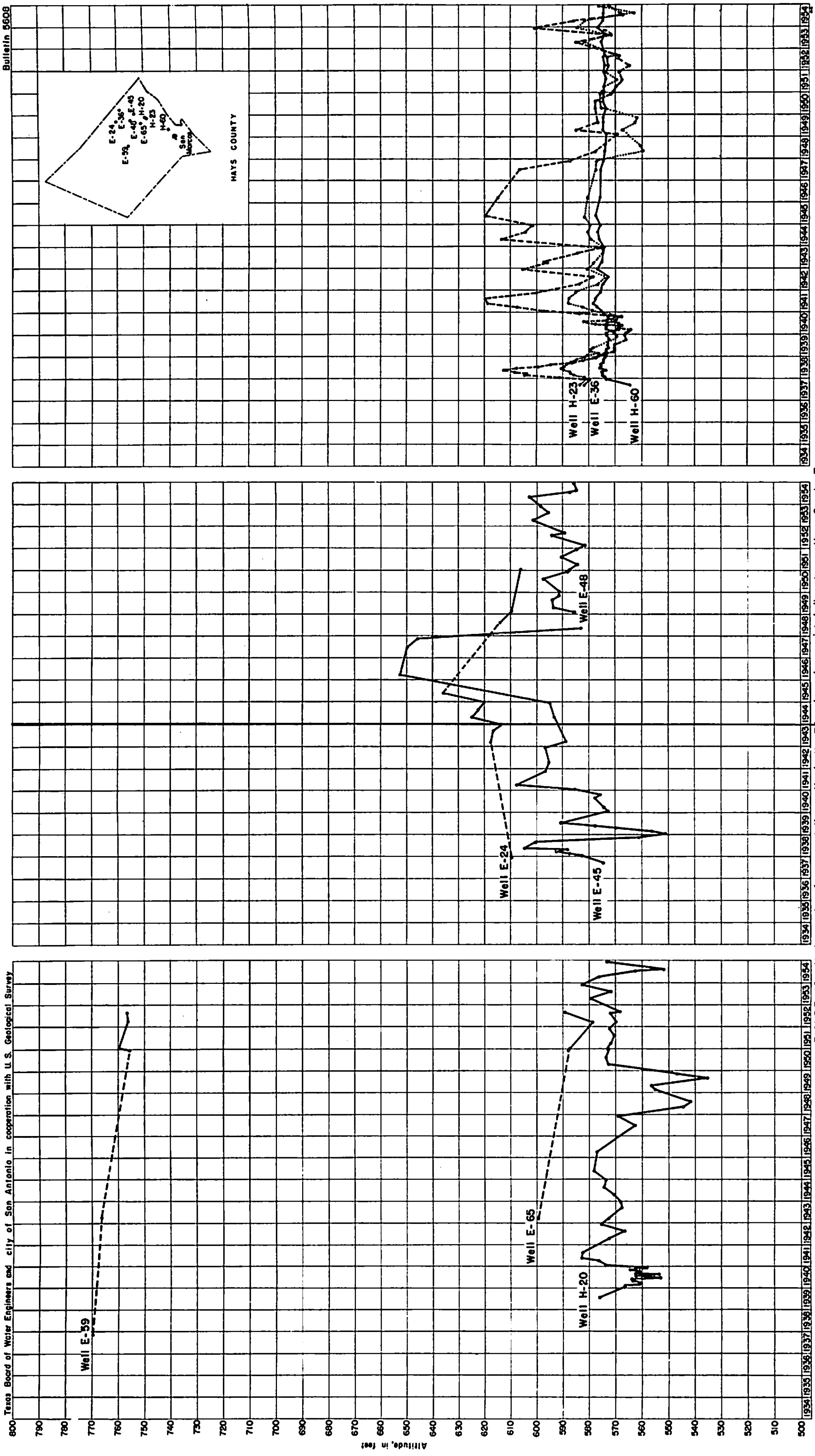


FIGURE 16.-Hydrographs of representative wells in the Edwards and associated limestones, Hays County, Tex.

Kinney County.- In general, the water levels do not fluctuate as much in Kinney County as they do in the rest of the area. (See the hydrographs of 8 representative wells in figure 10.) A ground-water divide is indicated by the elevation of the water surface in these wells. Wells 101 and 90 are west of the divide; wells 63, 62, and 137 are approximately along the divide; and wells 46, 41, and 182 are east of the divide. Wells 101, 63, and 46 are water-table wells and have a large range in fluctuation as compared to the rest of the wells, which are artesian. Well 137 is just below Las Moras Springs, and almost all the changes in artesian pressure can be correlated with changes in discharge of the springs. The water level throughout the period of record appears to be remarkably uniform.

Uvalde County.- The hydrographs of 9 wells in Uvalde County are shown in figure 11. Wells H-2-5 and H-2-4 are water-table wells and the rest are artesian. As is true in most of the San Antonio area, the water levels in water-table wells fluctuate widely as compared with those in artesian wells. All the hydrographs reflect the drought that began in 1947. Local rains in the Uvalde area in 1949 were sufficient to offset temporarily the decline of water levels occurring in the first part of the drought. In addition to the lack of recharge, the steady increase in the use of water for irrigation in the vicinity of Uvalde has increased the rate of decline in artesian head. (See hydrographs of wells H-5-56 and H-5-21).

Medina County.- The hydrographs of 9 wells in Medina County are shown in figure 12. With the exception of that for well I-3-75, the hydrographs indicate similar fluctuations of water level. The erratic pattern of fluctuation in well I-3-75 is probably related to a nearby zone of faulting.

Bexar County.- Figures 13 and 14 are hydrographs of water levels in wells in Bexar County. Wells D-1, D-12, and F-24 are probably water-table wells. All the water levels fluctuate similarly, even those in wells 175 and K-2, which are in the zone that yields water of poor quality. This suggests that the water of poor quality is connected hydraulically with the fresh water.

Wells H-16, I-57, and G-7 (fig. 14) are in a line trending in a northeasterly direction through the city of San Antonio from western Bexar County toward Comal Springs. Although a distance of approximately 20 miles separates well I-57 and well G-7, the water levels fluctuate in a remarkably similar manner. The small difference in altitude between the water levels in the wells indicates that the hydraulic gradient is small.

Comal County.- Figure 15 shows three groups of wells in Comal County. With the exception of wells G-77 and H-6, and possibly G-34, all are water-table wells. The range in fluctuations is small compared to that in wells west of Comal County.

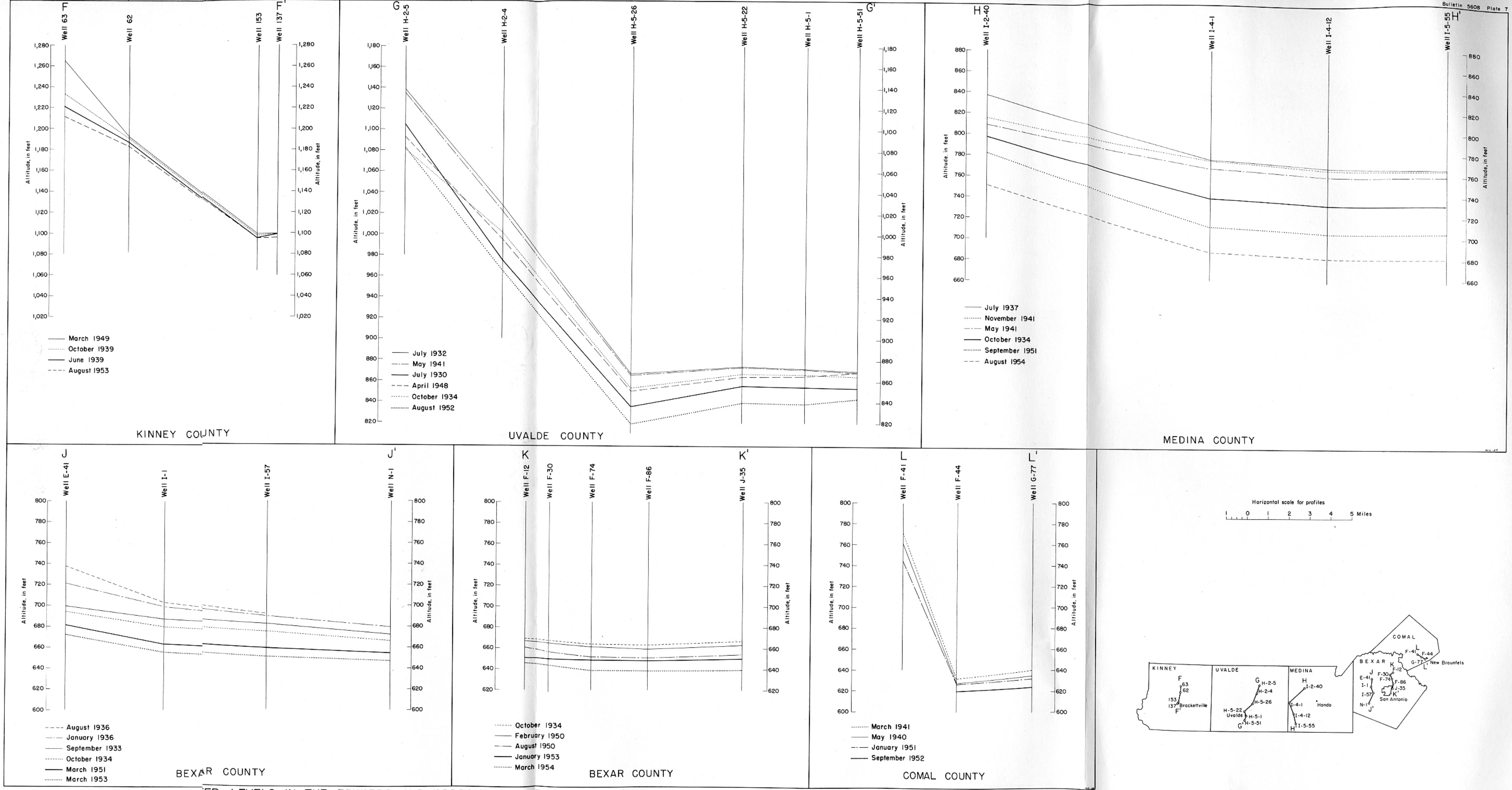
Some of the observation wells are close to major faults. Wells F-41, F-49, and G-30 are all very close to the Hueco Springs fault. According to George (1952, p. 50-51), Hueco Springs, approximately 5 miles north of New Braunfels, may be supplied by a ground-water reservoir that is separated from that supplying Comal Springs, as the Hueco Springs fault is believed to divide the two reservoirs. It has not been proved, however, that the fault acts as a barrier to the movement of ground water. Wells G-34, G-43, G-23, and G-25 are all close to the Comal Springs fault. Water table well F-44 is approximately midway between the Hueco Springs fault and the Comal Springs fault. Artesian well H-6 is about 1 mile south of the Comal Springs fault and about 4½ miles south of well F-44. The two wells fluctuate similarly, although well H-6 has a higher head and is located downdip from well F-44.

Hays County.- The hydrographs of representative wells in Hays County are shown in figure 16. The water levels fluctuate similarly within the county; however, the hydrographs do not correlate closely with those for the rest of the San Antonio area. A possible ground-water divide in the extreme eastern part of Hays County may have some effect on the fluctuations of water levels.

Summary.- A study of the records of miscellaneous measurements indicates that the fluctuations in water levels in most of the area follow the same trends, and the hydraulic gradients between wells remain relatively constant. The profile of water levels approximately parallel to the main zone of faulting (pl. 6) shows both the approximate average gradients between wells and the approximate range between high and low water levels. The ground-water divide in Kinney County has a steep hydraulic gradient on either side. The gradient is steepest in Kinney County, becomes less steep in Uvalde County, and is nearly flat from the Uvalde-Medina County line to Comal Springs, ranging from about 1.5 feet per mile in December 1942 to about 0.8 foot per mile in August 1954. The steep gradient in some places as compared to the nearly flat gradient in others may indicate that movement is along smaller or more tortuous channels.

Water levels fluctuate similarly throughout the area; however, small deviations occur locally because recharge is unevenly distributed along the 175-mile length of the profile (pl. 6). In May and June 1954, heavy rains caused floods on the West Nueces, Nueces, Frio, Dry Frio, and Sabinal Rivers. Most of the flodwater went into the underground reservoir and caused significant rises in water levels in wells in Uvalde County and small rises in part of Medina County. In August 1954 water levels were at an all-time low for the San Antonio area except in those wells in Uvalde and Kinney Counties.

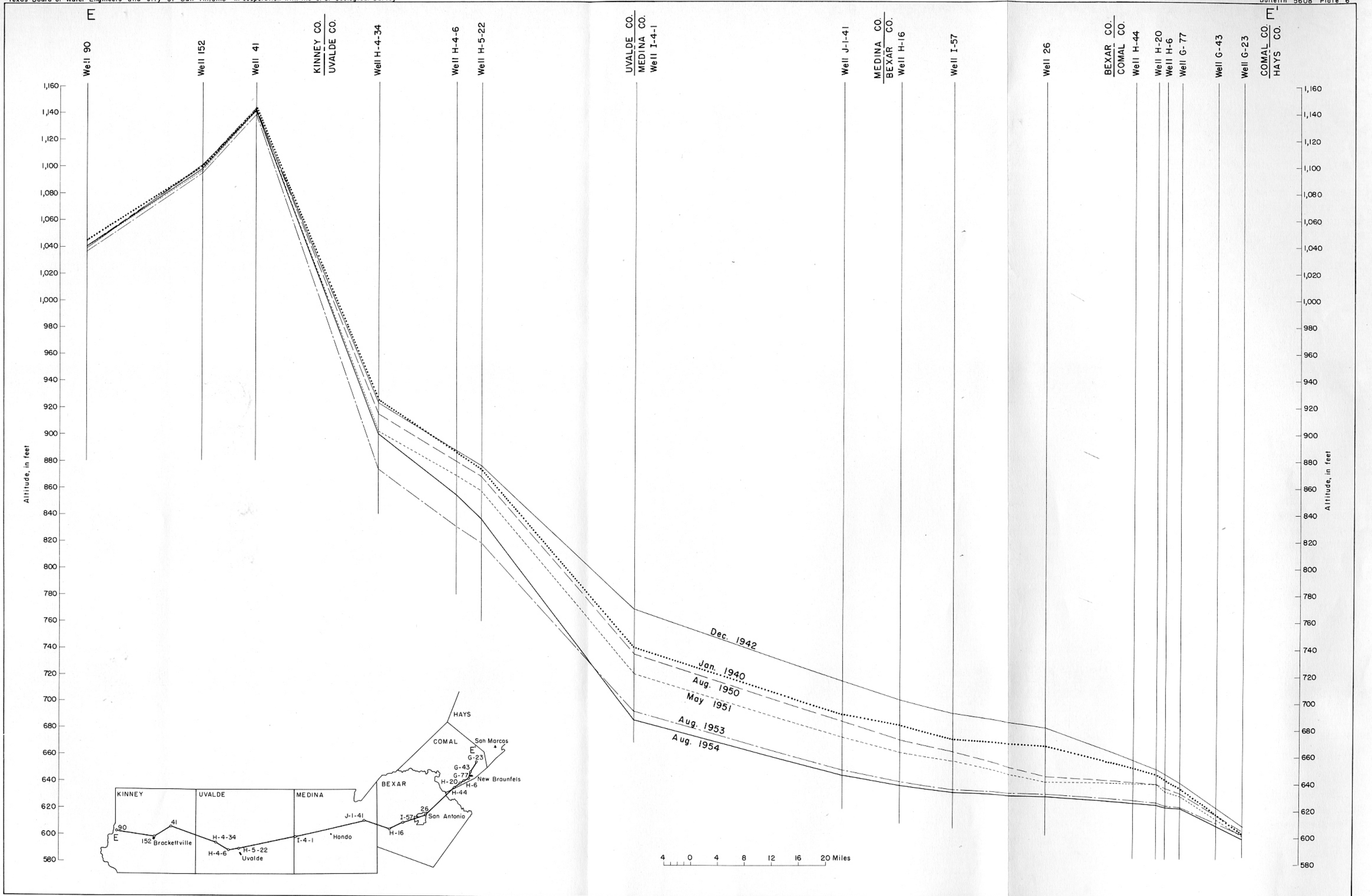
Plate 7 shows the profiles of the water table and piezometric surface at approximately right angles to the main zone of faulting. The profiles show that the piezometric surface fluctuates uniformly throughout the artesian section. In the water-table sections there is less uniformity, but the fluctuations do not materially affect the hydraulic gradients. The profiles show only slight gradients in Bexar County and the southern parts of Medina and Uvalde Counties.



PROFILES OF WATER LEVELS IN THE EDWARDS AND ASSOCIATED LIMESTONES IN KINNEY, UVALDE, MEDINA, BEXAR, AND COMAL COUNTIES, TEX.

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

Bulletin 5608 Plate 6



PROFILE OF WATER LEVELS IN THE EDWARDS AND ASSOCIATED LIMESTONES FROM KINNEY THROUGH COMAL COUNTIES, TEX.

Movement of Water in the Balcones Fault Zone

The water in an aquifer moves in the direction of the hydraulic gradient and the direction of movement can be determined if the shape of the water table or piezometric surface can be accurately mapped. The Edwards limestone is not homogeneous and the transmissibility of the formation varies from place to place. The openings in the Edwards range in size from caverns in which the water moves freely, to minute cracks in which large losses in head occur. The many faults that cross the area present additional problems; some faults act as principal avenues in which water is free to move with little loss of head, whereas others contain gouge, bring together permeable and impermeable rocks, or otherwise acts as barriers. Because of these conditions, the water table or piezometric surface cannot be mapped in sufficient detail to show all the changes in direction of movement, but the general movement can be shown.

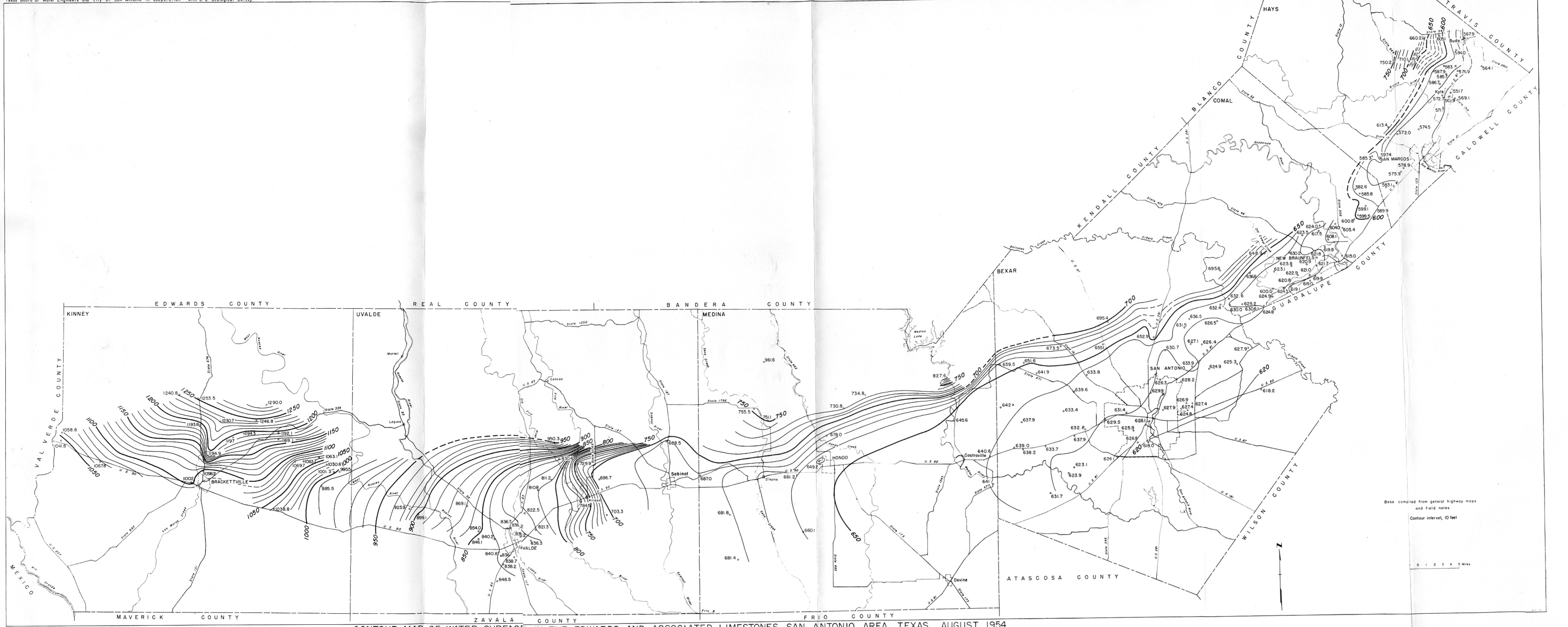
Plates 8 and 9 show the approximate altitude of the piezometric surface in January 1952 and August 1954. The contours are arithmetically proportioned between points of control without regard to probable differences in head across fault zones. Both maps show a ground water divide in Kinney County. Assuming that water moves normal to the contours, part of the water moves south and southwest toward the Rio Grande from that divide; the remainder moves south and southeast to the fault zone, and then east toward San Antonio.

A comparison of the estimated recharge with the estimated discharge for the period 1934-53 is further evidence that most of the water moves eastward. These figures indicate that the total recharge in Medina and Uvalde Counties and that part of Kinney County east of the ground-water divide was about 5.5 million acre-feet, as compared to a total discharge from the underground reservoir in these counties of about 0.4 million acre-feet. The total discharge from the underground reservoir for the same period in Bexar, Comal, and Hays Counties was about 9.9 million acre-feet as compared to about 2.9 million acre-feet of recharge. From these figures it is evident that the recharge west of Bexar County is in excess of the discharge, and east of the Bexar-Medina County line the discharge far exceeds the recharge, indicating movement of water to the east. In the southern part of the San Antonio area the water in the Edwards and associated limestones is highly mineralized, suggesting very little subsurface movement to the south.

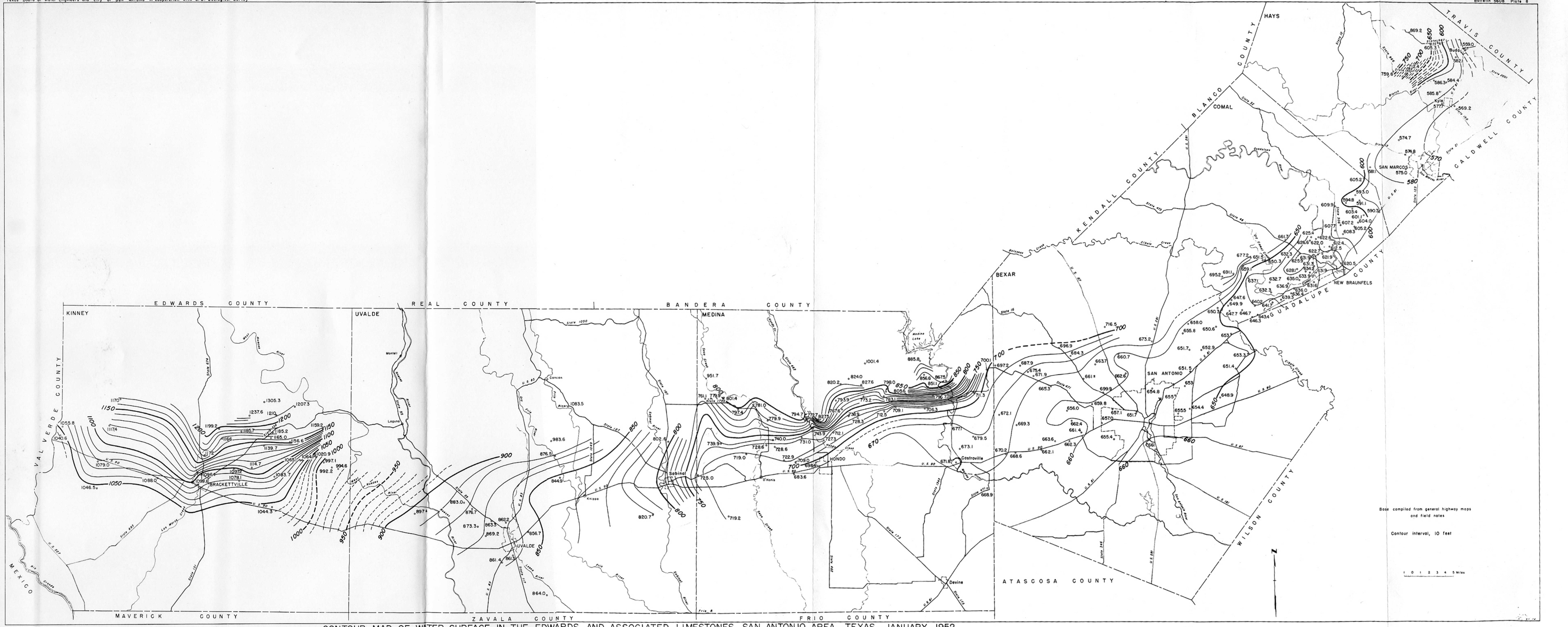
Altitudes of water levels in a few wells between Buda and Kyle in Hays County suggest the possibility of a ground-water divide in that area. If this divide exists, it must act as the northeastern limit of the hydrologic unit that supplied Comal Springs, San Antonio, and other springs and wells as far west as Kinney County.

Relation of Water Levels to Spring Flow

The delineation of the recharge areas for the reservoir supplying the springs in the San Antonio area is one of the most important objectives of the study of ground water in the Balcones fault zone. An attempt has been made to develop a method for defining the limits of these areas, involving the correlation of water levels with spring discharge. The water levels in some wells fluctuate in the same manner as does the spring discharge, and it is inferred that the portion of the reservoir penetrated by these wells is that tributary to the springs.



CONTOUR MAP OF WATER SURFACE IN THE EDWARDS AND ASSOCIATED LIMESTONES, SAN ANTONIO AREA, TEXAS, AUGUST 1954.



CONTOUR MAP OF WATER SURFACE IN THE EDWARDS AND ASSOCIATED LIMESTONES, SAN ANTONIO AREA, TEXAS, JANUARY 1952.

The discharge rate of Comal Springs correlates fairly well with the water level stages in Bexar County well 26 (see fig. 17A). Figure 17B shows a correlation curve drawn through points representing the lowest discharges of the spring and the highest water levels in the well. A comparison of precipitation data (fig. 4) with the deviation of these points from the curve reveal that some of the major deviations occurred during periods when intense storms were recharging localized areas. Because other storms of similar intensities in other suspected recharge areas produced little or no deviation, the presumption is that the route to the spring of the recharge water from those other storms was through the conduit system penetrated by well 26. Other routes from other recharge areas to the spring probably exist and it is the recharge from those areas that presumably causes the deviations in spring flow. If the preceding hypotheses are true, long-term records of water levels from carefully selected wells, of precipitation, and of the discharge of springs can be analyzed, and the effect of recharge in various areas on the spring flow can be determined. The relative importance of the recharge areas probably can be determined also.

Tentative correlation curves for several other wells are shown in figures 18, 19, 21, 22, and 24. These graphs indicate that much more information will be required before the positions of the curves can be definitely established. The deviation graphs for the wells for which correlation curves have been drawn are shown in figures 17, 20, 23, and 24. Theoretically, if the position of the curve is definitely established, the deviations represent the recharge that occurs outside the area contributing to the well, but inside the area contributing to the spring discharge. It is recommended that studies of this type be continued.

Relation of Reservoir Storage to Water Levels in Wells

Knowledge of the storage characteristics and capacity of the ground-water reservoir are helpful in planning water-supply development for the future.

According to Livingston, Sayre, and White (1936, p. 102), the area in Bexar County in which the Edwards and associated limestones contain water suitable for most purposes covers about 500 square miles. If the aquifer has an average thickness of 500 feet and a specific yield [1] of only 2 per cent, the total storage amounts to about 3,000,000 acre-feet. Bexar County, however, constitutes only about one-fifth of the San Antonio area as used in this report. This would suggest that the total storage in the San Antonio area under the foregoing assumptions would be about 15,000,000 acre-feet. Most of this water could not be recovered, however, without causing excessive lowering of the water levels in wells.

To determine accurately the storage characteristics and capacity of the reservoir, the following information is needed:

1. Continuous records of recharge to and discharge from the reservoir.
2. Average water levels throughout the reservoir at various times.
3. The areal extent of the reservoir.

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[1] The specific yield is defined as the ratio of (1) volume of water that the aquifer will yield by gravity to (2) its own volume.

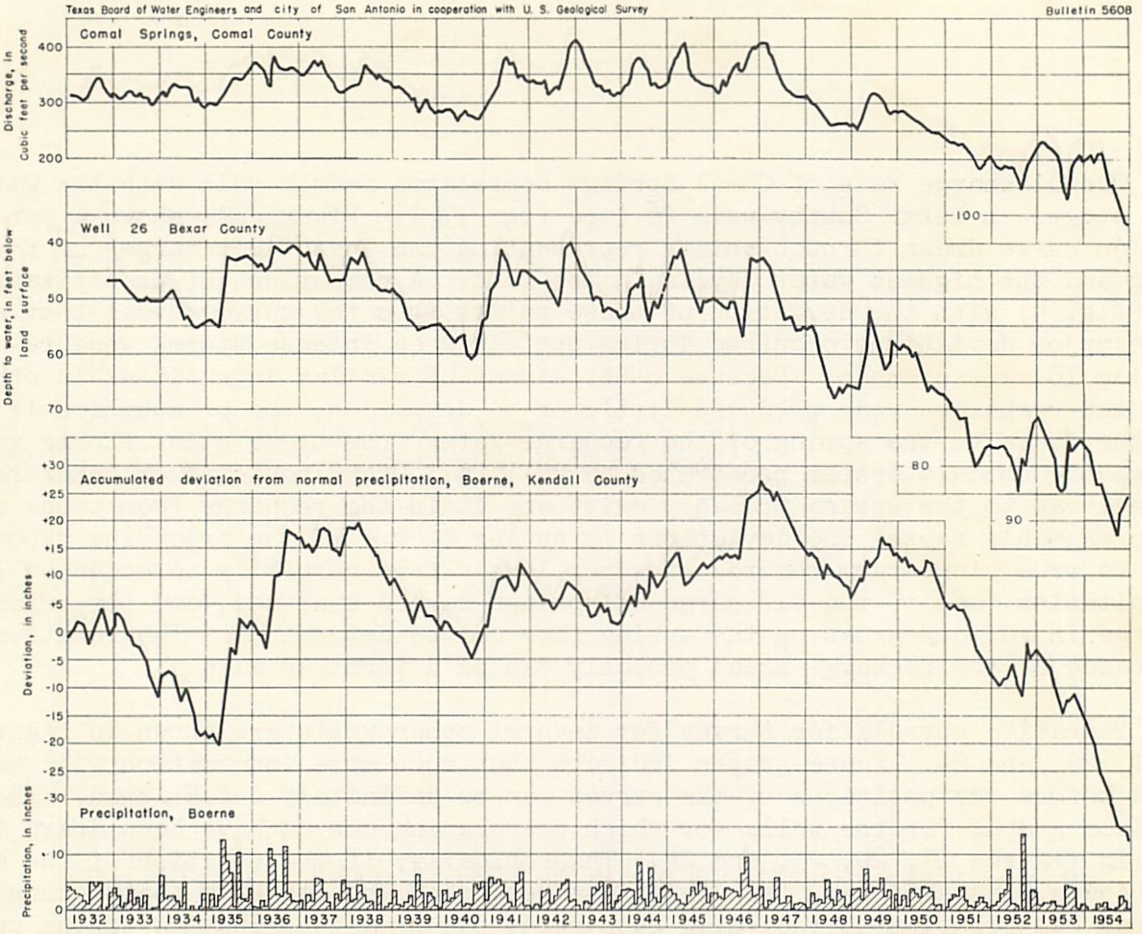

FIGURE 17 A.- Discharge of Comal Springs, water level in Bexar County well 26, and precipitation at Boerne, Tex., 1932-54.

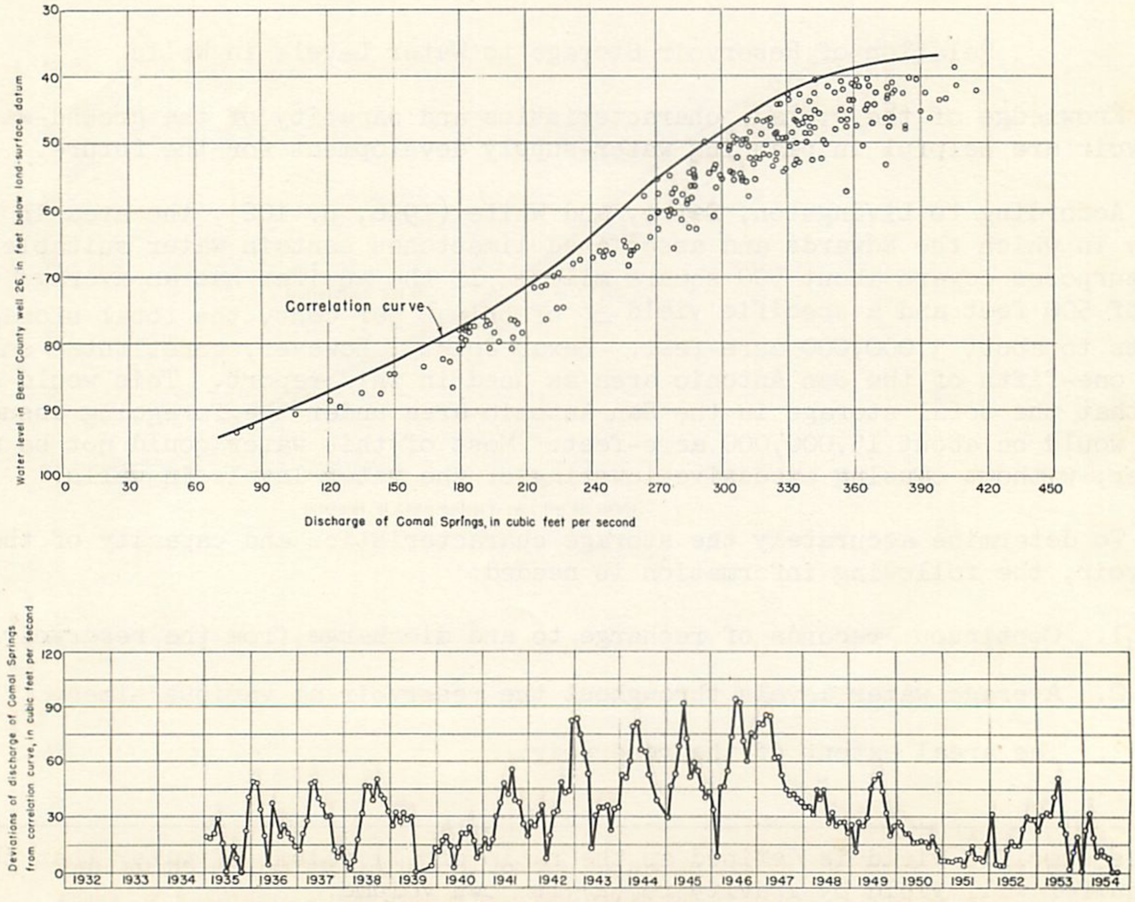

FIGURE 17 B.- Correlation of water levels in Bexar County well 26 with the discharge of Comal Springs.

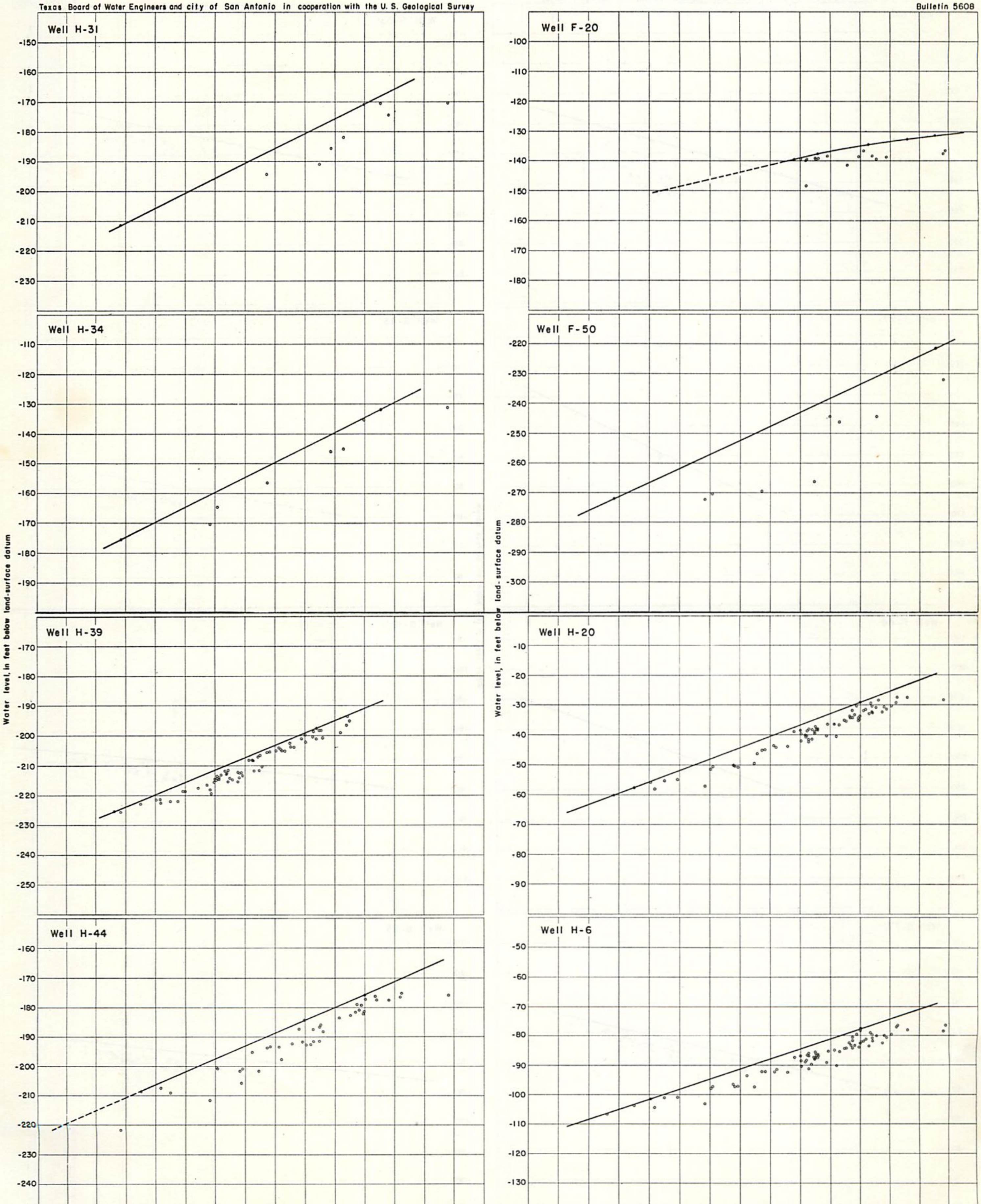

FIGURE 18.- Correlation of water levels in selected wells in Comal County with the discharge of Comal Springs.

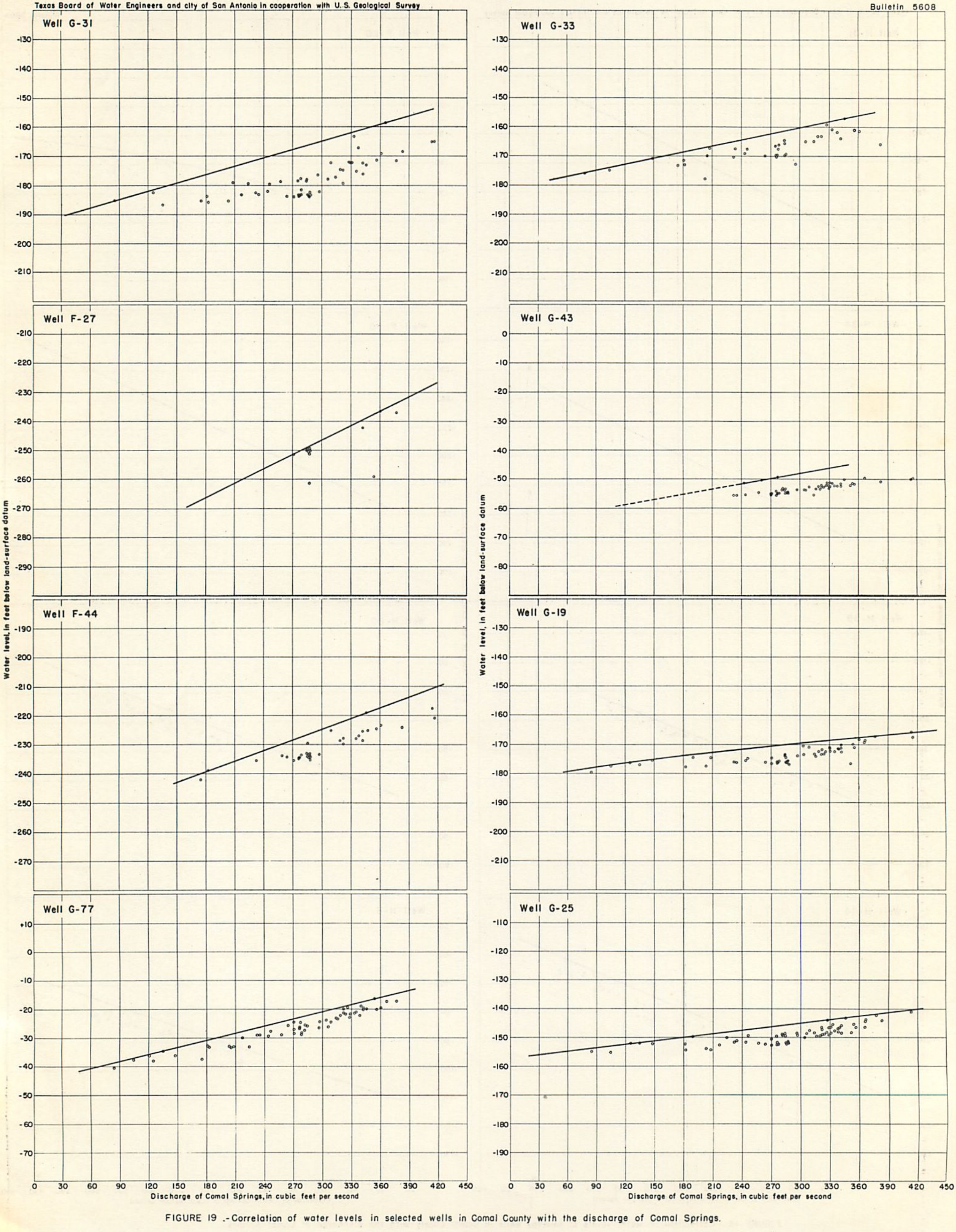

FIGURE 19 .-Correlation of water levels in selected wells in Comal County with the discharge of Comal Springs.

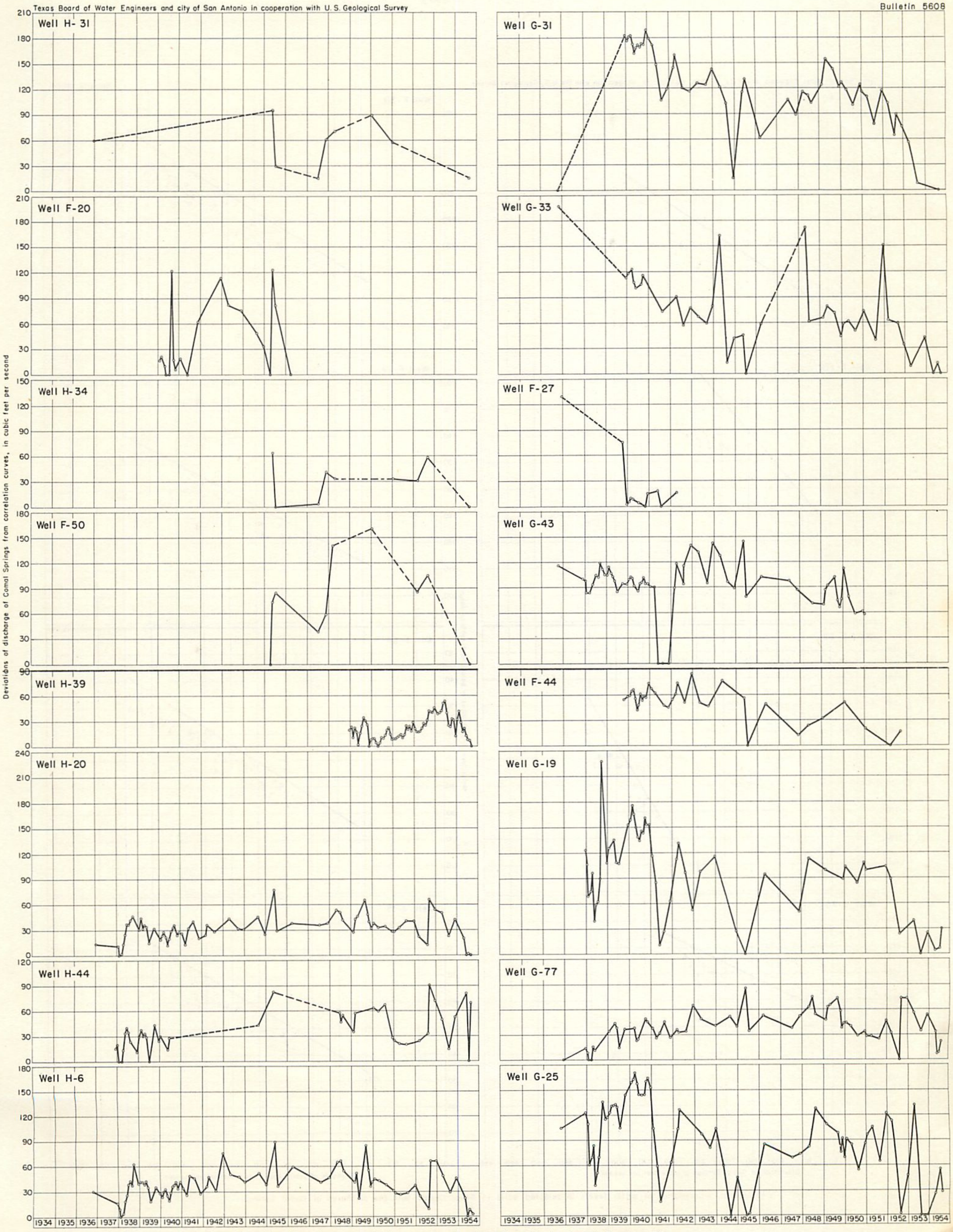

FIGURE 20.- Deviations in spring flow from correlation curves of selected wells in Comal County, Tex.

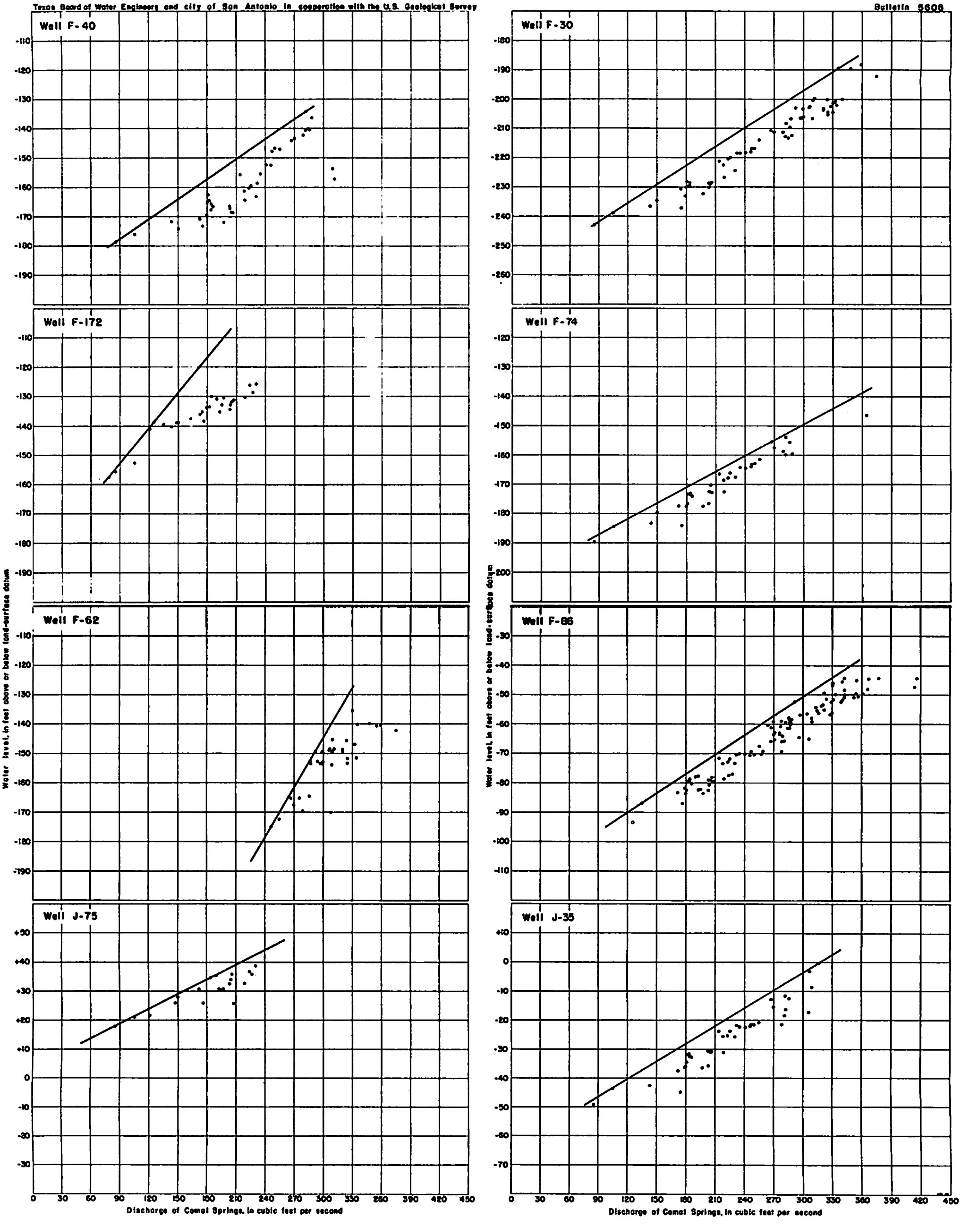

FIGURE 21 .- Correlation of water levels in selected wells in Bexar County with the discharge of Comal Springs.

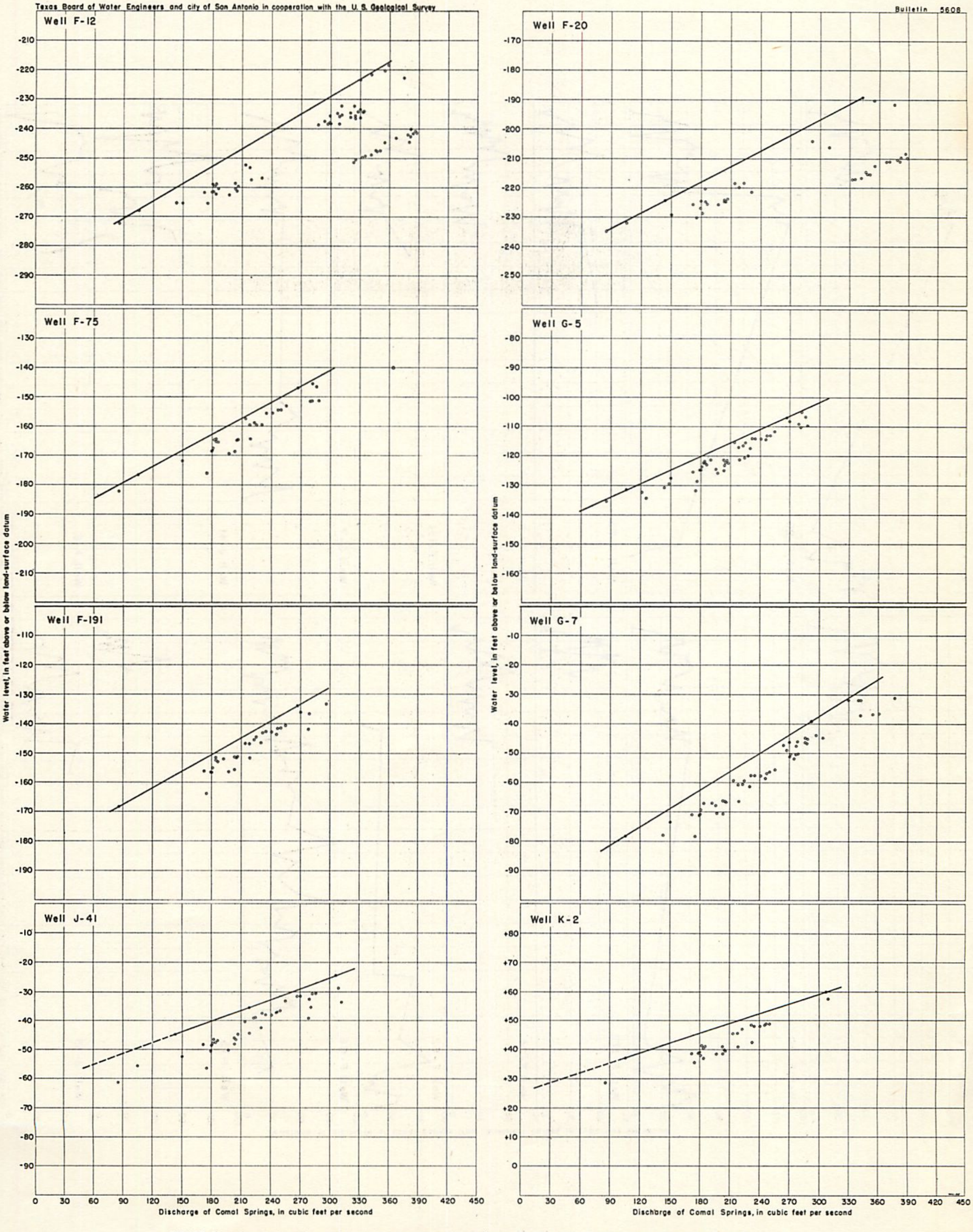

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FIGURE 22.- Correlation of water levels in selected wells in Bexar County with the discharge of Comal Springs.

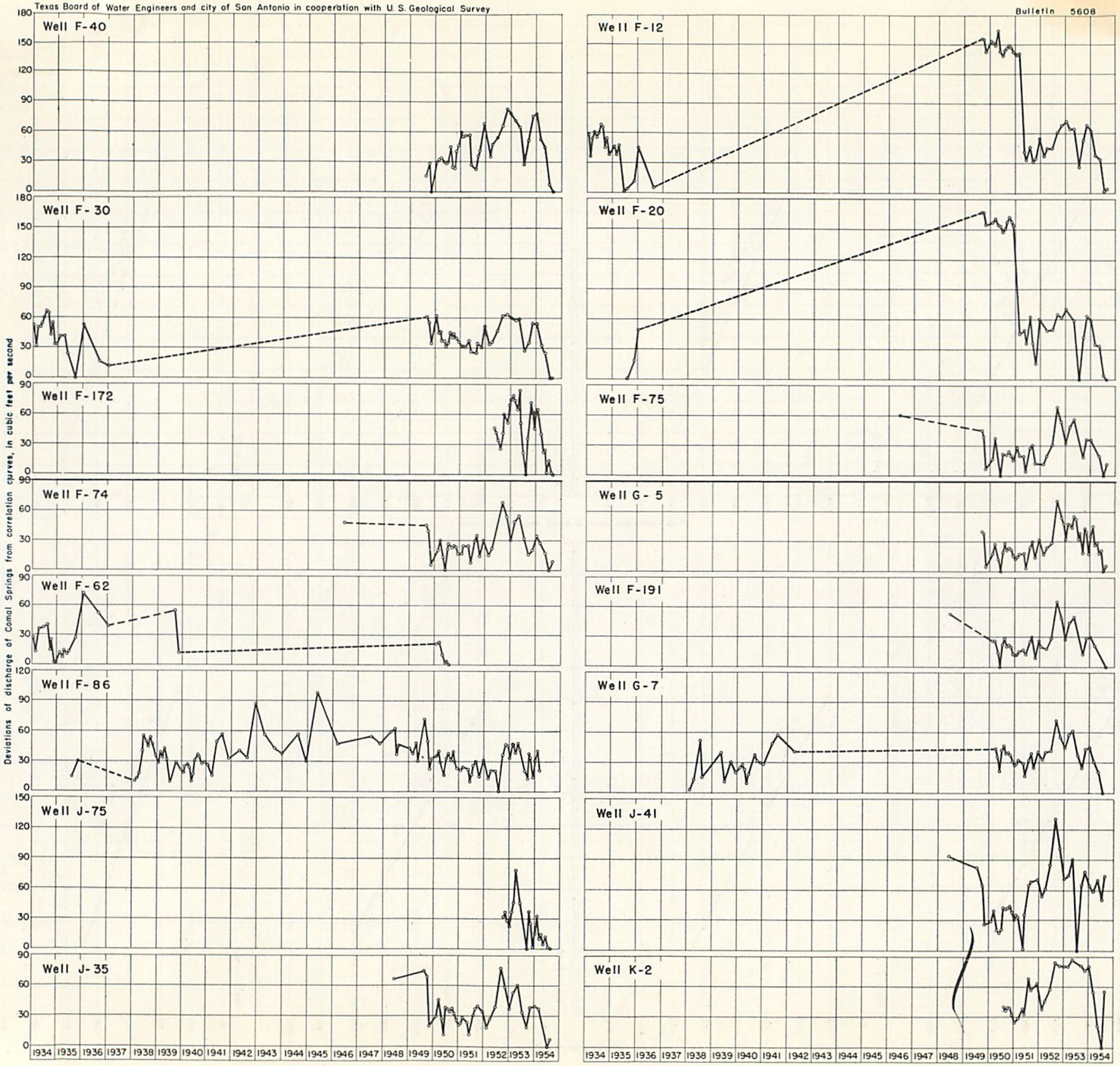

FIGURE 23 - Deviations in spring flow from correlation curves of selected wells in Bexar County, Tex.

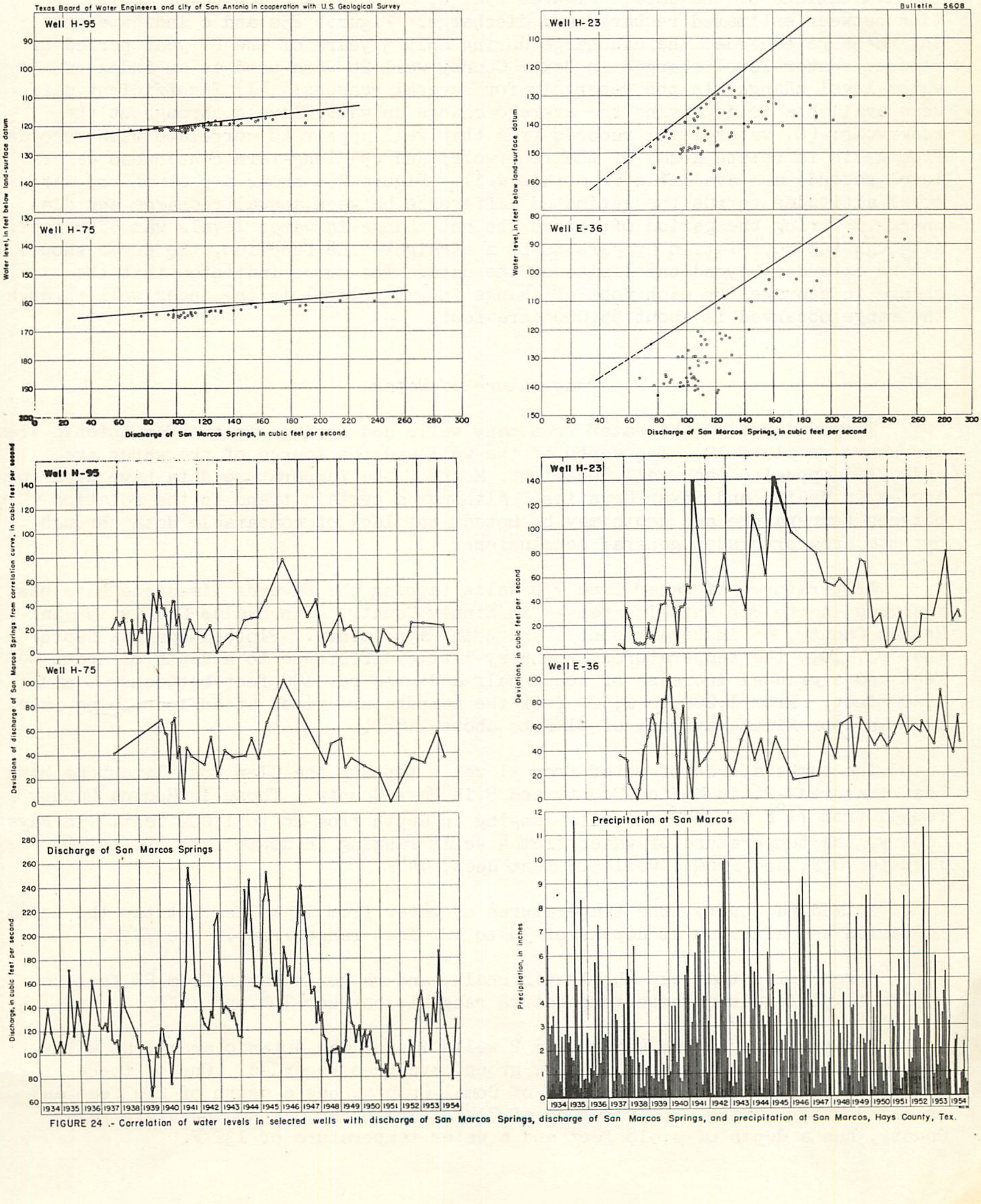
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FIGURE 24 .- Correlation of water levels in selected wells with discharge of San Marcos Springs, discharge of San Marcos Springs, and precipitation at San Marcos, Hays County, Tex.

Only rough estimates of the storage characteristics can be made because of the limitations of the data. Figures 25a, b, and c show graphically the relation between estimated recharge and discharge. Figures 25a and c indicate that the recharge exceeded the discharge during only 3 years of the 20-year period of record. Water-level changes in Bexar County well 26 were used as an index of water-level changes in the reservoir for several reasons: (1) Insufficient data were available to determine the average change in water levels throughout the reservoir; (2) water-level records from this well appear to correlate with records from wells in remote areas of the reservoir; and (3) long-term continuous water-level records are available from this well. Figure 25d shows a plot of the water-level altitudes versus the estimated difference between annual recharge and discharge. During the period of record the net change in water levels was 57.2 feet. Although the correlation appears to be a straight-line function, the curve should not be extended beyond the limits of the data. The curve indicates that the change in storage for each foot of change in water level in the index well through the range observed is about 55,000 acre-feet.

Temperature of Water

Temperatures of the water from many wells and springs in the San Antonio area are shown on plate 10. The depth of the well and the source of the water are indicated opposite each well location. Most of the temperature data have been collected in Medina and Bexar Counties. Although a certain trend in the relation between temperature and depth may be noted, the lack of comparable data throughout the area precludes general conclusions.

Temperatures of water from 170 wells tapping the Edwards limestone have been measured in the San Antonio area--4 in Kinney County, 4 in Uvalde County, 94 in Medina County, 65 in Bexar County, and 3 in Hays County. Plotted against depth (see pl. 10), the temperatures show very little difference to a depth of about 600 feet and a gradual increase of about half a degree per 100 feet between 600 and 1,200 feet. From 1,200 to 2,500 feet the temperature rises at an increasing rate from an approximate average of 81°F to about 117°F.

The temperatures of water from 31 wells tapping the Glen Rose limestone have been measured--26 in Medina County and 5 in Hays County. Those in Medina County ranged from 71°F to 78°F in wells ranging in depth from 26 to 1,009 feet. In Hays County, the temperature of water from 4 wells ranging in depth from 170 to 260 feet is 70°F, and from 1 well 525 feet deep, 74°F.

In Medina County, the temperatures of water from 11 wells that tap the Leona formation and alluvium at depths of 38 to 120 feet range from 74° to 77°F.

Seven wells that tap the Austin chalk, and range in depth from 22 feet to 295 feet, yield water whose temperature range is between 70° and 76°F.

Temperatures of the water from 2 wells in the San Antonio area that withdraw water from sands of the Trinity group have been recorded. One of these wells, in the extreme northern part of Comal County, has a depth of 226 feet and produces water having a temperature of 71°F. The other, in southwestern Bexar County, has a depth of 4,518 feet and a water temperature of 132°F.

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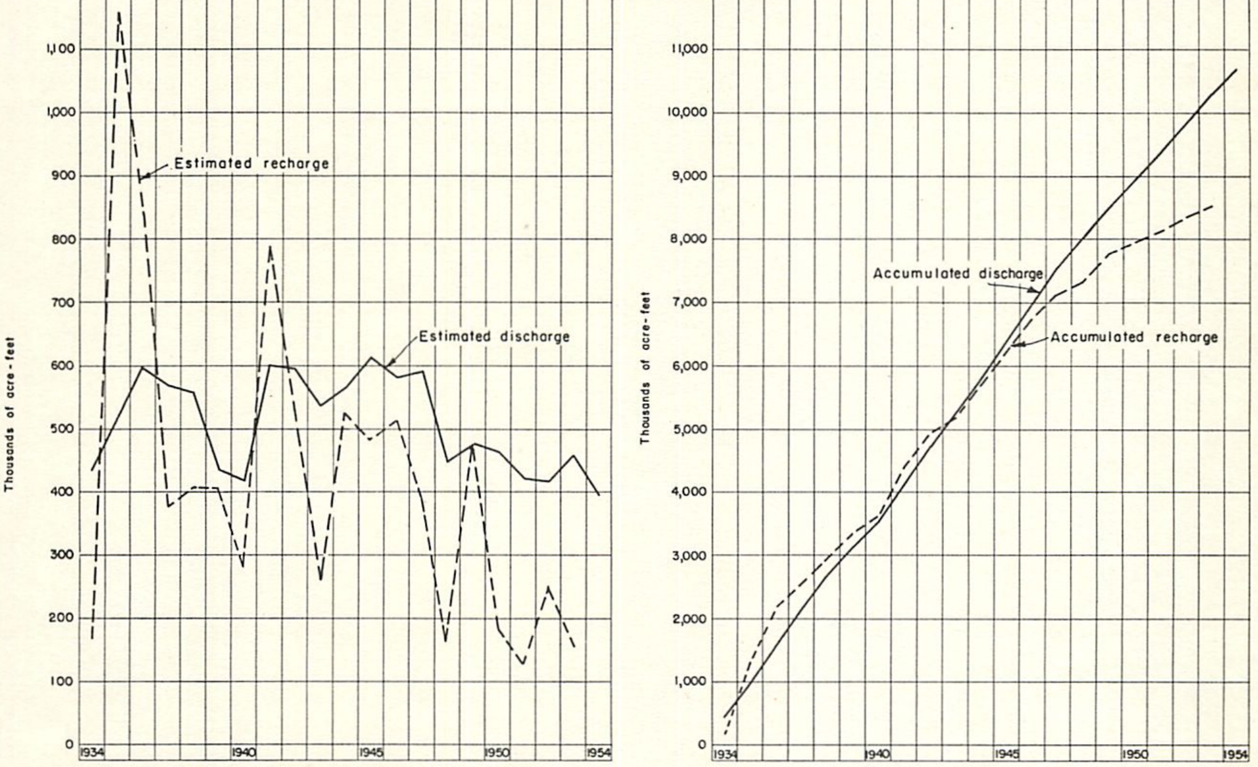
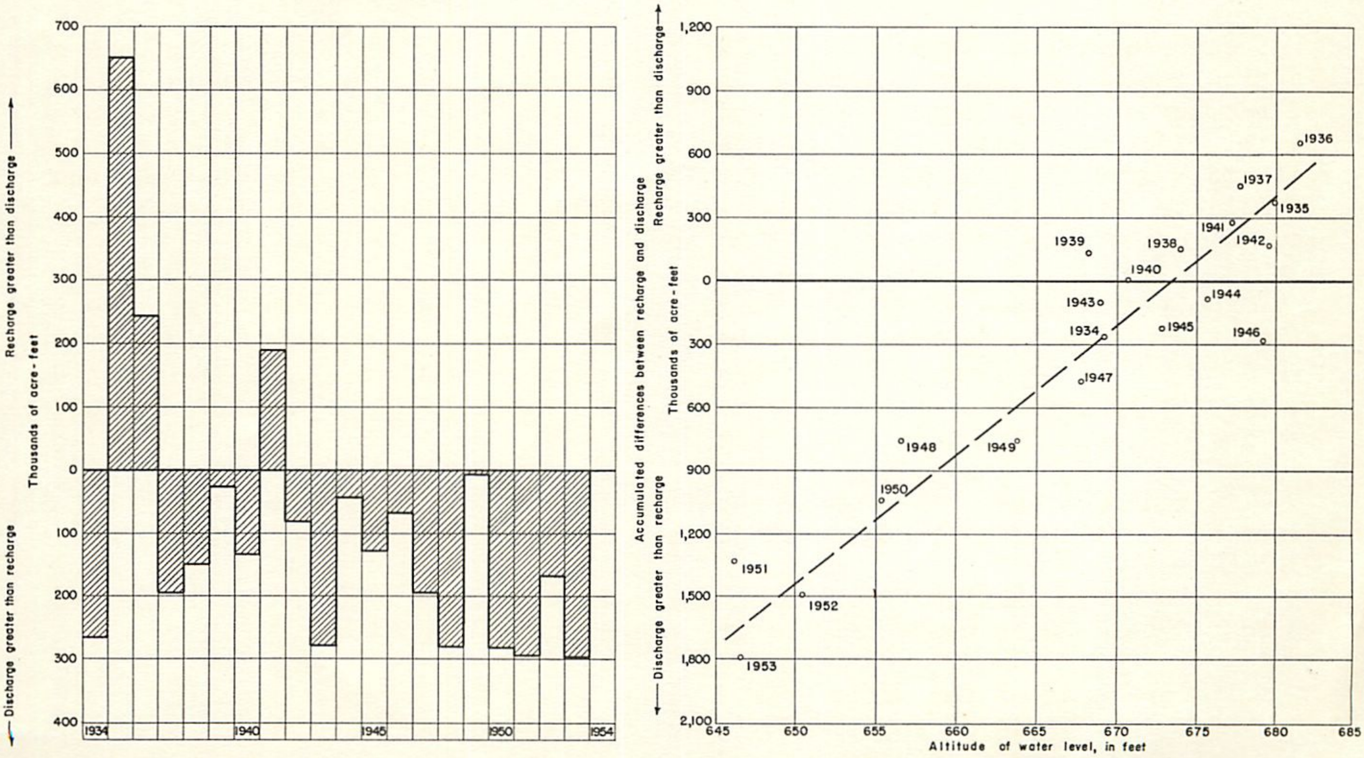


A.- Comparison of annual estimated recharge with estimated discharge.

B.- Comparison of accumulated recharge and accumulated discharge.



C.- Annual differences between recharge and discharge.

D.- Capacity curve of Edwards and associated limestones.

FIGURE 25.- Correlation of recharge, discharge, and water level in Bexar County well 26.

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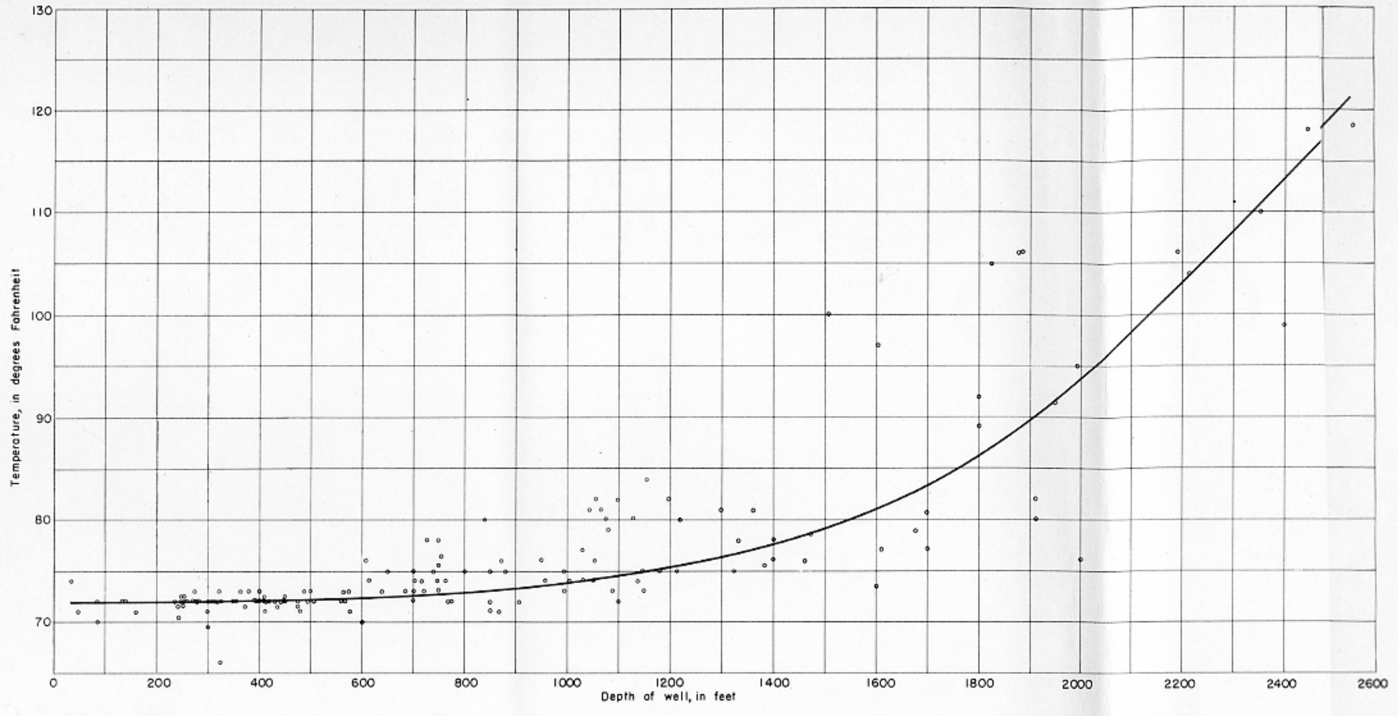
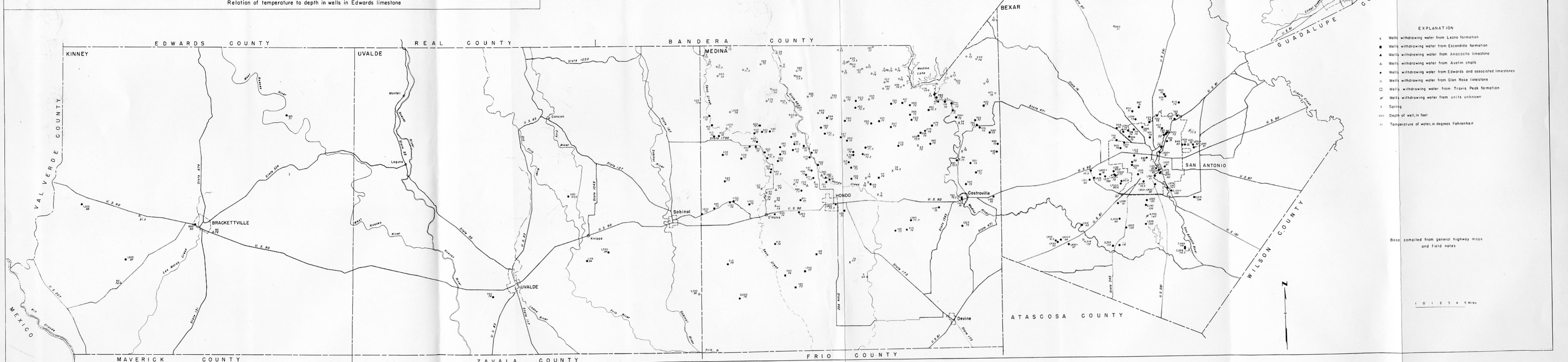


Relation of temperature to depth in wells in Edwards limestone



MAP SHOWING RELATION OF TEMPERATURE TO DEPTH OF WELLS IN THE SAN ANTONIO AREA, TEXAS

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Water temperatures ranging from 73° to 75°F were measured at 11 wells in Medina County that are finished in the Escondido formation at depths of 44 to 414 feet.

QUALITY OF WATER

All ground waters contain dissolved mineral matter in amounts depending in part on the type of rocks through which they have passed and in part on the length of time the water has been in contact with the rocks. Ground water from a given formation within a limited area usually is fairly constant in quality, but over a period of years the quality may change. Throughout a large area the quality of water within a formation may not be uniform.

Partial chemical analyses of water from wells, springs, and streams are listed in Volume II, Part 3. The analyses of ground water are tabulated by counties and are grouped according to formations; the analyses of surface waters are tabulated by streams.

Plate 11, which shows the dissolved solids, sulfate [1], and chloride concentration in water from selected wells in the different formations, indicates that the quality of the water in each formation varies greatly within short distances, but in general the dissolved-solids content of the water increases downdip. An increase in the dissolved-solids content of water from the Glen Rose limestone generally is reflected by a large increase in the sulfate content, and by a much smaller increase in the chloride content. However, in water from the Edwards limestone both the sulfate and the chloride contents increase with an increase in the concentration of dissolved solids. Water from the Edwards that has a dissolved-solids content below 500 ppm is almost identical in composition with water from the Glen Rose having a similar content of dissolved solids.

The water from the Edwards limestone in most of the San Antonio area is almost uniformly a calcium bicarbonate water of good quality, although somewhat hard. In the southern part of the area the water is charged with hydrogen sulfide; farther downdip it becomes highly mineralized.

The approximate boundary between water free of hydrogen sulfide and water charged with hydrogen sulfide or having a concentration of dissolved solids exceeding 1,000 ppm is shown in plate 11. In part of the area the boundary coincides with faulted zones, but in other parts of the area the faults appear to have little effect on the quality. Ground water generally is of poor quality where meteoric [2] water is not free to circulate. The water south of the boundary is not of uniformly poor quality; water from some wells having large yields is satisfactory for irrigation, although it is charged with hydrogen sulfide.

1/ In some of the older analyses, sulfate was determined by a method that may have indicated a zero content in waters in which there actually was a small amount of sulfate, up to perhaps 10 ppm.

2/ Meteoric water refers to water that is derived from the atmosphere.

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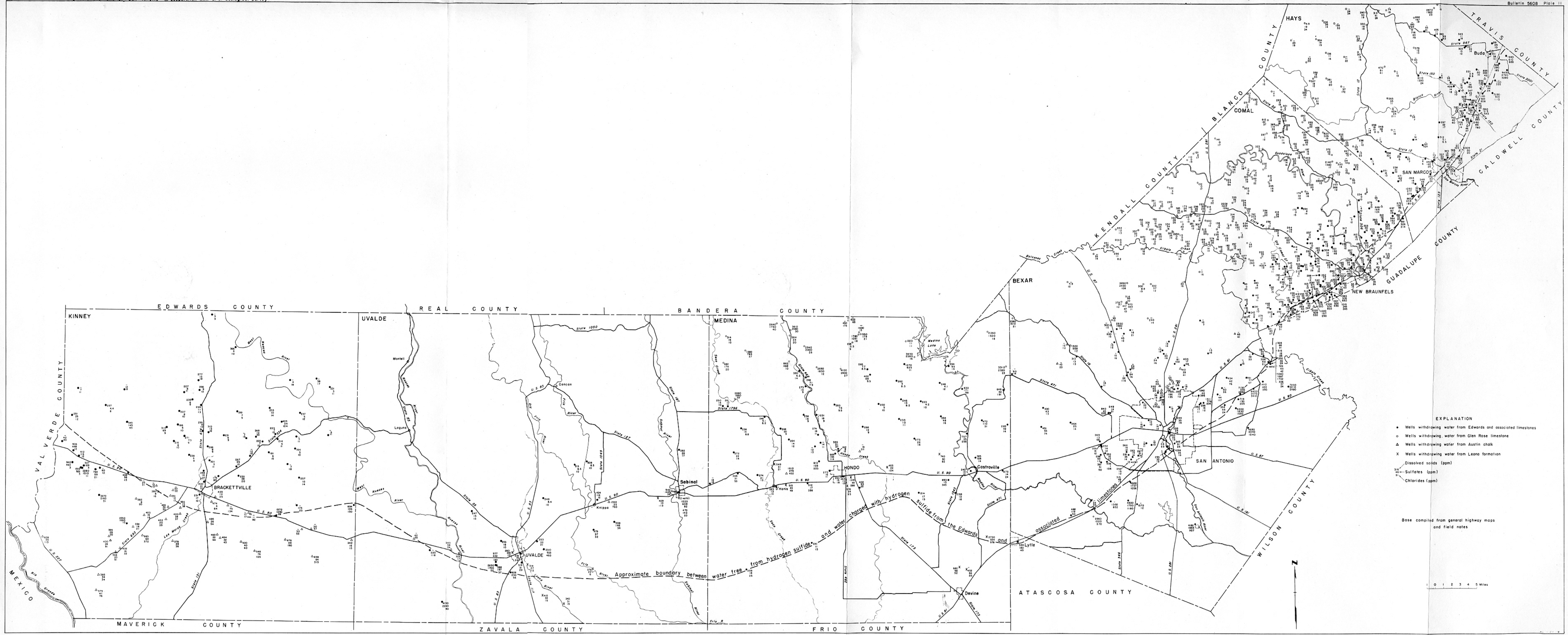
Bulletin 5608 Plate 11



MAP SHOWING DISSOLVED SOLIDS, SULFATES, AND CHLORIDES IN THE WATER IN THE SAN ANTONIO AREA, TEXAS

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Potable water is found in the Austin chalk in its outcrop and for a short distance downdip. The quality of water in the Austin chalk in much of the area is acceptable for domestic supplies. In places, however, the Austin chalk yields water having an odor of hydrogen sulfide, and it may be the source of contamination of several wells in the Edwards which are not tightly cased through the chalk.

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