TEXAS WATER DEVELOPMENT BOARD

REPORT 41

GROUND WATER IN THE FLOOD-PLAIN ALLUVIUM OF THE BRAZOS RIVER, WHITNEY DAM TO VICINITY OF RICHMOND, TEXAS

By

James G. Cronin and Clyde A. Wilson
United States Geological Survey

Prepared by the U.S. Geological Survey
in cooperation with the
Texas Water Development Board

March 1967

Second Printing
March 1976

Published and distributed
by the
Texas Water Development Board
Post Office Box 12386
Austin, Texas 78711

TABLE OF CONTENTS

TABLE OF CONTENTS (Cont'd.)

TABLES

TABLE OF CONTENTS (Cont'd.)

ILLUSTRATIONS

Figures

TABLE OF CONTENTS (Cont'd.)

GROUND WATER IN THE FLOOD-PLAIN ALLUVIUM OF THE BRAZOS RIVER, WHITNEY DAM TO VICINITY OF RICHMOND, TEXAS

ABSTRACT

The flood plain of the Brazos River between Whitney Dam and Richmond, Texas, is underlain by alluvial deposits that contain large quantities of ground water. Prior to about 1950, very little use was made of this water. The drought of the early 1950's made it necessary to acquire additional quantities of water to sustain farming on the flood plain of the river. Therefore, it was during this period that many irrigation wells were drilled to make use of the water in the alluvium.

In the report area, the Brazos River flows from the Central Texas section of the Great Plains physiographic province onto and across the West Gulf Coastal section of the Coastal Plain province. The bedrock underlying the river valley consists of rocks ranging in age from Late Cretaceous to Quaternary. All of the bedrock formations crop out in bands roughly parallel to the coast, and they dip gently toward the Gulf of Mexico at a rate slightly greater than the slope of the land surface. The Cretaceous exposed rocks consist chiefly of limestone, marl, and shale. Most of these rocks are consolidated and do not contain important aquifers in the report area. The Tertiary rocks consist chiefly of shale, clay, and sand, and they contain several of the major aquifers in the State.

The alluvium of the valley forms a series of terraces and the flood plain. The flood plain is of primary significance as a source of ground water in the Brazos River valley. The terrace alluvium in places immediately adjoins the flood plain and in other places it is separated from the flood plain by exposures of bedrock. The terrace alluvium consists of clay, silt, sand, and gravel, some of which is slightly cemented in places. These terrace deposits may be as much as 75 feet thick; however, the average would probably be considerably less.

The flood-plain alluvium consists of fine to coarse sand, gravel, silt, and clay. The lithology differs from place to place; the individual beds or lenses of sand and gravel pinch out or grade laterally and vertically into finer or coarser material within short distances. Generally, however, the coarsest part of the alluvium is in the lower part. The thickness of the flood-plain alluvium ranges from 0 to about 100 feet, and averages about 45 feet. The thickness increases downstream.

The hydrologic properties of the flood-plain alluvium range over wide limits. The permeability of samples taken during the test-drilling program ranged from 0.001 to as much as 18,000 gpd (gallons per day) per square foot. The lower permeabilities represented samples consisting almost entirely of clay or silt; the higher permeabilities represented gravel. Coefficients of transmissibility as determined in a few pumping tests ranged from about 50,000 to more than 300,000 gpd per foot. However, these tests were short, and particularly the higher values may not be reliable. On the basis of 351 determinations of specific capacity, the estimates of coefficients of transmissibility ranged between 7,300 and 208,000 gpd per foot, and averaged about 42,000. The specific yield as determined from samples obtained during the test drilling ranged from about 4 to 35 percent, and averaged about 24 percent. Because of the method used in the determinations, these values may be somewhat high. It seems likely that a conservative estimate of the average specific yield of the alluvium would be about 15 percent.

The water in the flood-plain alluvium occurs chiefly under water-table conditions, although artesian conditions may occur locally where extensive lenses of clay exist. The water table in the flood-plain alluvium occurs at depths ranging from less than 10 to almost 50 feet below the land surface. In general, the water table slopes toward the river, and generally is at a higher altitude than the river, indicating that the Brazos River is an effluent stream.

The recharge to the flood-plain alluvium is chiefly by precipitation on the flood-plain surface. Various methods used to estimate the recharge gave results ranging from less than 2 inches per year to more than 5 inches. The average during the period 1957-61 is estimated to have been slightly less than $3\frac{1}{2}$ inches per year. Rainfall during this period was somewhat above normal; therefore, the estimate of recharge during this period is probably high. However, if the figure is valid, the total recharge from this source would be about 155,000 acre-feet per year during the 1957-61 period. Other minor sources of recharge include infiltration from streams (both natural and induced), underflow from older terrace alluvium, vertical and lateral movement of water from adjoining bedrock, infiltration of surface water applied for irrigation, and inundation of the flood plain by flood waters.

Ground water is discharged from the alluvium chiefly by seepage into the Brazos River, by evaporation and transpiration, and by wells.

Most of the wells in the flood-plain alluvium are used for irrigation; in 1964 more than 1,100 irrigation wells were available for use in the report area. Most of the wells are equipped with casing 14 to 18 inches in diameter. The casing is generally slotted, and most of the wells are gravel packed. The irrigation wells range in yield from less than 250 to more than 1,000 gpm (gallons per minute); about 50 percent yield between 250 and 500 gpm.

The principal use of the water on the flood plain is for irrigation. During 1963 about 43,000 acre-feet was pumped, and in 1964 about 49,000 acre-feet was pumped to irrigate more than 72,000 acres. Other uses of ground water on the flood plain are insignificant.

The chemical quality of the water in the flood-plain alluvium ranges between wide limits. In general, the water is suitable for domestic and livestock purposes, except that it is hard or very hard. Most of the water has a low sodium hazard and a high salinity hazard for irrigation, according to the U.S. Salinity Laboratory Staff classification. However, under the conditions of irrigation and climate that are present in the report area, the water appears to be suitable for irrigation.

On the basis of the saturated thickness of the flood-plain alluvium and an assumed coefficient of storage of 15 percent, approximately 2,760,000 acre-feet of water was in storage in the flood-plain alluvium in the report area as of the spring of 1963. About 40 percent of this water was in the principal irrigated section in Falls, Robertson, Brazos, and Burleson Counties where about 95 percent of the irrigation water is used.

The report area has a rather high rate of average annual rainfall, ranging from about 32 to more than 43 inches, and the flood-plain alluvium is readily recharged during normal or above normal periods of precipitation. During the period 1957-61, the average annual rate of recharge in the report area is estimated to have been about 155,000 acre-feet per year. About 100,000 of this was in the area between the Hill-McLennan County line and Hempstead, which includes the principal irrigated area.

GROUND WATER IN THE FLOOD-PLAIN ALLUVIUM OF THE BRAZOS RIVER, WHITNEY DAM TO VICINITY OF RICHMOND, TEXAS

INTRODUCTION

Ground water pumped from the alluvial sand and gravel of the Brazos River flood plain between Whitney Dam and the city of Richmond is used almost exclusively for irrigation. Although in 1950 the quantity of water thus used was negligible and few irrigation wells existed in the area, by 1963 the use of water for irrigation had increased to an estimated 43,000 acre-feet per year. Both the increasing use of water and the probability of additional demands upon the supply in the future emphasized the need for an appraisal of the ground-water resources of the area.

In September 1962 the U.S. Geological Survey, in cooperation with the then Texas Water Commission, undertook a study of the ground water in the alluvium of the Brazos River between Whitney Dam and Richmond. The investigation and this resulting report were to include not only the following aspects of the alluvium--extent, thickness, and physical and hydrological properties; amount and areal extent of withdrawals and recharge; and quantity and quality of ground water available--but also the hydrologic relationships between the alluvium and the underlying or adjoining bedrock, and the interrelation between ground water in the alluvium and surface water in the Brazos River.

Previous reports of investigations in the area made little if any mention of the ground water in the alluvium of the flood plain, an indication that the water was not then widely used. Reports by the following authors include some parts of this report area. Hill (1901) discussed the geology and stratigraphy with special reference to artesian waters. Deussen (1914, 1924) likewise discussed the geology and underground waters, with emphasis on the artesian aquifers. Reports by Singley (1893), Darton (1905), and Taylor (1907) contained mainly records of deep (artesian) wells, although the availability of water from shallow wells was also mentioned briefly by Taylor. Between 1936 and 1946, the Texas State Board of Water Engineers published inventories of water wells in the following counties: Austin (May, 1938), Burleson (Clark, 1937a), Fort Bend (Elledge, 1937, and Livingston and Turner, 1939), Grimes (Turner, 1939, and Cromack, 1943), Milam (Clark, 1937b), Robertson (Davis, 1942), Waller (Turner and Livingston, 1939), and Washington (Follett, 1943). These reports contain tables of well records, well logs, and chemical analyses of water samples, as well as maps showing the well locations.

Fluellen and Goines (1952) reported on the water resources of Waller County. The development of ground water for irrigation from wells in the alluvium of the flood plain was summarized by Hughes and Magee (1962). Reconnaissance reports on the ground-water resources of the Brazos River basin (Cronin, Shafer, and Rettman, 1963) and of the Gulf Coast region (Wood, Gabrysch, and Marvin, 1963) included reconnaissance information on the ground water in the Brazos River alluvium. The U.S. Study Commission-Texas (1962, pt. 3, p. 115) reported on the availability of ground water from the alluvium in a part of the report area.

The field and laboratory data on which this report is based were collected during the period September 1962 to August 1964. Preliminary topographic maps on the scale of 1:24,000 were available for most of the area as were older topographic maps of varied scales for the remainder of the area. These maps were used in the preparation of field maps and of a base map. The altitudes of wells and test holes were taken directly or interpolated from the topographic maps. Only a few of the altitudes were determined by instrumental levels. In the initial phase of the investigation, the locations were determined for all existing large-capacity wells pumping from the alluvium (Figures 20, 21, and 22), and about 70 percent of these wells were inventoried (Table 9). Approximately 57 large-capacity wells drilled into the bedrock formations were also inventoried. Among the data collected during the well inventory were the measured depth to water in each well and the measured or reported depth of each well.

Measurements of water-level fluctuations were made quarterly in 124 wells (Table 11). During the 1963-64 irrigation season, drawdown and discharge measurements were made in 351 wells. In the spring of 1964, depth-to-water measurements were made in all the wells in which the drawdown and discharge were measured in 1963. Included also are water-level measurements made starting in 1957 as a part of the statewide observation-well program of the U.S. Geological Survey and the Texas Water Development Board. Power tests were made on several of the electrically operated irrigation wells, and records of power consumption were obtained from the utility companies. Geologic studies included the mapping of the alluvium and adjoining bedrock as well as the interpretation of electric logs of oil wells and of drillers' logs of water wells both in the alluvium and bedrock. Logs of test borings made at bridge sites along the Brazos River were obtained from the Texas State Highway Department, and several hundred logs of water wells and test holes drilled in the alluvium were obtained from well drillers.

To obtain additional geologic and hydrologic data, 122 test holes whose combined depths totaled about 5,725 feet were bored with a power auger. The locations of these test holes are shown in Figures 20, 21, and 22, and the depth, altitude, and other information are given in Table 9. The logs of 12 of the test holes are given in Table 10. The physical and hydrologic properties of selected samples (disturbed and undisturbed) from the test holes, river bank, and a gravel pit were determined in the U.S. Geological Survey's Hydrological Laboratory at Denver, Colorado.

Samples of water were collected from 158 wells in the flood-plain alluvium and from 34 wells in bedrock or terrace aquifers and were analyzed to determine their mineral content in the laboratory of the U.S. Geological Survey at Austin, Texas. The results of these analyses and some by previous investigators are included in Table 12.

The well-numbering system used in this report is one adopted by the Texas Water Development Board for use throughout the State and is based on latitude and longitude. Under this system, each 1-degree quadrangle in the State is given a number consisting of two digits. These are the first two digits appearing in the well number. Each 1-degree quadrangle is divided into $7\frac{1}{2}$-minute quadrangles which are also given two digit numbers from 01 to 64. These are the third and fourth digits of the well number. Each $7\frac{1}{2}$-minute quadrangle is subdivided into $2\frac{1}{2}$-minute quadrangles and given a single digit number from 1 to 9. This is the fifth digit of the well number. Finally, each well within a $2\frac{1}{2}$-minute quadrangle is given a 2-digit number in the order in which it is inventoried, starting with 01. These are the last two digits of the well number. Only the last three digits of the well numbers are shown beside the well symbols on the well-location maps (Figures 20, 21, and 22); the $7\frac{1}{2}$-minute quadrangles are numbered in their northwest corners, and the 1-degree quadrangles are shown with large bold numbers. In addition to the 7-digit well number, a 2-letter prefix is used to identify the county. The following prefixes apply to the counties included in this report.

County	Prefix	County	Prefix
Austin	AP	Hill	LW
Bosque	BB	McLennan	ST
Brazos	BJ	Milam	TK
Burleson	BS	Robertson	WK
Falls	JR	Waller	YW
Fort Bend	JY	Washington	YY
Grimes	KW		

The authors are indebted to the many residents of the report area who supplied information about their wells and granted permission to make depth-to-water measurements and other tests. The cooperation and assistance given by personnel of federal, state, county, and municipal agencies and departments are gratefully acknowledged. Special recognition is due the Commissioner's Courts of the counties in the report area and officials of the Texas State Highway Department for permission to drill test holes on the right-of-ways of county roads and state highways. Thanks are extended to the well drillers who furnished data on wells and test holes drilled by them, especially the James Seigert Drilling Co., Bryan, Texas, and the Dunn Drilling Co., Giddings, Texas. Appreciation is expressed for the help given by oil companies in furnishing geologic information and by utility companies for data concerning the use of electric power by wells.

Special thanks are extended to the personnel of the Geology Department of Texas A. & M. University, especially Professor F. E. Smith who gave much helpful information on the geology of central Texas, and to personnel of the Geology Department at Baylor University, especially Professors L. F. Brown, O. T. Hayward, and R. L. Bronaugh, for information on the geology of the Waco

and adjoining areas. B. N. Myers, G. H. Shafer, and G. D. McAdoo of the U.S. Geological Survey, Texas district, assisted the authors in the fieldwork at various times. W. D. Robbins, also of the Geological Survey, Texas district, assisted the authors on the boat trip down the Brazos River and took the photographs shown in Figure 2.

PHYSIOGRAPHY AND DRAINAGE

The area studied for this report is in a segment of the Brazos River valley between Whitney Dam in Bosque County and the city of Richmond in Fort Bend County (Figure 1). Richmond is upstream from the Gulf of Mexico at river mile 93, and Whitney Dam at river mile 442. The airline distance between these points is about 200 miles. The elevation of the streambed ranges from 427 feet below Whitney Dam to 20 feet at Richmond. The gradient of the streambed between these points is about 1.2 feet per mile. Within the report area the principal tributaries of the Brazos are the following rivers--Bosque, Little, Little Brazos, and Navasota.

The Brazos River flows in a southeasterly direction almost perpendicular to the northeastward-striking, gulfward-dipping bedrock strata. Between Whitney Dam and Waco, the river flows in a rather narrow valley in places bounded by almost vertical walls of limestone or chalk. South of Waco, the stream passes from the Central Texas section of the Great Plains physiographic province into the West Gulf Coastal section of the Coastal Plain province which is underlain by softer, less resistant rocks. In the West Gulf Coastal section, the hilly and gently rolling country inland merges with the smooth and nearly level area along the Gulf Coast. Bordered in some places by bedrock on one side and alluvium on the other, or in other places by either bedrock or alluvium on both sides, the Brazos River follows a sinuous course across the West Gulf Coastal Plain to the Gulf of Mexico.

The large tributaries of the Brazos, such as the Bosque, Little, and Navasota Rivers, originate outside of the report area. They flow across the flood plain in channels cut in the alluvium and locally in the bedrock.

Other streams, some of which originate on the uplands outside the report area, follow either short courses directly across the flood plain or meandering courses on the flood plain adjacent to the valley wall before reaching a junction with the Brazos River. Streamflow is small, and many of the streams are dry except during periods of heavy precipitation. In general, the channels of these streams are shallow except in some places adjacent to the Brazos River. The gradients are low, and water tends to pond in the channels. The principal drainageways in the report area are shown on Figures 23, 24, 25.

The channel of the Little Brazos River follows a course on the flood plain extending from southern Falls County to the Brazos River west of Bryan (Figures 23 and 24), a distance of about 55 miles. Throughout much of its course the channel is adjacent to or near the valley wall. Runoff from the upper reach of the Little Brazos enters the Brazos River about 6 miles south of the Falls-Robertson County line. Water ponds in the shallow channel, and streamflow is small except during periods of heavy rainfall.

The U.S. Geological Survey in cooperation with the Texas Water Development Board maintains five gaging stations on the Brazos River in the report area.

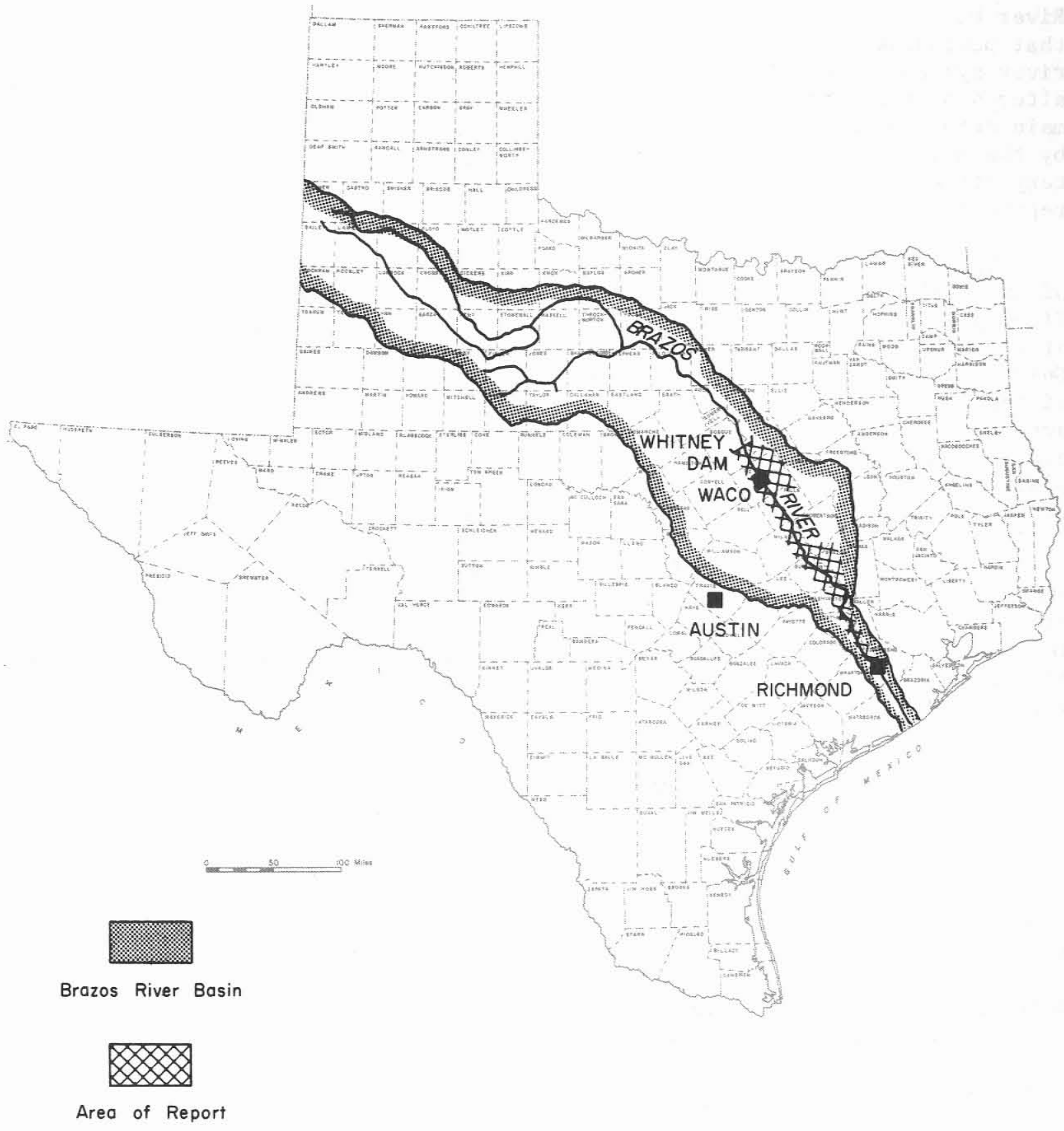


Figure I

Map of Texas Showing Area Covered by Report

U. S. Geological Survey in cooperation with the Texas Water Development Board

The average annual discharge for the period of record, and the date and amount of maximum and minimum discharge and corresponding gage-height reading at the five stations during the water year (October 1962 to September 1963), are given in Table 1.

The flood plain of the Brazos River, locally referred to as the Brazos River bottoms or bottomland, is the surface that borders the Brazos River and that periodically has been, at least in part, covered by flood waters of the river system. The natural regimen of streamflow of the Brazos River has been altered by the construction of dams upstream from the report area, both on the main stem and on some of its tributaries. The possibility of future flooding by the main stream may have been reduced somewhat; however, runoff from tributary streams and local storms may still inundate some of the flood plain in the report area.

The flood plain, composed of stream-deposited sediments, occupies an area of about 876 square miles between Whitney Dam and Richmond. The width of the flood plain varies throughout the report area, ranging from less than 1 mile at the upstream margin to more than 8 miles at the downstream boundary near the Gulf Coast (Figures 23, 24, and 25). In parts of the report area, the surface of the flood plain may be as much as 100 feet or more below the hilly upland surface; in other parts, such as in Fort Bend County near the Gulf Coast, the elevation of the flood plain may differ but little from the upland. The flood-plain surface is separated from the streambed by banks composed of alluvium ranging approximately 30 to 50 feet in height.

The surface of the flood plain is nearly flat. Some of the land slopes away from natural levees along the river bank toward the base of the valley wall or drainageways. The surface of the flood plain has been modified in places by the construction of levees and drainage canals. Ox-bow lakes stand out as prominent geomorphic features, and swampy areas and abandoned stream channels are a part of the land surface.

ECONOMIC DEVELOPMENT

The flood plain of the Brazos River is, and has been in the past, important because of the agricultural production on the land. Much of the farmland is irrigated, at least on a supplemental basis. Both ground water and surface water are used for irrigation; however, ground water is used more widely than surface water. Hughes and McGee (1962, p. 1) indicate that irrigation with ground water began in the late 1940's and expanded rapidly during the 1950-57 period. According to Cronin and others (1963, p. 116), this expansion is continuing, but probably at a reduced rate. Although cotton is still the principal crop on the flood plain, grain sorghum, alfalfa, and other crops also grow there; some of the remaining land is suitable for pasture, and some is wooded.

The principal irrigated section on the flood plain in the report area lies between Highbank in Falls County and Navasota in Grimes County (Figures 20, 21, and 22). According to information furnished the Texas Water Development Board by the Soil Conservation Service, U.S. Department of Agriculture, about 95 percent of the irrigated acreage in the report area in 1963 was in this section, and a large number of the irrigation wells in the study area, more than 1,000, are located here.

Table 1.--Maximum and minimum daily discharge and instantaneous gage-height readings for several stations on the Brazos River, October 1962 to September 1963, and average annual discharge

Gaging station	Gage datum above mean sea level (ft)	Date and gage reading (ft)				Date and discharge (cfs)				Average annual discharge and length of record	
		Date	Maximum reading	Date	Minimum reading	Date	Maximum discharge	Date	Minimum discharge	(cfs)	Number of years
Whitney	417.39	Oct. 10, 1962	13.64	Sept. 25, 1963	3.60	Oct. 10, 1962	14,800	Sept. 25, 1963	31	1,740	25
Waco[a]	356.80	Oct. 10, 1962	14.72	Sept. 26, 1963	2.0	Oct. 10, 1962	16,300	Sept. 26, 1963	53	2,535	65
Bryan[b]	192.33	Oct. 12, 1962	13.55	Sept. 30, 1963	2.43	Oct. 12, 1962	18,100	Aug. 15, 1963	299	5,444	47
Hempstead	117.90	Dec. 29, 1962	16.10	Sept. 9, 1963	1.02	Dec. 29, 1962	18,200	Aug. 22, 1963	398	6,755	25
Richmond	40.94	Dec. 30, 1962	12.02	Aug. 26, 1963	.07	Dec. 30, 1962	17,400	Aug. 26, 1963	229	7,375	43

[a] Maximum discharge, 1898-1963: 246,000 cfs, Sept. 27, 1963, gage height 40.90 ft.

[b] Maximum stage since at least 1854 was 54 ft on Sept. 12, 1921. Flood of Dec. 5, 1913 reached 51 ft. Present site and datum from information by Texas and New Orleans Railroad Co. at its bridge 5 miles upstream and from comparison of maximum stages reached by floods of 1913 and 1921 at gage near College Station. Flood in 1854 reached about the same stage as that of 1913.

Industries on the flood plain include the mining of sand and gravel and the production of oil as well as other industries allied with agriculture, such as cotton ginning or the distribution of agricultural equipment and supplies.

CLIMATE

The climate of the Brazos River basin below Whitney Dam is warm and humid. The summers are long, hot, and dry; temperatures above 100°F are common in the summer at Waco. The winters are short and mild; occasional cold spells may last as long as a week, but these are usually followed by periods of cool pleasant weather. Only two months, January and February, have much freezing weather.

The range in average annual temperature in the report area is not great. At Sugarland in Fort Bend County, the average annual temperature is 69°F, whereas in the upper part of the report area at Waco, it is about 67°F. The frost-free period ranges from about 275 days at Sugarland to about 251 days at Waco.

The average annual precipitation ranges more widely in the report area. At Sugarland the precipitation is slightly more than 43 inches, whereas at Waco it is about 32 inches. The precipitation is rather evenly distributed throughout the year; however, the month of May generally has the most precipitation. The precipitation usually falls more slowly in the winter than at other times of the year when it often occurs with thunderstorms and at times falls with great intensity. Droughts of varying duration and severity occur but seldom cause complete crop failures.

The total evaporation in 1963 as measured in standard U.S. Weather Bureau pans was 68 inches at Thompsons, Fort Bend County, about 15 miles downstream from the report area, and 93 inches at Whitney Dam 25 miles northwest of Waco. The range in total monthly evaporation in 1963 was from a maximum of 8.05 inches in June to a minimum of 1.76 inches in January at Thompsons, and from a maximum of 14.79 inches in July to a minimum of 1.89 inches in December at Whitney Dam.

GEOLOGY

Bedrock

Sedimentary rocks ranging in age from Cretaceous to Quaternary underlie and border the alluvium of the Brazos River between Whitney Dam and Richmond. The bedrock consists of both consolidated and unconsolidated rocks deposited under both marine and continental conditions. The lithology and water-bearing properties of the geologic units which comprise the bedrock are described briefly, and the outcrop areas of these units are shown on Figures 23, 24, and 25.

The bedrock strata dip in a generally southeasterly direction toward the Gulf of Mexico (Figures 26, 27, and 28). In this direction the dip becomes steeper, and most of the units become thicker. Details of the stratigraphy and structure of the geologic units comprising the bedrock are not considered pertinent to this report. For this information the reader is referred to the report by Cronin and others (1963).

The bedrock in the report area yields small--less than 100 gpm (gallons per minute)--to large--more than 1,000 gpm--quantities of water to a few wells, most of which tap the Wilcox Group. In the outcrop areas of the bedrock, water generally is under water-table conditions; in the downdip part, artesian conditions prevail. In general, water in and near the outcrop is fresh--less than 1,000 ppm (parts per million) dissolved solids--but becomes more saline downdip. The results of chemical analyses of selected samples of water from wells tapping the bedrock are given in Table 12.

Cross-valley profiles (Figures 26, 27, and 28) illustrate the relation of the buried bedrock surface to the present land surface, the relation of the present stream to the bedrock, the position of the present stream with reference to the valley walls, and the relief of the buried bedrock surface.

The walls of the river channel are composed of bedrock in many places with an alluvium cut-bank on the opposite side. In some reaches, the stream flows on bedrock, and in others it flows on a veneer of channel fill (bed material) which may be as much as 20 feet or more thick (according to test borings made at bridge sites by the Texas State Highway Department). In some places along the river bank, isolated exposures of bedrock overlain by alluvium project from a few feet to as much as 15 feet or more above the surface of the river. The locations of some of these isolated outcrops of bedrock are shown on Figures 23 and 24, and views of bedrock cropping out along the river are shown on Figure 2.

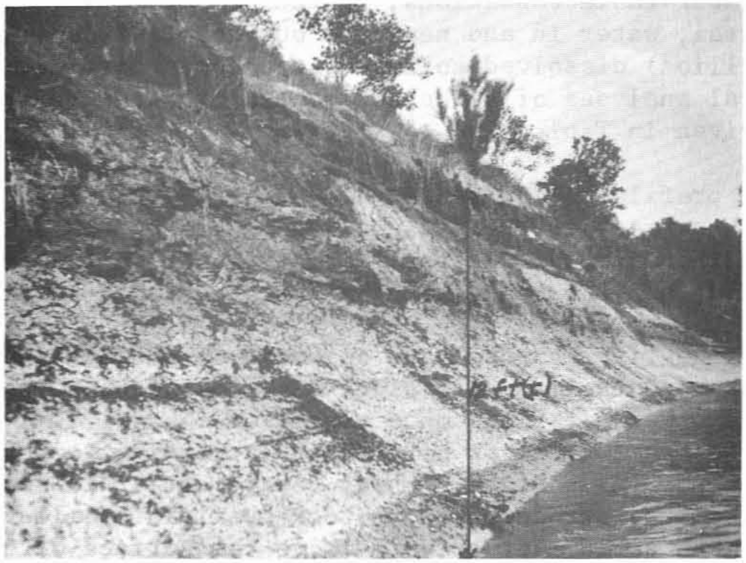
The approximate configuration of the buried bedrock surface in most of the area between Whitney Dam and Washington County is shown by means of contours on the base of the alluvium (Figures 3 and 4). Data were inadequate to show the base of the alluvium where it is not contoured.

Terrace Alluvium

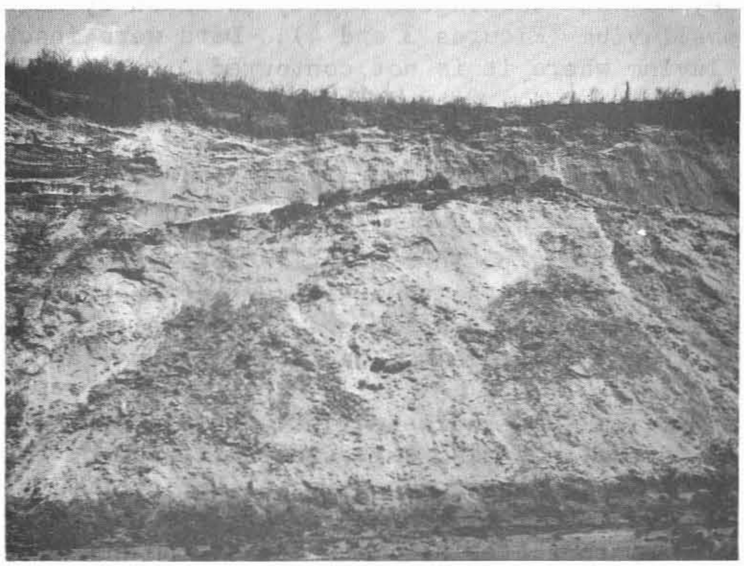
Sediments which in the past were deposited by the Brazos River at various levels above the present flood plain are herein referred to as terrace alluvium. The present flood plain, the youngest surface above the stream, is discussed as a separate physiographic unit, and the deposits underlying the flood plain and the river itself are referred to as the flood-plain alluvium.

Deussen (1924, p. 114) has indicated that the age of the terraces ranges from Pleistocene to Recent. He also suggested that some of the river terraces may be correlated with a seaward-facing terrace, but others may be local, because they may have been formed by temporary barriers on the stream and by changes in the nature of the material which the stream encountered in the erosion of the valley.

South of the outcrop of the Wilcox Group (Figure 24) are what Deussen (1914, p. 81, 83) has called the highest, middle, and lowest Pleistocene terraces. He correlated the lowest and middle terraces with the coastwise Beaumont and Lissie terraces. Similarly Bernard, LeBlanc, and Major (1962, p. 206-224), in a discussion of the Pleistocene geology of the lower Brazos River valley (somewhat the same area worked by Deussen in 1914), stated "...Each Pleistocene River terrace and the modern flood plain can be traced seaward to where they merge with equivalent coastwise deltaic plains also referred to as coastwise terraces." Deussen (1924, p. 114-115) recognized seven terraces on the



A.- Wilcox Group showing beds of lignite

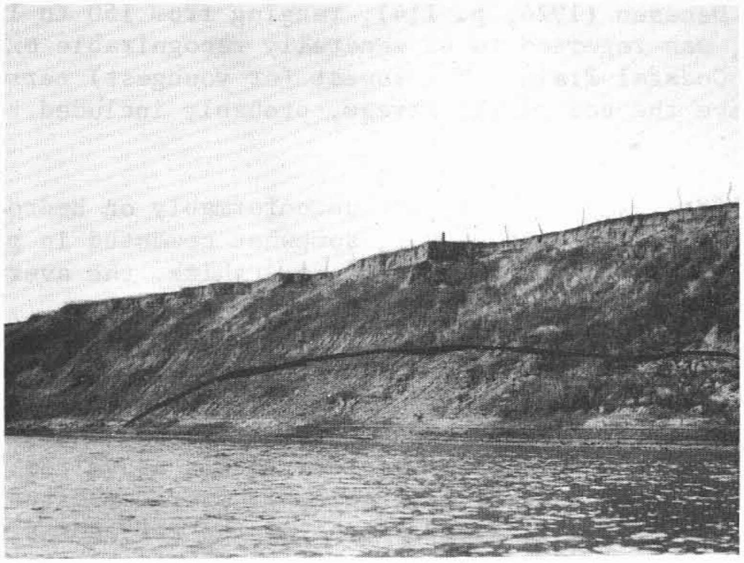


B.- Massive sand in alluvium. Notice slumping

Figure 2

Types of Exposures Along Brazos River Between Whitney Dam and Richmond (Sheet 1 of 2)

U. S. Geological Survey in cooperation with the Texas Water Development Board



C. Gravel lens in alluvium

D.- River channel in constricted zone - looking downstream. Wilcox Group exposed in banks

Figure 2

Types of Exposures Along Brazos River Between Whitney Dam and Richmond (Sheet 2 of 2)

U. S. Geological Survey in cooperation with the Texas Water Development Board

Brazos River near Waco. The highest (hence the oldest) to which he referred as the Uvalde terrace was about 310 feet above the bed of the Brazos River. Terrace number 5 of Deussen (1924, p. 114), ranging from 150 to 170 feet above the bed of the river, was reported to be generally recognizable except near the seaward edge of the Coastal Plain. The lowest (or youngest) terrace, ranging from 30 to 35 feet above the bed of the stream, probably included the flood plain of the river.

The terrace-forming materials rest unconformably on bedrock and consist mainly of clay, silt, sand, and gravel, somewhat cemented in places. Although the deposits may be as much as 75 feet or more thick, the average would probably be considerably less.

In general the older (higher) terraces, some of which extend beyond the report area, have been dissected more than the younger (lower) surfaces. Remnants of the terraces cap hilltops and stand as isolated bodies on the upland surface, or cap river-cut benches at various levels above the flood-plain alluvium. In some places the terrace materials, if ever deposited, have been removed by erosion. The locations and extent of the terraces are indicated on Figures 23, 24, and 25, and the relative positions of the terraces along the river banks are indicated on some of the profiles (Figures 26, 27, and 28).

This report is concerned with the terrace alluvium only where it is hydrologically connected with the flood-plain alluvium. Therefore, no further discussion is necessary concerning the higher (older) terraces, which have been both geologically and hydrologically isolated from the flood-plain alluvium itself or from the younger (lower) terraces bordering the flood-plain alluvium. However, ground water is derived from some of the isolated bodies of terrace alluvium where the depths of the wells indicate that the deposits may be as much as 40 or more feet thick.

The position of the terrace alluvium bordering the flood-plain alluvium at some places along the river is shown in the cross-valley profiles (Figures 26, 27, and 28). On these profiles, the surface of the bordering terrace alluvium, which usually slopes toward the river, ranges from about 10 to 30 feet above the surface of the flood-plain alluvium. Where the terrace alluvium is hydraulically connected to the flood-plain alluvium, the terraces contribute water directly into the flood-plain alluvium by underflow. The amount of ground water moving from the bordering terrace alluvium into the flood-plain alluvium depends not only on the thickness of the saturated zone but also on the gradient of the water table and permeability of the saturated material.

The permeability of the water-bearing materials of the terrace alluvium is not well known, but samples from test holes and the yields of some wells indicate it is rather low. These data suggest that the amount of water moving from the terrace alluvium into the flood-plain alluvium is rather small.

Flood-Plain Alluvium

The flood-plain alluvium (Figures 23, 24, and 25) rests unconformably on the truncated surfaces of the bedrock formations and is composed of fine to coarse red-tan sand, gravel, silt, and red-brown to brown clay. The deposition probably was in stream channels and on the flood plain by overbank flow.

The composition of the flood-plain alluvium differs from place to place. The individual beds or lenses of sand and gravel pinch out or grade laterally and vertically into finer or coarser materials. In general, the fine-grained material is in the upper part of the deposit; the gravel, whether mixed with sand or clean and well sorted, commonly occurs in the lower part.

Whether the gravel was mixed with sand or was clean and well sorted could not be determined from the samples collected from the test holes. Where the alluvium was laid down by stream-channel deposition, lenses of gravel with variable degrees of sorting could be expected. Such a gravel lens in the alluvium along the bank of the Brazos River is shown in Figure 2C.

Clay varying from red to red-brown and ranging in thickness from about 5 to as much as 30 feet commonly occurs in the upper part of the flood-plain alluvium. The composition and texture of the clay varies from place to place mainly because of differences in the amount of silt or sand intermixed with the clay. The clay may grade vertically into the underlying material, which is generally a fine-grained sand or silty sand, or the contact with the underlying material may be a distinct and abrupt change from clay to sand.

The thickness of the flood-plain alluvium, as indicated by the cross-valley profiles (Figures 26, 27, and 28), ranges from about 9 to more than 75 feet, the average being about 45 feet. Upstream from Waco the thickness, as indicated by the depth of wells (Table 9), is about 35 feet or less. South of Rosenberg near the downstream boundary of the report area, the thickness is about 100 feet. The thickness increases beyond the report area toward the Gulf of Mexico.

Large quantities of sand and gravel are mined from gravel pits on the flood plain, the largest being in the vicinity of Waco and Hearne (Figures 20 and 21). The thickness of the alluvium in the pits is approximately the same as indicated by the test drilling. A vertical section at one pit near Hearne included (starting from the surface): 15 feet of clay and silt; 3 feet of sand; 8 feet of sand and pea-size gravel; 6 feet of soft, dark clay; and 15 feet of clean gravel at the base. In a pit in Brazos County, the alluvium is more heterogeneous than that in other pits.

In general, considering the flood-plain alluvium as a unit, the sequence of deposition appears to grade from fine grained at the surface to coarse grained at the base. Although the general sequence does not change, the relative positions of the individual constituents and their grain size vary from place to place due to the interfingering or pinching out of the various beds or lenses. The change from one type of material to another, or the transition in grain size both laterally and vertically, ranges from sharp and distinct to gradual. The gravel ranges from pea size or less to cobbles about 5 inches in diameter, from clean and well sorted to unsorted. Boulders as much as 3 feet in diameter and similar lithologically to the bedrock were seen in the alluvium in a pit near Hearne. The gravel is composed of fragments of various types of rock such as limestone, frequently elongated and flat; siliceous, with an average or better degree of roundness; sandstone; conglomerate; clay balls; and concretions. The limestone gravels predominate in the Waco area, whereas the gravels seemed to be predominantly siliceous in the alluvium downstream from Navasota.

In most places the bedrock is harder and more compact than the flood-plain alluvium--thus the contact between the alluvium and the bedrock was readily determined in most of the test holes except where the bedrock consisted of sediments of Quaternary age. Due to the similarity in the lithologic characteristics, only a provisional identification of the contact could be made in test holes south of Hempstead.

Analyses of sand, silt, and small-size gravel from three disturbed samples and 15 undisturbed samples from test holes, river bank, or gravel pit are given in Table 2. Particle-size distribution curves for eight of the samples are shown in Figure 5. The samples, however, cannot be considered strictly representative of the flood-plain alluvium because gravel larger than the size of the sampler could not be obtained.

GROUND WATER IN THE FLOOD-PLAIN ALLUVIUM

Hydrologic Properties of the Flood-Plain Alluvium

The capacity of an aquifer to yield water to wells depends upon its hydraulic properties. The coefficients of permeability, transmissibility, and storage are terms used to describe these properties which may be measured by field or laboratory methods.

The coefficient of permeability is the rate of flow of water in gallons per day through a cross section of 1 square foot under a unit hydraulic gradient. The standard coefficient is defined for water at a temperature of 60°F. The field coefficient of permeability requires no temperature adjustment, and the units are stated in terms of the prevailing water temperature.

The coefficient of transmissibility is the number of gallons of water that will move in 1 day through a vertical strip of the aquifer 1 foot wide and having the height of the aquifer when the hydraulic gradient is unity (Theis, 1938, p. 894). This term represents the field coefficient of permeability times the thickness of the aquifer, in feet.

The coefficient of storage of an aquifer is the volume of water released from or taken into storage per unit surface area of the aquifer per unit change in the component of head normal to that surface. For an unconfined aquifer the coefficient of storage is virtually the same as the specific yield, which is defined as the unit volume of water that will drain by gravity from a unit volume of saturated material.

Some of the water contained in the interstices of the water-bearing material will drain by gravity; some will be retained by molecular attraction. The volume of water retained, expressed as the ratio to the total volume of the material, is called the "specific retention" of the material. The sum of the specific yield and specific retention is equal to the "porosity," or the percentage of void space contained in a material.

During the test-drilling program, undisturbed and disturbed samples of the flood-plain alluvium were collected at various depths in the test holes. Undisturbed samples were also collected along the river bank and from the wall of a

Table 2.--Particle-size distribution of samples of flood-plain alluvium of Brazos River from test holes[a], bank of river, and gravel pit

Well or sampling site	Depth samples (ft)	Depth to water below land surface (ft)	Particle-size diameter, in millimeters (percentage of sample)											
			Clay size	Silt size	Sand sizes					Gravel sizes				
			.004 mm	.004 - .0625 mm	Very fine .0625-.125	Fine .125-.25	Medium .25-.5	Coarse .5-1.0	Very coarse 1-2	Very fine 2-4	Fine 4-8	Medium 8-16	Coarse 16-32	Very coarse 32-64
JR-39-50-108	11 -12	11.1	67.7	32.1	0.1	0.1	--	--	--	--	--	--	--	--
JR-39-50-824	38- -39	25 b/	--	5.1	4.5	17.5	41.6	8.4	3.0	4.1	7.1	8.7	--	--
JR-39-50-826	19 -20	15.0	55.5	33.9	6.2	3.4	.6	.4	--	--	--	--	--	--
JR-39-50-826	31 -32	15.0	--	2.0	.8	12.4	77.0	7.8	--	--	--	--	--	--
WK-59-03-424	22 -23	20 b/	8.8	82.8	8.0	.2	.2	--	--	--	--	--	--	--
WK-59-03-424	36 -37	20 b/	--	5.4	7.9	44.0	37.2	3.8	.8	.8	.1	--	--	--
WK-59-03-423	20.5-21	Dry	--	3.7	1.5	7.3	17.6	13.1	13.3	13.6	14.0	15.9	--	--
WK-59-11-329	21 -22	19.8	64.5	35.3	.1	.1	--	--	--	--	--	--	--	--
WK-59-11-329	42 -43	19.8	2.2	14.0	44.2	38.0	1.6	--	--	--	--	--	--	--
WK-59-20-117	32.5-32.75	39.0	13.4	7.4	7.7	21.6	33.2	3.0	1.0	2.5	2.2	8.0	--	--
BS-59-29-435	27 -28	18.1	5.2	24.0	59.8	9.0	2.0	--	--	--	--	--	--	--
BS-59-29-811	About 46	14 b/	77.6	20.4	.6	.8	.5	.1	--	--	--	--	--	--
Sampling site 1	River bank	--	--	.7	1.4	3.6	12.5	7.8	4.1	5.0	8.5	21.3	35.1	--
Sampling site 2	do	--	--	.7	1.0	3.1	4.1	4.7	10.3	16.0	21.2	27.9	11.0	--
Sampling site 3	Bank of gravel pit	--	--	1.5	1.0	1.4	5.2	4.6	7.9	15.7	27.4	35.3	--	--
BJ-59-20-542	59 -64 c/	--	4.0	3.3	4.3	14.4	36.2	8.4	5.5	10.2	10.5	3.2	--	--
WK-59-12-725	40 -50 c/	36 b/	6.5	10.7	30.3	13.4	19.4	10.6	3.4	2.3	1.8	1.6	--	--
BS-59-29-525	50 -58 c/	31.8	3.6	5.4	10.6	8.3	18.0	6.0	6.3	11.7	15.6	11.2	3.3	--

a/ Collected with 1- or 2-inch sampler.
b/ Estimated water level.
c/ Bag (grab) sample collected from drill auger.

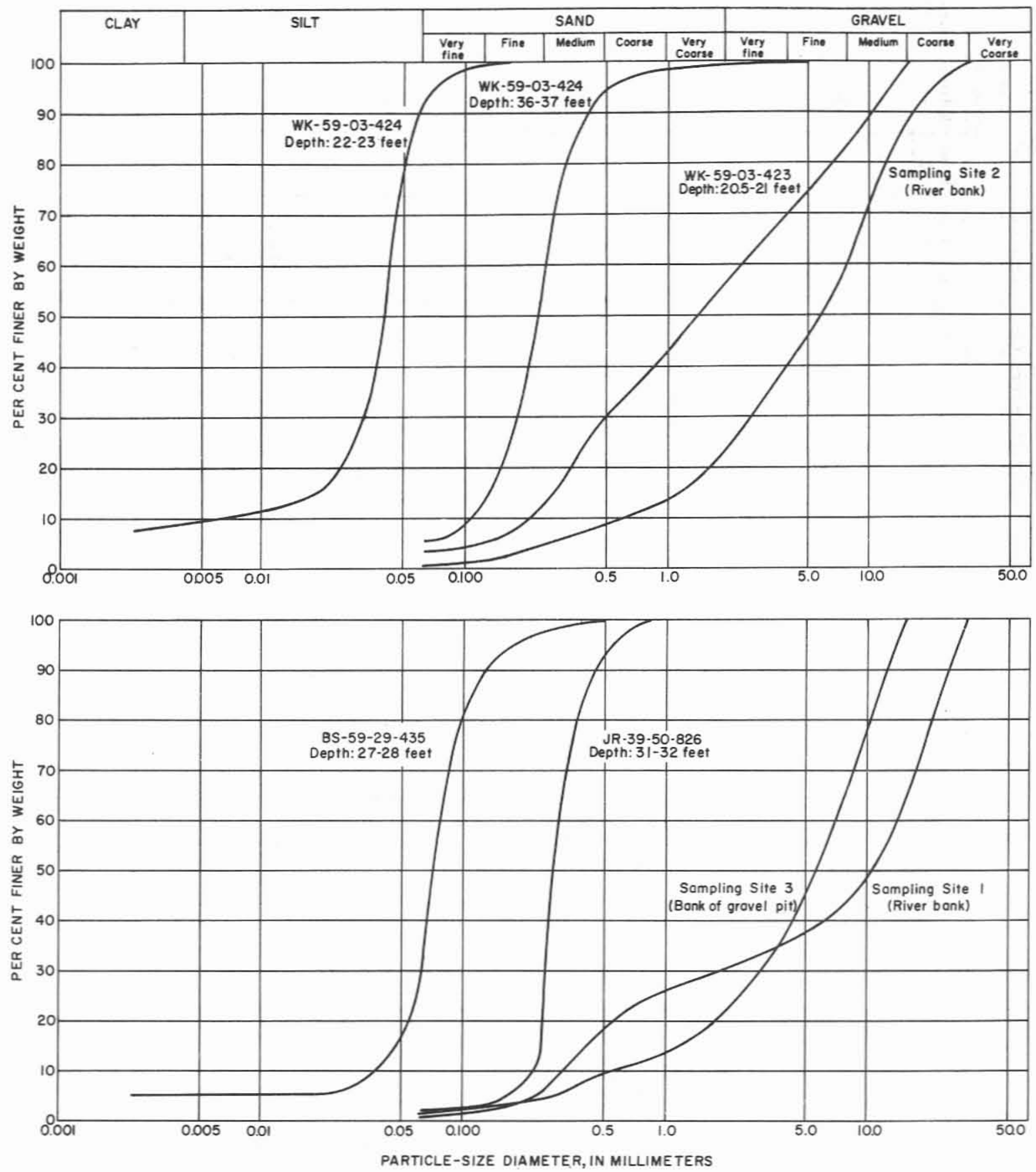


Figure 5

Particle - Size Distribution Curves of Eight Samples of Flood-Plain Alluvium of Brazos River

U.S. Geological Survey in cooperation with the Texas Water Development Board

gravel pit. The sampling points, other than test holes, are shown on the well-location map (Figure 20). The samples were analyzed in the U.S. Geological Survey's Hydrologic Laboratory at Denver, Colorado; the hydraulic properties of these samples are summarized in Table 3.

The permeability of the samples, as determined in the laboratory, ranged from 0.001 to 18,000 gpd (gallons per day) per square foot. Samples consisting almost entirely of clay and silt from test holes JR-39-50-108, JR-39-50-826 (taken at 19-20 feet), and BS-59-29-811 had permeabilities of 0.006, 0.002, and .001 gpd per square foot, respectively (Table 3). The data in Tables 2 and 3 for samples from sampling sites 1, 2, and 3 show that the percentage of clay, silt, and fine sand is low; the percentage of gravel-size material in each sample exceeded 50 percent; and the permeability of each sample is high.

Among the factors that determine the permeability of a material, other than grain size, are the sorting and shape of the grains. Well-sorted material has a higher permeability than poorly sorted material. In the latter, the pore spaces between the large particles are partly filled by smaller-size particles. The resultant pore spaces are successively filled with finer materials which eventually form a mass with a low degree of permeability. According to Tables 2 and 3, the sample taken at a depth of 31-32 feet from well JR-39-50-826 consisted of almost 85 percent medium- and coarse-grained sand, about 12 percent of fine sand, and minor amounts of very fine sand, clay, and silt; the permeability of this sample was 800 gpd per square foot. The same tables show that the sample from well JR-39-50-824 consisted of about 50 percent medium- and coarse-grained sand and lesser amounts of gravel, fine and very fine sand, clay, and silt; this sample had a permeability of 2.

Laboratory determinations indicate only the permeability of the sample--a minute part of the alluvial deposit. They do not reflect the complex relationships that exist between the various types and grain sizes of material in the deposit. The laboratory values are, therefore, an index of the expected range of permeabilities in the materials of the deposit.

The coefficient of transmissibility is best determined by field pumping tests if the tests are properly regulated. However, arranging for controlled tests to obtain reliable data is sometimes difficult. In the report area, the wells are closely spaced, the water table is at a shallow depth below the land surface at many places, and the soil is sandy in some places. Hence pumping tests made during the irrigation season would be subject to interference from nearby pumping wells and possible infiltration to the water table of irrigation water. On the other hand, if tests were run during the nonirrigating season, the pumped water would be wasted because it would have to be transported a long distance away to avoid possible local infiltration to the water table.

However, several short-term pumping tests, ranging from 3 to 24 hours in duration, were made during the investigation. The transmissibility values determined from the tests ranged from about 50,000 to over 300,000 gpd per foot. They should be used with caution, however, because the tests were too short and, in some tests, a part of the water discharged seeped downward to the water table.

The specific capacity of a well, which is the rate of its yield per unit of drawdown, is determined by dividing the discharge in gallons per minute by the drawdown, in feet. The value will vary with the hydraulic properties of

Table 3.--Laboratory determinations of hydrologic properties of samples of flood-plain alluvium of Brazos River[a]

Well or sampling site	Depth sampled (ft)	Specific retention (percent)	Porosity (percent)	Specific yield (percent)	Coefficient of permeability (gpd per sq ft)
JR-39-50-108	11 -12	--	--	--	.006
JR-39-50-824	38 -39	4.2	27.3	23.1	2
JR-39-50-826	19 -20	52.0	38.5	--	.002
JR-39-50-826	31 -32	1.1	36.5	35.4	800
WK-59-03-424	22 -23	15.6	43.5	27.9	15
WK-59-03-424	36 -37	3.5	34.8	31.3	150
WK-59-03-423	20.5-21	7.8	24.7	16.9	290
WK-59-11-329	21 -22	44.1	48.5	4.4	.8
WK-59-11-329	42 -43	4.4	35.4	31.0	29
WK-59-20-117	32.5-32.75[b]	13.5	40.1	26.6	3,400
BS-59-29-435	27 -28	7.5	35.8	28.3	9
BS-59-29-811	About 46	40.8	59.5	18.7	.001
Sampling site 1	River bank	3.8	28.6	24.8	2,600
Sampling site 2	do	11.3	32.3	21.0	14,000
Sampling site 3	Bank of gravel pit	12.4	34.7	22.3	18,000
BJ-59-20-542	59 -64[c]	5.4	29.1	23.7	43
WK-59-12-725	40 -50[c]	9.6	36.3	26.7	4
BS-59-29-525	50 -58[c]	9.4	25.4	16.0	1

[a] Collected with a 1- or 2-inch sampler.
[b] Sampler cylinder not full; probably disturbed.
[c] Bag (grab) sample collected from drill auger.

the aquifer and with well-construction factors, such as: the diameter of the well, the thickness of the aquifer, the type and amount of perforations in the casing, and the method and amount of well development. The length of time the well has been pumped prior to measurement and the rate of discharge also affect the specific capacity.

During the summers of 1963 and 1964, a total of 351 drawdown and discharge measurements were made in wells (143 in 1963, and 208 in 1964) pumping from the alluvium in the report area (Table 9). Many of the wells measured in 1963 were remeasured in 1964. The calculated specific capacities ranged from 6 to 134 gpm (gallons per minute) per foot of drawdown.

The specific capacities are useful in estimating the coefficients of transmissibility. In general, high specific capacities indicate high transmissibilities--low specific capacities, low transmissibilities. In most cases the factors affecting specific capacity do so adversely, and the actual coefficient of transmissibility is generally greater than that computed from specific-capacity data.

Based on the 351 specific capacities, most of which were measured in the principal irrigated section of the report area in Burleson, Brazos, Robertson, and Falls Counties, the coefficient of transmissibility ranged between 7,300 and 208,000 gpd per foot and averaged about 42,000 gpd per ft. Twenty-one percent of the values were less than 20,000 gpd per foot, 42 percent were in the range from 20,000 to 40,000, 19 percent in the range from 40,000 to 60,000, and 18 percent were above 60,000.

The specific yield of the samples from test holes, as determined by laboratory methods, ranged from 4.4 to 35.4 percent, averaging 23.6 percent (Table 3). The centrifuge moisture-equivalent method was used in the laboratory to determine the specific retention of the alluvium samples. Smith (1961, p. A-11) indicated that specific-yield values obtained from centrifuge moisture-equivalent data, especially for fine-grained material, may be too high because the centrifuge tends to expel more water than would drain by gravity. Thus, if the specific retention is low, the difference between it and the porosity (specific yield) would be high.

Cronin and others (1963, p. 119) assumed a specific yield of 15 percent in estimating the quantity of water in the flood-plain alluvium of the Brazos River. This assumed value is somewhat below the average of the specific-yield values determined in the laboratory (Table 3). Nevertheless, 15 percent probably is a reasonable, possibly conservative, estimate of the specific yield of the alluvium.

Occurrence of Ground Water

Ground water occurs in the interstices or pore spaces of the unconsolidated sand, gravel, silt, and clay of the flood-plain alluvium. Although the ground water is, in general, under water-table conditions, locally artesian conditions occur where lenses of permeable sand and gravel are interbedded with or overlain by less permeable material. Water-table conditions occur wherever the upper surface of the zone of saturation is under atmospheric pressure only and is free to rise or fall with the changes in the volume of water stored.

The level at which water stands in wells tapping an unconfined aquifer defines the surface known as the water table. Artesian (confined) conditions occur where water in an aquifer is confined under hydrostatic pressure by relatively impermeable beds and will rise in a well above the base of the confining bed. The level to which the water will rise in a tightly cased artesian well is called the piezometric surface.

During the test-drilling program, the water level was measured in each test hole wherever possible. These measurements and those made in other wells showed that the depth to water below land surface in the report area ranged from less than 10 to almost 50 feet (Table 9).

Ground-Water Movement

The configuration of the water table for parts of the report area during the winter of 1962 and the spring of 1963 is shown by means of contours on Figures 6 and 7. From these maps the direction of movement of the water and the relation of the water in the alluvium to the water in the river can be determined. Ground water tends to move in the direction of the greatest slope of the water table, which is perpendicular to the contour lines on the maps, from areas of recharge to areas of discharge.

The data on the cross-valley profiles (Figures 26, 27, and 28) and the water-table maps (Figures 6 and 7) indicate that the ground water in the alluvium normally is at or above the water surface in the river. From a high altitude near the valley walls the water table slopes downward toward the Brazos River. The upstream trend, or flexure, of the contours on the water table indicates that the Brazos River is an effluent or gaining stream. During high-water stages in the river, however, water from the river infiltrates the alluvium and the gradient of the water table in a small area adjacent to the stream is temporarily reversed. After the river stage becomes lower, the water drains from the alluvium, and the water table again returns to its normal position.

South of Waco the ground water moves toward the river in a direction roughly parallel to cross-valley profile 1 (Figure 26). Here the water table slopes at about 3 feet per mile. South of Hempstead the slope of the water table is about 4 feet per mile, and south of Richmond, near the downstream boundary of the report area, the water table slopes toward the river at a rate of about 10 feet per mile.

The slope of the water table in Falls, Robertson, Brazos, and Burleson Counties, the principal irrigated sections of the report area, can be determined from the contours on the water table (Figure 6). For example, along a line through wells JR-39-50-906 and JR-39-58-204, roughly parallel to the Falls-Robertson County line, the water table slopes toward the river at about 7 feet per mile. Southwest of Calvert, the slope of the water table is slightly less than 10 feet per mile along a line through wells WK-59-03-502 and WK-59-03-703. Along a line roughly parallel to U.S. Highway 190 near Hearne in Robertson County, the slope is about 7 feet per mile. Approximately 2 miles north of Farm Road 60 in Burleson County, the water table slopes at about 6.7 feet per mile along a line drawn through wells BS-59-28-901 and BS-59-29-522.

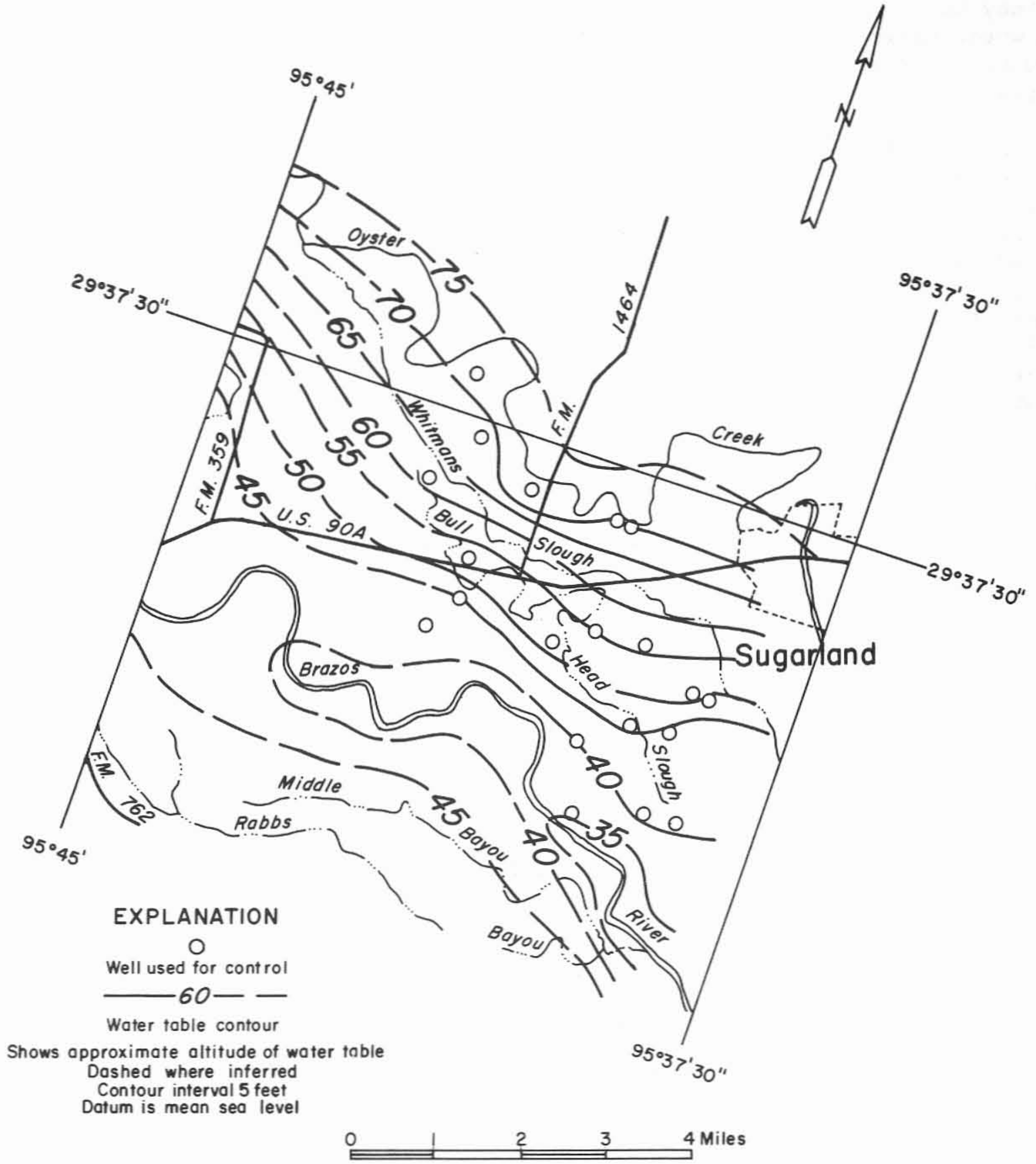


Figure 7

Water-Table Contour Map, Vicinity of Sugarland, 1962-63

U.S. Geological Survey in cooperation with the Texas Water Development Board

The slope of the water table along Farm Road 1373 in Robertson County in December 1940 and January 1941, prior to the completion of Morris Sheppard and Whitney Dams, and in March 1963 are shown in Figure 8. The profiles show that the water table sloped toward the Brazos River even before the natural streamflow of the river had been altered by the impoundment of water behind dams upstream from the report area.

Between the Robertson-Brazos County line and State Highway 21 the contours show a depression in the water table (Figure 6). The depressed area is separated from the Brazos River on the west and south by a ground-water ridge. The depression in the water table probably can be attributed to the withdrawals of ground water by wells from the Sparta Sand, which underlies the alluvium in the depressed area. About 4 miles south (downdip from the depressed area in the water table), ground water is pumped from the Sparta Sand for public supply from wells owned by the Texas A. & M. University (Figure 21). In addition, some water is pumped from wells tapping the Sparta Sand in the vicinity of well BJ-59-21-714 (Figure 21). Doubtlessly, the pumpage has resulted in a decline in the water levels or artesian pressure in the Sparta Sand, and as a consequence, ground water from the alluvium of the flood plain may now be moving downward into the Sparta Sand in response to a difference in head.

The rate of ground-water movement, which generally is very slow, is proportional to the permeability of the water-bearing material and the slope of the water table. Accordingly, in the alluvium of the flood plain this rate undoubtedly varies from place to place because of differences in the permeability of the water-bearing materials and changes in the hydraulic gradient.

If the permeability and porosity of the water-bearing materials and the slope of the water table are known, the average velocity of the ground water percolating through the materials can be computed by the formula (Wenzel, 1942, p. 71):

$$v = \frac{PI}{7.48p} ,$$

in which

v = velocity in feet per day,
P = permeability in gallons per day per square foot,
I = slope of the water table in feet per foot (expressed as a ratio),
p = porosity, expressed in percent, and 7.48 is a factor for converting gallons to cubic feet.

The permeability of a sample from test hole JR-39-50-826 was 800 gpd per square foot, and the porosity of the sample was 36.5 percent (Table 3). The slope of the water table in the vicinity of this test was 0.00064. Hence, the velocity was computed to be 0.187 feet per day, or about 70 feet per year.

Similarly, the slope of the water table in the vicinity of test hole WK-59-03-423 was 0.00133. The values for permeability and porosity of a sample from this test hole, as given in Table 3, were 290 gpd per square foot and 24.7 percent, respectively. By substituting these values in the same formula, the velocity of the ground water at the site of test hole WK-59-03-423 was computed to be 0.208 feet per day, or about 75 feet per year.

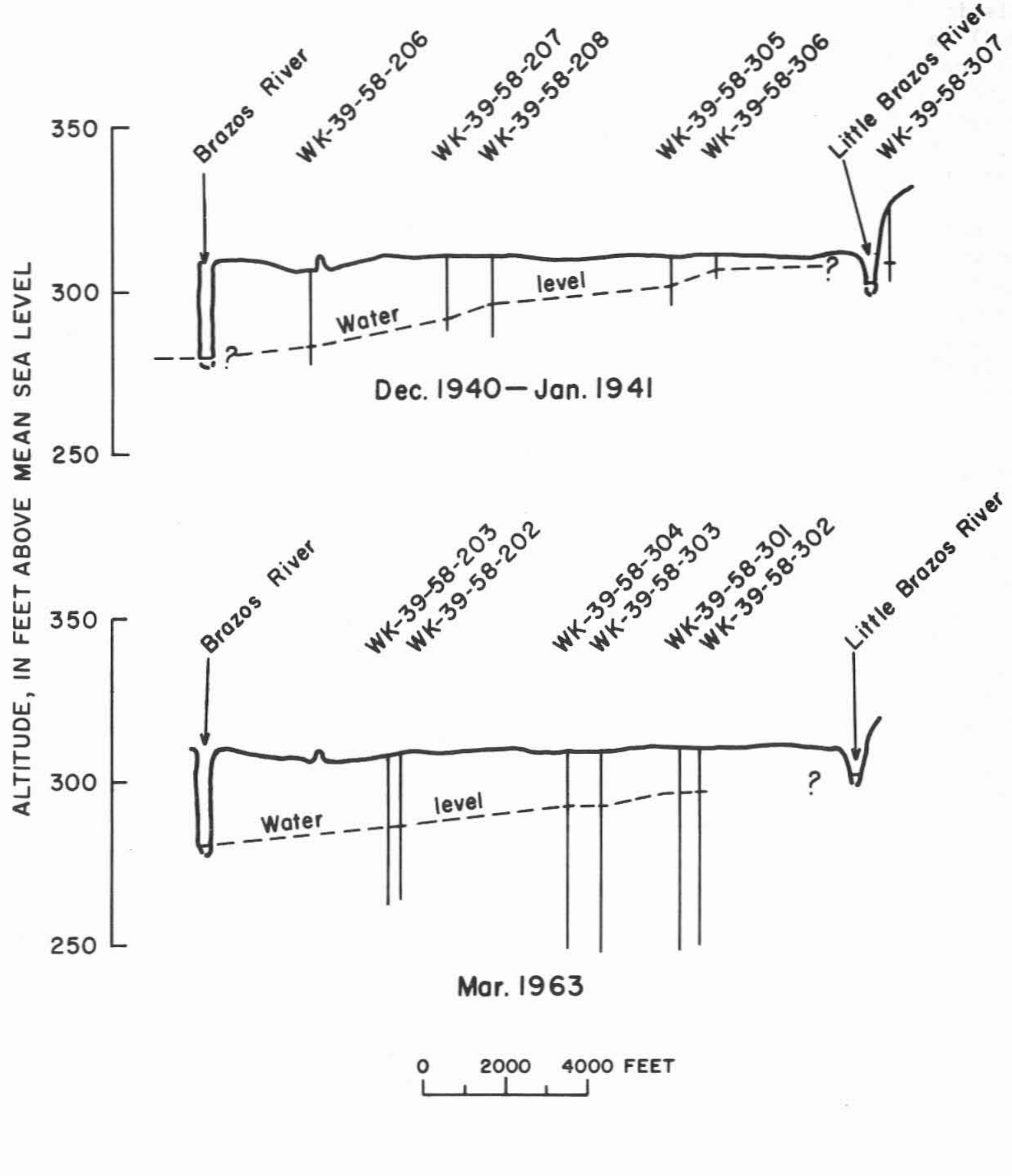


Figure 8

Profiles of Water Table Along Farm Road 1373, Robertson County, Winter of 1940 - 41 and Spring of 1963

U.S. Geological Survey in cooperation with the Texas Water Development Board

Water-Level Fluctuations

Prior to about 1956, few depth-to-water measurements had been made in wells in the flood-plain alluvium of the Brazos River. Measurements were made in some wells in 1956-57 in Robertson, Brazos, and Burleson Counties by Hughes and McGee (1962), and starting in 1957, the Texas Board of Water Engineers in cooperation with the U.S. Geological Survey established a network of 28 observation wells in the alluvium, which were measured at least once a year. Depth-to-water measurements in some wells were made in 1960 as a part of a reconnaissance study of the ground water in the Brazos River basin (Cronin and others, 1963). Records of all of these measurements have been incorporated into this report.

During the fieldwork for this report, a network consisting of 124 observation wells was established. Water levels in these wells were measured quarterly if possible, although many of the wells could not be measured in the summer when they were being pumped to supply water for irrigation. A large percentage of the observation wells are in the heavily irrigated section of the report area. The depth-to-water measurements for these and other wells are given in Tables 9 and 11.

The hydrographs of water-level measurements in 28 selected observation wells are shown in Figures 9 to 13. Many of the hydrographs show a pattern that is similar and related to the rainfall pattern. The drought period, which undoubtedly had been accompanied by large withdrawals of water for irrigation, ended about 1957. From 1957 to about 1960, rainfall was near or above normal (Table 4). Consequently, the decrease in pumpage was accompanied by an increase in recharge. As a result of the above normal rainfall in much of the report area in 1961, water levels reached near or record highs in most of the observation wells. During the next 3 years, 1962-64, however, rainfall was below normal in parts of the report area. Consequently, pumpage of ground water for irrigation increased markedly and water levels declined in most of the observation wells. Significantly, in the winter of 1963-64, the water level in many wells did not return to the level existing prior to the 1963 irrigation season. In fact, in 1964 the water levels in most of the observation wells were at record lows.

The hydrograph of well BJ-59-20-603 (Figure 13) in Brazos County shows that in general the water level in this well has declined steadily since 1957, except in 1960-61 when the level rose slightly. This well is in the area of the depression in the water table (Figure 6), and the declining water level may be attributed to the decline in artesian head in the underlying Sparta Sand, which is in direct hydraulic connection with the alluvium. As mentioned previously, large quantities of ground water are pumped from the Sparta Sand a few miles south of the well.

Recharge

The ground-water reservoir in the alluvium of the Brazos River flood plain is recharged principally by precipitation on the flood plain which is augmented to some extent by runoff from adjacent valley wall slopes.

Other sources of recharge to the alluvium are infiltration from streams (natural and induced), underflow from the terrace alluvium, vertical and lateral

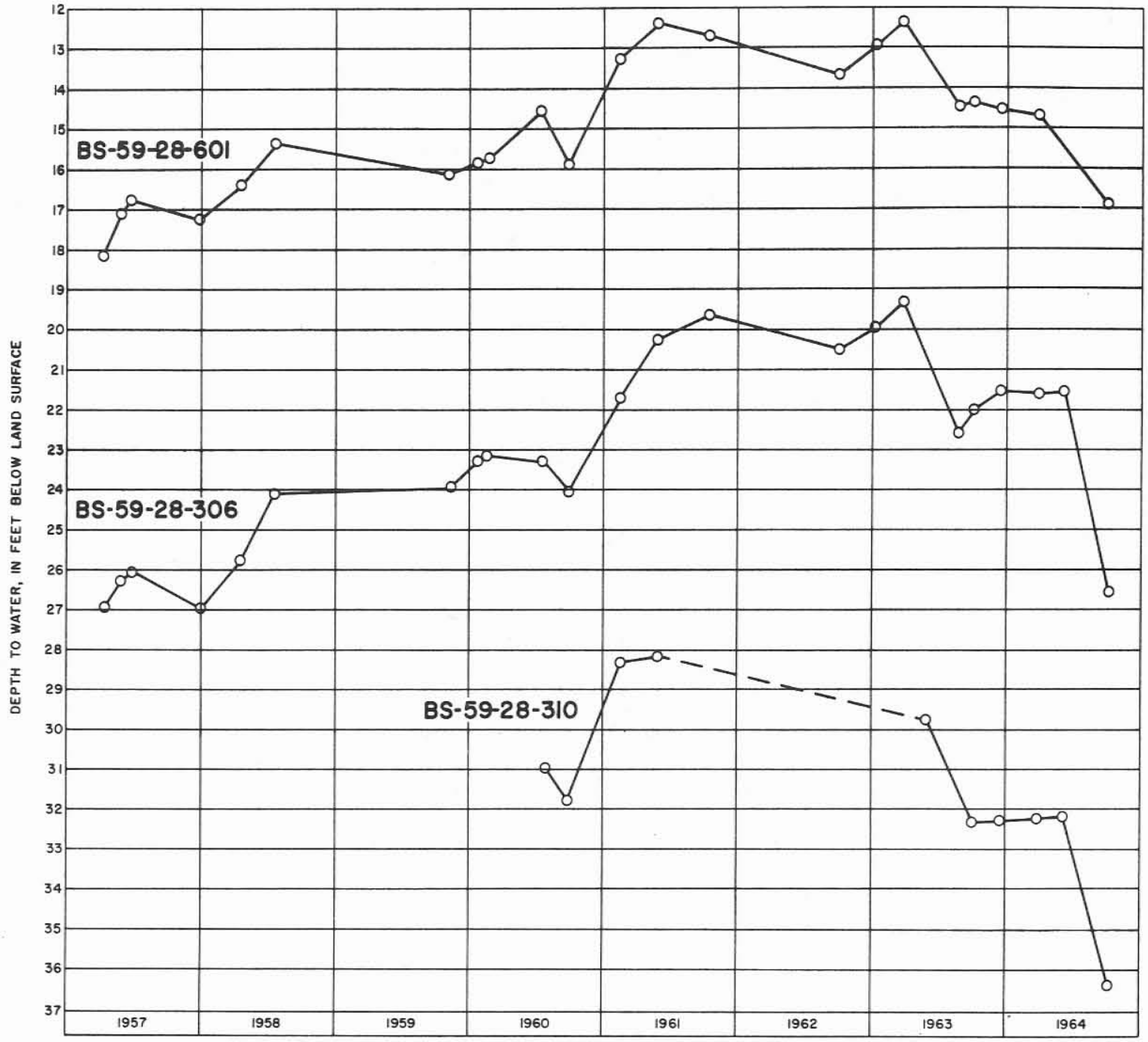


Figure 9

Hydrographs of Selected Wells in Burleson County (Sheet 1 of 3)

U. S. Geological Survey in cooperation with the Texas Water Development Board

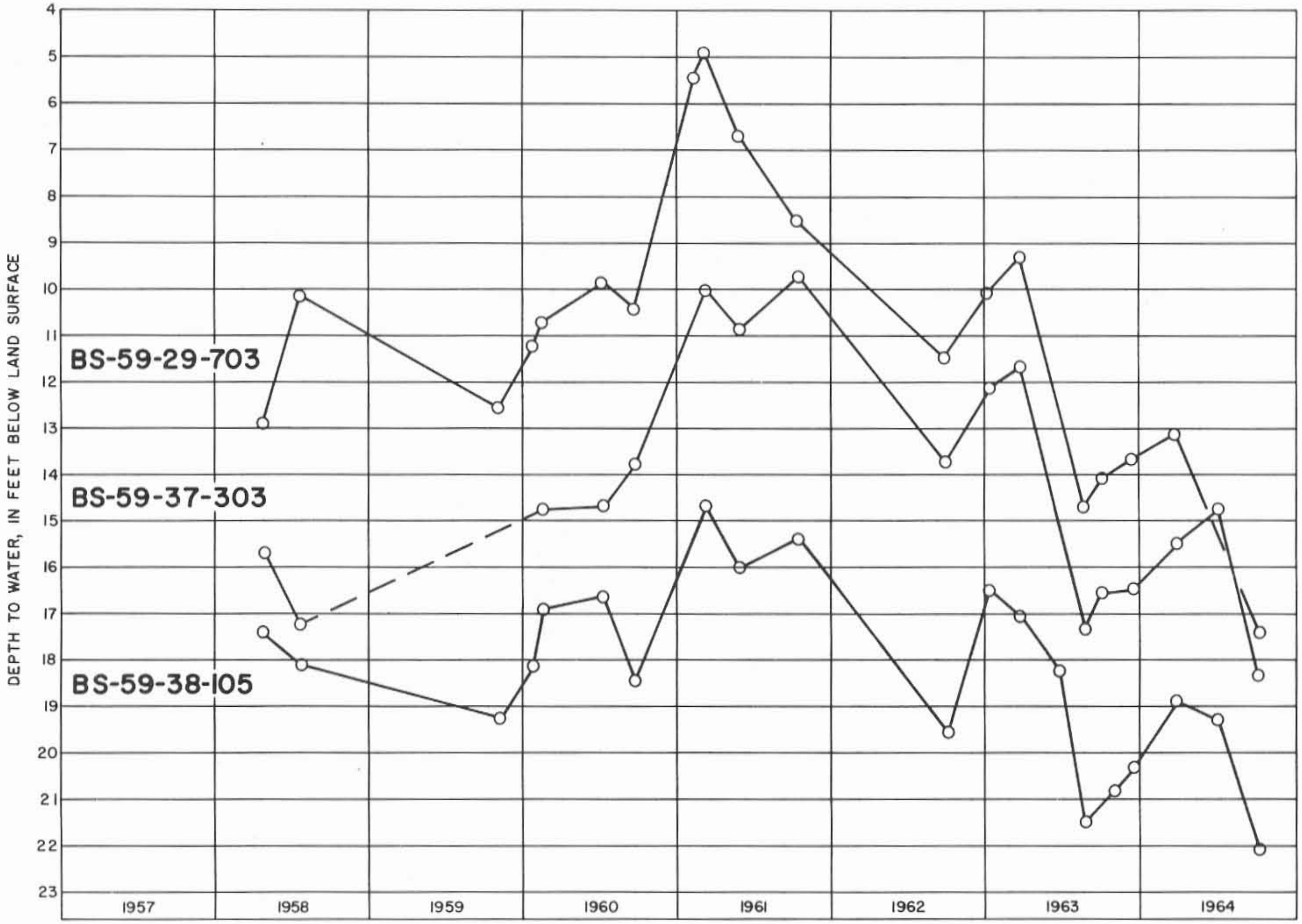


Figure 9

Hydrographs of Selected Wells in Burleson County (Sheet 2 of 3)

U. S. Geological Survey in cooperation with the Texas Water Development Board

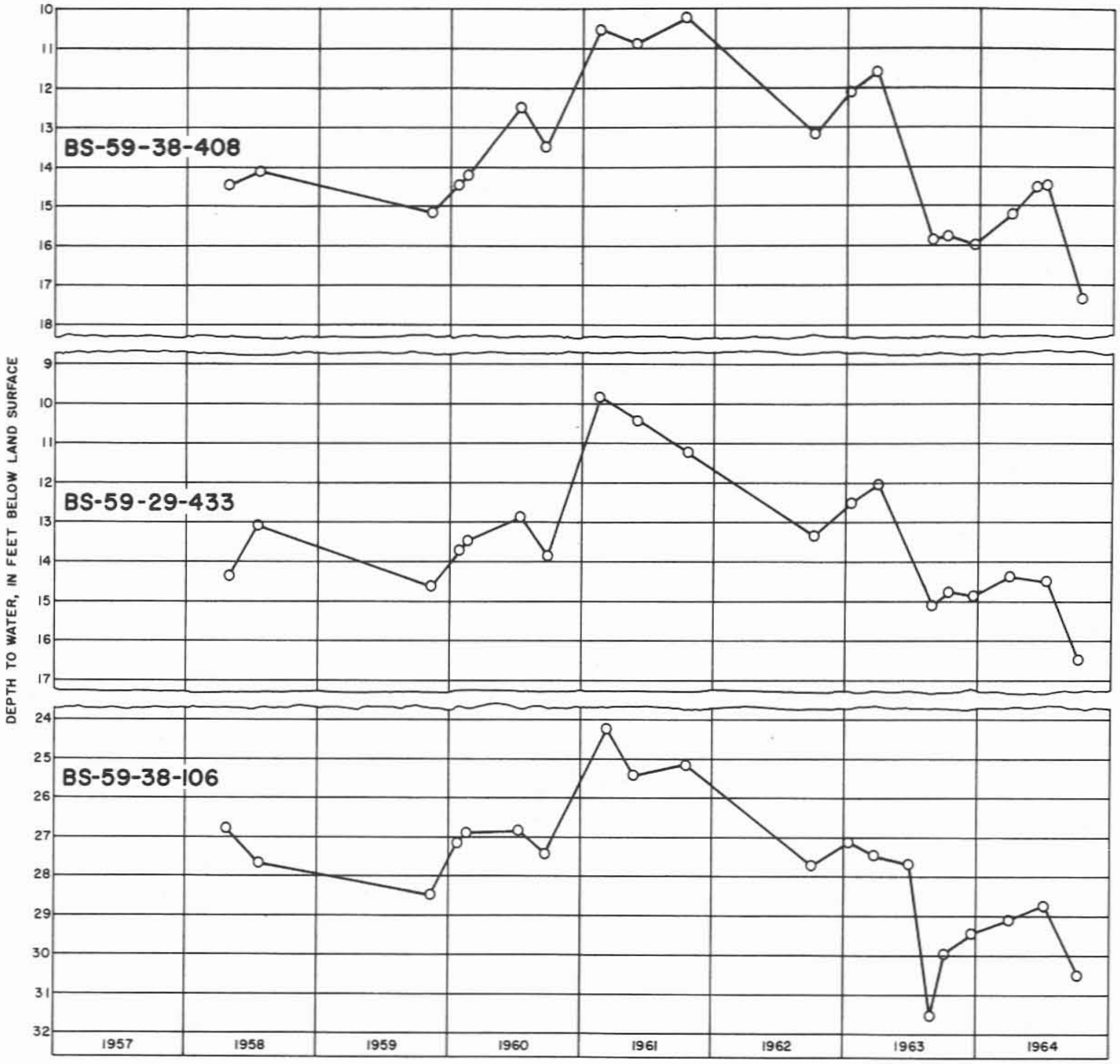


Figure 9

Hydrographs of Selected Wells in Burleson County (Sheet 3 of 3)

U. S. Geological Survey in cooperation with the Texas Water Development Board

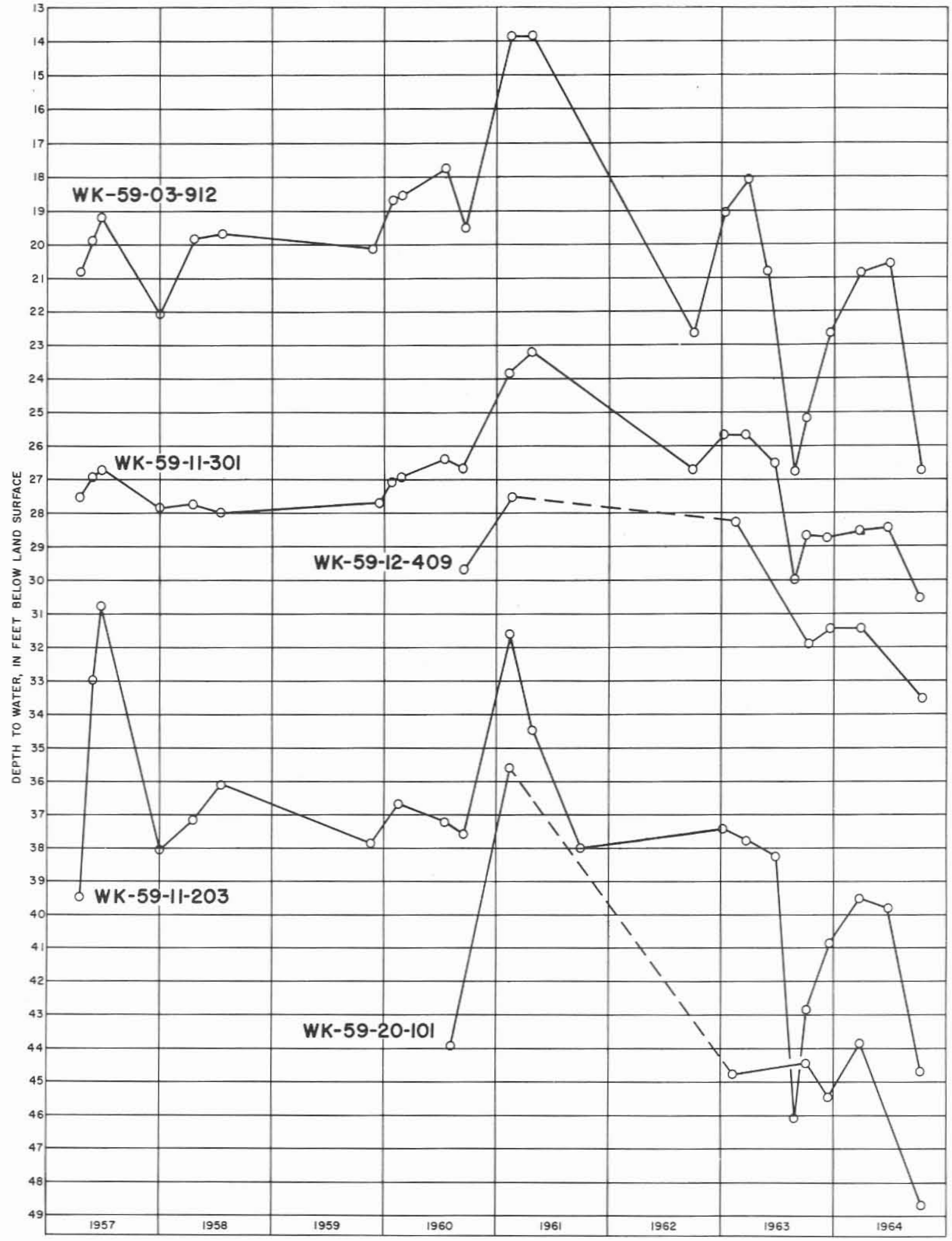


Figure 10

Hydrographs of Selected Wells in Robertson County (Sheet 1 of 2)

U.S. Geological Survey in cooperation with the Texas Water Development Board

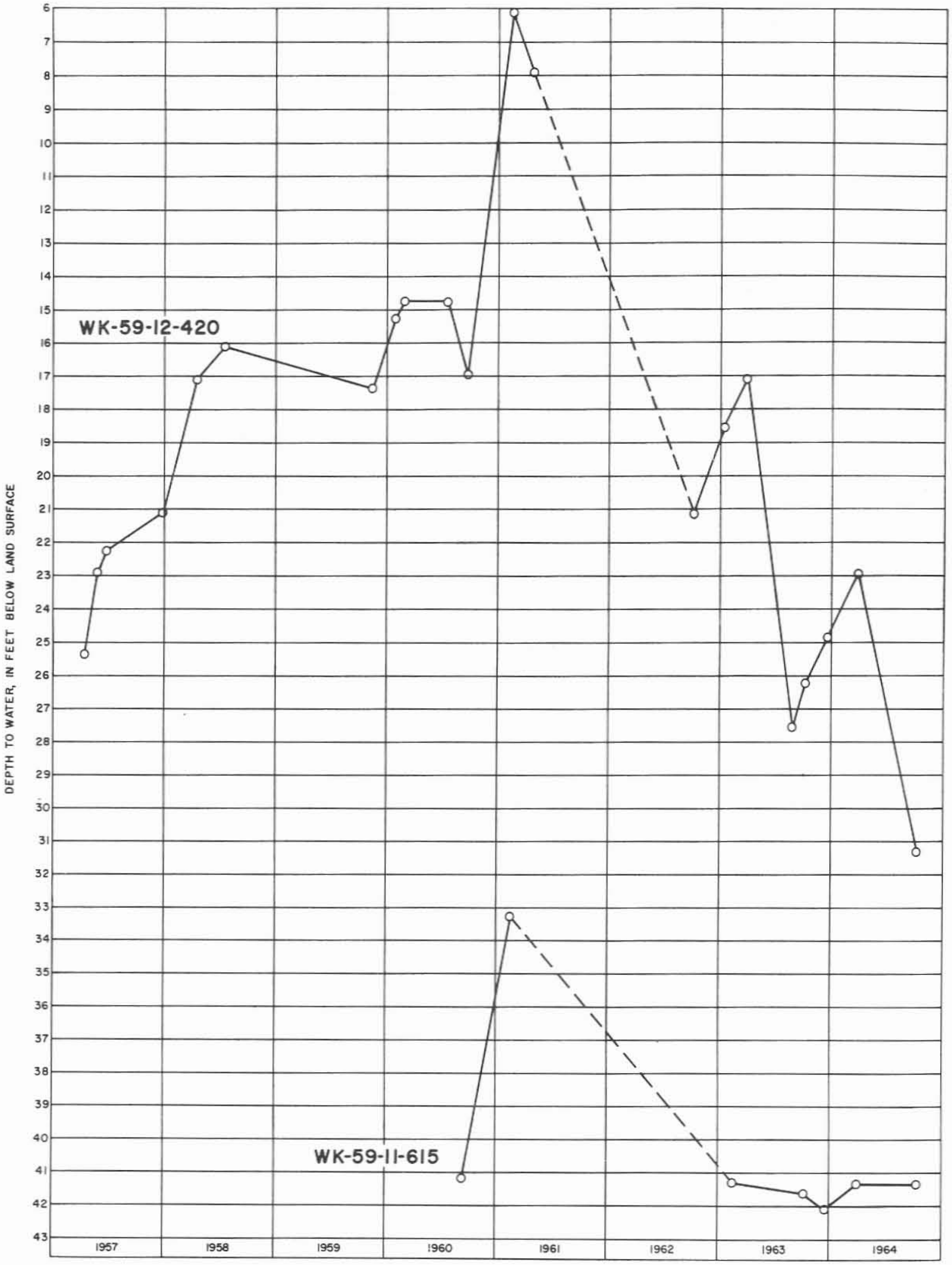


Figure 10

Hydrographs of Selected Wells in Robertson County (Sheet 2 of 2)

U.S. Geological Survey in cooperation with the Texas Water Development Board

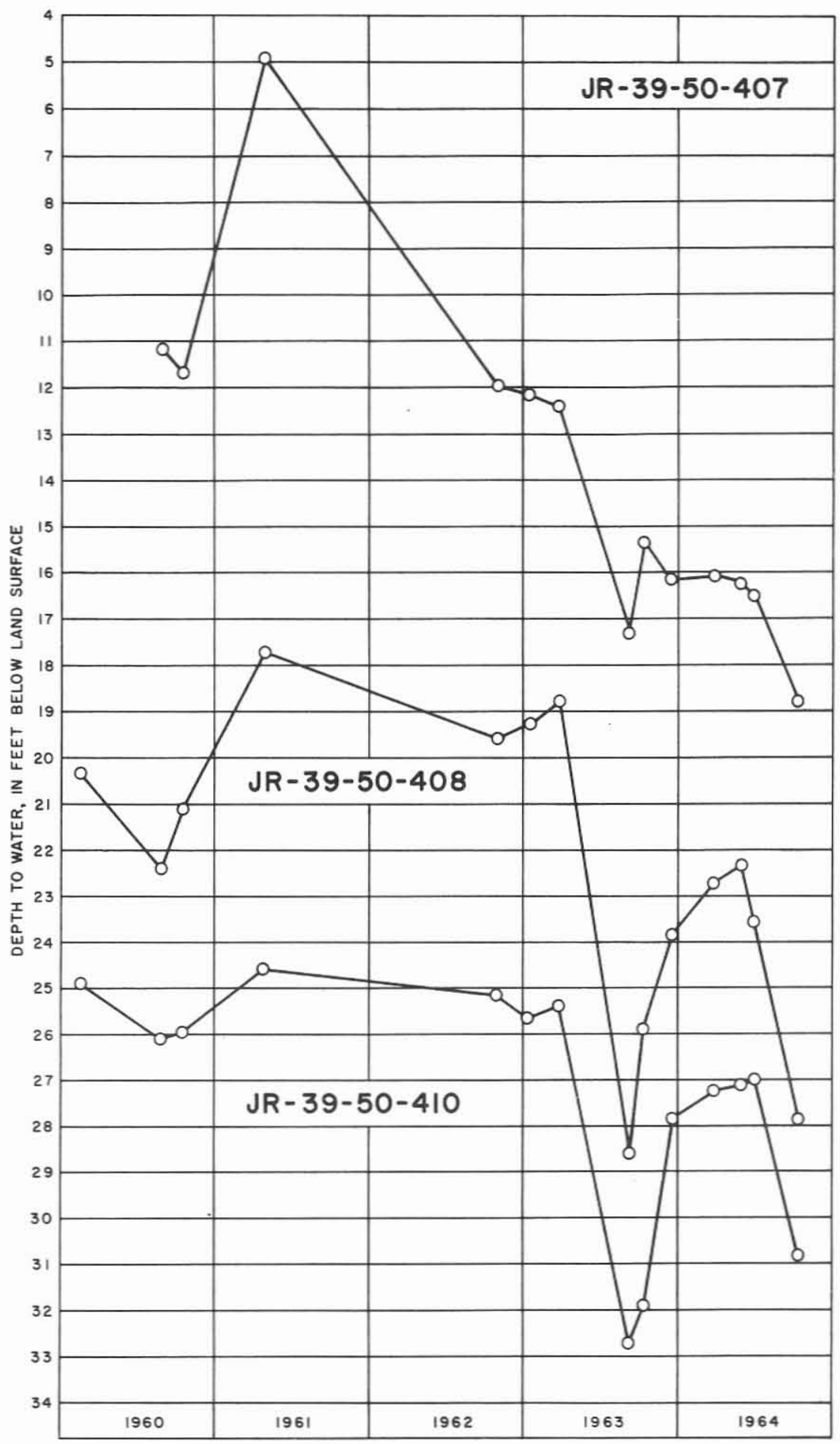


Figure 11

Hydrographs of Selected Wells in Falls County

U.S. Geological Survey in cooperation with the Texas Water Development Board

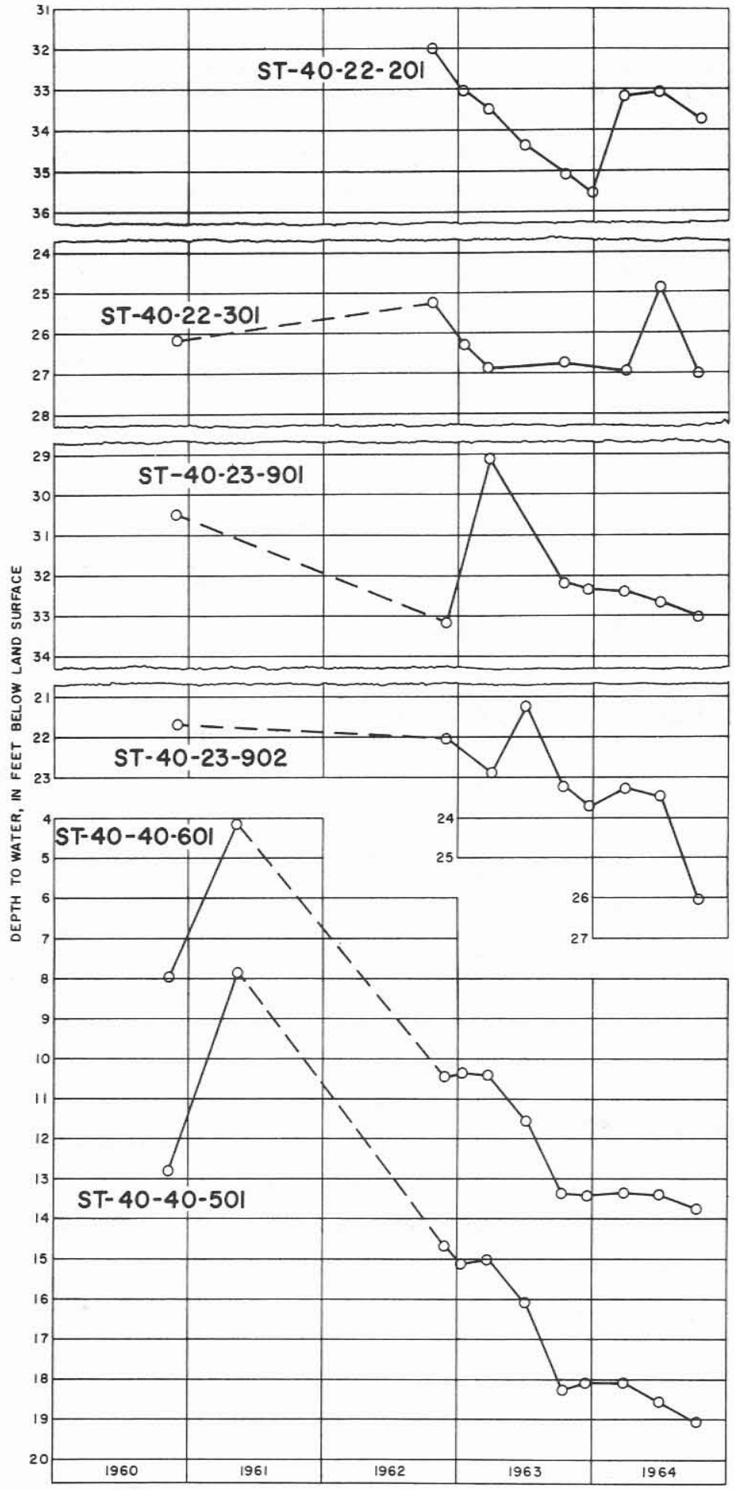


Figure 12

Hydrographs of Selected Wells in McLennan County

U.S. Geological Survey in cooperation with the Texas Water Development Board

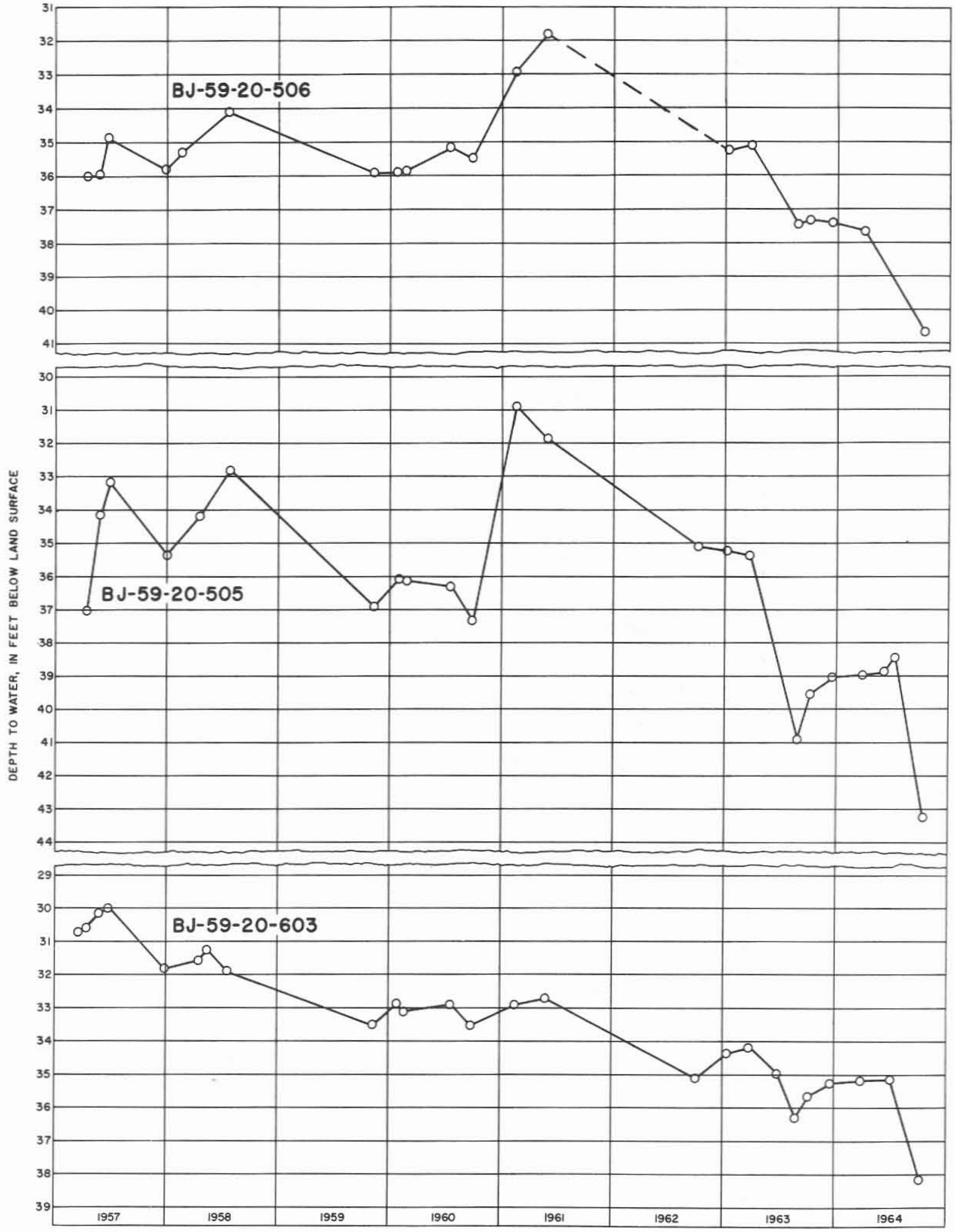


Figure 13

Hydrographs of Selected Wells in Brazos County

U. S. Geological Survey in cooperation with the Texas Water Development Board

Table 4.--Annual precipitation, in inches, at College Station, Sugarland, Waco, and Whitney Dam, 1957-64, and departure from normal precipitation at Sugarland and Waco
(From records of U.S. Weather Bureau)

	1957		1958		1959		1960	
	Precipi-tation	Departure from normal	Precipi-tation	Departure from normal	Precipi-tation	Departure from normal	Precipi-tation	Departure from normal
College Station	56.10	--	43.37	--	41.38	--	45.57	--
Sugarland	51.66	8.43	37.22	-6.01	62.94	18.32	59.18	14.56
Waco	48.91	15.96	35.31	2.36	33.81	.86	29.63	-3.42
Whitney Dam	43.64	--	31.91	--	41.41	--	32.72	--

	1961		1962		1963		1964	
	Precipi-tation	Departure from normal	Precipi-tation	Departure from normal	Precipi-tation	Departure from normal	Precipi-tation	Departure from normal
College Station	44.02	--	37.39	--	29.54	--	34.78	--
Sugarland	48.42	3.80	39.49	-5.62	30.85	-14.26	35.70	-9.41
Waco	42.71	9.76	22.60	-9.48	19.57	-12.51	29.32	-2.76
Whitney Dam	47.18	--	30.30	--	19.08	--	29.26	--

movement of water from adjoining bedrock, infiltration of surface water applied for irrigation, and inundation of the flood plain or parts of it by flood waters. Because recharge from most of these sources may be local and limited to small areas or because of an interrelationship between some of the sources, it was not feasible to estimate the amount of recharge from these sources. However, it is probably only a small part of the total amount of recharge.

Part of the precipitation falling on the flood plain is lost by surface runoff to the Brazos River and its tributaries; another part is retained temporarily in old river channels, canals, surface drainageways, and other depressions, or in the soil close to the land surface from which it evaporates or is transpired by plants. A small part, generally not more than a few percent in the report area, percolates downward below the root zone and eventually reaches the water table and becomes a part of the ground water in storage in the alluvium.

The amount of recharge to the flood-plain alluvium from precipitation can only be estimated. The procedure used in estimating the recharge from precipitation followed that described by Keech and Dreeszen (1959, p. 45-48) in which the difference in ground-water flow estimated between the upstream and downstream sections of saturated alluvium between two successive flow lines is equal to the estimated infiltration by precipitation.

On this basis, the estimated annual recharge between two sections in Burleson County about midway between the east-west highways 21 and 60 was about 5.5 inches. Using the same method, the annual recharge between two sections near highway 190 west of Hearne in Robertson County was estimated to be about 1.7 inches. Clay is predominant at or close to the land surface and above the water table in the vicinity of the sections near Hearne, whereas the material above the water table in the vicinity of the sections in Burleson County is more sandy. This suggests that the permeability of the soil is greater in the vicinity of the Burleson County sections--thus accounting for the higher rate of recharge.

Recharge was also estimated by the same method at four other locations in Falls, Robertson, and Burleson Counties, all in the principal irrigated section. The estimated annual recharge computed at each of those four locations was 2.1 inches in Falls County, 1.8 and 2.6 inches in Robertson County, and 5.3 inches in Burleson County. The average of the estimated annual recharge at the six locations was slightly more than 3.0 inches, or, in general, somewhat less than 10 percent of the annual precipitation. The estimates may include some recharge from sources other than precipitation, such as return water from irrigation; however, this quantity is probably small.

On the basis of water-level fluctuations, Cronin and others (1963, p. 119) estimated the recharge to the alluvium between the Hill-McLennan County line and about highway 290 west of Hempstead in Waller County at about 100,000 acre-feet per year during the 4-year period 1957-61. Table 4 shows the annual precipitation at four stations and departure from normal precipitation at two stations within or adjacent to the report area. The information given in the table shows that the annual precipitation was above normal at the stations during much of the period 1957-61. The area of the flood plain for which this estimate was made included about 565 square miles (361,600 acres). Assuming that the recharge was distributed evenly over the 565-square-mile area, the amount of recharge per square mile would have been about 177 acre-feet, or a little less than $3\frac{1}{2}$ inches per year. This figure is about the same as that determined by the other method described above. If the figure is valid for the entire report area, the total recharge from this source would be about 155,000 acre-feet per year.

Recharge to the flood-plain alluvium might be induced to a small extent in places by pumping large-capacity wells near the Brazos River. The pumping could reverse the hydraulic gradient so that the water would slope from the river toward the wells, thus causing the water to move in that direction. As of 1964, however, very few large-capacity wells were near the Brazos River (Figures 20, 21, and 22), and it seems likely that very little recharge is actually induced from the river.

The flood plain of the Brazos River, or parts of it in the report area, have been inundated at times in the past by floods from the Brazos River and its tributaries. The natural streamflow has been regulated somewhat by the construction of dams upstream from the report area on the main stem of the river and some of its tributaries. However, flooding will probably continue to occur, and at times parts of the flood plain will be inundated. The natural levees present in places along the stream are evidence of bank overflow in past history. Such overflow will probably occur again in places. The flood-plain alluvium would undoubtedly receive some recharge as a result of the flooding and inundation of the flood plain. However, there was no flooding during the fieldwork for this report, and data on which an estimate could be made of recharge due to past floods are not available.

Discharge

Ground water is discharged from the alluvium of the flood plain principally by seepage and spring flow into the Brazos River, evaporation and transpiration, and wells. Smaller quantities of ground water are discharged by springs and by downward percolation into the underlying bedrock.

Maps showing contours on the water table (Figures 6 and 7) and records of the altitude of the water table in individual wells indicate that ground water is being discharged from the alluvium into the Brazos River. The quantity of discharge was not measured; however, it can be estimated knowing the transmissibility of the alluvium and the approximate hydraulic gradient in the reach of the Brazos River between the Falls-Robertson County line and Bryan. The saturated thickness of the alluvium adjacent to the river in the 56.4-mile reach averages about 20 feet (Figure 19). The permeability of the alluvium along the line of 20-foot thickness is about 800 gpd per square foot, which multiplied by the thickness, gives a transmissibility of 16,000 gpd per foot. The average gradient of the water table along this line is about 9 feet per mile. On the basis of these values, the quantity of water moving through the 20-foot section of the alluvium on the left side to the Brazos River is approximately 25 acre-feet per day (8 mgd), or about 9,000 acre-feet per year. Thus in the 56.4-mile reach, seepage to the Brazos River from the left bank alluvium amounts to about 0.22 cfs (cubic feet per second) per mile. The small amount of alluvium along the right bank probably contributes a small quantity of flow to the river. The alluvium along both banks, therefore, is estimated to discharge about 0.3 cfs per mile in the 56.4-mile reach studied.

Records of streamflow at Waco, Marlin, and Bryan suggest that seepage of ground water from the alluvium into the Brazos River may be somewhat greater than the 0.3 cfs per mile estimated above.

The gain in low flow, exclusive of gaged tributary inflow, of the Brazos River between the gaging stations at Waco and Bryan was 67 cfs, or 0.56 cfs per mile during the period December 19, 1951 to January 31, 1952. The gain between Marlin and Bryan averaged about 54 cfs, or 0.63 cfs per mile of reach during the period October 3-11, 1948.

These values of low flow presumably reflect not only contributions from ground-water storage directly to the Brazos River, but also effluent from sewage treatment plants, ungaged tributary inflow, including interflow in the reaches. For purposes of comparison the ungaged tributary inflow was estimated from miscellaneous discharge measurements made on the Little Brazos River during the period 1962-64 (Table 7), drainage from the Little River below the gaging station at Cameron, and drainage from other smaller tributaries. Of the 67 cfs gain between Waco and Bryan, 11 cfs was sewage effluent and 10 cfs probably was inflow from tributary streams such as the Little Brazos River. Thus, the discharge from the alluvium (base-flow accretion) between Waco and Bryan probably was 46 cfs, or about 0.38 cfs per mile. Similarly the 54 cfs gain between Marlin and Bryan included at least 8 cfs of sewage effluent and ungaged tributary inflow. Of the 8 cfs, 7 cfs was attributed to inflow. On this basis, therefore, the gain in base flow between Marlin and Bryan was about 46 cfs, or 0.55 cfs per mile.

The above-described two methods of computing ground-water discharge (based on ground-water and streamflow data) give results ranging from 0.3 to 0.55 cfs per mile. Uncertainties are involved in both methods of computation, however, and the true value of discharge is probably somewhere between the two.

The quantity of ground water discharged by evapotranspiration is not known, but probably is substantial. In many places in the report area, the water table is shallow (Table 9), thus affording an opportunity for trees and other types of vegetation to withdraw ground water directly from the ground-water reservoir or the overlying capillary fringe.

Ground water is discharged also through wells, principally for irrigation. The quantity of water pumped from the alluvium in the report area was about 49,000 acre-feet in 1964 (Table 6). A part of this, however, probably was excess to the needs of the crops and was returned to the aquifer.

The movement of ground water downward to an underlying bedrock aquifer occurs only where the piezometric surface in that aquifer is lower than the water table in the alluvium. Such a condition may exist in a small area in Brazos County where the piezometric surface in the Sparta Sand is lower than the water table in the immediately overlying alluvium. Similar conditions may occur in the flood plain south of Navasota where large quantities of ground water have been withdrawn from formations (such as the Lissie Formation) that underlie the alluvium. Actually most of the pumpage was from wells outside the report area, but the effect of this pumpage has extended toward and possibly reached the river.

CONSTRUCTION AND PERFORMANCE OF WELLS

When an irrigation well is to be drilled into the alluvium, the area is usually explored by several test holes to find the most favorable location. The thickness and grain size of the water-bearing material are the most important hydrologic factors considered in selecting the well site. A reverse-circulation rotary-type drilling rig is used to drill the hole, which may be 36 or 42 inches in diameter. The hole is generally drilled about 2 to 5 feet below the base of the alluvium into the bedrock. The entire depth of the hole is cased. The casing used in the older wells generally consists of 18-inch corrugated galvanized culvert pipe, with $\frac{1}{2}$-inch mesh, woven-wire screen placed opposite the coarser sand and gravel. Many of the wells having this type of casing have been reworked, and torch-slotted steel liners have been placed inside the old casings. Currently, most of the wells being drilled are cased with torch-slotted steel casing 14 to 18 inches in diameter. Approximately pea-size gravel is used to fill the annular space between the casing and the wall of the hole. The well is then developed with a test pump; gravel is added, if necessary, to replace the sand pumped during the well development. Following development, a short test is run to determine the capacity of the well and the size of the pump and power plant needed. Throughout the report area, the typical well is equipped with a 6- or 8-inch turbine pump, set within approximately 2 feet of the bottom of the well, and operated with power supplied by an internal-combustion engine. Some wells are equipped with 4-, 5-, or 10-inch pumps. A large concentration of wells along Farm Road 50, between about Hearne and Mumford in Robertson County, is powered by electric motors.

A few dug wells cased with 30-inch concrete rings also are used for irrigation. In some places, mobile surface pumps are used to pump water from gravel pits for irrigation.

Some signs of caving around the irrigation wells were observed during the fieldwork. Such caving is an indication that when the wells are pumped, sand along with water has been withdrawn from the alluvium.

The ground water is conveyed from the well to the fields through unlined open ditches, by distribution pipe (generally 4- to 6-inch-diameter aluminum pipe, 20 feet in length), or by a combination of both. Sprinkler systems are used in a few places, chiefly where pastures are being irrigated.

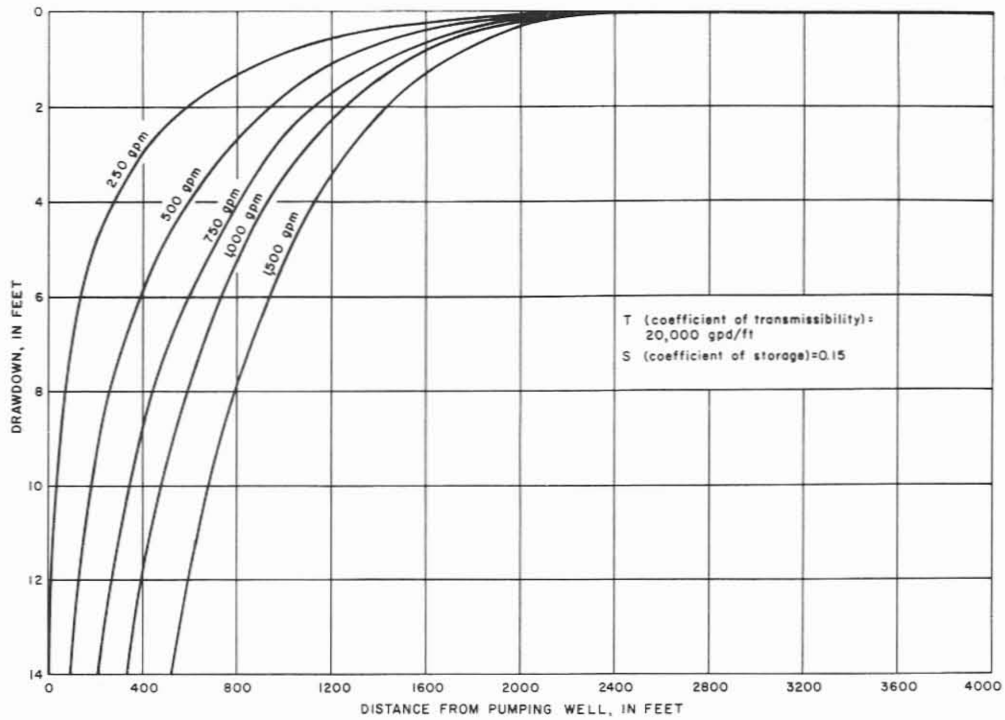
During the pumping seasons of 1963-64, 408 measurements were made of the yields of irrigation wells pumping from the alluvium of the flood plain and 351 drawdown measurements were also made. For comparison purposes, some of the wells were measured during both the 1963 and the 1964 pumping seasons. The yield and drawdown measurements, along with the other records of the wells, are given in Table 9.

The ranges of yield and specific capacity measured are shown in Table 5. Slightly more than 50 percent of the yield measurements were in the 250 to 500 gpm range, and almost 56 percent of the specific capacities were less than 25 gpm per foot of drawdown. On the basis of measurements made in irrigation wells on 12 farms in Burleson, Brazos, and Robertson Counties during the 1956-57 pumping seasons, Hughes and Magee (1962) have shown that the yields of the wells ranged from 112 to 1,380 gpm. The yields of 12 percent of these wells were below 250 gpm, and 33 percent were in the 250 to 500 gpm range; 35 percent, in the 500 to 750 gpm range; 16 percent, in the 750 to 1,000 gpm range; and 4 percent, in the over 1,000 gpm range.

Where irrigation wells are closely spaced, pumping lifts may be increased by interference between wells; and the yield of wells may also be reduced. The theoretical extent of the cone of depression of a well that has been pumping for 30 days at rates of 250, 500, 750, 1,000, and 1,500 gpm is shown in Figure 14. In the preparation of the graphs, three assumptions have been made: that the transmissibility is either 20,000 or 40,000 gpd per foot; that the storage coefficient (specific yield) is 15 percent; and that all the water is being withdrawn from storage. If the transmissibility is 20,000 gpd per foot, then for a well pumping 500 gpm for 30 days, the drawdown would be about 6 feet at a distance of 400 feet from the pumped well, and 2 feet at a distance of 1,000 feet. However, if the transmissibility is 40,000 gpd per foot, the drawdown would be almost 4 feet at a distance of 400 feet from the pumped well.

Table 5.--Specific capacity and yield of irrigation wells in the flood-plain alluvium of the Brazos River between Whitney Dam and Richmond, 1963-64.

Yield			Specific capacity		
Range (gpm)	Number of measure-ments	Proportion in range (percent)	Range (gpm per foot of drawdown)	Number of measure-ments	Proportion in range (percent)
Less than 250	40	9.8	Less than 25	196	55.8
250 to 500	206	50.5	25 to 50	116	33.0
500 to 750	117	28.7	50 to 75	23	6.6
750 to 1,000	26	6.4	75 to 100	10	2.8
1,000 +	19	4.7	100 +	6	1.7
Total	408	100	--	351	100



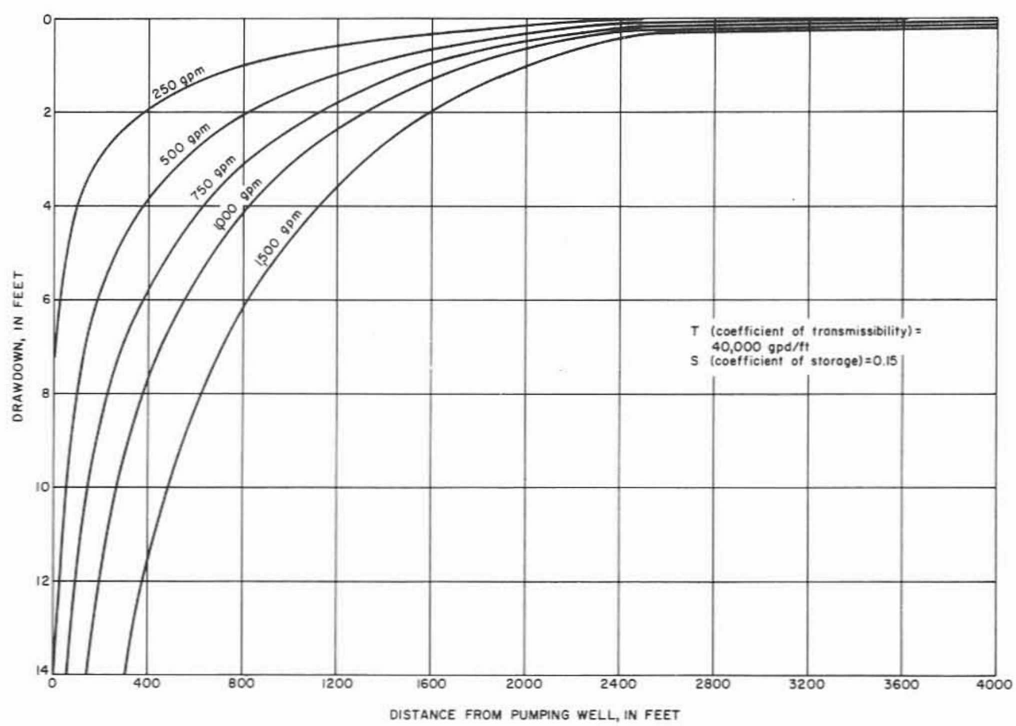


Figure 14

Theoretical Drawdown Caused by a Well Pumping Continuously for 30 Days

U. S. Geological Survey in cooperation with the Texas Water Development Board

USE OF GROUND WATER FOR IRRIGATION

Approximately 98 percent of the ground water pumped from the alluvium in the report area is used for irrigation principally of cotton, but also of grain sorghum, corn, alfalfa, and pastureland. Only a small amount is used for industrial purposes, principally in the processing of sand and gravel. No ground water is pumped from the alluvium for municipal use, although a small quantity is pumped for domestic and livestock needs. Most of the domestic needs are supplied by wells tapping the deeper aquifers.

Irrigation with water from the alluvium began in 1948 in Robertson County (Hughes and Magee, 1962, p. 1). The number of irrigation wells drilled and put in operation increased at a rapid rate during the drought of 1950-57. By August 1961, about 950 irrigation wells had been drilled between Waco and Hempstead (Cronin and others, 1963, p. 116), and by 1964, at least 1,112 irrigation wells tapping the alluvium were available for use. The locations of these wells are shown on Figures 20, 21, and 22; however, only those wells for which data are available are numbered and included in Table 9. Of the 1,112 irrigation wells located, probably less than 10 percent were unused in 1964.

Table 6 shows that about 43,000 acre-feet of ground water was pumped from the alluvium of the flood plain for irrigation during 1963 and about 49,000 acre-feet in 1964. The estimated acreage irrigated with ground water in 1964 was about 72,500 acres.

In the principal irrigated area in Falls, Robertson, Brazos, and Burleson Counties, the figures shown in the table were based on biweekly checks of the number of wells pumping, the average measured discharge of some of the wells, and the estimated number of hours the pumps were operated. In areas where few irrigation wells were in operation, the pumpage was based on field estimates of acres irrigated and on the duty of water. The estimate of acres irrigated with ground water in 1964 (Table 6) was based on information furnished to the Texas Water Development Board by the Soil Conservation Service, U.S. Department of Agriculture.

In 1958, about 47,000 acre-feet of ground water was pumped on an estimated 58,000 acres between Whitney Dam and Hempstead (Cronin and others, 1963, p. 116-117). The same source noted that only about 20,000 acre-feet of water was pumped for irrigation in each of the years 1959 and 1960 when precipitation was near or above normal.

Ground water for irrigation also is obtained from at least 20 wells that tap the formations underlying the alluvium. In Robertson County, five wells reportedly are screened opposite the Carrizo Sand or Wilcox Group, or both. The wells are fairly shallow, the maximum depth being about 320 feet. South of Hempstead, about 15 wells on the flood plain obtain water for irrigation from depths ranging from 160 to 500 feet or more. The formations screened in these wells could not be determined, but probably include the Willis Sand, Lissie Formation, and the Beaumont Clay. In Washington County, the depths of several wells indicate that some water is obtained from the formations underlying the alluvium. Some of these wells pump water probably from both the alluvium and the underlying formations. Although the quantity of water pumped from the deeper formations was not estimated, it undoubtedly is small compared to the amount of water pumped from the alluvium.

Table 6.--Summary of pumpage from the flood-plain alluvium for irrigation, 1963-64, and acres irrigated with ground water in 1964 on the flood plain of the Brazos River between Whitney Dam and Richmond

County	1963	1964	
	Pumpage for irrigation[a] (acre-feet)	Acres irrigated[b]	Pumpage for irrigation[a] (acre-feet)
Austin	300	344	300
Bosque	0	0	0
Brazos	7,000	15,100	9,900
Burleson	9,300	15,911	10,100
Falls	4,200	4,200	4,700
Fort Bend	800	1,000[c]	800
Grimes	150	100	150
Hill	0	0	0
McLennan	150	217	150
Milam	200	250	300
Robertson	20,600	34,290	22,000
Waller	150	517	150
Washington	300	644	300
Total	43,150	72,573	48,850

[a] Estimated from bi-weekly check of number of wells pumping, estimated hours pumped, and measured well discharges.
[b] From estimates furnished to the Texas Water Development Board by Soil Conservation Service, U.S. Department of Agriculture.
[c] Field estimate of 1,000 acres, or less.

USE OF SURFACE WATER FOR IRRIGATION

An estimated 24,000 acre-feet of surface water was pumped from the Brazos River within the report area to irrigate an estimated 23,000 acres of crops and pastureland on the flood plain in 1964 according to data furnished the Texas Water Development Board by the Soil Conservation Service, U.S. Department of Agriculture. Most of the surface water used for irrigation on the flood plain is applied to land which is within approximately 1 mile of the river.

QUALITY OF WATER

The discussion of the chemical quality of the water is based on the analyses of 173 samples collected during the investigation from wells pumping from the flood-plain alluvium, 29 samples from wells tapping bedrock aquifers, 5 samples from wells producing water from the terrace alluvium, and 80 samples from various aquifers collected during previous investigations. The analyses of the present samples and some of the previously-collected samples were made in the laboratory of the U.S. Geological Survey, Austin, Texas. The same organization undertook the collection and analysis of surface-water samples from the Brazos River. Those samples collected and analyzed by agencies other than the U.S. Geological Survey are identified in Table 12. The locations of the wells from which samples of water were collected are indicated by lines over the well numbers on Figures 20, 21, and 22. The locations of some of the wells and the surface-water sampling points are also shown on Figures 15, 16, and 17.

Tables 7 and 12 contain the results of the chemical analyses of the ground-water samples and of the surface-water samples from the Brazos River and some of its tributaries.

The types of water represented by the chemical analyses are shown graphically (Figures 15, 16, and 17) by means of patterns modified from a system suggested by Stiff (1951, p. 15). In this modified system, three parallel horizontal axes and one vertical axis have been used, with the latter defining the zero points. Concentrations in epm (equivalents per million) for three cations can be plotted--one along each axis to the left of the zero point--and three anions, in a similar manner, on the right. When an analysis is plotted, two series of points result--one on each axis to the left, and one on each axis to the right of the center zero. Connecting together the points representing anions and the points representing cations creates a closed figure or "pattern" whose shape is more or less characteristic of a given type of water.

The analyses of the ground-water samples from the flood-plain alluvium (Table 12 and Figures 15, 16, and 17) show that the chemical composition of the water varies from place to place, even within short distances. In numerous samples the principal cation and anion are calcium and bicarbonate, respectively. On the other hand, many variations from this type of water occur, probably because of such environmental factors as mineralogical differences in the sediments that comprise the flood plain and the underlying bedrock; variations in the rate of ground-water movement; and possibly differences in the rate of evapotranspiration.

The analyses of some water samples collected from wells in the vicinity of the Falls-Robertson County line show high sodium, chloride, and dissolved-solids

Table 7.--Chemical analyses of surface water in the lower Brazos River basin

(Analyses are in parts per million except specific conductance, pH, percent sodium, and sodium-adsorption ratio.)

Location	Measured discharge (cfs)	Date of collection	Silica (SiO_2)	Calcium (Ca)	Magnesium (Mg)	Sodium and potassium (Na + K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Sodium-adsorption ratio (SAR)	Dissolved solids (calculated sum)	Total hardness as $CaCO_3$	Percent sodium	Specific conductance (micromhos at 25°C)	pH
Brazos River at Whitney Dam, near Whitney[a]	867 [b]	Oct. 1962-Sept. 1963	7.9	95	18	197	129	189	309	0.3	0.8	4.9	896	310	--	1,520	7.1
Little River at Cameron[a]	475 [b]	Oct. 1962-Sept. 1963	9.9	57	11	35	181	44	46	--	4.1	1.1	301	187	--	516	7.3
Brazos River at State Hwy. 21, near Bryan[a]	1,896 [b]	Oct. 1962-Sept. 1963	7.9	84	16	143	153	146	217	--	1.3	3.8	703	274	--	1,200	7.1
Brazos River at Richmond[a]	2,759 [b]	Oct. 1962-Sept. 1963	11	66	12	97	140	100	145	--	1.3	2.8	513	215	--	871	7.2
Bosque River near Waco	15.4	May 22, 1963	4.8	53	5.8	24	162	39	23	.4	.05	.8	230	156	25	391	6.8
Little Brazos River at State Hwy. 21, near Bryan	3.94	Oct. 24, 1962	13	43	8.7	68	209	40	55	.4	.0	2.5	331	144	51	573	7.5
Do.	30.4	Jan. 2, 1963	15	51	11	60	152	76	70	.3	.0	2.0	358	172	43	596	6.5
Do.	24.2	Mar. 13, 1963	11	56	13	68	146	94	86	.3	.0	2.1	400	193	43	681	6.6
Do.	90.6	May 22, 1963	15	59	13	84	200	89	88	.4	1.5	2.6	448	200	48	734	6.9
Do.	6.66	July 25, 1963	13	84	23	234	318	178	258	.3	1.8	5.8	948	304	63	1,560	6.8
Do.	.15[c]	Oct. 8, 1963	9.8	45	17	59	176	23	100	.4	1.0	1.9	342	182	41	618	7.2
Do.	3.80	Dec. 18, 1963	7.3	51	10	134	350	62	76	.5	.2	4.5	513	168	63	880	7.1
Do.	9.06	Feb. 24, 1964	6.1	48	10	87	188	79	76	.3	.0	3.0	402	161	54	658	8.4
Do.	28.2	Mar. 24, 1964	12	41	11	38	98	71	52	.3	1.5	1.4	275	148	36	488	6.8
Do.	11.1	June 19, 1964	11	60	14	127	280	93	106	.4	8.1	3.8	558	207	57	932	7.0
Do.	4.14	Aug. 26, 1964	12	53	28	260	430	153	212	.3	.0	7.2	929	247	70	1,550	7.4

a/ Discharge-weighted-average analysis for the 1963 water year.
b/ Mean discharge for 1963 water year.
c/ Field estimate.

content. The reasons for this are not definitely known; however, they may be related to the close association of the flood-plain alluvium with the underlying rocks of the Midway Group (Figures 23 and 24) which contain highly mineralized water.

Several of the wells listed in Table 12 were sampled more than once. Well WK-59-12-102, for example, was sampled in 1961, 1963, and 1964. The analyses indicate that the dissolved-solids content decreased from 1,840 to 1,250 ppm (parts per million) during the interval between samplings. Furthermore, these analyses indicate a decrease in the quantity of some constituents, such as calcium, sodium, sulfate, and chloride, and an increase in the bicarbonate content. The total hardness of the water decreased from 1,090 to 751. However, in general, a comparison of analyses of water samples collected previously and recently does not indicate any major change in the chemical composition of the ground water in the flood-plain alluvium.

Oil is produced from several oil fields wholly or partly in the flood plain. The concentrations of dissolved solids in samples of water from two wells about 1 mile apart in or adjacent to a small oil field in Falls County were 1,940 and 575 ppm, respectively (Table 12). The sulfate, chloride, and sodium content of water from well JR-40-48-301 were 408, 575, and 295 ppm, respectively--and from well JR-39-41-101, they were 43, 16, and 83 ppm. The analyses suggest possible contamination from the oil field, but direct evidence of this is not available.

The Calvert oil field is on the flood plain about 3 miles west of the town of Calvert. Wells WK-59-02-305, WK-59-02-306, WK-59-02-601, and WK-59-03-101 are in or adjacent to the oil field. The concentration of dissolved solids in samples of water from these wells ranged from 911 to 1,360 ppm (Table 12). The sodium, sulfate, and chloride content in samples of water from these wells, while more than in some water samples from the alluvium, were not as high as in some of those from wells in non-oil-producing areas. This comparison suggests that contamination of the ground water in the flood-plain alluvium by oil-field brines is not a problem in the Calvert oil field. According to reports by operators, salt water produced with the oil in this field is used in the secondary recovery of oil.

In the downstream part of the report area, oil fields in Austin and Waller Counties occupy a part of the flood plain. Because wells tapping the flood-plain alluvium in or adjacent to these well fields were not in operation, samples of water for chemical analysis were not collected.

Definition of Terms

In the following parts of this report, many technical terms concerning quality of water are used which may not be familiar to all readers. These terms are defined as follows:

Alkalinity is caused primarily by the presence of carbonates and bicarbonates, and less frequently by hydroxides, borates, silicates, and phosphates. These components are determined collectively by titration with a standardized solution of a strong acid and are reported as carbonate and bicarbonate.

Equivalents per million (epm) is a unit for expressing the concentration of chemical constituents in terms of the interreacting values of the electrically charged particles, or ions, in solution. One equivalent per million of a positively charged ion will react with one equivalent per million of a negatively charged ion. Parts per million are converted to equivalents per million by multiplying by the reciprocal of the combining weight of the ion, as follows:

Cation	Factor	Anion	Factor
Calcium (Ca^{++})	0.0499	Carbonate (CO_3^{--})	0.0333
Magnesium (Mg^{++})	.0823	Bicarbonate (HCO_3^-)	.0164
Sodium (Na^+)	.0435	Sulfate (SO_4^{--})	.0208
Potassium (K^+)	.0256	Chloride (Cl^-)	.0282
		Fluoride (F^-)	.0526
		Nitrate (NO_3^-)	.0161

Parts per million (ppm) is a unit for expressing the concentration of chemical constituents by weight, usually as grams of constituents per million grams of solution.

Percent sodium is a ratio, expressed in percentage, of sodium to the sum of the positively charged ions (calcium, magnesium, sodium, and potassium)--all ions in equivalents per million.

Residual sodium carbonate (Eaton, 1950) is the amount of carbonate plus bicarbonate, expressed in equivalents per million, that would remain in solution if all the calcium and magnesium were precipitated as the carbonate. Residual sodium carbonate =

$(CO_3^{--} + HCO_3^-) - (Ca^{++} + Mg^{++})$.

Salinity is the dissolved-mineral content or total concentration of solids in solution.

Sodium-adsorption ratio (SAR) is related to the adsorption of sodium by the soil and is an index of the sodium, or alkali, hazard of the water. Concentrations of constituents are in equivalents per million.

$$SAR = \frac{Na^+}{\sqrt{\frac{Ca^{++} + Mg^{++}}{2}}},$$

Specific conductance is a measure of the ability of a water to conduct an electrical current, and is expressed in micromhos at 25°C. Being related to the number and specific chemical types of ions in solution, the specific conductance can be used for approximating the salinity of the water. The following general relations are applicable:

$$\text{Specific conductance} \times 0.65 = \text{ppm dissolved solids.}$$

$$\frac{\text{Specific conductance}}{100} = \frac{\text{total epm}}{2}.$$

Weighted average represents approximately the chemical character of the water if all the water passing a point in the stream during the year were impounded and mixed in a reservoir. Weighted average is calculated by dividing the sum of the products of water discharge and concentration of individual analyses by the sum of the water discharged for the period that the analyses represent.

Comparison of Water in Flood-Plain Alluvium with Surface Water

The discharge-weighted-average chemical analyses for the Brazos River at Whitney Dam, near Bryan, and at Richmond and for the Little River at Cameron, during the water year 1963 (October 1962 to September 1963) given in Table 7, are based on samples collected daily at sampling stations operated by the U.S. Geological Survey in cooperation with the Texas Water Development Board and the Brazos River Authority. The sampling station on Little River is about 20 miles west of the report area. Also in Table 7 are the analyses of miscellaneous samples of water collected from the Bosque and the Little Brazos Rivers, both tributary streams of the Brazos River. The weighted-average analyses and analyses of some of the miscellaneous samples are shown on Figures 15, 16, and 17, as are the locations of the sampling points.

Both the weighted-average analyses of the Little River at Cameron and the analysis of a sample of water collected from the Bosque River near Waco on May 22, 1963 indicate that the principal cation and anion in the water of these streams are calcium and bicarbonate. As indicated by the weighted average and the analysis, the dissolved-solids concentrations were 301 ppm for water in the Little River at Cameron and 230 ppm for water in the Bosque River at the sampling points. These streams originate outside the report area; they have their headwaters in, and flow across, areas underlain chiefly by limestone and other rocks of Cretaceous age. The only exception is in the lower reach of the Little River, where the stream flows over rocks of Tertiary age (Figure 24). These streams are considered to be effluent streams where they cross the alluvium of the flood plain. Therefore, the chemical quality of the water in the streams would not affect that of the ground water in the flood-plain alluvium.

Samples of water from the main stem of the Brazos River are collected daily at three scheduled sampling stations which are immediately below Whitney Dam, at State Highway 21 near Bryan, and at Richmond (Figures 20, 21, and 22). The weighted averages of the constituents in these samples during the water year 1963 (Table 7 and Figures 15, 16, and 17) indicate that the water at the station below Whitney Dam is of a sodium-chloride type and at State Highway 21 near Bryan and at Richmond the water is of a mixed type. The dissolved-solids concentration was 896 ppm below Whitney Dam, 703 ppm at State Highway 21 near Bryan, and 513 ppm at Richmond. The sodium and chloride concentrations decreased about 50 percent between the samplings taken at the station below Whitney Dam and those at the station at Richmond.

The quality of the ground water in the alluvium adjacent to the Brazos River may be affected by water in the river if, when the stream is at high stage, surface water moves into the alluvium as bank storage or possibly as recharge, either natural or induced by pumping. Similarly, the quality of the ground water in the alluvium could be affected by floods which inundate the flood plain and which would probably furnish some recharge to the flood-plain alluvium. The water-table contours (Figures 6 and 7) indicate, however, that the ground water in the flood-plain alluvium is moving toward the Brazos River. This fact suggests that the quality of water in the flood-plain alluvium is not, in general, affected by the quality of the water in the Brazos River.

The quantity of water discharged by the Little Brazos River is normally small as indicated by the miscellaneous discharge measurements made at State Highway 21 in Brazos County (Table 7). Because of its position near the base of the valley wall, the stream receives surface-water runoff from the adjacent bedrock, the older alluvium terraces, and the alluvium of the flood plain. A part of the stream discharge is also due to ground-water discharge in the lower reach of the stream as indicated by the contours on the water table shown on Figure 6. In the upper reaches the stream is frequently dry.

The dissolved-solids concentration in the samples of water collected from the Little Brazos River at State Highway 21 in Brazos County ranged from 331 to 948 ppm. The highest concentrations of dissolved solids were in samples collected July 25, 1963 and August 26, 1964, when the concentrations were 948 and 929 ppm, respectively. The reason for the high dissolved-solids content is not known definitely; however, some of it may have come from surface runoff of ground water used for irrigation.

The discharge of the Little Brazos River at State Highway 21 was 3.80 cfs when a sample of water was collected on December 18, 1963. The small amount of discharge suggests that the flow consisted of ground-water discharge. The results of the analysis of this sample (Table 7 and Figure 16) are similar to those of the analyses of water samples collected from well BJ-59-20-603 near the Little Brazos River and upstream from the sampling point (Figure 16 and Table 12).

Comparison of Water in Flood-Plain Alluvium with Water in Bedrock

The scope of this investigation did not include a detailed discussion of the occurrence of ground water in the bedrock adjoining and underlying the flood-plain alluvium. Further information on the subject is available in such reports as those by Deussen (1914 and 1924) and by Cronin and others (1963).

In Table 12 appear the results of the analyses of water samples collected during the current and former investigations from some wells tapping bedrock. Some of the analyses also are illustrated graphically on Figures 15, 16, and 17.

Ground water occurs under water-table conditions in the outcrop areas of the bedrock; and downdip, as the depth increases, it is under artesian conditions. Most of the foregoing samples were collected from the artesian parts of the aquifers.

The analyses show that in contrast to the water in the flood-plain alluvium the principal constituents are sodium and bicarbonate. In general, the analyses also indicate that the dissolved-solids content of the water in the bedrock is lower than that in the ground water from the flood-plain alluvium.

Suitability of Water from the Flood-Plain Alluvium

Domestic and Livestock Purposes

Water used for domestic purposes should be clear, pleasant to taste, of reasonable temperature, and free from pathogenic organisms. This report is concerned only with the chemical constituents of the ground water. To insure against bacterial contamination, users should avail themselves of the services of their appropriate public health agencies.

The only nationwide standards pertaining to potable water are those prescribed by the U.S. Public Health Service (1962). These standards, which apply specifically to water used for culinary and drinking purposes on common carriers engaged in interstate commerce, have also been endorsed by the American Water Works Association as minimum standards for all public water supplies (U.S. Public Health Service, 1962, p. 4). The standards pertaining to chemical constituents are, in part, as follows:

Constituent	Suggested maximum concentration (ppm)
Chloride	250
Fluoride	0.8 to 1.0[a]
Iron	0.3
Manganese	0.05
Nitrate	45
Sulfate	250
Total dissolved solids	500

a/ Based on annual average of maximum daily air temperatures of 80.0, 79.6, and 78.1°F at Sugarland, College Station, and Waco, respectively.

Excessive concentrations of certain chemical constituents may be undesirable for various reasons. Iron and manganese in high concentrations are objectionable because they not only impart a disagreeable taste to the water but also stain fabrics, cooking utensils, and plumbing fixtures. Water containing large quantities of magnesium in combination with sulfate has cathartic properties. Chloride in excess of 250 ppm imparts a characteristically salty taste to the water.

The results of the analyses of water samples from the flood-plain alluvium (Table 12) indicate that almost 80 percent of the analyses exceeded the limit for dissolved solids in the preceding table of standards, and about 60 percent of the samples exceeded the limit for iron. The concentrations of chloride and sulfate exceeded the limits in about 20 and 15 percent of the analyses, respectively.

Hardness of water is caused principally by calcium and magnesium and generally is expressed as parts per million of calcium carbonate. Excessive hardness adversely affects the suitability of water for domestic and other uses. Hard water is objectionable in washing processes, because in combination with soap it produces an insoluble curd and further requires large quantities of soap to produce a lather. The use of hard water in boilers, water heaters, radiators, and pipes is objectionable because of formation of scale. Specific limits cannot be set for hardness, but the following numerical ranges and adjective ratings are generally used to classify hardness.

Hardness range (ppm)	Classification
0 to 60	Soft
61 to 120	Moderately hard
121 to 180	Hard
More than 180	Very hard

According to this classification, practically all of the water in the flood-plain alluvium is hard or very hard.

The U.S. Public Health Service limit on fluoride given in the preceding table of standards is based on the annual average of maximum daily air temperatures. The optimum fluoride level for a given community depends on climatic conditions, because the amount of water (and consequently the amount of fluoride) ingested by children is influenced primarily by air temperatures. Excessive concentration of fluoride in water may cause teeth to become mottled. Optimum fluoride concentrations may reduce the incidence of tooth decay in children with no ill effects and caries rates may be 60 to 65 percent below the rates in communities using water supplies with little or no fluoride (Dean, Arnold, and Elvove, 1942, p. 1155-1179; and Dean and others, 1941, p. 761-792).

The optimum level of fluoride content in the report area, according to the Public Health Service standards, is 0.7 to 0.8 ppm. The fluoride content of the water in the flood-plain alluvium ranged from 0.1 to 1.2 ppm; however, the content in only one of the samples was greater than 0.8 ppm, and the great majority was below 0.7 ppm.

The concentration of nitrate in water is important because nitrate-rich water may cause illness when used for infant feeding. Some nitrate can be dissolved from nitrate-bearing rocks; but, more commonly, large concentrations of nitrate are derived from surficial sources. Dug wells or other shallow wells, which generally are not well sealed, could be susceptible to contamination from surficial sources. Nitrate is considered the final oxidation product of nitrogeneous matter, and its presence in water in concentrations of more than several parts per million may indicate previous contamination by sewage or other organic matter (Lohr and Love, 1954, p. 10). In areas where the nitrate content of the water is in excess of 45 ppm, the public should be warned of the potential dangers of using the water for infant feeding. Concentrations of nitrate in excess of 45 ppm in water used for infant feeding have been related to the incidence of infant cyanosis (methemoglobinemia or "blue baby" disease), a reduction of the oxygen content in the blood constituting a form of asphyxia (Maxcy, 1950, p. 271).

The concentration of nitrate was about 45 ppm in seven of the samples of water collected from wells pumping water from the flood-plain alluvium. Five of the samples were from wells in McLennan County. The nitrate content in some other samples was rather high but did not exceed 45 ppm.

The relation of the quality of water to the health of livestock is not well defined. Quality-of-water limits for livestock are variable, and the limit of tolerance depends on many factors, such as the kind of animal, age, physiological condition, and season of the year. Heller (1933, p. 22) has suggested that the total amount of soluble salts in the drinking water, rather than the kind of salt, is the important factor. McKee and Wolf (1963, p. 113) have indicated that some investigators have found that concentrations as high as 15,000 ppm are safe for limited periods but dangerous for continuous use. All of the water in the flood-plain alluvium in the report area is suitable for livestock use.

Irrigation Purposes

The suitability of water for irrigation depends primarily on its chemical quality and, in lesser degrees, on other factors such as soil texture and composition; types of crops; irrigation practices; climate; and, to some extent, economic considerations. The chemical analyses of water identify the more important elements and compounds present and their concentrations. Different approaches have been used in the classification of water for irrigation. However, difficulty would arise in the use of any classification which attempts to adequately relate water quality to all of the variables that must be considered in the evaluation of water for irrigation.

In this report, the indices used to show the suitability of water for irrigation are SAR (sodium-adsorption ratio), specific conductance, RSC (residual sodium carbonate), and boron content.

The U.S. Salinity Laboratory Staff (1954, p. 79-81) has developed a rating diagram (Figure 18) for classifying irrigation waters in terms of salinity and sodium (alkali) hazards. The SAR is used to indicate the sodium or alkali hazard. A high percentage of sodium commonly causes clay particles in soil to disperse and thereby reduces the permeability of the soil. The specific conductance is used to indicate the salinity hazard.

In classification of irrigation waters, the assumption is that the water will be used under average conditions with respect to soil texture, infiltration rate, drainage, quantity of water used, climate, and salt tolerance of

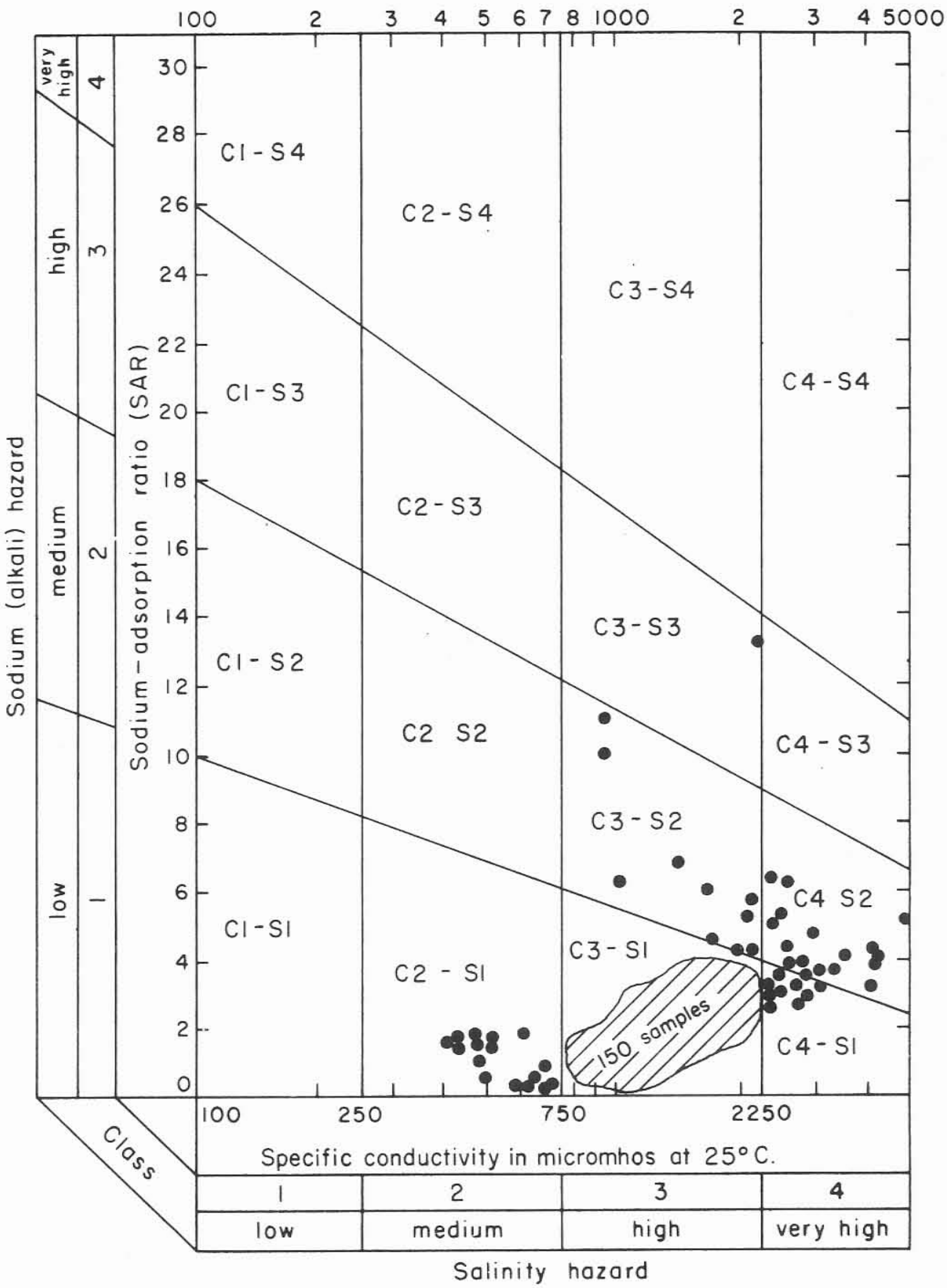


Figure 18

Classification of Water Used for Irrigation

(Diagram after U. S. Salinity Laboratory Staff, 1954, p. 80)

U. S. Geological Survey in cooperation with the Texas Water Development Board

crops. Large deviations from the average for one or more of these variables may make unsafe the use of water which, under average conditions, would be good--or may make safe the use of water which, also under average conditions, would be of doubtful quality. This relationship to average conditions must be kept in mind in connection with any general method for the classification of irrigation waters. Wilcox (1955, p. 15) stated that the system of classification used by the U.S. Salinity Laboratory Staff "...is not directly applicable to supplemental waters used in areas of relatively high rainfall." Thus, in part or possibly in all of the report area, the system may not be directly applicable. The U.S. Salinity Laboratory Staff (1954, p. 81) has given the following interpretation of the diagram for the classification of irrigation waters:

"Salinity Hazard

"Low-salinity water (C1) can be used for irrigation with most crops on most soils with little likelihood that soil salinity will develop. Some leaching is required, but this occurs under normal irrigation practices except in soils of extremely low permeability.

"Medium-salinity water (C2) can be used if a moderate amount of leaching occurs. Plants with moderate salt tolerance can be grown in most cases without special practices for salinity control.

"High-salinity water (C3) cannot be used on soils with restricted drainage. Even with adequate drainage, special management for salinity control may be required and plants with good salt tolerance should be selected.

"Very high salinity water (C4) is not suitable for irrigation under ordinary conditions, but may be used occasionally under very special circumstances. The soils must be permeable, drainage must be adequate, irrigation water must be applied in excess to provide considerable leaching, and very salt-tolerant crops should be selected.

"Sodium Hazard

"The classification of irrigation waters with respect to SAR is based primarily on the effect of exchangeable sodium on the physical condition of the soil. Sodium-sensitive plants may, however, suffer injury as a result of sodium accumulation in plant tissues when exchangeable-sodium values are lower than those effective in causing deterioration of the physical condition of the soil.

"Low-sodium water (S1) can be used for irrigation on almost all soils with little danger of the development of harmful levels of exchangeable sodium. However, sodium-sensitive crops such as stone-fruit trees and avocados may accumulate injurious concentrations of sodium.

"Medium-sodium water (S2) will present an appreciable sodium hazard in fine-textured soils having high cation-exchange capacity, especially under low-leaching conditions, unless gypsum is present in the soil. This water may be used on coarse-textured or organic soils with good permeability.

"High-sodium water (S3) may produce harmful levels of exchangeable sodium in most soils and will require special soil management--good drainage, high leaching, and organic matter additions. Gypsiferous soils may not develop harmful levels of exchangeable sodium from such waters. Chemical amendments may be required for replacement of exchangeable sodium, except that amendments may not be feasible with waters of very high salinity.

"Very high sodium water (S4) is generally unsatisfactory for irrigation purposes except at low and perhaps medium salinity, where the solution of calcium from the soil or use of gypsum or other amendments may make the use of these waters feasible."

The values for specific conductance and SAR (Table 12) for 204 water samples obtained from wells tapping the flood-plain alluvium in the report area are shown on Figure 18. Approximately 75 percent of the values fall in the subdivision of the diagram labeled C3-S1, indicating a low sodium hazard and a high salinity hazard. Most of the values that plot in the medium or high sodium hazard and high or very high salinity hazard (subdivisions C3-S2, C4-S2, and C3-S3) are from wells in the vicinity either of the Falls-Robertson County line or in the area of the cone of depression in the water table in Brazos County. One value from a well in the latter vicinity exceeded the SAR scale values shown on the diagram.

According to the U.S. Salinity Laboratory Staff's (1954, p. 71) discussion on the quality of irrigation water, "...Waters in the range of 750 to 2,250 micromhos per centimeter are widely used and satisfactory crop growth is obtained under good management and favorable drainage conditions, but saline conditions will develop if leaching and drainage are inadequate."

Bicarbonate concentrations greatly in excess of calcium and magnesium concentrations in irrigation water may result in residual sodium carbonate in the soil, thereby causing the soil to obtain a high pH and to become gray or black due to the solution of organic matter. Such a soil condition is known as black alkali. Wilcox (1955, p. 11) states that, according to laboratory and field studies, water containing more than 2.5 epm RSC is not suitable for irrigation. Water containing 1.25 to 2.5 epm is marginal, while water containing less than 1.25 epm RSC probably is safe. However, good irrigation practices and the use of proper amendments might make possible the successful use of marginal water for irrigation. Furthermore, the degree of leaching will modify the permissible limit to some extent (Wilcox, Blair, and Bower, 1954, p. 265). Eighteen of the samples of water collected from irrigation wells pumping from the flood-plain alluvium had RSC values greater than 2.5 epm, 15 of the samples had between 1.25 and 2.5, and 139 had less than 1.25 epm RSC.

Boron, one of the most critical elements in irrigation water, is essential for proper plant growth in small amounts but may be toxic to some plants in concentrations only slightly above the needed amounts. Because of this sensitivity, the tolerance to boron of the crop to which water is applied is considered in evaluating the suitability of water for irrigation. Scofield (1936, p. 286) indicated that boron concentrations of as much as 1 ppm are usually permissible for irrigating boron-sensitive crops, and concentrations of as much as 3 ppm are permissible for the more boron-tolerant crops.

The following table shows a classification of water according to boron content.

Classes of water		Sensitive crops (ppm)	Semitolerant crops (ppm)	Tolerant crops (ppm)
Rating	Grade			
1	Excellent	Less than 0.33	Less than 0.67	Less than 1.00
2	Good	0.33 to 0.67	0.67 to 1.33	1.00 to 2.00
3	Permissible	.67 to 1.00	1.33 to 2.00	2.00 to 3.00
4	Doubtful	1.00 to 1.25	2.00 to 2.50	3.00 to 3.75
5	Unsuitable	More than 1.25	More than 2.50	More than 3.75

The results of the analyses given in Table 12 show that only five of 184 samples of water from wells in the flood-plain alluvium contained boron in excess of 1.0 ppm. The boron concentration in these samples ranged from 1.1 to 1.8 ppm. Two of the samples were from wells in Falls County, two from Robertson County, and one from Brazos County. The analyses indicate that, in general, boron is not a problem in water from the flood-plain alluvium.

AVAILABILITY OF GROUND WATER IN THE FLOOD-PLAIN ALLUVIUM

Approximately 2,760,000 acre-feet of ground water was stored in the alluvium of the flood plain of the report area in the spring of 1963 (Table 8). The estimate is based on an assumed coefficient of storage of 15 percent and the saturated thickness of the alluvium as indicated on Figure 19 or by the saturated thickness in individual wells or test holes in areas where data were insufficient for further interpretation.

In some sections of the report area, as indicated by the locations of the wells (Figures 20, 21, and 22), the ground water in the alluvium is little used. Although the total amount of ground water in storage in the alluvium is important, of equal or greater importance is the amount in storage in sections of the report area where large quantities of ground water are pumped for irrigation.

Table 8.--Water in storage in the flood-plain alluvium of the Brazos River between Whitney Dam and Richmond, 1963

County	Volume of water in storage (acre-feet)
Austin	192,000
Bosque	3,000
Brazos	199,000
Burleson	344,000
Falls	266,000
Fort Bend	808,000
Grimes	85,000
Hill	3,000
McLennan	112,000
Milam	13,000
Robertson	307,000
Waller	307,000
Washington	118,000
Total	2,757,000

In the spring of 1963 about 40 percent of the ground water available was in the principal irrigated section in Falls, Robertson, Brazos, and Burleson Counties. Wells in that section pumped about 95 percent of the total withdrawn from the alluvium in the report area during each of the years 1963 and 1964. Approximately 65 percent of the water estimated to have been pumped in Brazos County in 1964 was from wells north of State Highway 21, an area which contained only about one-fourth of the estimated amount of ground water available in the county in the spring of 1963. In Falls County, the estimated total amount of ground water available in the spring of 1963 appears to have been rather large when compared with the estimated pumpage in 1964. However, over 85 percent of the ground water estimated to have been pumped in 1964 was withdrawn from wells in the area south of Highbank. About 45 percent of the estimated amount of ground water available in Robertson County in the spring of 1963 was in the area south of U.S. Highway 79 where about 62 percent of the water was pumped in 1964.

In any discussion of availability of ground water, one of the most important elements to consider is the rate of recharge to the aquifer. At the end of the recent drought period in 1957, the water table was at a low level for the period of record. However, during the 4-year period 1957-61 (a period of above-normal precipitation), the water levels rose to levels equal to or above those occupied previous to the development of ground water for irrigation. This indicates that the aquifer in the flood-plain alluvium of the Brazos River is readily replenished by rainfall. If the period 1957-61 can be considered as representative, the average annual rate of recharge in the report area is about 155,000 acre-feet per year. The recharge in the area between the Hill-McLennan County line and Hempstead (which includes the principal irrigated area) during the 1957-61 period was estimated to be about 100,000 acre-feet per year (Cronin and others, 1963, p. 119).

The foregoing estimates of recharge indicate that intermittent lowering of the water table by large withdrawals of water for short periods of time might be offset if followed by periods of normal or above normal rainfall when recharge would increase and pumpage would decrease. However, continuous withdrawals of ground water in excess of recharge would result in a lowering of the water table accompanied by a decrease in the yield of the wells due to the decrease in thickness of the water-bearing materials.

REFERENCES CITED

Bernard, H. A., LeBlanc, R. J., and Major, C. R., 1962, Recent and Pleistocene geology of Southeast Texas, in Geology of the Gulf Coast and Central Texas, guidebook of excursions: Houston Geol. Soc., p. 175-224.

Burkett, J. M., Jr., 1959, Geology of the city of Waco and its environs: Baylor Univ. unpub. Master's thesis, 139 p.

Clark, W. I., 1937a, Records of wells, drillers' logs, water analyses, and map showing location of wells in Burleson County, Texas: Texas Board Water Engineers duplicated rept., 46 p.

______, 1937b, Records of wells, drillers' logs, water analyses, and map showing location of wells in Milam County, Texas: Texas Board Water Engineers duplicated rept., 57 p.

Cromack, G. H., 1943, Records of wells and springs, drillers' logs, water analyses, and map showing locations of wells and springs in Grimes County, Texas: Texas Board Water Engineers duplicated rept., 37 p.

Cronin, J. G., Shafer, G. H., and Rettman, P. L., 1963, Reconnaissance investigation of the ground-water resources of the Brazos River basin, Texas: Texas Water Comm. Bull. 6310, 152 p.

Darton, N. H., 1905, Preliminary list of deep borings in the United States: U.S. Geol. Survey Water-Supply Paper 149, 153 p.

Darton, N. H., Stephenson, L. W., and Gardner, Julia, compilers, 1937, Geologic map of Texas: U.S. Geol. Survey geologic map.

Davis, L. G., 1942, Records of wells and springs, drillers' logs, water analyses, and map showing locations of wells and springs in Robertson County, Texas: Texas Board Water Engineers duplicated rept., 61 p.

Dean, H. T., and others, 1941, Domestic water and dental caries: Public Health Repts., v. 56, p. 761-792.

Dean, H. T., Arnold, F. A., and Elvove, Elias, 1942, Domestic water and dental caries: Public Health Repts., v. 57, p. 1155-1179.

Deussen, A., 1914, Geology and underground waters of the southeastern part of the Texas Coastal Plain: U.S. Geol. Survey Water-Supply Paper 335, 365 p.

______, 1924, Geology of the Coastal Plain of Texas west of the Brazos River: U.S. Geol. Survey Prof. Paper 126, 138 p.

Eaton, F. M., 1950, Significance of carbonates in irrigation waters: Soil Sci., v. 69, p. 123-133.

Elledge, G. A., 1937, Records of wells, drillers' logs, and water analyses, and maps showing locations of wells in Fort Bend County, Texas: Texas Board Water Engineers duplicated rept., 91 p.

Fluellen, T. R., and Goines, W. H., 1952, Water resources of Waller County, Texas: Texas Board Water Engineers Bull. 5208, 57 p.

Follett, C. R., 1943, Records of wells and springs, drillers' logs, water analyses, and map showing locations of wells and springs in Washington County, Texas: Texas Board Water Engineers duplicated rept., 45 p.

Heller, V. G., 1933, The effect of saline and alkaline waters on domestic animals: Oklahoma Agr. and Mech. College Expt. Sta. Bull. 217, 23 p.

Hill, R. T., 1901, Geography and geology of the Black and Grand Prairies, Texas: U.S. Geol. Survey 21st Ann. Rept., 666 p.

Hughes, W. F., and Magee, A. C., 1962, An economic analysis of irrigated cotton production, Middle Brazos River Valley, 1955-58: Texas Agr. and Mech. College, MP-580, 12 p.

Keech, C. F., and Dreeszen, V. H., 1959, Geology and ground-water resources of Clay County, Nebraska: U.S. Geol. Survey Water-Supply Paper 1468, 157 p.

Livingston, Penn, and Turner, S. F., 1939, Records of wells, drillers' logs, and water analyses, and map showing location of wells in Fort Bend County, Texas: Texas Board Water Engineers duplicated rept., 11 p.

Lohr, E. W., and Love, S. K., 1954, The industrial utility of public-water supplies in the United States, 1952, pt. 2: U.S. Geol. Survey Water-Supply Paper 1300, 462 p.

McKee, J. E., and Wolf, H. S., 1963, Water quality criteria, 2nd ed.: State of California Water Quality Control Board, Pub. no. 3-A, 548 p.

Maxcy, K. F., 1950, Report on the relation of nitrate concentrations in well waters to the occurrence of methemoglobinemia: Nat'l Research Council Bull. Sanitary Eng., p. 265-271, App. D.

May, R. E., 1938, Records of wells and springs, drillers' logs, water analyses, and map showing location of wells and springs in Austin County, Texas: Texas Board Water Engineers duplicated rept., 36 p.

Renick, B. C., and Stenzel, H. B., 1931, Contributions to geology, Lower Claiborne on the Brazos River, Texas: Univ. Texas Bull. 3101, pt. e, 239 p.

Russell, W. L., 1960, Jackson Group, Catahoula and Oakville Formations and associated structures of northern Grimes County, Texas, in Guidebook for annual field trip: Gulf Coast Section of SEPM, Houston Geol. Soc., 49 p.

Scofield, C. S., 1936, The salinity of irrigation water: Smithsonian Inst. Ann. Rept., 1934-35, p. 275-287.

Singley, J. A., 1893, Preliminary report on the artesian wells of the Gulf Coastal Slope: U.S. Geol. Survey 4th Ann. Rept., 111 p.

Smith, F. E., 1956, Lower Claiborne field trip, in Guidebook Lower Claiborne field trip: South Texas Geol. Soc., 7 p.

Smith, F. E., 1962, Tertiary and uppermost Cretaceous of the Brazos River Valley, Southeastern Texas, in Geology of the Gulf Coast and Central Texas, guidebook of excursions: Houston Geol. Soc., p. 132-174.

Smith, F. E., and others, 1958, Upper and Middle Tertiary of the Brazos River Valley, Texas, in Guidebook for annual field trip: Gulf Coast Section of SEPM, Houston Geol. Soc., 26 p.

Smith, W. O., 1961, Mechanism of gravity drainage and its relation to specific yield of uniform sands: U.S. Geol. Survey Prof. Paper 402-A, 12 p.

Stiff, H. A., Jr., 1951, The interpretation of chemical water analysis by means of patterns: Jour. Petroleum Technology, p. 15.

Taylor, T. U., 1907, Underground waters of the Coastal Plain of Texas: U.S. Geol. Survey Water-Supply Paper 190, 73 p.

Theis, C. V., 1935, The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using ground-water storage: Am. Geophys. Union Trans., pt. 2, p. 519-524.

______1938, The significance and nature of the cone of depression in ground-water bodies: Econ. Geology, v. 33, p. 889-902.

Turner, S. F., 1939, Records of wells, drillers' logs, water analyses, and map showing locations of wells in Grimes County, Texas: Texas Board Water Engineers duplicated rept., 5 p.

Turner, S. F., and Livingston, Penn, 1939, Records of wells, drillers' logs, water analyses, and map showing location of wells in Waller County, Texas: Texas Board Water Engineers duplicated rept., 20 p.

U.S. Army Corps of Engineers, 1946, Report on survey of Brazos River and tributaries, Oyster Creek, and Jones Creek, Texas: U.S. 81st Congress, 2nd Session, House Document No. 535.

U.S. Public Health Service, 1962, Public Health Service drinking water standards: Public Health Service Pub. 956, 61 p.

U.S. Salinity Laboratory Staff, 1954, Diagnosis and improvement of saline and alkali soils: U.S. Dept. Agr., Agr. Handb. 60, 160 p.

U.S. Study Commission, 1962, The report of the U.S. Study Commission-Texas, Pt. I, The Commission Plan, 199 p.; Pt. II, Resources and problems, 365 p.; Pt. III, The eight basins, 217 p.

Walton, W. C., 1962, Selected analytical methods for well and aquifer evaluation: Illinois State Water Survey Bull. 49, 81 p.

Wenzel, L. K., 1942, Methods for determining permeability of water-bearing materials with special reference to discharging-well methods: U.S. Geol. Survey Water-Supply Paper 887, 192 p.

Wilcox, L. V., 1955, Classification and use of irrigation waters: U.S. Dept. Agr. Circ. 969, 19 p.

Wilcox, L. V., Blair, G. Y., and Bower, C. A., 1954, Effect of bicarbonate on suitability of water for irrigation: Soil Sci., v. 77, no. 4, p. 259-266.

Wood, L. A., Gabrysch, R. K., and Marvin, Richard, 1963, Reconnaissance investigation of the ground-water resources of the Gulf Coast region, Texas: Texas Water Comm. Bull. 6305, 123 p.