TEXAS WATER COMMISSION

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RECONNAISSANCE INVESTIGATION OF THE GROUND-WATER RESOURCES OF THE BRAZOS RIVER BASIN, TEXAS

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FOREWORD

The ground-water reconnaissance study is the first phase of the State's water-resources planning concerning ground water as outlined in the progress report to the Fifty-Sixth Legislature entitled "Texas Water Resources Planning at the End of the Year 1958." Before an adequate planning program for the development of the State's water resources can be prepared, it is necessary to determine the general chemical quality of the water, the order of magnitude of ground-water supplies potentially available from the principal water-bearing formations of the State, and how much of the supply is presently being used. To provide the data necessary to evaluate the ground-water resources of Texas, reconnaissance investigations were conducted throughout the State under a cooperative agreement with the U. S. Geological Survey. The ground-water reconnaissance investigations were conducted by river basins so that the results could be integrated with information on surface water in planning the development of the State's water resources. The river basins of the State were divided between the Ground Water Division of the Texas Water Commission and the U. S. Geological Survey for the purpose of conducting and reporting the results of the ground-water investigations.

This bulletin presents the results of the Brazos River Basin ground-water reconnaissance investigation. It provides a generalized evaluation of the ground-water conditions in the basin and points out areas where detailed studies and continuing observations are necessary. The additional studies will be required to provide estimates of the quantity of ground water available for development in smaller areas, to provide more information on changes in chemical quality that may affect the quantity of fresh water available for development, and to better determine the affects of present and future pumpage. This report was prepared by personnel of the U. S. Geological Survey.

TEXAS WATER COMMISSION

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Joe D. Carter, Chairman

TABLE OF CONTENTS

TABLE OF CONTENTS (Cont'd.)

TABLE OF CONTENTS (Cont'd.)

TABLE OF CONTENTS (Cont'd.)

TABLE OF CONTENTS (Cont'd.)

TABLES

TABLE OF CONTENTS (Cont'd.)

TABLE OF CONTENTS (Cont'd.)

ILLUSTRATIONS

Figures

TABLE OF CONTENTS (Cont'd.)

Plates

[All plates in pocket]

TABLE OF CONTENTS (Cont'd.)

RECONNAISSANCE INVESTIGATION OF THE GROUND-WATER RESOURCES OF THE BRAZOS RIVER BASIN, TEXAS

ABSTRACT

The Brazos River Basin in Texas extends from the New Mexico State line southeastward to the Gulf of Mexico. The basin is about 600 miles long and ranges in width from 1 to 120 miles--an area of about 42,000 square miles, which includes all or parts of 69 counties. About 1,385,000 persons reside in the basin.

The economy of the basin is dependent largely on agriculture and industry. Irrigation is practiced throughout the area. In the semiarid part of the basin in the High Plains and Osage Plains, it is an implement to successful farming; in the more humid eastern part of the basin, it is practiced chiefly on a supplemental basis, except for the growing of rice. The production of oil and gas is the most widespread industrial activity in the basin. The production and processing of other mineral products, such as sand and gravel, gypsum, building stone, clay products, cement, salt, and sulphur, are important locally. Lignite is mined in Milam County where it is used to produce electricity for the processing of aluminum ores shipped in from other states or imported from foreign countries. Some of the industrial development is associated closely with areas of agricultural production. The raising of beef cattle is important in many places in the basin.

The Brazos River Basin in Texas includes parts of four physiographic sections--the High Plains and the Central Texas sections of the Great Plains Province, the Osage Plains section of the Central Lowlands Province, and the West Gulf Coastal Plain section of the Coastal Plain Province. The basin ranges in elevation from about 4,150 feet above sea level at the western boundary to sea level at the Gulf of Mexico. The topography is characterized by the nearly flat elevated surface of the High Plains, the gently sloping plain dissected by entrenched streams in the adjoining Osage Plains, the heavily dissected area of the Central Texas section, and the hilly, gently rolling country of the inland part of the West Gulf Coastal Plain, which merges with the nearly flat land along the Gulf of Mexico. The annual precipitation increases eastward from about 18 inches at Lubbock on the High Plains to about 49 inches at Angleton near the Gulf of Mexico.

Rocks cropping out in the basin range in age from Early Ordovician to Recent and consist of many lithologic types totaling several thousands of feet in thickness. The consolidated rocks consist mainly of shale, sandstone, conglomerate, limestone, and evaporites. The unconsolidated rocks consist chiefly of sand, gravel, silt, and clay.

Primary aquifers in the Brazos River Basin are the Trinity Group of Cretaceous age in the West Gulf Coastal Plain, the Ogallala Formation of Tertiary age in the High Plains, the Carrizo Sand and Wilcox Formation, undifferentiated, and the Catahoula Sandstone, Oakville Sandstone, and Lagarto Clay, undifferentiated, of Tertiary age, and the Goliad Sand, Willis Sand, and Lissie Formation, undifferentiated, of Tertiary age and Quaternary age in the West Gulf Coastal Plain, and the Quaternary alluvium in the West Gulf Coastal Plain and in the Osage Plains. Secondary aquifers include the Dockum Group of Triassic age in the Osage Plains, the Trinity Group in the Central Texas section, and the Mount Selman Formation, Sparta Sand, and Yegua Formation of Tertiary age, and the Beaumont Clay of Quaternary age in the West Gulf Coastal Plain.

The formations of the Ellenburger Group of Ordovician age are the oldest known rocks that yield fresh to slightly saline water in the Brazos River Basin. The Ellenburger Group yields only small quantities of fresh to slightly saline water to a few wells in a small area in the Brazos River Basin, and it is not considered to be either currently or potentially an important source of water supply in the Brazos River Basin.

The rocks of Pennsylvanian age, which crop out in the Osage Plains and Central Texas sections of the Brazos River Basin, do not contain either primary or secondary aquifers; they produce only small quantities of fresh to slightly saline water from wells in the outcrop area or a short distance downdip. In general, the water becomes more saline with depth.

The Permian rocks, which crop out in the Osage Plains section of the Brazos River Basin, do not contain either primary or secondary aquifers, the only production being, in general, small quantities of water, most of which is of poor chemical quality. The beds of gypsum, anhydrite, and salt in the Permian rocks are the source of most of the natural contamination of the Brazos River.

The Fredericksburg and Washita Groups of Cretaceous age in region III are not important sources of ground water. However, the Edwards Limestone of the Fredericksburg Group yields large amounts of hard but otherwise good-quality water in Bell and Williamson Counties.

The Woodbine Formation, Eagle Ford Shale, Austin Chalk, rocks of Taylor age, and Navarro Group of Cretaceous age, and the Cook Mountain Formation, Yegua Formation, and Jackson Group of Tertiary age in the West Gulf Coastal Plain are not considered as important sources of water supply.

The chemical quality of water differs from place to place in each aquifer and is different in different aquifers. Many of the cities and towns in the basin use ground water for public-supply purposes and ground water is used for irrigation and industrial purposes in many places in the basin.

The total amount of ground water pumped from major wells in the Brazos River Basin in 1959 was about 2,400,000 acre-feet. Of this amount, about 68,000 acre-feet was for public supply and about 24,000 acre-feet for industrial use, the remainder being for irrigation. The Ogallala Formation in the heavily irrigated High Plains supplied about 2,200,000 acre-feet, or 90 percent, of the total amount of water pumped in the basin. In 1959, about 140,000 acre-feet of ground water was pumped from the Quaternary alluvium, almost 70 percent of which was withdrawn from wells in the Osage Plains, the remainder of the pumpage being from wells in region III of the West Gulf Coastal Plain.

Water levels are declining in the areas of heavy development. The amount of decline ranges from a few feet to several tens of feet in the aquifers which have large withdrawals of ground water. The amount of water withdrawn from the Ogallala Formation in the High Plains each year exceeds even the most optimistic estimates of recharge and the ground-water supply is being depleted. Large declines in artesian pressure have occurred in heavily pumped areas of the Trinity Group and as a result yields of wells have decreased; moreover, many wells that once flowed have ceased to flow. Little change in water levels has taken place in the Carrizo Sand and Wilcox Formation, undifferentiated. In the Quaternary alluvium in region III, water levels rose and the amount of ground water in storage increased about 250,000 acre-feet during the 4-year period 1957-61.

The amount of fresh to slightly saline ground water in storage is estimated to be about 300,000,000 acre-feet in the Carrizo Sand and Wilcox Formation, undifferentiated. The amount of ground water in storage in the Quaternary alluvium in region III is estimated to be 1,800,000 acre-feet. In the High Plains, an estimated 89,000,000 acre-feet of ground water was in storage in the Ogallala Formation in 1958. However, only a part of the water in storage in these aquifers will be available to wells.

The problem common to many primary and secondary aquifers is one of declining water levels; in some aquifers the declines are regional and in others they are local. The problem of contamination of fresh-water sands by seepage of oilfield brine from surface disposal pits is present in some parts of the basin. Lack of sufficient data in much of the basin does not permit a complete appraisal of many of the aquifers. More geologic and hydrologic data need to be gathered and analyzed in order to more correctly ascertain the ground-water reserves and availability for future development.

RECONNAISSANCE INVESTIGATION OF THE GROUND-WATER RESOURCES OF THE BRAZOS RIVER BASIN, TEXAS

INTRODUCTION

Purpose and Scope

The Texas Water Planning Act of 1957, Senate Bill 1, First Called Session of the 55th Legislature, created a water-planning division within the Texas Board of Water Engineers (name changed to Texas Water Commission, January 1962). The act directed that the Board submit a statewide report on the water resources of the State and make recommendations to the Legislature for the maximum development of the water resources of the State. The report entitled, "Texas Water Resources Planning at the End of the Year 1958, A Progress Report to the Fifty-Sixth Legislature," was submitted in December 1958. The report states (Texas Board of Water Engineers, 1958, p. 78), "...Initial planning for development of the State's water resources will require that reconnaissance ground-water studies be made in much of the State because time is not available to complete the recommended detailed investigations. Studies of this type will be made chiefly to determine the order of magnitude of the ground-water supplies potentially available from the principal water-bearing formations."

To implement the directive of the Legislature, a cooperative project between the Texas Board of Water Engineers (Commission) and the U. S. Geological Survey was begun in September 1959. The project was titled, "Reconnaissance ground-water investigations in Texas." The Planning Division of the Texas Board of Water Engineers based its approach to water-resource development planning upon the needs and availability of both surface water and ground water of each river basin and subdivision of a basin. Therefore, the cooperative program between the Ground Water Branch of the U. S. Geological Survey and the Texas Board of Water Engineers was planned by major river basins. The Geological Survey is reporting on the Red, Sulphur, Cypress, Brazos, Upper and Lower Rio Grande, Guadalupe, Nueces, and San Antonio Basins, and on the Gulf Coast region. The Texas Water Commission is reporting on the Canadian, Sabine, Neches, Trinity, Colorado, and Middle Rio Grande Basins. All the reports were scheduled for completion in 1962, except for the Canadian Basin report, which was completed in 1960 (Texas Board of Water Engineers, 1960), the Gulf Coast region report completed in 1961 (Wood and others, 1963), and a report on the Guadalupe, Nueces, and San Antonio Basins, which will be completed in 1963.

The reconnaissance studies of the river basins were to have their principal emphasis on the following items (Texas Board of Water Engineers, 1958, p. 78):

"...(1) Inventory of large wells and springs; (2) compilation of readily available logs of wells and preparation of generalized cross sections and maps showing subsurface geology; (3) inventory of major pumpage; (4) pumping tests of principal water-bearing formations; (5) measurements of water levels in selected wells; (6) determination of areas of recharge and discharge; (7) compilation of existing chemical analyses of water and sampling of selected wells and springs for additional analyses; (8) correlation and generalized analysis of all data to determine the order of magnitude of supplies available from each major formation in the area and general effects of future pumping; and (9) preparation of generalized reports on principal ground-water resources of each river basin."

Location and Extent

The Brazos River Basin in Texas extends from the New Mexico State line southeastward to the Gulf of Mexico. The basin is about 600 miles long and ranges in width from 1 to 120 miles--an area of about 42,000 square miles, which includes all or parts of 69 counties (Figure 1).

The basin in Texas is bounded artificially on the west by the New Mexico-Texas State line, on the north by the Red River Basin, on the northeast and east by the Trinity and San Jacinto River Basins, and on the south by the Colorado River Basin.

Economic Development and Cultural Features

The Brazos River Basin occupies about one-sixth of the area of Texas and has about one-sixth of the State's population. Among the larger centers of population which serve as distribution and service centers for large areas are Lubbock in the High Plains, the largest city in the basin, having a population of 128,691 (1960 census); Abilene in the central part having a population of 90,368; and Waco and Temple in the eastern part having populations of 97,808 and 30,419, respectively. In general, the population of the four regions shown on Figure 1 are region I, 285,000; region II, 250,000; region III, 570,000; and region IV, 280,000 (U. S. Study Commission, 1962, pt. 2, pl. 8, table 42). During the period 1940-60, the population increased in most of the counties in the High Plains portion of the basin, whereas in most of the other counties, the population decreased except in the counties where the larger cities are located.

The production of oil and gas is the most widespread and perhaps the most important industrial activity in the basin. Oil is produced in almost all of the counties in the basin and natural gas and gas liquids (natural gasoline, butane, and propane) are produced in several counties. The many supporting activities connected with the production of oil and gas, such as refining, distribution of supplies, distribution and servicing of equipment, and technical services further enhance the economy of the areas.

Some of the other industrial activities concerned with the production and processing of mineral products are the operation of sand and gravel pits and stone quarries, the mining and processing of gypsum, the production of clay and manufacture of brick and tile products, the production of cement materials and manufacture of cement, and the production of salt and sulphur. Lignite is mined in

Milam County where it is used to produce electricity for the processing of aluminum ores shipped in from other states or imported from foreign countries.

The principal manufacturing plants in the basin are in or near the larger cities. However, other plants also process local products, especially those related to agriculture. The cities of Waco and Temple in the eastern part of the basin in McLennan and Bell Counties, respectively, (Figure 1) are important manufacturing centers, where some of the products produced include auto tires for national distribution, glass and glass containers, textiles, clothing, furniture, rock wool insulation, shoes, clay products, cement, cottonseed oil, food, and feed stuff. Lubbock, the largest city in the basin, is the third ranking inland cotton market in the world. The cottonseed oil mills in the vicinity of Lubbock have a combined production which is the largest of any city in the world.

Agriculture has contributed substantially to the economy of the basin; however, the development of ground water for irrigation has greatly increased the production of agricultural products and improved the standard of living on farms in some parts of the basin. In 1958, about 2,653,000 acres were under irrigation in the Brazos Basin, about 98 percent being irrigated with ground water (Texas Board of Water Engineers and others, 1960, p. 23).

In the 1930's and 1940's, cattle raising and dryland farming gave way to large-scale irrigation farming in the High Plains. Irrigation increased in many areas in the basin during the drought of the early 1950's, and as of 1962 the part of the Brazos River Basin in the High Plains, along with other parts of the High Plains, constituted one of the largest intensively cultivated regions of the State. As a result of the large-scale development of irrigation in the High Plains, the population, both rural and urban, increased. The towns and cities of the irrigated areas became distribution centers for large quantities of equipment and supplies necessary in the development and operation of irrigated farms.

As a result of the drought of the 1950's, irrigation was developed in other parts of the basin wherever ground water was available, notably in the Osage Plains section. Here again, the value of the agricultural production increased and the standard of living improved.

In the eastern part of the basin where dryland farming is generally successful, irrigation is used chiefly as a supplement to the usually adequate rainfall. Cotton, grain sorghums, and wheat are the principal crops in the western part of the area; in the eastern part, cotton and grain sorghums are the main crops and vegetables and alfalfa are minor crops.

The raising of beef cattle is an important part of the agricultural economy in the Brazos River Basin; however, the areas of greatest beef cattle production have shifted. In the early years, the High Plains section and parts of the Osage Plains section were important cattle raising areas. Although cattle raising is still important to the economy of these sections, the number of cattle on farms and ranches has decreased, whereas the number of cattle on farms and ranches in the area along the inner Coastal Plain has increased.

There are several colleges in the Brazos River Basin, such as Wayland College at Plainview; Texas Technological College and Lubbock Christian College, both at Lubbock; Hardin Simmons and Abilene Christian College at Abilene; Baylor

University at Waco; Southwestern University at Georgetown; and Texas A. & M. College at College Station.

The Brazos River Basin is served by several rail, air, and bus lines, and many hundreds of miles of paved Federal and State highways and secondary roads.

Previous Investigations

The geology and ground-water resources of parts of the Brazos River Basin and of some adjoining areas have been discussed in reports based on investigations made by various Federal and State agencies. Special aspects of the geology in and adjoining the basin also have been discussed in articles published in technical journals. Most of the reports and articles are listed in the bibliography (p. 137).

The earliest reports concerning ground water in or adjacent to the Brazos River Basin were by Singley (1893), Hill (1901), Taylor (1907), Gordon (1913), Deussen (1914 and 1924), and Baker (1915). Most of the early reports concerning ground water were generalized, covering large areas which included several counties.

Between 1936 and 1946, a statewide inventory of water wells by counties was undertaken by the Texas Board of Water Engineers (now Texas Water Commission) in cooperation with the U. S. Geological Survey. Part of this work was financed by the Works Progress Administration. The reports resulting from this program covered many counties in the Brazos Basin. The reports include tables of well records, well logs, and chemical analyses of water samples, together with maps showing the locations of the wells. The reports are especially important in that the depth to water measurements included form the basis for a historical record of water levels in many areas.

Periodic measurements of water levels are made in a statewide network of observation wells by the Texas Water Commission. Many of the observation wells are in the Brazos River Basin, especially in the High Plains. The records of these measurements, by counties, are published periodically by the Texas Water Commission. Since 1938, the annual Water-Supply Papers of the U. S. Geological Survey on water levels and artesian pressures in the United States also have included information on the depth-to-water measurements made in observation wells in the Brazos River Basin.

The public water supplies of the principal cities and towns in the basin were described by Sundstrom, Hastings, and Broadhurst (1948), Sundstrom, Broadhurst, and Dwyer (1949), and Broadhurst, Sundstrom, and Weaver (1951).

Since 1936, eight progress reports on the geology and ground water in the irrigated areas of the Southern High Plains have been published by the Texas Board of Water Engineers in cooperation with the U. S. Geological Survey. The most recent report was by Cronin (1961).

Detailed investigations of the geology and occurrence of ground water in parts of the basin include those for Lamb County (Leggat, 1957), Lynn County (Leggat, 1952), Hale County (Cronin and Wells, 1960), and Haskell and Knox Counties (Ogilbee and Osborne, 1962). Other less comprehensive county reports include those for Lubbock County (Lang, 1945) and Jones County (Winslow, Doyel, and Gaum, 1954). Discussions of the lower part of the basin were included in reports by Wood (1956b) and Wood, Gabrysch, and Marvin (1963).

Many reports covering local areas smaller than counties have not been published but are in the open files of the U. S. Geological Survey and the Texas Water Commission.

Methods of Investigation

Fieldwork on the reconnaissance of the Brazos River Basin was done during the period September 1, 1959 to August 31, 1961. The report was prepared between September 1, 1961 and August 31, 1962. The basic data included primarily an inventory of the major wells throughout the basin. For the purpose of this report, major wells include public-supply, industrial, and irrigation wells having yields of about 50 gpm (gallons per minute) or more. All public-supply wells were included in the inventory regardless of capacity.

During the well inventory, the locations of the major wells were recorded and the water-bearing formation from which the wells were pumping was noted. Information concerning the type of well, depth, yield, type of pump, and kind of power was obtained for a select number of wells. Records for other types of wells--domestic, livestock, and miscellaneous--were obtained in selected areas for purposes of quality-of-water studies or use as other hydrologic control points. In the High Plains, the number of irrigation wells was estimated from collected data and from the records of the High Plains Underground Water Conservation District No. 1 at Lubbock. The total amount of ground water pumped in the basin was estimated from data obtained during the well inventory except in the High Plains. In the High Plains, the amount of water-bearing material dewatered was calculated from the decline of the water levels and the amount of water pumped was then calculated using a specific yield of 15 percent.

Samples of water for chemical analysis were collected from wells. The results of these analyses and several hundred others from previously collected samples were used in delineating areas of usable water and as a guide in interpreting the quality of water from electric logs and in a general study of the quality of water in the various aquifers.

During the investigation, a search was made of the data available from previous studies, both published and unpublished. Wherever pertinent, such data were used in preparing this report. Pumping tests were made to determine the hydraulic characteristics of the aquifers in several places.

The locations of the major wells or areas of concentration of the major wells are shown on maps which also show the areal geology. A geologic section extending the length of the basin was constructed from drillers' and electric logs of water wells and oil tests. Other maps showing the geologic or hydrologic characteristics of some of the aquifers include contour maps on the top and bottom of formations, saturated thickness maps, depth to water maps, and water-table contour maps.

Well-Numbering System

The numbers assigned to wells and springs in this report conform to the statewide system used by the Texas Water Commission. The system is based on the division of Texas into 1-degree quadrangles bounded by lines of latitude and longitude. Each 1-degree quadrangle is divided into 64 smaller quadrangles, 7-1/2 minutes on a side, each of which is further divided into 9 quadrangles, 2-1/2 minutes on a side. Each of the 89 1-degree quadrangles in the State has been assigned a 2-digit number for identification (Figure 2). The 7-1/2 minute quadrangles are numbered with 2-digit numbers consecutively from left to right beginning in the upper left-hand corner of the 1-degree quadrangle, and the 2-1/2 minute quadrangles within each 7-1/2 minute quadrangle are similarly numbered with a 1-digit number. Each well inventoried in each 2-1/2 minute quadrangle is assigned a 2-digit number. The well number is determined as follows: From left to right, the first 2 numbers identify the 1-degree quadrangle, the next 2 numbers identify the 7-1/2 minute quadrangle, the fifth number identifies the 2-1/2 minute quadrangle, and the last 2 numbers designate the well in the 2-1/2 minute quadrangle.

In addition to the 7-digit well number, a 2-letter prefix is used to identify the county. The prefixes for the 69 counties that are all or partly in the Brazos River Basin are as follows:

Prefix	County	Prefix	County	Prefix	County
AJ	Archer	JR	Falls	SD	Limestone
AP	Austin	JU	Fisher	SP	Lubbock
AR	Bailey	JW	Floyd	SR	Lynn
AT	Bastrop	JY	Fort Bend	ST	McLennan
AU	Baylor	KA	Freestone	TK	Milam
AX	Bell	KJ	Garza	TL	Mills
BA	Borden	KW	Grimes	UA	Nolan
BB	Bosque	KY	Hale	UK	Palo Pinto
BH	Brazoria	LA	Hamilton	UP	Parker
BJ	Brazos	LP	Haskell	UR	Parmer
BR	Brown	LW	Hill	WK	Robertson
BS	Burleson	LX	Hockley	WZ	Scurry
BT	Burnet	LY	Hood	XA	Shackelford
BX	Callahan	PL	Jack	XL	Stephens
DD	Castro	PX	Johnson	XR	Stonewall
DP	Cochran	PY	Jones	XT	Swisher
DY	Comanche	RH	Kent	XW	Taylor
HB	Coryell	RL	King	XY	Terry
HK	Crosby	RS	Knox	XZ	Throckmorton
HS	Dawson	RU	Lamb	YW	Waller
HY	Dickens	RW	Lampasas	YY	Washington
JD	Eastland	RZ	Lee	ZK	Williamson
JP	Erath	SA	Leon	ZU	Young

In this report only the degrees of latitude and longitude are shown on maps; the 7-1/2 minute and 2-1/2 minute lines are not shown as they would obscure other details. However, a well whose number is known can be approximately located by identifying the 1-degree quadrangle from Figure 2 and using the degree lines on the individual well maps. Similarly, a well located on a map can be approximately identified by dividing a 1-degree quadrangle into 7-1/2 minute quadrangles.

Acknowledgments

The collection of basic data was greatly facilitated by the cooperation of the well owners, well drillers, personnel of oil companies, and officials of municipalities and ground-water conservation districts. The writers take this opportunity to express their appreciation.

GEOGRAPHY

The Brazos River Basin in Texas includes parts of four physiographic sections--the High Plains and the Central Texas sections of the Great Plains Province, the Osage Plains section of the Central Lowlands Province, and the West Gulf Coastal Plain section of the Coastal Plain Province (Figure 1).

The High Plains section within the Brazos River Basin is characterized by a nearly flat surface sloping, in general, southeastward at an average rate of about 8 to 10 feet per mile. Minor features of relief are shallow undrained depressions ranging from a few feet to 50 feet or more in depth and from a few hundred feet to a mile or more in diameter, sand dunes, a few large water-table lakes which contain saline water, and shallow stream valleys which become deeper toward the eastern edge of the High Plains. The eastern margin of the High Plains is marked by a prominent escarpment, along which is a rough stretch of land referred to as the "breaks of the plains."

The Osage Plains within the Brazos River Basin adjoins the High Plains and is bounded on the east and south by the Central Texas section of the Great Plains Province. The area is essentially an eastward-sloping plain having areas of level to undulating land on the interstream divides. The topography becomes more broken along the entrenched streams. The gently sloping surface is modified somewhat, in places, by low escarpments formed by beds of gypsum, sandstone, and dolomite.

The Central Texas section within the Brazos River Basin is bounded by the Osage Plains on the west and north and the West Gulf Coastal Plain on the east. The section has been heavily dissected by erosion, leaving mesas (plateau remnants) along the western part which nearly connect the section with the High Plains. In the remaining part of the section where Cretaceous rocks dip eastward toward the Gulf of Mexico, plateau remnants having undulating to rolling surfaces form the interstream divides. Rough hillsides and valleys border most of the deeply entrenched streams.

In the West Gulf Coastal Plain, the hilly and gently rolling country of the inland part merges with the smooth and nearly level area along the Gulf Coast.

The Double Mountain Fork of the Brazos River, the longest of three streams which form the headwaters of the Brazos River in Texas, heads in eastern New Mexico and crosses the Texas State line at an altitude of about 4,150 feet. From this point, the stream continues in a southeasterly direction across the High Plains to the escarpment of the plains where the altitude is approximately 3,000 feet.

From the High Plains, the stream descends to an altitude of about 1,500 feet at a point in northeastern Stonewall County where it joins the Salt Fork of the Brazos, a stream having its headwaters in the breaks of the High Plains in southern Crosby County. The main stem of the river formed by the confluence of the Salt Fork and Double Mountain Fork flows northeast through Knox County to the vicinity of Seymour in Baylor County, whence it continues in a southeasterly direction to south-central Young County where it is joined by the Clear Fork of the Brazos, which has its headwaters in western Fisher County. From Young County, the stream continues in a southeasterly direction, being joined by several tributaties before reaching the mouth at the Gulf of Mexico.

The area of the Brazos Basin in the High Plains contributes virtually no runoff to the river. The average annual discharge of the river at Seymour in Baylor County is about 319,000 acre-feet; near Hempstead in Waller County near the coast, it is about 5,000,000 acre-feet.

CLIMATE

The climate of the Brazos River Basin in Texas is humid in the eastern part and semiarid in the western part. Precipitation in the basin ranges from an annual mean of about 16 inches in the semiarid western part on the High Plains to more than 48 inches in the humid eastern part of the basin on the lower part of the Coastal Plain (Figure 3).

The average or normal monthly precipitation at Lubbock, Spur, College Station, and Angleton (adjacent to the basin about 15 miles north of Freeport) is shown on Figure 4. In the eastern part of the basin, precipitation is heavy throughout the year, although the months of maximum precipitation generally are in the spring or summer. The graphs shown on Figure 4 for Lubbock on the High Plains and Spur in the Osage Plains indicate that in the semiarid part of the basin, the rainfall is relatively light during the winter months, increasing during the spring to a peak in May, which is about three times the normal for the winter months. Precipitation continues throughout the summer months at about twice the average rate for the winter months and climbs to a second peak in September slightly lower than the earlier peak.

Snowfall is rare in the eastern part of the basin, but its incidence increases inland, and in the High Plains it is an important source of moisture in some years.

The monthly temperature and evaporation at Lubbock, Spur, College Station, and Angleton are shown in Figure 5. The graphs indicate that the evaporation potential increases inland from the Gulf Coast. The average annual evaporation potential of about 56 inches at College Station is about 1-1/2 times the average annual precipitation. At Lubbock, where the humidity is low and strong breezes prevail, the average annual evaporation potential of about 64 inches is about 3-1/2 times the average annual precipitation. Evaporation is greatest during the summer months at all stations.

The average annual temperature at Angleton near the coast is about 69°F and at Lubbock in the High Plains it is about 59°F, indicating that the average annual temperature decreases inland from the coast. However, the average difference between summer and winter temperatures is about 25 degrees at Angleton and

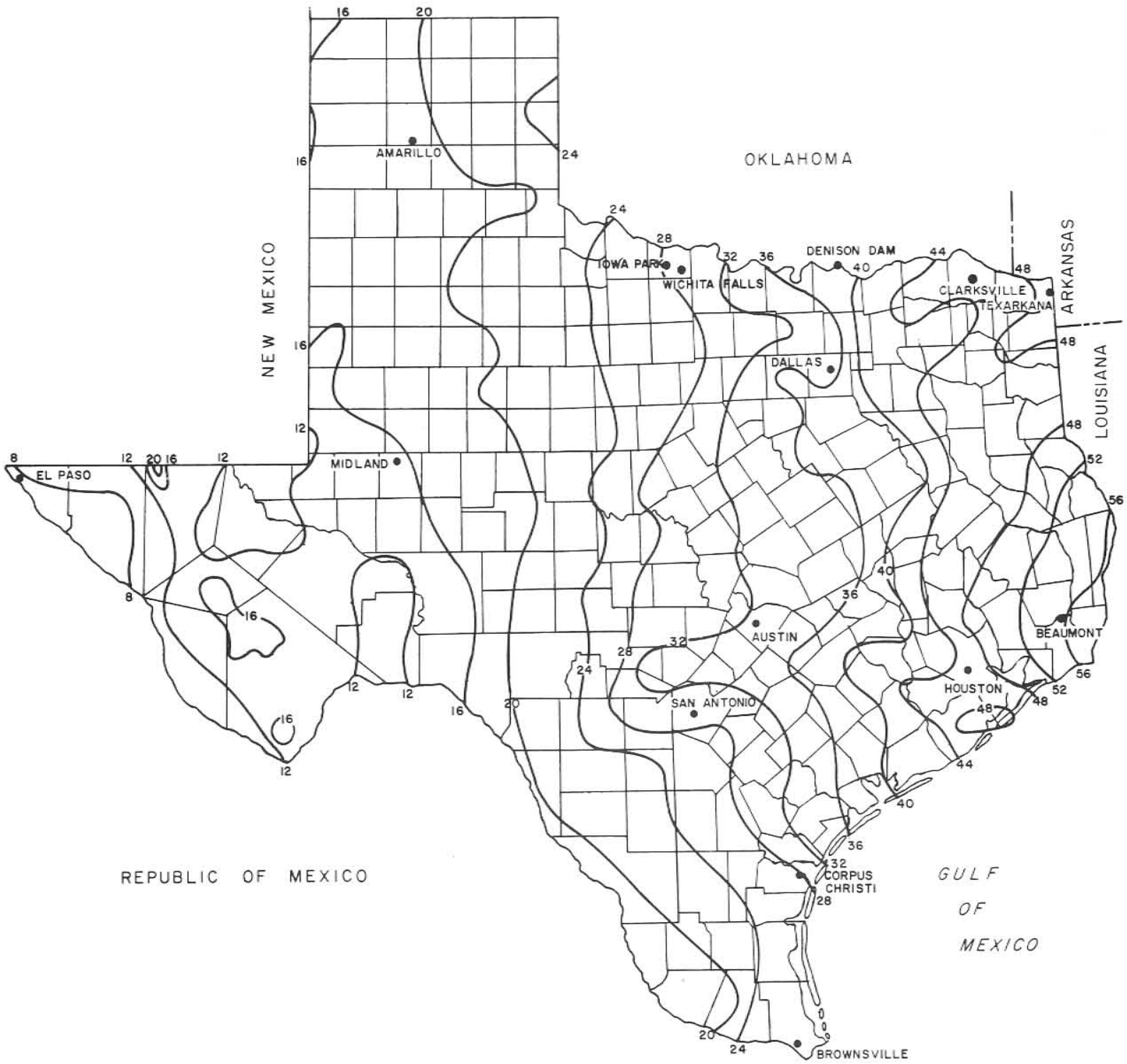

Figure 3

Map of Texas Showing Mean Annual Precipitation, in Inches, Based on the Period 1931-55

(After map prepared by U. S. Weather Bureau)

U. S. Geological Survey in cooperation with the Texas Water Commission

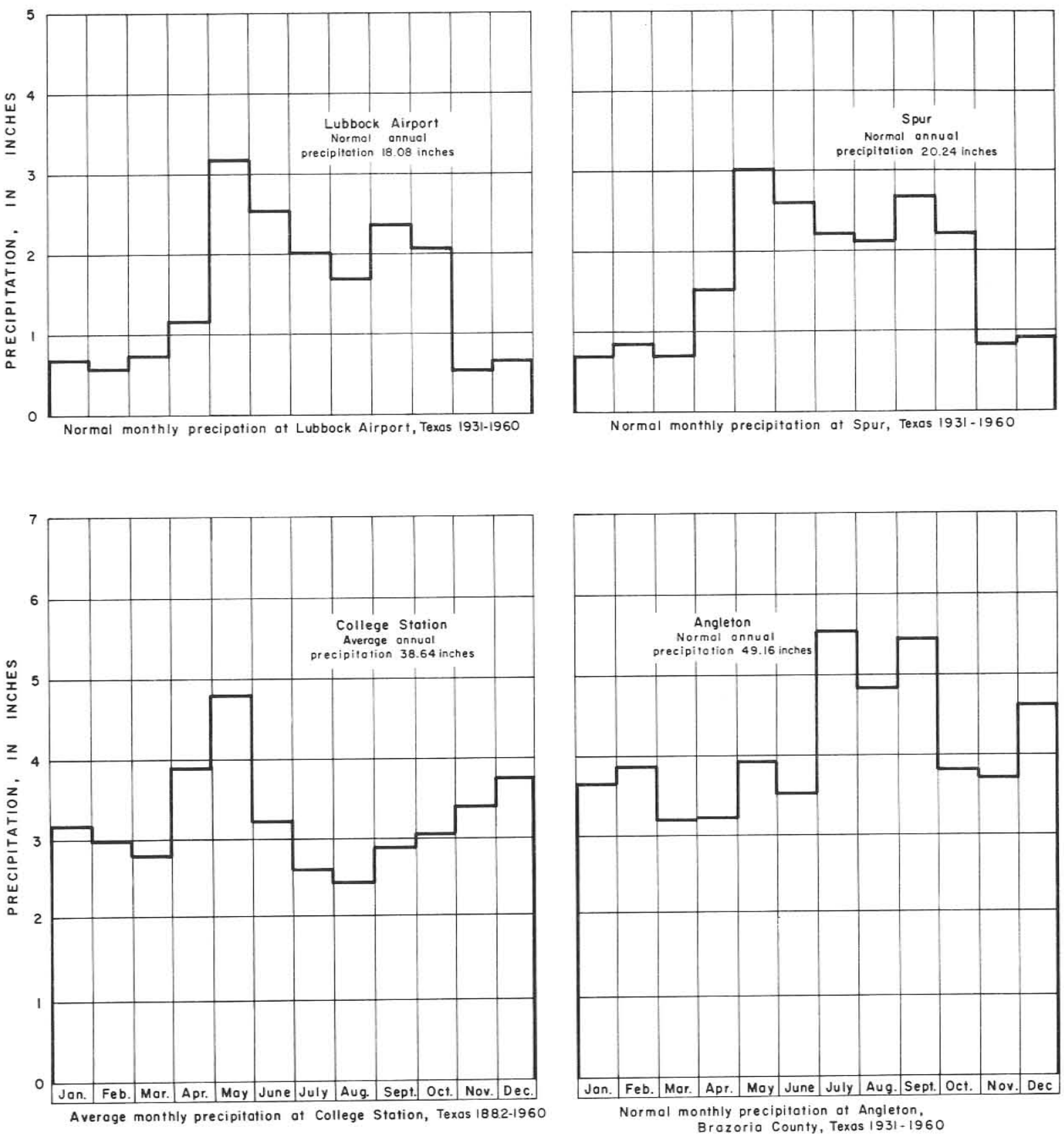

Figure 4

Average Monthly Precipitation at College Station and Normal Monthly Precipitation at Angleton, Lubbock Airport, and Spur

(From Bloodgood, Patterson and Smith, 1954, and records of the U. S. Weather Bureau)

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134

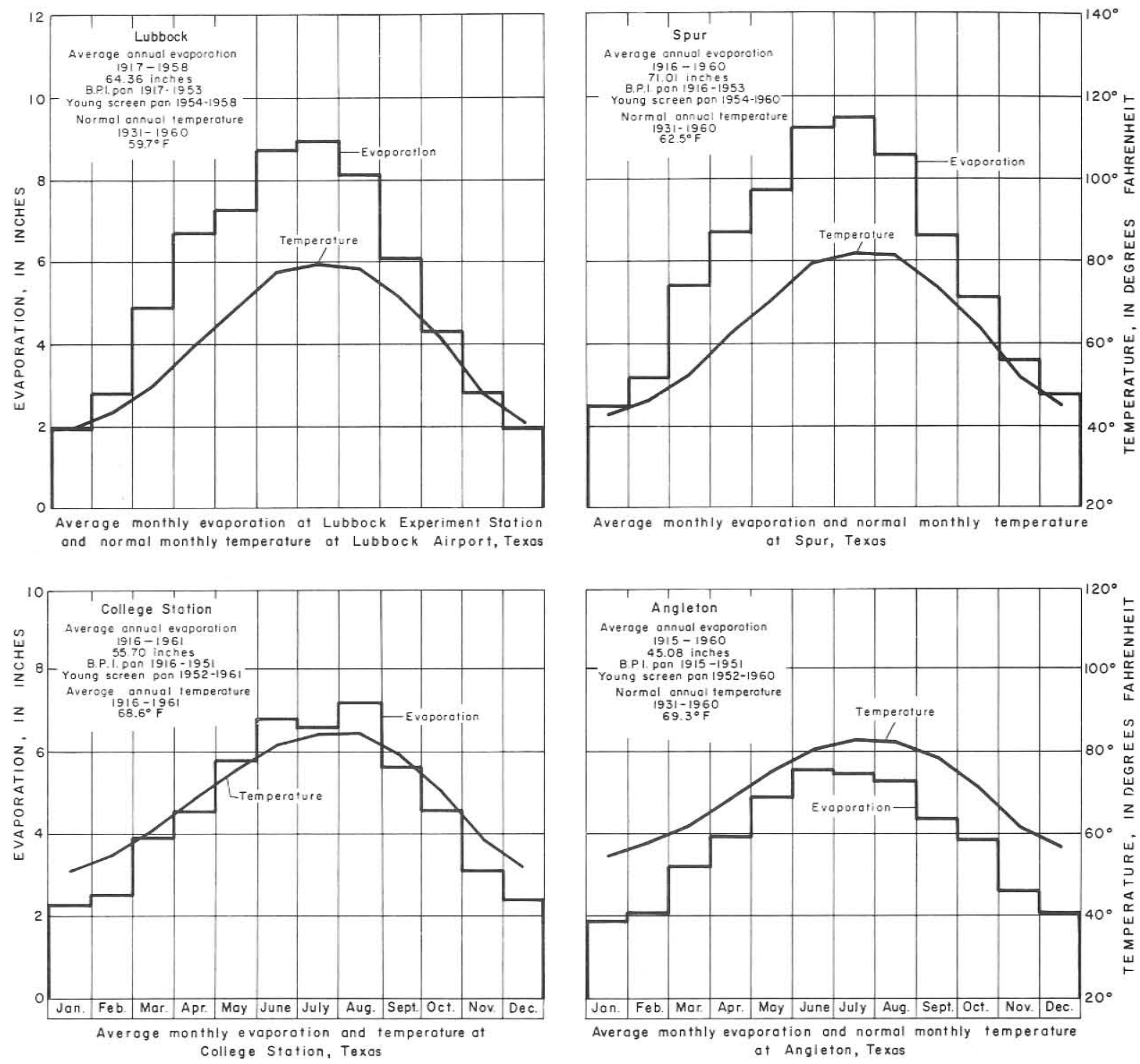

Figure 5

Monthly Evaporation and Temperature at Lubbock, Spur, College Station, and Angleton

(From Bloodgood, Patterson, and Smith, 1954, the U.S. Weather Bureau, and the Texas Water Commission)

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134

about 40 degrees at Lubbock, showing that the winters are more severe in the western part of the basin.

The length of the growing season (frost-free period) varies from year to year, but on the average is about 290 days in the basin near the coast and about 200 days at Lubbock in the High Plains.

GENERAL GEOLOGY

Geologic History

The present geologic structure and succession of rock formations in the Brazos River Basin are the result of a series of events during geologic time. The advance and retreat of the seas has resulted in periods of sediment accumulation alternating with periods of erosion. Structural deformation has subsequently altered the attitude of the formations.

Throughout most of the Paleozoic Era, the Brazos River Basin was part of a large sedimentary basin which was receiving sediment in the seas. In Middle Pennsylvanian time, a period of mountain building caused a general westward tilting of the land and the seas moved westward. Mountain-building activity to the north and south of the basin marked the end of Pennsylvanian time and the beginning of Permian time.

In Early Permian time, tilting of the land toward the west caused a migration of the shoreline farther westward and the resulting oscillating seas caused deposition of lagoonal sediments. The seas were restricted during the middle and late parts of the Permian and hundreds of feet of red beds, evaporites, and other chemical precipitates were deposited in what is now the Osage Plains.

The area of the Brazos River Basin was above sea level at the beginning of the Mesozoic Era and remained above sea level throughout Triassic time. During Late Triassic time, continental sediments were deposited on the eroded surface of the Permian rocks.

Much of the Brazos Basin remained above sea level during Jurassic time. While the western part of the basin was being subjected to erosion, eastern Texas was inundated by Jurassic seas and several thousand feet of sediments were deposited before the sea withdrew. Although the absence of Jurassic rocks in much of the western part of the area of the Brazos River Basin probably is due to nondeposition, the rocks may have been deposited and subsequently removed by erosion prior to Cretaceous time.

During Early Cretaceous time, the sea advanced from the south and east and all of Texas was submerged, resulting in the ultimate deposition of thousands of feet of sediments. During Late Cretaceous time, the land was elevated and the sea retreated, this being more pronounced in the Osage Plains and the High Plains where uppermost Cretaceous rocks probably were not deposited.

The Cenozoic history of the Brazos River Basin is marked by the alternation between the encroachment of the sea and deposition from the heavily loaded streams. At times the sea advanced over the land and the rivers deposited clastic sediments in the form of deltas; at times the advance of the sea prevailed and at other times the land-building processes predominated.

In much of the Osage Plains and High Plains areas, the Cenozoic Era was marked by erosion and deposition of continental sediments derived largely from the rising mountains to the west and northwest. Streams flowing eastward during Pliocene time from the newly formed mountains deposited several hundred feet of sediment over the eroded Triassic and older strata of the High Plains and much of the Osage Plains.

The depositional history of the Cenozoic on the West Gulf Coastal Plain is cyclical. At the beginning of each cycle, a gradual tilting or elevation of the land occurred and the rivers were rejuvenated and erosion increased. Large volumes of material were transported to the coast and deposited on alluvial plains, deltas, or on the continental shelf to form the thick continental or transitional beds of gravel, sand, and clay, and the marine deposits of fine sand, silt, and clay.

The continuous gradual subsidence of the coast under the depositional plains and continental shelf facilitated the formation of thick deposits. During periods of rapid erosion, large coalescing deltas were built. They were subsequently attacked by the waters of the Gulf and overrun during periods of lesser deposition of sediments and continued crustal subsidence. Thus, the cycle continued, and as the shoreline moved back and forth, the clastic materials tended to become finer grained. A new cycle began with another gradual tilting of the coast and a new elevation of the land. The shoreline moved gulfward with each cycle until it reached its present position.

During late Eocene time, volcanic activity took place at times in areas near the Gulf Coast. As a result, volcanic ash has been deposited in some of the sediments of that time. Volcanic activity also occurred during the Oligocene Epoch and culminated during Miocene time when the volcanoes were most active. As a result, a great amount of pyroclastic material was deposited in the Miocene strata, some of it being reworked when a previous depositional plain was elevated and subjected to stream erosion.

During Pleistocene time, extensive terrace deposits were formed along the coast reflecting the advance and retreat of the seas during the glacial epochs. Inland from the coast during Pleistocene time, erosion and deposition by streams was predominant and the present boundaries of the physiographic provinces were established. Surfaces of the area were modified by the downward cutting of streams and the subsequent formation of terraces and alluvial deposits along the watercourses and in parts of the western region by the shifting of windblown deposits.

Stratigraphy and Structure

The rocks exposed in the Brazos River Basin consist of many different lithologic types totalling many thousands of feet in thickness. The rocks range in age from Ordovician to Recent. Plates 1 through 4 show the outcrop areas of the various geologic units, and Figures 6 through 9 show by geologic sections the geologic structure of the basin and the stratigraphic relation between the geologic units. Table 1 lists the stratigraphic units in the basin and gives brief descriptions of their lithology and water-bearing properties.

For purposes of this report, the more important water-bearing units are referred to either as primary or secondary aquifers, depending on whether they yield large quantities of water in relatively large areas (primary), or whether they yield either large quantities of water in relatively small areas or small quantities of water in relatively large areas (secondary).

The rocks underlying the High Plains in the Brazos River Basin, which are significant as hydrologic units, are of Tertiary and Quaternary age (Plate 1). Rocks of Tertiary and Quaternary age immediately underlie the surface. The principal formation and the only primary aquifer in the High Plains is the Ogallala Formation, which consists of a maximum of about 500 feet of sand, gravel, clay, silt, and caliche. The Ogallala Formation is, in places, overlain by Quaternary deposits which consist chiefly of stream channel fillings, sheets of windblown material, and sand dunes. These deposits are thin, probably not more than about 50 feet in thickness. The Ogallala Formation was deposited chiefly by eastward-flowing streams draining ancestral mountains to the west. The deposits were laid down on the eroded surface of gently eastward dipping Cretaceous and Triassic rocks. The Ogallala Formation itself dips gently toward the southeast at the rate of about 10 feet per mile (Figure 6).

The Tertiary and Quaternary rocks are not structurally deformed in the High Plains, the most pronounced structural features being in the deeply buried Permian and older strata. The presence of thick or thin sections of the Ogallala Formation may be related to the buried basins or uplifts.

The rocks exposed in the Osage Plains in the Brazos River Basin range in age from Pennsylvanian to Recent (Plate 2). The Pennsylvanian rocks rest on older Paleozoic rocks which do not yield fresh water in this part of the basin.

The Pennsylvanian rocks in the Osage Plains consist of more than 5,000 feet of sandstone, conglomerate, shale, limestone, and a few beds of coal. The Pennsylvanian rocks contain no important aquifers, the only production of water being small quantities of fresh to slightly saline water.

The Permian rocks in the Osage Plains consist of nearly 6,000 feet of shale, sandstone, limestone, dolomite, gypsum, and anhydrite. None of the Permian rocks contain either primary or secondary aquifers, the only production being small quantities of water most of which is of poor chemical quality. The beds of gypsum and anhydrite in the Permian rocks are the source of most of the natural contamination of the Brazos River.

Rocks of Triassic age crop out in the western part of the Osage Plains and disappear beneath the younger formations of the High Plains to the west. The Triassic rocks consist of a maximum of about 1,600 feet of chiefly shale, sandstone, and conglomerate. The Triassic rocks form a secondary aquifer in the Osage Plains, furnishing small to moderate quantities of water.

Quaternary alluvial deposits mantle the older rocks in parts of the Osage Plains, occurring chiefly as channel fillings of ancestral streams, terraces, flood plains, and sheets of windblown material and sand dunes. The Quaternary alluvial deposits consist chiefly of sand, gravel, silt, and clay, and they form the only primary aquifer in the Osage Plains.

Although there are many small faults and flexures in the Pennsylvanian and Permian rocks in the Osage Plains, there are no large structural features which profoundly affect the occurrence of water. The Pennsylvanian and Permian rocks dip gently toward the northwest or west at an average rate of about 50 feet per mile. The Triassic rocks and Quaternary alluvium dip toward the southeast at a rate of about 15 feet per mile.

The rocks cropping out in the Central Texas section of the Brazos River Basin are chiefly Cretaceous in age, although in a few places Ordovician and Pennsylvanian rocks are exposed (Plates 2 and 3). Limestones of Ordovician and Pennsylvanian age in the section are the oldest fresh water-bearing rocks in the Brazos River Basin; however, they yield only small quantities of fresh to slightly saline water in very small areas.

Most of the region is immediately underlain by Cretaceous rocks consisting of sandstone, conglomerate, shale, and limestone. There are no primary aquifers in the Central Texas section, the principal water-bearing unit, rocks of Trinity Group (Early Cretaceous), being classified as a secondary aquifer.

The water-bearing units in the Central Texas section are affected by two major structural features--the Llano uplift and the Balcones fault zone. Although the Llano uplift is not in the Brazos River Basin itself, it affects the rocks of Ordovician and Pennsylvanian age. The uplift lies in the Colorado River Basin immediately adjoining the Brazos River Basin on the west and consists of a central core of igneous and metamorphous rocks from which the Paleozoic rocks dip away in all directions. The affect of the uplift in the Brazos River Basin is to create steep dips to the north and northeast in the Ordovician and Pennsylvanian rocks. The Cretaceous rocks dip gently toward the southeast at a rate of about 25 to 30 feet per mile (Figure 8).

The Central Texas section is bounded on the east by the Balcones fault zone which separates it from the West Gulf Coastal Plain. The Balcones fault zone consists of numerous normal faults dipping toward the southeast along which the Cretaceous rocks have been downfaulted, the displacement being about 400 feet near West (18 miles north of Waco) in McLennan County (Holloway, 1961, p. 20). The fault zone has no apparent effect on the occurrence or movement of the ground water.

Rocks cropping out in the West Gulf Coastal Plain range in age from Cretaceous to Recent (Plates 3 and 4). The Cretaceous rocks consist chiefly of limestone, shale, and sandstone; the Tertiary rocks are chiefly shale, clay, and sand. The most prolific aquifers in the Brazos River Basin occur in the West Gulf Coastal Plain. These include as primary aquifers the Trinity Group of Cretaceous age; the Carrizo Sand and Wilcox Formation, undifferentiated, of Tertiary age; the Catahoula Sandstone, Oakville Sandstone, and Lagarto Clay, undifferentiated, of Tertiary age; the Goliad Sand, Willis Sand, and Lissie Formation of Tertiary and Quaternary age; and the Quaternary alluvium. Secondary aquifers in the West Gulf Coastal Plain include the Mount Selman Formation and Sparta Sand of Tertiary age, and the Beaumont Clay of Quaternary age.

Table 1.--Geologic units and their water-bearing properties, Brazos River Basin

Era	System	Series and Group	Unit	Thickness (feet)	Lithology	Water-bearing properties	Occurrence
Cenozoic	Quaternary	Recent and Pleistocene Series, undifferentiated	Alluvium (includes river alluvium, terraces, sand dunes, and the Seymour Formation)	0- 200+	Windblown sand and silt, sand, clay, gravel, volcanic ash, and caliche.	Yields small to large quantities of water. Water in Seymour Formation and Brazos River Valley used chiefly for irrigation. Sand dunes form excellent recharge areas.	Regions I, II, III, and IV.
		Pleistocene Series	Beaumont Clay	0- 1,300	Principally a poorly bedded variegated, calcareous clay, and thin beds of silt and fine sand.	Yields small to moderate supplies of water for public supply, industry, and irrigation.	Regions III and IV.
			Lissie Formation	0- 1,100+	Alternating thin to thick beds of light-colored fine sand, gravel, sandy clay, and clay.	Yields small to large supplies of water for public supply, industry, and irrigation.	Do.
	Tertiary(?)	Pliocene(?) Series	Willis Sand	0- 350	Sand and gravel interbedded with silt and clay.	Yields small to large supplies of water for public supply, industry, and irrigation.	Do.
	Tertiary	Pliocene Series	Goliad Sand	0- 250	Bentonitic clay interbedded with sand and gravel cemented with lime.	Yields small to moderate quantities of fresh to slightly saline water for public supply.	Do.
			Ogallala Formation	0- 500	Fine to coarse sand and gravel, clay, silt, and caliche.	Yields large quantities of water throughout the High Plains for industry, irrigation, public supply, and domestic and livestock supply.	Regions I and II.
		Rocks of Miocene and Miocene(?) age, undifferentiated	Lagarto Clay, Oakville Sandstone, and Catahoula Sandstone, undifferentiated.	0- 4,100±	Alternating beds of clay and shale with layers of coarse sand and lime-cemented sandstone.	Yields small to large quantities of water to domestic and livestock, irrigation, industrial, and public-supply wells.	Regions III and IV.
		Eocene Series: Jackson Group		0- 1,200±	Fine and medium tuffaceous sand, clay, sandy or ashy clay, and interbedded lignite.	Yields small to moderate quantities of water to domestic, irrigation, and public-supply wells at some places.	Region III.
		Eocene Series: Claiborne Group	Yegua Formation	0- 1,000	Alternating beds of fine to medium sand, clay, sandy clay, and lignite.	Yields small to moderate quantities of water to domestic and public-supply wells at a few places.	Do.
			Cook Mountain Formation	0- 700	Clay, shale, and sandy shale. Sand, some limestone, glauconite, and ferruginous concretions.	Yields small to moderate quantities of fresh to moderately saline water to domestic and industrial wells.	Do.
			Sparta Sand	0- 300±	Consolidated and unconsolidated fine to medium sand, sandy shale, and clay. Sands are highly cross-bedded and locally contain limonite.	Yields small to moderate quantities of water to domestic and public-supply wells.	Do.
			Mount Selman Formation	0- 1,200	Fine to medium sand, glauconite, clay, fine sandstone, lignite, greensand, glautonitic clay, and ironstone.	Yields small to moderate quantities of fresh to moderately saline water to domestic and public-supply wells.	Do.

(Continued on next page)

The rocks of the West Gulf Coastal Plain dip gently toward the Gulf of Mexico at rates ranging from about 160 feet per mile in the older rocks to 10 feet per mile in the Beaumont Clay near the coast. The Quaternary alluvium occurs in a narrow belt mantling the older rocks in the Brazos River Valley.

Although minor folds and faults interrupt the regional southeast dip of the water-bearing units of the West Gulf Coastal Plain, the major structural feature is the Luling-Mexia-Talco fault zone. The zone trends in a north-northeasterly direction, crossing the Brazos River Basin in Lee, Burleson, Milam, Falls, and Limestone Counties. The zone consists of a series of normal faults with the downthrown side to the west. The fault zone has an insignificant effect on the ground-water resources in the Brazos River Basin because in most of its extent its trace is in rocks of the Midway Group, which are practically non-water bearing. In a few places, particularly in Lee and Burleson Counties, the faults cut younger rocks and may have a local effect on the movement of the ground water.

GENERAL GROUND-WATER HYDROLOGY

The following discussion of some of the general principles of ground-water hydrology is presented as a review to aid in understanding the hydrologic discussions of the aquifers in the Brazos River Basin.

Source and Occurrence of Ground Water

The source and occurrence of ground water are integral parts of the hydrologic cycle, through which water follows paths of various length and complexity (Figure 10). The primary source of all ground water is precipitation. Water from precipitation, which is not evaporated at the surface, transpired by plants, or retained by capillary forces in the soil, migrates downward by gravity through the zone of aeration until it reaches the zone of saturation where the rocks are saturated with water. The upper surface of the zone of saturation is the water table. Open spaces in the rocks--interstices or pore spaces between grains in clastic rocks, such as sand and gravel, and cracks, fissures, or solution cavities in carbonate and evaporite rocks, such as limestone and gypsum deposits--contain the water in the zone of saturation.

Aquifers may be divided into two classes--water table or unconfined aquifers and artesian or confined aquifers--depending on the mode of occurrence of the water. Unconfined water occurs in water-table aquifers wherever the upper surface of the zone of saturation is under atmospheric pressure only and is free to rise or fall with changes in the volume of water stored. A well penetrating a water-table aquifer becomes filled with water to the level of the water table. Confined water occurs in artesian aquifers which are separated from the zone of aeration by rocks of lower permeability; hence, the water is confined and under pressure. A well that penetrates an artesian aquifer becomes filled with water to a level above the point where the water was found. The level or surface to which the water will rise under pressure is called the piezometric surface. If the pressure is sufficient to cause the water to rise above the land surface, the well will flow.

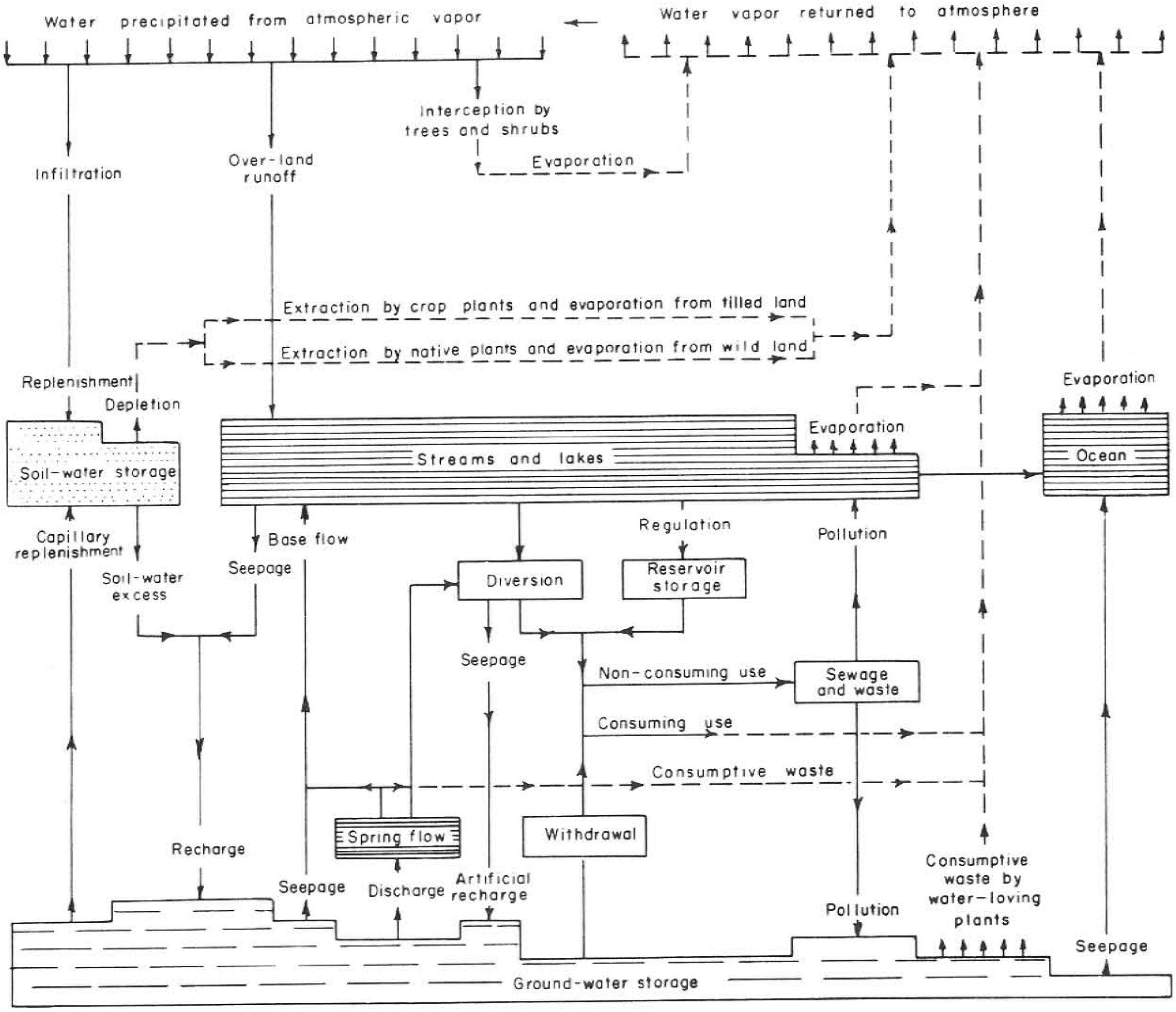

Figure 10

The Hydrologic Cycle in the Brazos River Basin

(Modified from Piper, 1953, p. 9)

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134

Recharge, Movement, and Discharge of Ground Water

Recharge of water to aquifer may result from either natural or artificial processes. Natural recharge comes from rain, either at its place of fall or by runoff en route to a water course, melting snow or ice, water from streams, lakes, or other natural bodies of water, subsurface transfer of water from one saturated rock unit to another, and infiltration resulting from irrigation, and disposal of industrial wastes and sewage. Artificial recharge, or the process of replenishing ground water by planned introduction of water into an aquifer, is accomplished by injection through wells and infiltration basins of various kinds.

The natural source of water for recharge is precipitation. In general, the greater the seasonal precipitation on the intake area of an aquifer, the greater is the recharge. Also, a given amount of rainfall occurring in a short period usually produces less recharge than the same amount of rainfall occurring over a longer period, although there are exceptions. A larger proportion of the precipitation infiltrating during the dormant or nongrowing season will reach the zone of saturation than during the season of active plant growth.

Gravity is the motivating force in the movement of water. After initial infiltration, the dominant direction of movement through the zone of aeration is vertical. After reaching the zone of saturation, the movement of the water generally has a large horizontal component in the direction of decreasing head or pressure. The movement is seldom uniform in direction or velocity. The water may be impeded by structural barriers such as faults and folds or by masses of impervious material, or the water may follow a devious path along courses of material having the least resistance to flow.

The rate of movement of ground water is a direct function of the size of the open spaces and interconnecting passages in rocks. The movement of ground water may range from velocities and volumes approaching zero to those of rapidly flowing streams. In most sand and gravel, the movement of ground water is very slow, ranging from tenths of a foot per day to many feet per year. Faster rates of movement usually are associated with cavernous gypsum or limestone aquifers, where water flowing in subterranean channels may have velocities comparable to surface streams.

Water is discharged from aquifers both naturally and artificially. The most obvious method of natural discharge is by springs. Other means of natural discharge include seepage to streams, lakes, and marshes that intersect the water table, transpiration by vegetation, and evaporation through the soil where the water table is close to the land surface. Ground water also is discharged naturally beneath the land surface by transfer of water from one aquifer to another in response to differences in head. Because gravity is the motivating force in its movement, ground water is always discharged naturally from an aquifer at a lower altitude than the intake or recharge area of that aquifer. Withdrawal of water from pumping and flowing wells represents artificial discharge of ground water.

Changes in Water Levels

Water levels in wells respond continuously to natural and artificial factors acting on the aquifers. In general, the major factors that control changes in water levels are the rates of recharge to and discharge from the aquifers. Changes of water levels are caused also by variations in atmospheric pressure, variations in the load on aquifers commonly caused by changes in the level of streams, lakes, and other bodies of water overlying artesian aquifers, tidal effects, and other less common disturbances. The fluctuations usually are gradual, but in some places the water levels rise or fall from several inches to feet in a few minutes.

Fluctuations due to natural factors generally occur in cycles--daily, annual, or other periods. Daily fluctuations are caused chiefly by barometric fluctuations, tidal effects, or changes in the rate of evapotranspiration. Annual fluctuations are the result generally of changes in the amount of precipitation and evapotranspiration throughout the year; hence, the amount of water available for recharge.

Water-level fluctuations of considerable magnitude may result from withdrawals of water from wells. In water-table aquifers, fluctuations of water level due to pumping are less pronounced generally than in artesian aquifers, the decline of the water level being the result of a decrease in the storage of water. In artesian aquifers, water levels fluctuate primarily from an increase or decrease in pressure; the change in the amount of water in storage may be small even though the change in water level may be great.

Hydraulic Characteristics of Aquifers

The extraction of water from a well establishes a hydraulic gradient toward the well, the gradient being either that of the water table or, in the case of an artesian aquifer, the piezometric surface. In a pumping or flowing well, the elevation of the water table or piezometric surface is lower than before the discharge was started, and the difference between the discharging level and the static level is the drawdown. The water table or piezometric surface surrounding a discharging well assumes more or less the shape of an inverted cone, called the cone of depression.

Formulas have been developed to show the relations among the discharge of a well, the shape and extent of the cone of depression, and the characteristics of the material composing the aquifer, such as permeability (capacity for transmitting water under pressure, quantitatively expressed as the rate of discharge of water in gallons per day through a cross section of 1 square foot under a unit hydraulic gradient), specific yield (the quantity of water that a formation will yield under the pull of gravity if it is first saturated and then allowed to drain), and porosity (the ratio, in percent, of the aggregate volume of interstices in a rock to its total volume). These formulas indicate that, within limits, discharge from a well varies directly, or nearly so, with drawdown--that is, doubling the drawdown of a well will double or nearly double its discharge. The discharge per unit of drawdown, or specific capacity, is of value in estimating the probable yield of a well drilled in a given formation.

Aquifer tests employing these formulas also supply hydraulic information about the aquifer with which the coefficients of transmissibility and storage may be computed. The coefficient of transmissibility is the rate of flow of water in gallons per day through a vertical strip of the aquifer 1 foot wide extending through the vertical thickness of the aquifer at the hydraulic gradient of 1 foot per foot and at the prevailing temperature of the water. Thus, the volume of water that will flow each day through each foot of the water-bearing material is the product of the coefficient of transmissibility and the hydraulic gradient. The transmission capacity of an aquifer is defined as the quantity of water that can be transmitted through a given width of an aquifer at a given hydraulic gradient.

The coefficient of storage is the volume of water that the aquifer releases from or takes into storage per unit surface area, per unit change in the component of the head normal to that surface. Under artesian conditions, the coefficient of storage is a measure of the ability of the formation to yield water from storage by compression of the formation and the expansion of the water as the piezometric surface is lowered. The coefficient of storage for an artesian aquifer is small compared to that of a water-table aquifer; consequently, after a well starts discharging, a cone of depression is developed over a wide area in a short time. In a water-table aquifer, the coefficient of storage is much larger, as it reflects removal of water from storage by gravity drainage of the aquifer, and under these conditions, it is nearly equal to the specific yield.

Figure 11 shows the theoretical relation between drawdown and distance for different coefficients of transmissibility. The calculations of drawdown are based on a withdrawal of 1 million gallons per day over a 1-year period from aquifers having coefficients of transmissibility and storage as shown. For example, if the coefficients of transmissibility and storage are 5,000 gpd per foot (gallons per day per foot) and 0.0001, respectively, the drawdown or decline in the water level would be 85 feet at a distance of 1 mile from a well or group of wells discharging 1,000,000 gallons a day for 1 year.

Figure 12 shows the relation of drawdown to time with pumpage from an artesian aquifer of infinite areal extent. It shows that the rate of drawdown decreases with an increase of time. The equilibrium curve shows the time-drawdown relation when a line source of recharge is 20 miles from the point of discharge.

Figure 13 shows the relation of drawdown to time with pumpage from a water-table aquifer of infinite areal extent. The drawdown is less than that in an artesian aquifer because of the larger coefficient of storage, other factors being equal.

Wells drilled close together commonly create cones of depression that intersect, thereby excessively lowering the water table or piezometric surface. The overlapping of cones of depression or interference between wells may cause a serious decrease in yield of the wells, an increase in pumping costs, or both.

In discussing relative well yields in this report, small yields are less than 100 gpm (gallons per minute), moderate yields are from 100 to 1,000 gpm, and large yields are more than 1,000 gpm.

Chemical Quality of Ground Water

The mineral constituents of ground water are dissolved principally from the soil and rocks through which the water has passed; consequently, the differences in chemical character of ground water reflect in a general way the nature of the geologic formations that have been in contact with the water. Deeply occurring

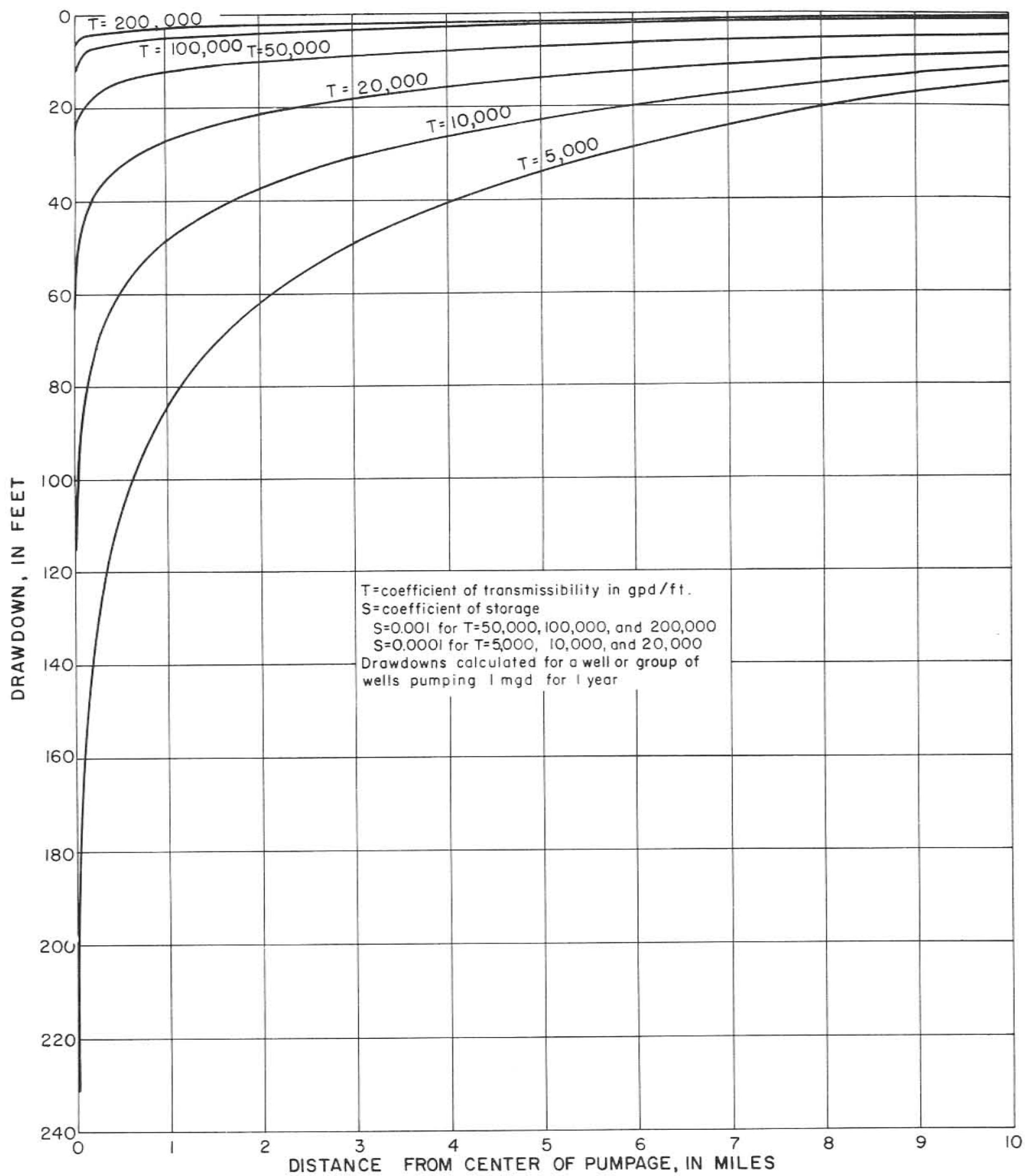

Figure 11

Graph Showing Relation of Drawdown to Transmissibility

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134

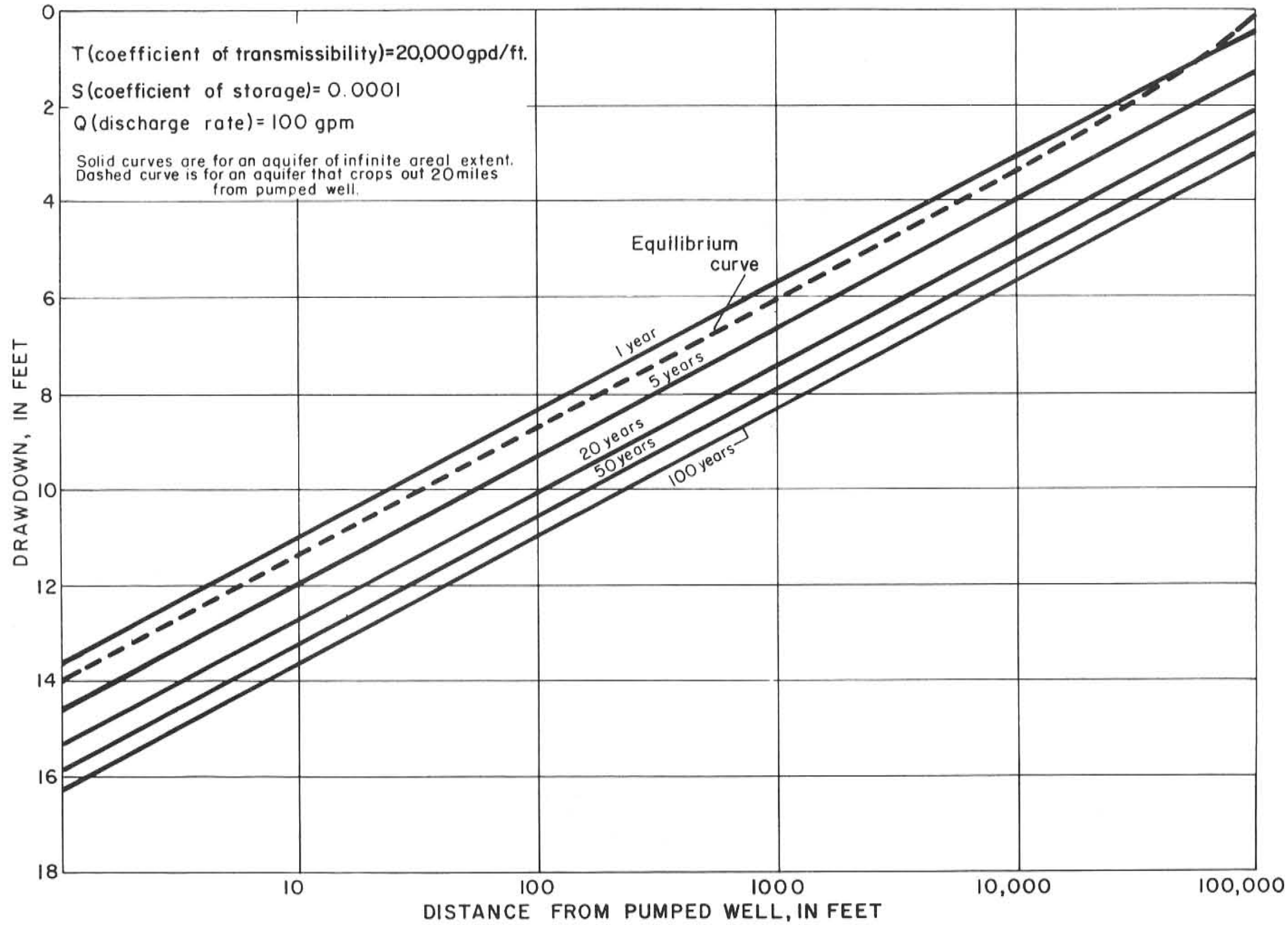

Figure 12

Graph Showing Relation of Drawdown to Time in an Artesian Aquifer

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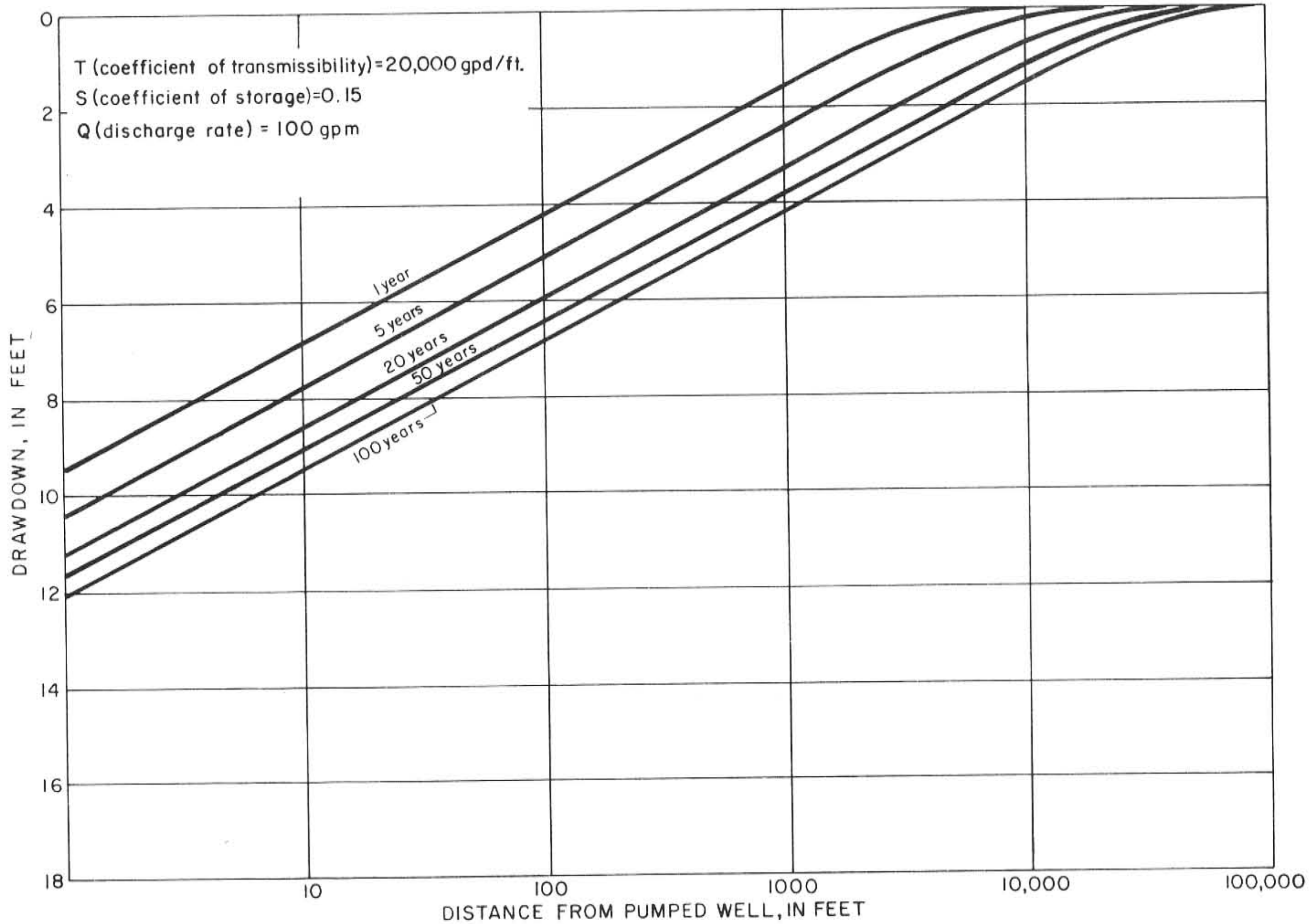

Figure 13

Graph Showing Relation of Drawdown to Time in a Water-Table Aquifer

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134

waters mostly are free from contamination by organic matter, but the chemical content of ground water generally increases with depth. The temperature of ground water near the land surface generally approximates the mean annual air temperature of the region and increases with depth.

The major factors used that determine the suitability of a water supply are the limitations associated with the contemplated use of the water. Various criteria for water-quality requirements have been developed covering most categories of water quality, including bacterial content, physical characteristics, and chemical constituents. Usually, water-quality problems of the first two categories can be alleviated economically, but the removal or neutralization of undesirable chemical constituents can be difficult and expensive. For many purposes the total dissolved-mineral content constitutes a major limitation on the use of the water. A general classification of water based on dissolved-solids content is as follows (Winslow and Kister, 1956, p. 5):

Description	Dissolved-solids content, in parts per million
Fresh	Less than 1,000
Slightly saline	1,000 to 3,000
Moderately saline	3,000 to 10,000
Very saline	10,000 to 35,000
Brine	More than 35,000

The United States Public Health Service has established and from time to time revises standards of drinking water to be used on common carriers engaged in interstate commerce. The standards are designed to protect the traveling public and may be used to evaluate public water supplies. According to the standards, chemical constituents should not be present in a water supply in excess of the listed concentrations shown in the following table except where other more suitable supplies are not available. Some of the standards adopted by the U. S. Public Health Service (1962, p. 2152-2155) are as follows:

Substance	Concentration (ppm)
Chloride (Cl)	250
Fluoride (F)	*
Iron (Fe)	0.3
Manganese (Mn)	0.05
Nitrate (NO_3)	45
Sulfate (SO_4)	250
Total dissolved solids	500

* When fluoride is present naturally in drinking water, the concentration should not average more than the appropriate upper limit shown in the following table.

Annual average of maximum daily air temperatures (°F)	Recommended control limits of fluoride concentrations (ppm)		
	Lower	Optimum	Upper
50.0 - 53.7	0.9	1.2	1.7
53.8 - 58.3	.8	1.1	1.5
58.4 - 63.8	.8	1.0	1.3
63.9 - 70.6	.7	.9	1.2
70.7 - 79.2	.7	.8	1.0
79.3 - 90.5	.6	.7	.8

Water having concentrations of chemical constituents in excess of the recommended limits may be objectionable for various reasons. In areas where the nitrate content of water is in excess of 45 ppm (parts per million), a potential danger exists. Concentrations of nitrate in excess of 45 ppm in water used for infant feeding has 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). High concentrations of nitrate may be an indication of pollution from organic matter, commonly sewage. Excessive concentrations of iron and manganese in water cause reddish-brown or dark-gray precipitates that stain clothes and plumbing fixtures. Water having a chloride content exceeding 250 ppm may have a salty taste, and sulfate in water in excess of 250 ppm may produce a laxative effect. Excessive concentrations of fluoride in water may cause teeth to become mottled; however, fluoride in concentrations of about 1 ppm may reduce the incidence of tooth decay (Dean, Arnold, and Elvove, 1942, p. 1155-1179).

Calcium and magnesium are the principal constituents in water that cause hardness. Excessive hardness causes increased consumption of soap and induces the formation of scale in hot water heaters and water pipes. The commonly accepted standards and classifications of water hardness are shown in the following table.

Hardness range (ppm)	Classification
60 or less	Soft
61 - 120	Moderately hard
121 - 180	Hard
More than 180	Very hard

The quality of water for industry is not necessarily referred to potability. A water suitable for industrial use may or may not be acceptable for human consumption. Ground water used for industry may be classified into three principal categories--cooling water, process water, and boiler water.

Cooling water usually is selected on the basis of its temperature and source of supply, although its chemical quality also is significant. Any characteristic which may affect adversely the heat exchange surfaces is undesirable. Chemical substances such as calcium, magnesium, aluminum, iron, and silica may cause the formation of scale. Corrosiveness, another objectionable feature, is that property which makes the water aggressive to metal surfaces. Calcium and magnesium chloride, sodium chloride in the presence of magnesium, acids, and the gases, oxygen and carbon dioxide, are among the substances that make water corrosive.

The quality of water for the production of steam must meet rigid requirements. Here the problems of corrosion and encrustation are intensified greatly. Some treatment of boiler water may be needed, and it may be better to appraise the water source from the viewpoint of suitability for treatment rather than for direct use of raw water. The presence of silica in boiler water is undesirable because it forms a hard scale or encrustation, the scale-forming tendency increasing with pressure in the boiler.

Process water, water incorporated into or coming in contact with manufactured products, is subject to a wide range of quality requirements. Usually rigidly controlled, these requirements commonly involve physical, chemical, and biological factors. In general, water used in the manufacture of textiles must be low in dissolved-solids content and free of staining effects of iron and manganese. The paper industry, especially where high-grade paper is made, requires water in which all heavy metals are either absent or in small concentrations. Water free of iron, manganese, and organic substances normally is required by many beverage industries. Unlike cooling and boiler water, much of the process water is consumed or undergoes a change in quality in the manufacturing process and generally is not available for reuse.

The suitability of water for irrigation is dependent on the chemical quality of the water and other factors such as soil texture and composition, crop types, irrigation practices, and climate. Many classifications of irrigation water express the suitability of water in terms of one or more of these variables and offer a criteria for evaluating the relative overall suitability of irrigation water rather than placing rigid limits on the concentrations of certain chemical constituents. The most important chemical characteristics pertinent to the evaluation of water for irrigation are the proportion of sodium to total cations, an index of the sodium hazard; total concentration of soluble salts, an index of the salinity hazard; residual sodium carbonate; and concentration of boron.

Sodium can be a significant factor in evaluating the quality of irrigation water because of its potential effect on soil structure. A high percentage of sodium in water tends to break down soil structure by deflocculating the colloidal soil particles. Consequently, soils can become plastic, movement of water through the soil can be restricted, drainage problems can develop, and cultivation can be rendered difficult. A system of classification commonly used for judging the quality of water for irrigation was proposed in 1954 by the U. S. Salinity Laboratory Staff (1954, p. 69-82). The classification is based primarily on the salinity hazard, as measured by the electrical conductivity of the water, and the sodium hazard, as measured by the sodium-adsorption ratio (SAR). This classification of irrigation water is diagrammed in Figure 14.

Wilcox (1955, p. 15) stated that the system of classification used by the Salinity Laboratory Staff "...is not directly applicable to supplemental waters

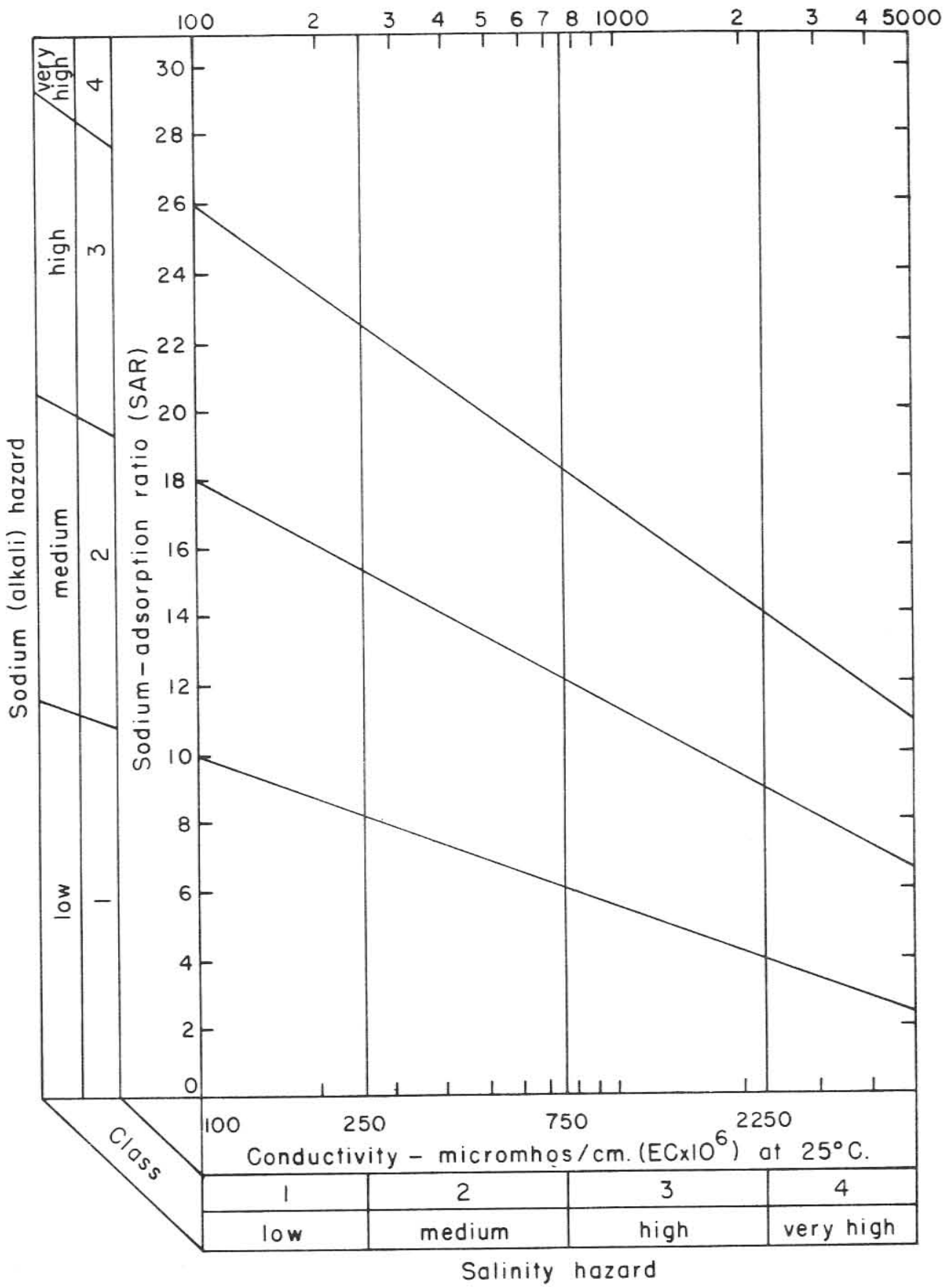

Figure 14

Diagram for the Classification of Irrigation Waters

(After United States Salinity Laboratory Staff, 1954, p. 80)

U. S. Geological Survey in cooperation with the Texas Water Commission

134

used in areas of relatively high rainfall." Thus, in regions III and IV of the Brazos River Basin, the system probably is not directly applicable.

An excessive concentration of boron will render a water unsuitable for irrigation. Scofield (1936, p. 286) indicated that boron concentrations up to 1 ppm are permissible for irrigating most boron-sensitive crops and concentrations up to 3 ppm are permissible for the more boron-tolerant crops. His suggested permissible limits of boron for irrigation waters are shown in the following table:

Classes of water		Sensitive crops (ppm)	Semitolerant crops (ppm)	Tolerant crops (ppm)
Rating	Grade			
1	Excellent	<0.33	<0.67	<1.00
2	Good	0.33 to .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	>1.25	>2.50	>3.75

Quality limits for livestock are variable. The limit of tolerance depends principally on the kind of animal and, according to Heller (1933, p. 22), the total amount of soluble salts in the drinking water, more so than the kind of salt, is the important factor. Heller also suggests that as a safe rule 15,000 ppm dissolved-solids content should be considered the upper limit for most of the more common stock animals.

GROUND-WATER RESOURCES OF THE GEOLOGIC UNITS

Ordovician System

Ellenburger Group

The formations of the Ellenburger Group of Early Ordovician age are the oldest rocks known that yield potable water in the Brazos River Basin. The Ellenburger Group crops out in only a very small area in Burnet County south of Lampasas (Plate 3). Larger, more extensive outcrops of the Ellenburger occur on the flanks of the Llano uplift immediately west of the Brazos River Basin in Burnet and San Saba Counties. The rocks dip toward the east or northeast away from the uplift.

The Ellenburger Group in the Brazos Basin consists of as much as 2,000 feet of chiefly crystalline dolomite, dense fine-grained limestone much of which is fossiliferous, and minor amounts of chert. The Ellenburger Group occurs as a potential water-bearing unit only in parts of major subdivisions 63 in Lampasas County and 65 and 66 in Burnet County. Although the Ellenburger Group yields an abundance of water of satisfactory quality to wells and springs in the region of the Llano uplift in the Colorado River Basin, just west of the Brazos River Basin, no large supplies have been found in the Ellenburger in the Brazos River Basin. In the Lampasas area, several wells have been drilled into the Ellenburger strata, one of which in the northern part of the city of Lampasas was drilled to a depth of about 2,000 feet, penetrating sulphur-bearing water at about 540 feet and saline water at 1,110 and 1,560 feet. Another well, in Burnet County about 14 miles southeast of Lampasas, had a natural flow of about 30 gpm from a depth of 950 to 957 feet in the Ellenburger. The water from this well contained only 326 ppm of dissolved solids and is presently being used for livestock purposes. Little is known concerning the hydrology of the Ellenburger Group; however, the principal areas of recharge probably are along the flanks of the Llano uplift in the Colorado River Basin in Burnet and San Saba Counties. The potential development of the Ellenburger for ground-water supplies is not known; however, it is probable that only small supplies of water could be obtained from it in the Brazos River Basin.

Pennsylvanian System

Bend Group

The Bend Group of Early and Middle Pennsylvanian age in Texas consists of the Marble Falls Limestone and the overlying Smithwick Shale; however, only the Marble Falls Limestone is present in the outcrop in the Brazos River Basin, and it is the only formation of the Bend Group considered in this report.

The Marble Falls Limestone crops out in two small areas in the Brazos River Basin, one at the southwest edge of Lampasas and the other a few miles to the southeast (Plate 3). It is extensively exposed around the flanks of the Llano uplift in the Colorado River Basin, particularly in Burnet and San Saba Counties. At the surface, the Marble Falls is chiefly a fossiliferous limestone containing thin beds of shale; generally, the rocks are dark gray or black, but light-colored strata are also present at some places. In Lampasas County, the formation dips east and northeast at 125 to 150 feet per mile and has a thickness of about 450 feet.

The importance of the Marble Falls Limestone as an aquifer in the Brazos River Basin is limited by the small areal extent of its outcrop, the formation being overlain by more productive aquifers in most of the basin. In the vicinity of Lampasas, it supplies water to many ranch wells and is the primary source of the public supply for Lampasas through the media of springs, which had a combined flow ranging from 3 to 32 mgd (million gallons per day) during the period 1957-60. In the vicinity of Lampasas, the water from the Marble Falls Limestone generally is suitable for most purposes, but as the water moves downdip toward the east and northeast, it becomes increasingly mineralized within relatively short distances.

Data are not sufficient to estimate the potential ground-water development from the Marble Falls Limestone; however, only small supplies of fresh to slightly saline water should be expected from wells in the formation in the Brazos River Basin.

Strawn Group

The Strawn Group of formations of Middle Pennsylvanian age in the Brazos River Basin crops out in a northeastward-trending belt in parts of Parker, Palo Pinto, Eastland, and Erath Counties (Plates 2 and 3). The Strawn Group consists of shale, sandstone, conglomerate, thin beds of coal, and lentils of limestone; it has a total thickness of about 3,000 feet in the Brazos River Basin. The beds dip generally northwest about 75 feet per mile, but locally the dip varies due to thickening and thinning of the formations and to minor geologic structures.

Potable water in the Strawn is found chiefly in sandstones and conglomerates which receive recharge chiefly by precipitation on the outcrop areas. At most places along the outcrop and for short distances downdip, water wells drilled into the sandstones and conglomerates are capable of yielding small supplies of fresh to slightly saline water, but no major wells are known to tap the Strawn.

Table 2 shows chemical analyses of three wells (DY-31-51-804, UK-31-16-401, and UK-31-32-401) tapping the Strawn Group. Two of the samples of water would be classed as fresh, meeting the standards of the U. S. Public Health Service for most constituents. The third sample was slightly saline.

In the Mineral Wells area in Palo Pinto County, the Brazos River Conglomerate Member of the Garner Formation of the Strawn Group is of interest in that it is the source of the famous Mineral Wells mineral water which is sold commercially. The commercial mineral water is especially high in sodium sulfate content and contains smaller amounts of other minerals (Turner, 1934, p. 4). Small supplies of slightly saline water also are derived from the upper part of the Brazos River Conglomerate Member.

The potential development of ground water from the Strawn Group cannot be estimated with existing information; however, only small supplies of fresh to slightly saline water should be expected from the group in the Brazos River Basin.

Canyon Group

The Canyon Group of Late Pennsylvanian age crops out in the Brazos River Basin in a northeastward-trending belt which ranges from about 6 to 20 miles in width, occupying parts of Comanche, Eastland, Stephens, Palo Pinto, Young, and Jack Counties (Plates 2 and 3). The Canyon Group consists chiefly of limestone and shale and minor amounts of sandstone and conglomerate, the group having a total thickness of about 1,000 feet in the Brazos River Valley (Sellards, Adkins, and Plummer, 1932, p. 110). The beds dip generally to the northwest at the rate of about 75 feet per mile.

At some places along the outcrop of the Canyon Group and for short distances downdip, wells are capable of yielding small supplies of fresh to slightly saline water. The city of Perrin in Jack County uses three wells tapping the Canyon Group at depths ranging from 230 to 305 feet. The wells yield about 10 gpm each, and in 1960 the city used an average of about 23,000 gpd. The chemical analysis of water from one of the wells (PL-20-64-801, Table 2) shows that the water is fresh although it exceeds slightly the U. S. Public Health standards for

Table 2.--Chemical analyses of water from selected wells in rocks of Pennsylvanian age, Brazos River Basin
[Analyses given are in parts per million except specific conductance, pH, percent sodium, and sodium adsorption ratio (SAR).]

Well	Screened interval (feet)	Date of collection	Silica (SiO_2)	Iron (Fe) (total)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3) a/	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Boron (B)	Dissolved solids	Hardness as $CaCO_3$	Percent sodium	Sodium adsorption ratio (SAR)	Specific conductance (micromhos at 25°C)	pH
DY-31-51-804	? -193	Jan. 14, 1960	10	--	4.5	0.7	b/ 307		554	0.6	157	2.1	0.0	--	754	14	98	36	1,280	8.4
c/ JD-31-43-401	58	Apr. 29, 1937	--	--	--	--	--	--	201	466	1,170	--	--	--	2,660	--	--	--	--	--
PL-20-53-901	? -245	Feb. 22, 1961	11	--	14	7.6	b/ 267		406	122	130	1.0	2.8	--	759	66	90	14	1,280	7.4
PL-20-64-801	220-230	do	9.4	--	1.0	.7	b/ 223		496	40	28	.7	1.8	--	554	6	99	40	911	8.2
UK-31-16-401	260-380	Dec. 20, 1960	14	d/ 0.00	14	7.0	215	2.3	386	74	95	.8	2.2	0.45	615	69	87	11	1,020	7.7
UK-31-32-401	? -140	Dec. 21, 1960	10	--	14	5.5	b/ 1,150		756	80	1,300	3.8	2.0	--	2,940	58	98	66	4,990	7.7
ZU-20-44-401	360	Aug. 9, 1961	10	--	5.0	1.5	606	3.4	720	204	382	4.1	3.8	1.7	1,580	18	98	62	2,630	7.9
ZU-20-44-901	264	do	8.9	--	40	20	107	4.0	300	104	46	.7	.8	.48	480	182	55	3.4	799	7.0

a/ Includes the equivalent of any carbonate (CO_3) present.
b/ Sodium and potassium calculated as sodium (Na).
c/ Analyzed by Work Projects Administration.
d/ Iron in solution.

dissolved solids. Much of the water pumped from the small wells drilled for domestic use is of poor quality, and with increasing distance downdip from the outcrop, the water tends to become even more saline. At some places, very saline water has been reported at depths of less than 500 feet.

The potential development from the Canyon Group cannot be estimated from presently available data, but probably only small supplies should be expected from the group and much of the water will be at least slightly saline.

Cisco Group

The Cisco Group of formations of Late Pennsylvanian age crops out in a northeastward-trending belt which ranges from about 8 to 40 miles in width. The group is exposed in parts of Callahan, Eastland, Stephens, Shackelford, Throckmorton, Young, Jack, and Archer Counties, although it is mapped with the Wichita Group on Plates 2 and 3 and Figure 7. The Cisco Group consists of shale, sandstone, limestone, conglomerate, and beds of coal, the group reaching a thickness of about 1,200 feet in the Brazos River Basin. The group dips generally northwest at the rate of about 75 feet per mile.

The Cisco Group is probably the most productive of the Pennsylvanian rocks in the Brazos River Basin, yielding small supplies of fresh to slightly saline water to numerous domestic and livestock wells and to a few public-supply and industrial wells. In Stephens County, wells from about 12 to 365 feet deep in and near the outcrop of the Cisco Group yield small quantities of water for domestic and livestock use; however, the quality of the water is very poor and most farm residents prefer to use cisterns and surface-water supplies from earthen tanks. The lack of wells in the western half of Stephens County indicates the presence of less favorable ground-water conditions than elsewhere in the county, and salt water has been reported from wells in some parts of the area at a depth of about 200 feet.

In Young County, the sands of the Cisco Group at most places along the outcrop are reported to yield small supplies of water which generally range from slightly saline to saline. The wells range from about 20 to 300 feet in depth, and the thickness of the water sands ranges from 10 to 30 feet (Criswell, 1942, p. 3). The town of Jean in Young County, about 9 miles southeast of Olney, is supplied by a well 360 feet deep in rocks of the Cisco Group. The well yields about 30 gpm and in 1960 pumped an average of about 10,000 gpd. The chemical analysis of water from this well (ZU-20-44-401, Table 2) shows that the water was very soft but slightly saline, exceeding the U. S. Public Health Service standards for dissolved-solids, chloride, and fluoride content.

In Jack County, the town of Bryson is supplied by wells tapping the Cisco Group at depths ranging from about 215 to 365 feet. The wells range in yield from 5 to 8 gpm, and in 1960 the city used an average of about 24,000 gpd. The water is classed as fresh, although the dissolved-solids content exceeded the standards of the U. S. Public Health Service, as indicated by the chemical analyses in Table 2 (PL-20-53-901).

The potential development of ground water from the Cisco Group cannot be determined from existing data, but the group should be expected to yield only small supplies of water in the Brazos River Basin.

Permian System

Wichita Group

The Wichita Group of Early Permian age crops out in the Brazos River Basin in parts of Callahan, Taylor, Shackelford, Jones, Haskell, Throckmorton, Baylor, and Archer Counties; it is shown mapped with the underlying Cisco Group in Plate 2 and Figure 7. The outcrop trends in a general northerly direction and forms a belt ranging in width from about 8 to 20 miles. The group consists predominantly of gray and red shale, but limestone, sandstone, siltstone, conglomerate, and coal also are present. The thickness of the group ranges from zero to about 1,800 feet. The dip is west-northwest at a rate of about 50 feet per mile; however, minor structures cause local variations in the direction and amount of dip.

The Wichita Group yields only very small quantities of saline water to a few domestic and livestock wells which tap the limestones and sandstones of the group.

Clear Fork Group

The Clear Fork Group of Permian (Leonard) age lies conformably on the underlying Wichita Group in the Brazos River Basin. The outcrop area of the group in the basin is a north-south trending belt about 30 to 35 miles wide, extending the full width of the basin through Taylor, Jones, Haskell, Knox, and Baylor Counties (Plate 2). The Clear Fork Group consists of the Arroyo, Vale, and Choza Formations, which consist mainly of shale and relatively thin layers of limestone, dolomite, gypsum, marl, and some sandstone. The maximum thickness of the group is about 1,800 feet.

The Clear Fork Group, in general, yields small quantities of water for domestic and livestock uses; however, in Jones County small to moderate quantities of water for irrigation and industrial use are obtained from shales in the Clear Fork Group. The wells range in depth from 42 to 125 feet. The depth to water below land surface in 1959-60 ranged from 9 to 62 feet. One well was reported to yield 500 gpm when drilled, probably from the Bullwagon Dolomite Member of the Vale Formation, but the yield eventually declined to an estimated 60 gpm (Winslow, Doyel, and Gaum, 1954, p. 11).

The chemical analyses of several samples of water obtained from wells pumping from the Clear Fork Group are shown in Table 3. The locations of these wells are shown on Plate 2 with a bar above the well symbol. The analyses show that the water in well LP-21-58-301 probably is fresh, but in the rest of the wells it is very hard and ranges from slightly to moderately saline. In all of the samples, the dissolved-solids content, estimated from the specific conductance in some cases, exceeded the limit recommended for drinking water by the U. S. Public Health Service. The sulfate and chloride content of most of the samples was above the recommended limit, and the nitrate exceeded the recommended limit in two samples.

In 1959, about 420 acre-feet of water was pumped from the Clear Fork Group. A little less than 2 percent of the water pumped was used for industrial purposes; the remainder was used for irrigation.

Table 3.--Chemical analyses of water from selected wells in rocks of Permian age, Brazos River Basin
[Analyses given are in parts per million except specific conductance, pH, percent sodium, and sodium adsorption ratio (SAR).]

Water-bearing unit: Pc, Clear Fork Group; Pp, Pease River Group; Pw, Whitehorse Group.

Well	Depth of well (ft.)	Date of collection	Water-bearing unit	Silica (SiO_2)	Iron (Fe) (total)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3) a/	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Boron (B)	Dissolved solids	Hardness as $CaCO_3$	Percent sodium	Sodium adsorption ratio (SAR)	Specific conductance (micromhos at 25°C)	pH
AU-21-30-601	24	Mar. 14, 1950	Pc	31	b/ 0.02	154	76	596	6.0	543	524	640	1.4	129	0.83	2,430	696	65	9.8	3,810	7.6
JU-29-13-301	87	Dec. 16, 1943	Pw	--	--	810	232	c/ 350		135	1,780	1,220	--	64	--	4,520	2,980	20	2.8	--	--
JU-29-21-601	100	Nov. 25, 1943	Pw	--	--	558	147	c/ 404		112	2,310	268	--	1.0	--	3,740	2,000	31	3.9	--	--
LP-21-44-701	41	Nov. 8, 1956	Pc	26	.07	33	24	547	2.2	525	355	382	.4	28	--	1,660	180	87	18	2,660	7.9
LP-21-44-801	45	Oct. 31, 1956	Pc	--	--	--	--	--	--	524	--	495	--	--	--	--	210	--	--	3,370	8.8
LP-21-58-301	30	Oct. 29, 1956	Pc	--	--	--	--	--	--	440	--	72	--	--	--	--	205	--	--	1,300	8.6
LP-30-01-301	50	Nov. 27, 1956	Pc	--	--	--	--	--	--	146	--	690	--	--	--	--	2,100	--	--	5,020	7.7
PY-29-31-901	91	July 30, 1953	Pp(?)	17	11	880	371	c/ 1,140		314	1,740	1,870	2.8	1,840	--	8,020	3,720	40	8.1	10,400	7.4
d/ PY-30-09-902	85	--	Pc	--	--	592	91	c/ 277		256	1,590	391	.8	49	--	3,450	1,850	25	--	--	7.5
PY-30-25-101	120	June 24, 1953	Pc	24	b/ .00	94	39	36	--	270	130	67	1.4	34	.25	584	395	16	.8	921	7.3
RH-22-42-303	220	June 1, 1961	Pw	26	--	592	136	c/ 135		80	1,820	260	1.1	.0	--	3,010	2,040	13	1.3	3,290	6.9
RL-22-38-301	30	June 13, 1961	Pp	13	--	580	47	c/ 60		243	1,490	14	.4	.0	--	2,320	1,640	7	.6	2,450	7.0
RS-21-26-401	34	Oct. 11, 1945	Pc	--	--	181	103	c/ 102		355	475	220	--	.5	--	1,260	875	20	1.5	--	--
RS-21-26-501	22	do	Pc	--	--	284	97	c/ 206		204	986	248	--	17	--	1,940	1,110	29	2.7	--	--
RS-21-26-502	23	do	Pc	--	--	--	--	--	--	222	2,030	352	--	3.0	--	--	2,020	--	--	--	--
e/ XR-22-46-101	--	July 22, 1959	Pp	--	--	--	--	94	12	--	1,720	110	--	--	--	--	1,940	9	.9	3,040	--

a/ Includes the equivalent of any carbonate (CO_3) present.
b/ Iron in solution.
c/ Sodium and potassium calculated as sodium (Na).
d/ Analysis by Texas State Department of Health.
e/ Spring in cliff at falls on Salt Croton Creek.

Pease River Group

The Pease River Group (Leonard Series) is separated from the underlying Clear Fork Group by a pronounced erosional unconformity. The formations in this group, in ascending order, are the San Angelo Sandstone, Flowerpot Shale, Blaine Gypsum, and Dog Creek Shale. The formations consist mainly of shale, anhydrite, gypsum, limestone, dolomite, and sandstone. The total thickness of the Pease River Group is about 900 feet. The outcrop area is about 20 miles wide along the north edge of the Brazos River Basin, narrowing to about 12 miles in width in Nolan County where the group is overlapped by Cretaceous rocks (Plate 2).

No major wells are known to be pumping water from the Pease River Group in the Brazos River Basin. The San Angelo Sandstone, the oldest formation of the group, yields small quantities of generally slightly to moderately saline water; however, in a few places the quality of the water is such that it can be used for domestic purposes. Small quantities of water are obtained from shallow wells in other formations of the group, but the quality of the water is poor.

The chemical analyses of two samples of water obtained from wells pumping from the Pease River Group and one spring in the group are shown in Table 3. The locations of the wells and springs are shown on Plate 2. The analyses show that the water from the Pease River Group is very hard and slightly to moderately saline. The dissolved-solids content in both samples exceeded the limit recommended by the U. S. Public Health Service for drinking water. The sulfate content in both samples and the chloride content in one sample were also above the limit recommended for drinking water. The nitrate content of 1,840 ppm (parts per million) in one sample was excessively high.

Brine springs issuing from rocks of the Pease River Group contaminate the water in the Brazos River and its tributaries. In northern Stonewall County and southern King County, large salt flats along tributaries of the Salt Fork of the Brazos River are a major source of contamination of the water in the river.

Whitehorse Group

The Whitehorse Group, the youngest of the Permian System in the Brazos River Basin, overlies the Pease River Group. The outcrop area of the Whitehorse Group is a north-south trending belt from 30 to 40 miles wide near the western edge of the Osage Plains where Triassic rocks overlie the Permian rocks (Plates 1 and 2).

In the Brazos River Basin, the Whitehorse Group consists of as much as 1,000 feet of fine sand, gypsum, anhydrite, shale, and dolomite.

Only one major well, an irrigation well in Kent County, is known to be pumping water from the Whitehorse Group. The well was drilled to a depth of 133 feet and the water level was about 87 feet below land surface in 1961. The total amount of water pumped from the well for irrigation use in 1959 was estimated to be 35 acre-feet, less than 1 percent of the total amount of ground water pumped by major wells from the Permian rocks in the Brazos River Basin.

Another well in the vicinity of the above well was reported to have yielded 130 gpm during a 24-hour test. This well, now used for domestic purposes, was drilled to a depth of 220 feet. The depth to water below land surface in 1958 was about 48 feet. Small quantities of water are obtained from the Whitehorse Group in some places for domestic or livestock use, but no public-supply wells tap the group.

The chemical analyses of three samples of water obtained from the Whitehorse Group are shown in Table 3. The locations of these wells are shown with a bar over the well symbol on Plate 2. The results of the chemical analyses show that the water from the Whitehorse Group is moderately saline and very hard. The concentrations of dissolved solids, sulfate, and chloride were above the limits recommended for drinking water by the U. S. Public Health Service in all of the samples. The nitrate content exceeded the limit on one sample.

Availability of Water From the Permian Rocks

The availability of ground water from Permian rocks in the Osage Plains of the Brazos River Basin may be summarized as follows: In general, the rocks have low permeabilities and will yield only small quantities of water. Where permeable zones exist in the sand or cracks or crevices occur in the shale, small to moderate amounts of water may be obtained. The quality of the water generally is poor in shallow wells and can be expected to deteriorate with depth. In general, the water would be undesirable for public supply because of the quantity available, quality, or a combination of both. The water would, in general, be limited to irrigation of land having good drainage on which crops with a tolerance for salt are grown. The water would be limited also for some industrial uses.

Triassic System

Dockum Group

The Dockum Group, of Late Triassic age, is a secondary aquifer in the Brazos River Basin in Texas. In the High Plains, no wells are known that produce water from the Dockum Group; however, east of the escarpment of the High Plains, the Dockum furnishes small to moderate quantities of water for irrigation, public supply, and industrial use.

Rocks of the Dockum Group underlie the entire High Plains section of the Brazos River Basin in Texas and parts of Scurry and Fisher Counties, and crop out east of the escarpment of the High Plains (Plates 1 and 2). The Dockum Group, consisting mainly of clay, shale, sandy shale, cross-bedded sandstone, conglomerate, and minor amounts of gypsum and anhydrite, is of continental origin and was probably laid down as river-channel and flood-plain deposits. It is underlain unconformably by Permian rocks and unconformably overlain by rocks of Cretaceous or Cenozoic age. The thickness of the Dockum Group ranges from zero at the outcrop to at least 1,600 feet.

Although no wells are known that produce water from the Dockum Group in the High Plains, several exploratory wells have been drilled to test the group as a source of water, and from these tests water samples for chemical analyses and information concerning the water-bearing properties of the rocks have been obtained.

Electric logs of tests for oil and gas also have been used to determine the quality of the water in the Dockum Group in the High Plains.

The chemical analysis of a water sample from a well (SP-23-17-901) about 4 miles northwest of the city of Lubbock drilled to a depth of 2,000 feet, showed a dissolved-solids content of 20,600 ppm and a chloride content of 10,800 ppm (Table 4). The water was obtained from a sandstone of the Dockum Group at a depth of 953 to 999 feet. In southwestern Floyd County, a sample of water from a well (JW-23-04-901) drilled to a depth of 800 feet contained 6,020 ppm dissolved solids, 3,020 ppm chloride, and 2,170 ppm sodium (Table 4). Broadhurst (1957c, p. 4) in summarizing the results of the test has said, "(1) the static water level stood 290 feet below the land surface; (2) with a pumping level of 480 feet, the well produced only 75 gallons of water a minute; and (3) the water was too salty for irrigation."

Electric logs of tests for oil and gas in Lamb County indicate the presence of water in the Dockum too saline for irrigation or public use (Leggat, 1957, p. 13). An exploratory well testing the Dockum Group in eastern Bailey County was reported to have yielded an insufficient supply of water for irrigation after a 10-minute period of pumping. The chemical analysis of a water sample obtained from a drill-stem test of the Dockum Group in Cochran County showed 2,070 ppm of dissolved solids and 590 ppm of chloride. In a preliminary pumping test, the well produced only 15 gpm with a large drawdown.

Although the Dockum Group has been tested in only a few places in the High Plains section of the Brazos River Basin, the information currently available indicates that the yield of wells pumping from aquifers in the Dockum Group in the High Plains would range from low to moderate. Furthermore, the water would be rather saline, probably unsuitable in most instances because of the quality or quantity, or a combination of both, to be used for irrigation or public supply. Because of the quality, it probably would be limited to certain industrial uses.

In Scurry and Nolan Counties where the Triassic rocks crop out in a southeast-trending belt and also underlie the Ogallala Formation, wells ranging in depth from less than 100 feet to more than 300 feet pump small to moderate quantities of water for irrigation, public supply, and industrial use. The location of these and other major wells that tap the Triassic rocks are shown in Plates 1 and 2. According to measurements made in 1960 or 1961, the depth to water below land surface in wells tapping the Triassic rocks in this area ranged from about 50 feet to slightly more than 200 feet.

In eastern Scurry County in region II (Plate 2), the Dockum Group was described by Lang (1944, p. 4-6) as consisting of dark-red clay only slightly sandy, gray and red medium to coarse-grained sandstone, and a basal conglomerate, the sandstone being thin bedded to massive and in places cross-bedded and micaceous. From his study of the Triassic along the outcrop and a limited number of well logs, Lang indicated that the strata are extremely irregular and that they cannot be traced for any considerable distance. He also indicated that the Dockum contained two water-bearing strata. Whether conditions would be similar in other places where the Triassic occurs is not known.

Table 4.--Chemical analyses of water from selected wells in rocks of Triassic age, Brazos River Basin

[Analyses given are in parts per million except specific conductance, pH, percent sodium, and sodium adsorption ratio (SAR).]

Well	Depth of well (ft.)	Date of collection	Silica (SiO_2)	Iron (Fe) (total)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3) [a]	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Boron (B)	Dissolved solids	Hardness as $CaCO_3$	Percent sodium	Sodium adsorption ratio (SAR)	Specific conductance (micromhos at 25°C)	pH
JU-29-19-901	90	Nov. 24, 1943	--	--	84	60	[b] 122		396	199	135	--	0.2	--	795	456	37	2.5	--	--
JU-29-20-501	62	Oct. 7, 1943	--	--	80	77	[b] 51		393	193	69	--	8.4	--	722	516	18	1.0	--	--
JW-23-04-901	800	Sept. 5, 1957	13	--	87	45	2,170	10	419	463	3,020	2.0	--	--	6,020	402	92	47	9,910	7.9
[c] SP-23-17-901	2,000	Feb. --, 1949	8.4	1.4	284	122	[b] 7,420		230	1,850	10,800	.6	--	2.1	20,600	1,210	93	92	31,400	7.4
UA-29-36-601	165	Mar. 22, 1960	21	[d] .00	94	27	31	6.0	258	74	75	1.6	20	.34	511	346	16	.7	8,170	7.1
UA-29-36-905	180	Apr. 13, 1960	15	--	79	12	16	2.0	275	22	19	--	4.0	.00	307	246	12	.4	529	7.1
WZ-29-01-601	147	July 23, 1960	26	--	74	32	[b] 33		351	67	21	.3	.0	--	426	316	18	.8	682	7.2
WZ-29-09-201	285	do	12	--	9.5	4.5	[b] 149		318	44	40	.7	.5	--	416	42	89	10	669	8.0
WZ-29-10-401	190	do	26	--	62	19	[b] 40		282	47	24	1.0	2.2	--	360	232	27	1.1	573	7.3
WZ-29-10-503	320	May 4, 1961	14	--	30	10	122	2.5	326	68	32	1.7	.0	--	440	116	69	4.9	726	7.6
[e] WZ-29-19-101	Spring	Dec. 20, 1943	--	--	63	21	[b] 16		253	29	25	--	6.9	--	286	244	13	.4	--	--
WZ-29-19-202	41	Dec. 2, 1943	--	--	69	17	[b] 31		275	29	32	--	12	--	326	242	22	.7	--	--

[a] Includes the equivalent of any carbonate (CO_3) present.
[b] Sodium and potassium calculated as sodium (Na).
[c] Drill-stem test 953 to 999 ft.
[d] Iron in solution.
[e] Known as Green Spring.

The city of Rotan in Fisher County developed a well field in the Triassic rocks in eastern Scurry County in about 1940, from which water was piped 15 miles to the town. According to reports, the yields of the wells have declined and the city is seeking a new source of water supply. According to Knowles (1947, p. 1), the Gulf Refining Co. formerly obtained water for its Sweetwater refinery from 10 wells about 3 miles south of Roscoe in Nolan County (Plate 2). These wells ranged in depth from 225 to 250 feet and they had an average yield of about 85 gpm each, when first put into operation, but the yields had decreased to less than 50 gpm at the time of abandonment. Information is not available to determine whether these conditions prevail throughout the aquifer or if it is a local condition due to overdevelopment in a small area.

The quantity of water pumped in 1959 from the Triassic rocks in the Brazos River Basin for irrigation, industrial, and public supplies was estimated at 3,400 acre-feet, all of which was from wells in major subdivisions 11, 27, and 28 (Table 20). Of this pumpage, about 2 percent was for industrial and public-supply use.

The chemical analyses of water samples from 11 wells and 1 spring that tap the Triassic rocks are given in Table 4. The locations of the wells and spring are shown on Plates 1 and 2. The results of the chemical analyses indicate that the water from the Triassic rocks in Scurry, Nolan, and Fisher Counties would be classed as fresh, although in some samples the fluoride or dissolved-solids content exceeded the standards for drinking water established by the U. S. Public Health Service. The fluoride content was 1.7 and 1.6 ppm in samples from wells WZ-29-10-503 (Scurry County) and UA-29-36-601 (Nolan County), and the dissolved-solids content was 795 and 722 ppm in wells JU-29-19-901 and JU-29-20-501 in Fisher County. These two wells are near the east edge of the Triassic outcrop where the sandstone beds are thin, and it is possible that the relatively high dissolved-solids content as well as the high sulfate content may be due to contamination from underlying gypsiferous Permian beds.

A comparison of the chemical analyses of water from the Triassic rocks east of the escarpment of the High Plains with those from the Triassic rocks in Floyd and Lubbock Counties (JW-23-04-901 and SP-23-17-901) indicates that the water in the Triassic rocks underlying the High Plains section in the basin is much more saline than the water east of the escarpment.

Only a meager amount of information is available concerning the ground water in the Dockum Group in the High Plains section of the Brazos River Basin. East of the escarpment, where several wells pump from the Dockum Group, some information is available concerning mainly the depth and yield of the wells and chemical quality of the water. The areal extent of the aquifer from which water of good quality can be obtained is unknown, and there is practically no information concerning recharge and movement of the water and the hydraulic properties of the water-bearing materials. Therefore, it is not possible to estimate the availability of water from the group. Consideration of these needs should be given in planning future detailed studies.

Cretaceous System

Trinity Group and Equivalents

Physical Description

The Trinity Group crops out principally in the northwestern part of region III (Plate 3) of the Brazos River Basin, and rocks of Trinity age extend northwestward into Jack, Palo Pinto, Erath, Eastland, Stephens, and Callahan Counties in region II (Plate 2). South and east of its outcrop where water-table conditions prevail, the Trinity Group dips gulfward beneath younger rocks where it is an artesian aquifer (Figure 8). North and west of the main outcrop, rocks of Trinity age occur as outliers in Callahan, Taylor, Nolan, and Stonewall Counties in region II. Rocks of Trinity age also underlie the High Plains section, but this area will be discussed in the section on Cretaceous rocks in the High Plains. The Trinity Group is a primary aquifer in the West Gulf Coastal Plain, generally yielding small to large quantities of water for public-supply, irrigation, industrial, domestic, and livestock purposes.

The Trinity Group consists of a basal conglomerate and gravel overlain predominantly by fine to coarse white to light-grayish, poorly consolidated, massive, cross-bedded sand interbedded with variegated clay. Overlying these sandy beds is a sequence of alternating beds of limestone, clay, and some sand, this unit, in turn, being overlain by fine to medium sand and interbedded shale. The Trinity attains a maximum thickness of about 2,350 feet near the downdip limit of fresh to slightly saline water (Figure 8 and Plate 5) in Falls County. Where it contains fresh to slightly saline water, the altitude of the Trinity ranges from about 1,400 feet above sea level in the outcrop in Eastland County to about 2,200 feet below sea level in Milam County (Plate 5). The dip of the Trinity Group is southeastward, ranging from about 25 to 30 feet per mile west of the Balcones fault zone (Figure 8) to more than 60 feet per mile east of the fault zone (Plate 5).

The Trinity Group is divided into the Travis Peak Formation, Glen Rose Limestone, and Paluxy Sand, which are listed from oldest to youngest (Table 1). The division applies only to the main area of outcrop and the eastward extension of the Trinity Group in the subsurface. Where the rocks of Trinity age occur as outliers north and west of the area, they are not divided into formations. The group is shown also as a unit in the geologic maps (Plates 1, 2, and 3).

In Callahan, Taylor, and Nolan Counties, the undivided Trinity Group furnishes small quantities of fresh water for public supply and industrial use. The maximum thickness is not known, but wells range in depth from less than 50 feet near Baird in Callahan County to almost 300 feet in Nolan County. Analyses of water from five wells in Callahan (BX), Taylor (UA), and Nolan (XW) Counties are shown in Table 5. In general, the water is very hard and the dissolved-solids content is less than 1,000 ppm.

The Travis Peak Formation, referred to locally by well drillers as the Trinity sand, consists of a basal conglomerate, gravel, fine to coarse white to reddish sand, locally interbedded with calcite and red and green shale. The

Table 5.--Chemical analyses of water from selected wells in the Trinity Group and equivalents, Brazos River Basin

[Analyses given are in parts per million except specific conductance, pH, percent sodium, and sodium adsorption ratio (SAR).]

Well	Screened interval (feet)	Date of collection	Silica (SiO_2)	Iron (Fe) (total)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3) a/	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Boron (B)	Dissolved solids	Hardness as $CaCO_3$	Percent sodium	Sodium adsorption ratio (SAR)	Specific conductance (micromhos at 25°C)	pH
AX-40-60-904	b/ 743-965	May 25, 1954	13	0.10	13	7.9	c/ 683		436	286	628	3.6	0.2	--	1,850	65	96	37	3,160	8.2
AX-40-62-801	2,200-2,366	Apr. 21, 1961	16	.13	5.8	2.2	379	3.1	432	211	205	1.8	1.2	0.80	1,040	24	97	34	1,740	8.1
AX-58-07-301	b/ 2,886-3,496	Nov. 9, 1960	23	--	10	2.6	c/ 395		492	304	118	2.8	.0	--	1,100	36	96	29	1,810	8.0
BB-32-61-701	680-780	Apr. 27, 1960	12	--	2.5	1.9	c/ 198		391	75	32	--	.0	--	513	14	97	23	840	8.2
BB-40-12-101	110-130	Apr. 6, 1960	10	--	2.2	2.1	c/ 272		532	122	21	4.0	3.2	--	698	14	98	32	1,100	8.0
BX-30-36-901	25	Feb. 5, 1946	28	.05	152	28	121	11	478	123	162	.6	26	--	919	494	34	2.4	1,360	7.3
BX-30-37-801	63	Aug. 11, 1961	23	.84	120	24	c/ 138		358	126	169	.5	40	--	850	398	43	3.0	1,380	6.6
DY-31-53-706	40-128	Dec. 9, 1959	17	--	78	6.9	16	3.1	234	18	25	--	20	.22	299	223	13	.5	453	--
HB-40-35-802	b/ 478-677	Sept. 9, 1955	14	.05	13	7.2	c/ 483		445	309	295	3.0	4.0	--	1,350	62	94	27	2,250	7.6
JD-30-56-901	35- 65	Jan. 10, 1961	19	--	95	23	44	2.7	385	24	57	--	22	.10	496	332	22	1.1	822	7.1
JP-31-61-301	96-188	Dec. 1, 1959	14	--	93	33	18	2.6	330	20	80	--	8.8	.06	431	368	10	.4	794	6.9
JR-38-64-601	3,352-3,692	June 13, 1944	--	--	270	42	c/ 1,420		209	3,320	214	--	.2	--	5,370	846	78	21	--	--
LA-41-21-601	250-470	Jan. 25, 1960	14	--	104	8.6	c/ 32		313	36	24	.5	44	--	417	296	19	.8	680	7.1
LA-41-22-501	? -200	Mar. 19, 1946	12	3.6	63	24	147	16	411	144	74	.6	2.5	--	686	256	54	4.0	1,110	7.7
d/ LW-40-08-801	1,955-2,083	Feb. --, 1959	--	.01	3.0	1.0	c/ 213		364	75	52	.8	1.1	--	594	11	--	--	990	8.0
LY-32-26-801	55-100	Oct. 5, 1960	17	--	67	9.6	59	2.1	328	36	20	--	1.8	0.22	374	206	38	1.8	613	6.9
PX-32-36-501	440-490	Sept. 13, 1942	12	2.6	18	8.3	c/ 121		342	33	18	.4	.0	--	382	79	77	5.9	--	7.9
PX-32-37-302	? -630	Feb. 11, 1943	9.2	.05	1.7	.7	175	4.2	414	33	12	.4	2.0	--	442	7	97	29	--	9.0
PX-32-53-302	? -510	Apr. 19, 1961	12	.02	1.5	.4	268	1.5	540	79	44	2.2	3.0	1.0	692	5	99	52	1,110	8.5
ST-40-24-803	2,253-2,492	Apr. 6, 1961	22	.08	2.8	.8	c/ 235		444	81	50	.9	.0	--	611	10	98	32	988	8.1
d/ TK-58-07-901	3,191-3,413	Jan. --, 1959	--	.94	60	17	c/ 534		245	900	151	1.8	.4	--	1,980	220	--	--	3,300	7.3
UA-29-53-102	262	Mar. 21, 1960	13	--	74	19	c/ 20		282	28	30	--	4.5	--	334	262	14	.5	579	7.1

See footnotes at end of table.

Table 5.--Chemical analyses of water from selected wells in the Trinity Group and equivalents, Brazos River Basin--Continued

Well	Screened interval (feet)	Date of collection	Silica (SiO_2)	Iron (Fe) (total)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3) a/	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Boron (B)	Dissolved solids	Hardness as $CaCO_3$	Percent sodium	Sodium adsorption ratio (SAR)	Specific conductance (micromhos at 25°C)	pH
XJ-32-50-303	? -325	Mar. 3, 1949	15	--	24	22	c/	99	391	20	16	--	1.2	1.4	391	150	59	3.5	652	7.7
XW-29-56-301	90	Aug. 10, 1961	11	--	61	18	c/	14	262	9.2	16	0.5	12	--	272	226	12	.4	477	7.0
e/ XW-30-41-801	304	June 23, 1961	--	--	--	--	--	--	340	41	18	--	--	--	--	292	--	--	641	6.7
ZK-58-29-604	b/ 2,780-3,346	Mar. 1, 1960	24	f/ 0.11	18	1.9	455	5.8	452	341	230	3.2	.0	--	1,300	53	94	27	2,140	8.1

a/ Includes the equivalent of any carbonate (CO_3) present.
b/ Not screened throughout interval.
c/ Sodium and potassium calculated as sodium (Na).
d/ Analyzed by Texas State Chemist.
e/ Geologic formation uncertain.
f/ Iron in solution.

thickness of the formation increases downdip, ranging from about 230 feet near its outcrop to almost 1,200 feet in Falls County at the site of well 46 in section C-C' (Figure 8). Electric and drillers' logs show that in McLennan and adjoining counties, the Travis Peak contains two easily identified sand bodies, an upper and lower, each of which yields small to moderate quantities of fresh to slightly saline water to wells. Where large yields are required, however, both sand bodies are screened.

The Travis Peak Formation is the chief aquifer in the Trinity Group and is the principal source of moderate to large supplies of fresh to slightly saline ground water in approximately the northwest two-thirds of region III of the Brazos River Basin. Yields of wells that tap the entire thickness of the Travis Peak Formation range from less than 100 gpm in and near the outcrop to as much as 1,000 gpm of water of good quality in Temple in Bell County. Yields of more than 2,000 gpm have been reported in several wells further downdip, but the water was too highly mineralized for public supply or irrigation.

The Glen Rose Limestone consists of alternating beds of limestone, marl, clay, anhydrite, and some sand. In the subsurface, the Glen Rose has a maximum thickness of at least 800 feet in eastern McLennan County and possibly as much as 1,200 feet in Falls County (Figure 8). The Glen Rose Limestone is not a significant aquifer in the Brazos River Basin, although it yields small quantities of fresh water to shallow wells in places in the outcrop. In the downdip part of the aquifer, however, the Glen Rose furnishes small to moderate quantities of slightly saline water to a few widely scattered wells. The wells are used only to supplement the supply from the Travis Peak Formation.

The Paluxy Sand, the youngest formation of the Trinity Group, crops out principally in Hood, Bosque, Erath, and Hamilton Counties. It consists of light gray to reddish, cross-bedded, unconsolidated to slightly indurated, fine to medium sand interbedded with calcareous shale and minor amounts of clay and ferruginous material. The Paluxy Sand has a maximum thickness of about 190 feet in northwestern Erath County (Hill, 1901, p. 187), but thins to extinction southward in southern Hill, McLennan, and Coryell Counties. Small to moderate quantities of fresh to slightly saline water are obtained from the Paluxy Sand, the water being used for public supply and domestic and livestock purposes.

Recharge, Movement, and Discharge of Ground Water

Recharge to the Trinity Group is primarily from precipitation on the outcrop, but also by seepage from streams that cross the outcrop. In the outcrop, the Trinity is characterized by loose friable sand that affords favorable conditions for infiltration of precipitation. The average annual precipitation along the outcrop ranges from 27 to 34 inches, but only a small part of this becomes recharge. From the recharge area, ground water moves southeast toward the Gulf of Mexico at a rate that probably does not exceed a few feet per year. Available data do not indicate that the Balcones fault zone greatly affects the generally southeastward movement of ground water, although locally ground water may move for short distances parallel with the northeast-trending faults.

Ground water is discharged from the Trinity Group naturally by evapotranspiration, springs, and seepage to streams, and artificially through wells. Some upward migration of water may occur along or across faults in the Balcones and Luling-Mexia-Talco fault systems. A determination of the volume of ground water discharged naturally was beyond the scope of this report.

Most of the artificial discharge of ground water is through pumped wells, although some ground water is discharged by flowing wells. In 1959, about 23,000 acre-feet of water was pumped or flowed from wells in the Trinity Group and equivalents in the Brazos River Basin.

Chemical Quality of Ground Water

The area of occurrence of fresh to slightly saline water in the Trinity Group is shown in Plate 5. Most of the water in the zone of fresh to slightly saline water is in the Travis Peak Formation; water in the Paluxy Sand generally is higher in dissolved solids than the water in the Travis Peak. In the deeper part of the Paluxy, the water becomes unsuitable for public supply; however, the water in the underlying Travis Peak is of good quality. Chemical analyses of water from selected wells in the Trinity Group and equivalents are given in Table 5. The analyses shown are only a few of the total number on record, but they may be considered as representative of the quality of the water in the Trinity and equivalents at the general depth and vicinity of the wells.

In the zone of fresh to slightly saline water, the Trinity Group contains water that generally is soft and high in sodium bicarbonate content. Normally, the softer but more mineralized water occurs at greater depths. For example, water from well LY-32-26-801 in the outcrop in Hood County contained 374 ppm dissolved solids and a hardness of 206 ppm as compared to 594 ppm dissolved solids and a hardness of 11 ppm in well LW-40-08-801 in Hill County. The public supplies of a large number of cities and towns are obtained from the Trinity Group, although the concentrations of dissolved solids, iron, and fluoride in many of the wells exceed the U. S. Public Health Service standards.

Ground water from the Trinity Group is suitable for most types of industries, but high concentrations of sodium bicarbonate may make it undesirable as boiler-feed water and for use in laundries. Most industries requiring cooling water obtain their supply from shallow wells in which the temperature of the ground water approximates the mean annual air temperature. The temperature of ground water in the Trinity Group ranges from about 65°F in the outcrop to as much as 151°F in well JR-38-64-601 in Falls County, which is 3,692 feet deep.

In the outcrop, the Trinity yields water that generally is suitable for irrigation, whereas only two wells in the downdip part of the Trinity furnish water for irrigation. Table 5 shows that water from wells in the outcrop has a low percent sodium, increasing to as much as 97 percent in wells downdip from the outcrop.

Utilization and Development of Ground Water

Table 6 shows the amount of ground water pumped from the Trinity Group and equivalents for public supply, industrial use, and irrigation in the Brazos River Basin in 1959. Pumpage for domestic and livestock purposes was not determined,

Table 6.--Pumpage from major wells tapping the Trinity Group and equivalents in the Brazos River Basin, 1959

Major subdivision	Public supply		Industrial		Irrigation		Total*	
	mgd	acre-ft./yr.	mgd	acre-ft./yr.	mgd	acre-ft./yr.	mgd	acre-ft./yr.
BR-28	--	--	0.13	145	--	--	0.13	150
29	0.03	15	--	--	--	--	.03	30
30	.01	30	--	--	--	--	.01	15
34	.09	100	--	--	--	--	.09	100
44	.32	356	.01	6	0.02	2	.35	360
46	.08	90	.02	22	.22	240	.32	350
48	2.25	2,520	.14	151	--	--	2.4	2,700
50	.95	1,062	--	--	.06	71	1.0	1,100
51	1.62	1,810	.01	8	.22	250	1.9	2,100
52	.17	189	--	--	--	--	.17	190
53	3.17	3,541	2.12	2,374	.22	250	5.5	6,200
56	.28	312	--	--	--	--	.28	310
57	.41	462	.03	33	1.6	1,800	2.0	2,300
59	.36	403	.04	45	.47	530	.87	980
60	.86	958	--	--	.10	110	.96	1,100
61	.03	37	.01	6	--	--	.04	40
62	.15	171	--	--	--	--	.15	170
66	.22	243	--	--	.01	8	.23	250
68	.88	991	.22	243	--	--	1.1	1,200
69	1.66	1,857	.19	213	.22	250	2.1	2,300
71	.58	648	--	--	--	--	.58	650
Total*	14	16,000	2.9	3,100	3.1	3,500	20	23,000

* Figures are approximate because some of the pumpage is estimated. Irrigation figures are shown to no more than two significant figures. Public-supply and industrial pumpage figures are shown to the nearest 0.01 mgd and to the nearest acre-foot. Totals are rounded to two significant figures.

but is believed to be relatively small because of the great depth of the aquifer in a large part of the area and the accessibility of shallower aquifers at some places.

In 1959, about 23,000 acre-feet of ground water was pumped from the Trinity Group and equivalents in the Brazos River Basin, all but 300 acre-feet of which was from region III. About 6,200 acre-feet of the pumpage was from major subdivision BR-53, which includes the Waco area, and 2,700 acre-feet was from major subdivision 48, which includes parts of Bosque, Hill, and Johnson Counties.

Public-supply systems accounted for about 70 percent or about 14 mgd of the water pumped from the Trinity Group and equivalents in 1959. Among the larger towns using water from the Trinity are Stephenville, Cleburne, Hillsboro, and Taylor. Waco supplements its surface-water supply with water from the Trinity Group. An additional 60 smaller towns and communities in the Brazos River Basin derive their supplies from the Trinity.

Industry used about 14 percent of the ground water from the Trinity Group and equivalents in the basin in 1959, half of which was pumped in the Waco area, where the water was used chiefly by processing mills, by large office buildings, and for manufacturing rubber tires. In other parts of the basin, relatively small quantities of ground water are used for cooling purposes, for filling ponds used in minnow culture, and for processing lime.

About 4,500 acre-feet of ground water was pumped from the Trinity Group for irrigation in 1959, most of which was in the outcrop area, principally in Comanche, Erath, and Eastland Counties. In this area, about 3,000 acre-feet was pumped in 1959 from about 120 irrigation wells. Irrigation from wells in the Trinity Group developed largely as a result of the drought years of the early 1950's. Since that time, it has continued to expand at a slow but uniform rate.

Changes in Water Levels

Prior to large development of wells in the Brazos River Basin, the water level or piezometric surface in the Trinity Group and equivalents was close to or above the land surface. The water levels declined rapidly after development began. Fiedler (1934, p. 24) estimated that in Glen Rose in Somervell County, the artesian head declined 71 feet, or 2.2 feet a year, during the period 1897 to 1929. Since 1930, the water level has continued to decline in well XJ-32-50-202 in the heavily pumped Travis Peak Formation but at a much reduced rate (Figure 15). In the lightly pumped Paluxy Sand, the water level declined only about 2 feet in well XJ-32-51-701 in approximately the same period.

A part of the decline in water levels in the Travis Peak Formation in the Glen Rose area probably can be attributed to heavy pumping at Waco, Hillsboro, and Cleburne. Figure 16 shows that during the period 1913 to 1959 the water level in the heavily pumped Waco area declined about 400 feet, nearly half of the decline occurring since 1948. A part of the decline since 1948 is reflected in the hydrograph of well LW-40-14-101, which is 23-1/2 miles from well ST-40-24-801.

As a result of the decline in artesian pressure in the Trinity Group, yields of wells have decreased; moreover, many wells that once flowed have ceased to

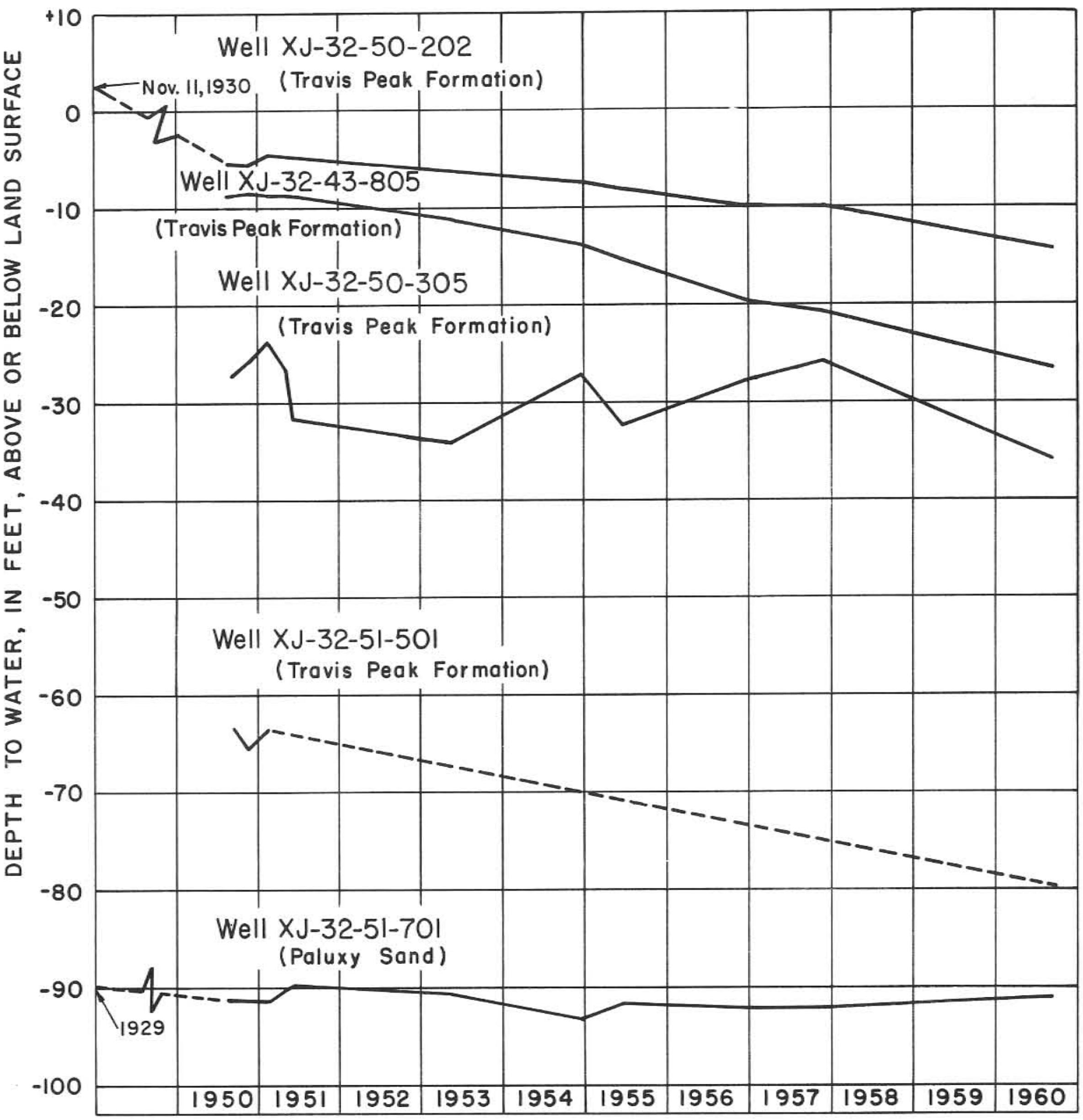

Figure 15

Changes in Water Levels in Wells in the Travis Peak Formation and in the Paluxy Sand in Somervell County

U. S. Geological Survey in cooperation with the Texas Water Commission

134

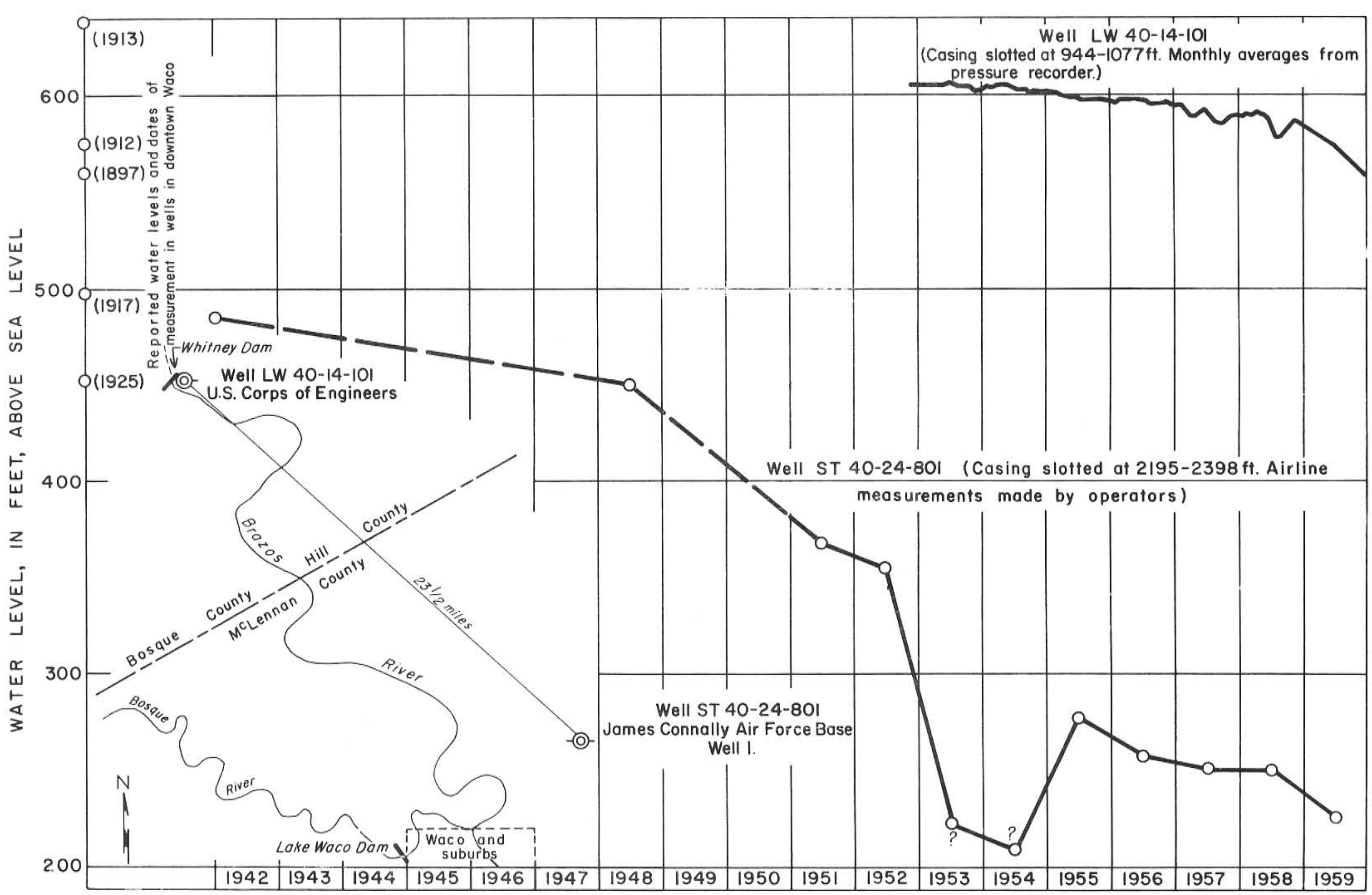

Figure 16

Changes in Water Levels in Wells in the Trinity Group in Hill and McLennan Counties

U. S. Geological Survey in cooperation with the Texas Water Commission

flow. The static water levels in some public-supply wells have declined to serious levels; pumps have been lowered in some wells nearly to the top of the aquifer.

Records of a few wells in the outcrop of the Trinity Group indicate that since 1937 water levels have changed only slightly, and at some places the water levels have risen.

Availability and Potential Development of Ground Water

The coefficient of transmissibility of the Trinity Group in the Brazos River Basin in Texas is small in comparison to those of most of the primary aquifers in Texas. The coefficient of transmissibility measured in 7 widely scattered wells in region III ranged from 3,700 to 12,400 gpd per foot and averaged about 9,000 gpd per foot. The coefficient of storage in 3 of the wells averaged about 0.00005.

The specific capacities of the wells in the Trinity Group also are low because of the low transmissibilities. In 16 wells in the basin, the specific capacity ranged from 0.28 to 3.7 gpm per foot and averaged about 2.22 gpm per foot. Wells having the highest coefficients of transmissibility, largest yields, and largest specific capacities generally are screened opposite all the water-bearing sands.

The saturated thickness of the fresh to slightly saline water-bearing sands in the Trinity Group ranges from zero to about 400 feet in region III. The saturated thickness in the outcrop area averages about 60 feet. The estimated volume of fresh to slightly saline water stored in the sands in the Trinity and equivalents in the Brazos River Basin is estimated to be in the order of 300,000,000 acre-feet; however, only a very small fraction of the water stored in the sands is recoverable by known methods at present costs.

In order to compute the order of magnitude of the water available from the Trinity Group for comparison purposes, it is necessary to make a number of assumptions, none of which are precisely true. A line of discharge was postulated about parallel with the outcrop in region III. The line of discharge in region III was assumed to be 139 miles long, extending from a point on the boundary of the Brazos River Basin about 7 miles east of Cleburne in Johnson County to the intersection of the Burnet-Williamson County line and the boundary of the Brazos River Basin. The line averages about 48 miles from the assumed line source of recharge in the outcrop. The transmission capacity of the aquifer from the outcrop to the line of discharge was computed using the following assumptions:

1. Water levels will be lowered to a maximum depth of 400 feet below land surface along the line of discharge.

2. No water moves downward into the aquifer except in the outcrop area where all recharge is assumed to occur along a line parallel with the strike of the outcrop and in the middle of the outcrop.

3. The altitude of the water levels is the same and remains the same at all points along the centerline of the outcrop (assumed effective line source of

recharge); the altitude of the water levels is the same at all points along the fresh-salt-water interface; and the altitude of the water levels is the same at all points along the line of discharge.

4. The slope of the water surface will be constant after drawdown to 400 feet at the line of discharge.

5. The hydraulic gradient is the slope of a straight line from the water level at the line source of recharge to the water level along the line of discharge.

6. All the sands between the line source of recharge and the line of discharge transmit water from the outcrop area to the line of discharge. The average coefficient of transmissibility of the Trinity Group is 9,000 gpd per foot.

7. The amount of recharge along the line source is sufficient to supply the water that can be transmitted to the line of discharge at the assumed gradients.

8. The average hydraulic gradient is the average of the present hydraulic gradient and the maximum hydraulic gradient that can be attained with a water level of 400 feet at the line of discharge.

9. The only increment to the water moving toward the line of discharge from the downdip side is that water released from storage as a result of lowering water levels.

The transmission capacity of the Trinity Group from the assumed line source to the assumed line of discharge in region III would be about 16,000 acre-feet per year at the average hydraulic gradient during the time that the water level was being lowered to 400 feet. The transmission capacity at the maximum hydraulic gradient would be about 19,000 acre-feet per year. The amount of water withdrawn from artesian storage as the water level was lowered to 400 feet would be about 53,000 acre-feet. At the present rate of withdrawal by the wells tapping the Trinity Group in region III (23,000 acre-feet per year), the water level could be lowered to 400 feet along the assumed line of discharge in about 8.2 years.

The maximum transmission capacity of the Trinity Group, about 19,000 acre-feet a year, is actually smaller than the 23,000 acre-feet pumped in 1959. The present water levels along the assumed line of discharge are less than 400 feet (except locally in areas of heavy pumping) because not all of the assumptions were applicable. The present pumpage is not along the assumed discharge line, but is distributed over the entire area where fresh to slightly saline water is available; about 3,000 acre-feet of the total 23,000 acre-feet pumped in 1959 was from water-table wells along the outcrop and part was water released from storage as a result of the decline in the water levels.

The amount of recharge on the outcrop necessary to replace the water moving downdip at the maximum transmission capacity (about 19,000 acre-feet per year) would be about 0.16 inch per year.

Problems

One of the most serious problems associated with the development of ground water from the Trinity Group is the decline of artesian pressure in areas of large ground-water withdrawals. Continuing declines of water levels in some areas, particularly near Cleburne, Hillsboro, Stephenville, and Waco, have resulted in the costly process of lowering pumps in wells, installing larger motors, and thereby increasing the over-all lifting costs. Wells drilled into the Trinity Group in more recent years, have deep original pump settings to cope with expected declines.

In some instances, there has been evidence of contamination of fresh-water sands in the lower part of the Trinity Group, resulting from differential artesian pressure, where the artesian pressure of a lower sand member is lowered to an extent that water of inferior quality from a higher sand invades the lower sand. The problem of contamination of fresh-water sands from oil-field brines is present in some areas also, particularly along the outcrop of the lower part of the Trinity Group where, in the past, salt water stored in earthen tanks was reported to have rendered water from nearby wells unfit for drinking.

Because of the many water-bearing sands in the Trinity Group, more information is needed in regard to sand thicknesses and the quality of water contained in each sand member. The beds of sand in the Glen Rose Limestone are known to contain water that is highly mineralized at some places. This condition presents the problem of possible contamination unless wells penetrating these sands are properly cased. Because the sands in the Glen Rose Limestone are lenticular, a more detailed study is needed to determine their extent and water-bearing properties.

Fredericksburg and Washita Groups, Undifferentiated

Rocks of the Fredericksburg and Washita Groups, undifferentiated, are exposed in a belt of irregular width trending northeast across region III (Plate 3). For the purposes of this report, they are not mapped separately in region III; however, in region II only the rocks of Fredericksburg age are shown in the geologic mapping because of the absence of rocks of Washita age (Plate 2). In region I, the rocks of Fredericksburg age are exposed along the escarpment of the High Plains (Plate 1) and are discussed under the succeeding section on rocks of Cretaceous age in the High Plains.

The Fredericksburg and Washita Groups, undifferentiated, overlie the Trinity Group and consist of more than 580 feet of chiefly fossiliferous limestone and marl and minor amounts of shale, clay, shell agglomerate, and sand. These sediments are relatively impermeable except for the Edwards Limestone of the Fredericksburg Group, which is the principal aquifer in the Fredericksburg and Washita Groups, undifferentiated.

The Edwards Limestone consists of soft to hard, dense, massive fossiliferous limestone. In the northern part of the outcrop, the Edwards is thin and only slightly honeycombed, but it thickens and becomes more fractured and honeycombed southward. The thickness of the Edwards ranges from about 35 feet in Hood County to more than 200 feet in Williamson County.

Only small quantities of fresh water are obtained from the Edwards Limestone approximately north of the Leon River (Plate 3). South of the river, however, the Edwards increases in thickness and permeability and furnishes large quantities of water to public-supply, industrial, and irrigation wells, and to springs. Yields as high as 2,000 gpm have been obtained from wells. The combined flow of the springs that comprise Salado Springs, about 16 miles southwest of Temple, ranged from 3.4 cfs (cubic feet per second), or 2.2 mgd in 1955, to 29.7 cfs, or 19.2 mgd, in 1960, and averaged 12.3 cfs or about 8.0 mgd during the period 1948 to 1960.

The results of chemical analyses of water from two wells that tap the Edwards Limestone in region III are shown in Table 7 (ZK-58-19-802 and ZK-58-27-801). The wells, which furnish the public supply of Georgetown and Round Rock 4 miles south of Georgetown, yielded water suitable for a wide range of uses. The water is very hard but the concentrations of chemical constituents generally are within the recommended limits as established for drinking water by the U. S. Public Health Service except that one well (ZK-58-19-802) had a high nitrate content. Because of its hardness, the water may require treatment for some industrial uses.

Approximately 1,200 acre-feet of water was pumped from the Edwards Limestone in region III in 1959 (Table 20), of which 840 acre-feet was from major subdivision BR-66. Public-supply systems pumped about 1,000 acre-feet, or about 90,000 gpd, and industrial use was slightly more than 100 acre-feet.

The changes in water levels in three wells in the Edwards Limestone in Williamson County are shown in Figure 17. From 1945 to 1957, the trend of the water levels was downward, reflecting the drought of those years. The general leveling off of water levels in wells ZK-58-77-805 and ZK-58-27-203 from about 1953 to 1957 suggests that pumpage was fairly uniform. The water levels rose rapidly in response to the above-normal rainfall in 1957-58, reaching levels higher than in 1941.

The lack of sufficient data precludes an accurate evaluation of the Edwards Limestone as to its potential development. However, the flow of Salado Springs and the yields of wells in the Georgetown area indicate that the Edwards is capable of furnishing additional quantities of water, particularly in Bell and Williamson Counties.

Much information is needed regarding the amount of natural recharge to and the extent of fresh water in the aquifer before the availability of water from the Edwards can be determined accurately.

Rocks of Cretaceous Age in the High Plains

Rocks of Cretaceous age underlie the Ogallala Formation and rest on the eroded surface of rocks of Triassic age in the High Plains in the Brazos River Basin. They underlie approximately the southern one-third of the High Plains in the basin and crop out along the margins of some of the deeper playa lakes (not shown on Plate 1 because of small area), and in places along the eastern escarpment of the High Plains south of the Double Mountain Fork of the Brazos River (Plate 1). The rocks dip southeastward at about 7 to 8 feet per mile.

Table 7.--Chemical analyses of water from selected wells in the Edwards Limestone and Kiamichi Formation and equivalents, and in the Woodbine Formation, Brazos River Basin

[Analyses given are in parts per million except specific conductance, pH, percent sodium, and sodium adsorption ratio (SAR).]

Well	Screened interval (feet)	Date of collection	Silica (SiO_2)	Iron (Fe) (total)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3) a/	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Boron (B)	Dissolved solids	Hardness as $CaCO_3$	Percent sodium	Sodium adsorption ratio (SAR)	Specific conductance (micromhos at 25°C)	pH
Edwards Limestone and Kiamichi Formations and Equivalents																				
BA-28-03-602	57	June 29, 1961	52	--	118	52	b/ 180		270	240	270	3.5	47	0.42	1,100	508	43	3.5	1,750	7.1
RU-24-05-401	60	Apr. 18, 1952	12	--	180	204	b/ 455		344	1,070	620	2.0	.5	2.8	2,710	1,290	43	5.5	3,980	7.8
ZK-58-19-802	? -100	Feb. 10, 1941	10	0.05	124	23	b/ 12		360	36	35	.0	60	--	484	404	6	.3	--	7.2
ZK-58-27-801	? -222	Mar. 30, 1941	--	.02	109	23	b/ 6.7		374	40	15	.2	14	--	408	367	4	.2	--	--
Woodbine Formation																				
LW-32-55-905	? -300	May 19, 1960	12	--	32	16	b/ 308		307	466	56	--	0.2	--	1,040	146	82	11	1,580	7.0
LW-32-63-901	? -200	Jan. --, 1943	10	c/ 0.02	2.7	1.1	278	11	508	160	35	0.2	2.5	--	762	12	95	35	--	8.3

a/ Includes the equivalent of any carbonate (CO_3) present.
b/ Sodium and potassium calculated as sodium (Na).
c/ Iron in solution.

Figure 17

Changes in Water Levels in Wells in the Edwards Limestone in Williamson County

U. S. Geological Survey in cooperation with the Texas Water Commission

134

Rocks of Cretaceous age in the High Plains yield small to moderate amounts of water to wells in several places. The importance of these water-bearing sediments may increase slightly with further exploration, but they are fairly certain to remain of secondary importance except perhaps locally.

The source of the ground water in the rocks of Cretaceous age in the High Plains is precipitation on the outcrop area and recharge from the ground-water reservoir in the Ogallala Formation that overlies the Cretaceous rocks. Perhaps some recharge moves into Cochran and Bailey Counties in Texas by underflow from the rocks of Cretaceous age in the adjoining Causey-Lingo area in Roosevelt County, New Mexico.

Cretaceous rocks in the High Plains are of Trinity, Fredericksburg, and Washita ages, in ascending order.

Rocks of Trinity age are represented in the High Plains by the Paluxy Sandstone of Brand (1953, p. 8), consisting of fine to coarse-grained sandstone ranging in thickness from zero to as much as 30 feet.

Rocks of Fredericksburg age include the Walnut Clay equivalent which consists mainly of limestone, shale, and sandstone, having a thickness of as much as 40 feet in places; the Comanche Peak Limestone equivalent, which has a thickness of about 50 feet and consists of thinly bedded to massive clayey limestone and thin beds of shale; the Edwards Limestone equivalent, which ranges in thickness from zero to as much as 35 feet and consists of hard, thickly bedded to massive, fine to coarse-grained limestone with some porous beds; and the Kiamichi Formation equivalent, which ranges in thickness from zero to as much as 100 feet or more and consists of yellow and blue clay, sandy shale, sandstone, limestone, and in places a basal sand and gravel 30 feet or less in thickness.

Rocks of Washita age in the High Plains of the Brazos River Basin include only the equivalent to the Duck Creek Limestone, the oldest formation of the Washita Group. The Duck Creek equivalent ranges in thickness from zero to about 35 feet and consists of shale and thin beds of limestone.

All the formations equivalent to the three groups, representing the Cretaceous in the High Plains, have been identified in the vicinity of Lynn and Borden Counties (Plate 1). However, Leggat (1957, p. 13) has indicated that in southwestern Lamb County, the formation which he called Kiamichi rests directly on rocks of Triassic age and consists of shale, sandstone, and limestone, and a basal sand and gravel 15 feet or less thick. Brand (1953, p. 8) has indicated that this basal sand and gravel was assigned to the Kiamichi because of its position in the section and lack of fossils upon which a definite age could be determined.

Drillers' logs of test holes that were drilled through the rocks of Cretaceous age into the underlying rocks of Triassic age in southern Bailey County and northern Cochran County (Plate 1) indicate that in these areas the rocks of Cretaceous age range in thickness from less than 25 to about 165 feet and average about 85 feet. The logs show that in southern Bailey County and northern Cochran County, they consist of shale, sandstone, thin beds of limestone, and in most places a basal sand or sand and gravel 30 feet or less thick. The rocks of Cretaceous age in southern Bailey County and northern Cochran County probably correlate with the rocks described by Leggat (1957, p. 13) in southwestern Lamb County.

Lang (1945, p. 12a-24a) indicated that rocks of Cretaceous age, ranging in thickness from 35 to 73 feet, are present in the subsurface northeast, north, and west of the city of Lubbock. Remnants of rocks assumed to be equivalent to the Kiamichi Formation and Duck Creek Limestone are present in southeastern Hale County. Although drillers' logs generally do not indicate their presence in Floyd County, Brand (1953, p. 54) measured a 7-foot section of Edwards Limestone near Floydada.

From the limited amount of information available, the Paluxy Sandstone (Brand, 1953) of Trinity age and the Walnut Clay, Comanche Peak Limestone, and Edwards Limestone equivalents of Fredericksburg age are probably the only formations of Cretaceous age in the eastern and southeastern parts of the High Plains in the Brazos River Basin; the Kiamichi Formation equivalent of Fredericksburg age and the Duck Creek Limestone equivalent of Washita age are probably the only formations of Cretaceous age in the western part of the High Plains.

Water is pumped from the ground-water reservoir in the rocks of Cretaceous age in several places in the High Plains in the Brazos River Basin. In some places the wells pump from both the Ogallala Formation and the rocks of Cretaceous age, and because it is not feasible to separate the amount of water pumped from each formation, the pumpage is assigned to the Ogallala Formation in Tables 9 and 20. In some places the ground-water reservoirs in the rocks of Cretaceous age and the Ogallala Formation are hydraulically connected and they can be considered as one aquifer.

The ground-water reservoir in the rocks of Cretaceous age in the southeastern part of Hale County yields small to moderate amounts of water from fractures or caverns in limestone. Recharge is from the overlying Ogallala Formation. Ground water occurs under similar conditions in north-central Lubbock County.

Leggat (1957, p. 13) has reported that small quantities of slightly to moderately saline water are obtained from the basal sand and gravel of what he called the Kiamichi Formation in the southern part of Lamb County. The salinity of the water in the Kiamichi equivalent in this area may be because the circulation is slower in the basal sand and gravel than in the Ogallala Formation and/or in part due to the movement of saline water into the formation from the alkali lakes that are bottomed below the water table.

The chemical analysis of a sample of water from well RU-24-05-401 in the basal sand and gravel in southern Lamb County is shown in Table 7. The results of the analysis show that the water is very hard and slightly saline. The dissolved-solids, sulfate, and chloride content of the water exceeds the limits recommended for drinking water by the U. S. Public Health Service. The poor quality of the water probably is due to poor circulation rather than from movement of saline water into the formation from the alkali lakes.

Wells that penetrated both the Ogallala Formation and the underlying rocks of Cretaceous age in southwestern Lamb County have been abandoned because of insufficient water for irrigation or because of the poor quality of the water, or both.

The Causey-Lingo area in Roosevelt County, New Mexico, adjoins Bailey and Cochran Counties on the west (Plate 1). Cooper (1959, p. 14) has indicated that a few wells in the Causey-Lingo area obtain small amounts of water from the consolidated rocks of Cretaceous age. However, he also indicated that the largest yields were obtained from the unconsolidated sand and gravel of Cretaceous age in the erosion channels in the underlying Triassic rocks.

Electric logs of test holes drilled in southern Bailey County and northern Cochran County indicate that the basal sand and gravel of Cretaceous age in these areas is water bearing, but the quality of the water is not known. The basal sand and gravel is 30 feet thick, or less. It is possible that the water-bearing sand and gravel, from which small to moderate amounts of water are pumped in the Causey-Lingo area, may extend eastward into adjoining Cochran and Bailey Counties in Texas. Some irrigation wells in southern Bailey County reportedly are pumping water from thin sections of sand and gravel of Cretaceous age.

Some of the irrigation wells in the western, southwestern, and southern parts of Lubbock County, and in the northern part of Lynn County are reported to be pumping water from both the Ogallala Formation and the underlying rocks of Cretaceous age. Several public-supply wells in Lubbock County also are reported to draw water from both aquifers (Lang, 1945, p. 3a; Leggat, 1952, p. 13).

The log of a well drilled in southeastern Lynn County penetrated 30 feet of sand overlying a red shale, probably of Triassic age. The sand, probably of Trinity age, was reported to be "dry." The water obtained from overlying formations was reported to be unsuitable for domestic or irrigation use, and the well was abandoned. Ground water in the southern and southeastern parts of Lynn County is in some places contaminated by the movement of water from the alkali lakes.

Forty-five irrigation wells are pumping small to moderate amounts of water from the Edwards equivalent and possibly from the Comanche Peak equivalent in northwestern Borden County and northeastern Dawson County. Owners report that the wells are about 60 feet in depth; the depth to water below land surface in two of these wells was 27 feet and 34 feet in 1961. The estimated total amount of water pumped from the 45 wells in 1959 was 900 acre-feet which was assigned to the Edwards Limestone and equivalent in Table 20. However, a part of this pumpage may have come from the Comanche Peak equivalent. In northwestern Borden County, about 14 wells are being used to artificially recharge the ground-water reservoir in the rocks of Cretaceous age with water from wet-weather lakes.

The results of a chemical analysis of a sample of water from an irrigation well in Borden County (BA-28-03-602) is shown in Table 7. The water is very hard and the dissolved-solids, chloride, fluoride, and nitrate contents exceed the limits recommended for drinking water by the U. S. Public Health Service. The analysis indicates, however, that the water would be satisfactory for irrigation of salt-tolerant crops on land having good drainage.

Based on the limited information available at this time, the saturated thickness of the rocks of Cretaceous age probably does not exceed 30 feet, and the occurrence of ground water in these rocks may be somewhat erratic. In places, the quality of the water makes it unfit for domestic or irrigation use.

In places where the ground water occurs in fractures or caverns in limestone, it is difficult to obtain a reliable estimate of the specific yield. However, from the information available, the ground-water supply in the rocks of Cretaceous age in the High Plains may be important locally but is of secondary importance to the High Plains in the Brazos River Basin.

Woodbine Formation

The Woodbine Formation crops out in region III of the Brazos River Basin, forming a belt of irregular width extending from the south line of Hill County northward through Johnson County (Plate 3). Water-table conditions prevail in the outcrop; south and east of the outcrop, it dips gulfward beneath younger rocks and becomes an artesian aquifer.

The Woodbine Formation consists of red to light-gray sand, cross-bedded ferruginous sandstone, clay, and sandy clay interbedded with lignite and gypsiferous clay. The sand thins rapidly southward, being replaced by shale. In general, the thickest sand beds occur near the base and the upper third of the formation. The thickness of the Woodbine Formation ranges from zero to about 185 feet.

The Woodbine Formation is not an important source of ground water in the Brazos River Basin, although it does yield small to moderate quantities of fresh to slightly saline water to wells in Johnson and Hill Counties. In its outcrop, the Woodbine is tapped by only a few wells, principally for domestic and livestock purposes. In some places on the outcrop, as east of Cleburne, the water in the upper part of the formation is not suitable for drinking purposes because of its high iron content. Downdip from the outcrop, the formation yields small to moderate quantities of water for public and industrial supplies at Itasca and Hillsboro. The city of Itasca obtains its supply from two wells in the Woodbine; the public supply of Hillsboro, which is principally from sands of Trinity age, is augmented by several wells that tap the Woodbine Formation.

Approximately 220,000 gpd (240 acre-feet) of ground water was pumped from the Woodbine in 1959 for public and industrial supplies, of which 108,000 gpd was for public supplies at Itasca and Hillsboro (Table 20). The quantity of water withdrawn from the Woodbine for domestic and livestock supplies is not known, but it is probably less than that for public and industrial supplies. The yields of individual wells tapping the Woodbine in the Brazos River Basin range from a few gallons per minute to a maximum of 180 gpm.

The chemical quality of the water from the Woodbine Formation ranges widely. The results of only two samples are shown in Table 7 but additional analyses of water from wells in the Brazos River Basin and in the adjoining Trinity River Basin, all of which are in the files of the U. S. Geological Survey and Texas Water Commission, show that the water in the Woodbine is typically high in iron and bicarbonate content. Water from relatively shallow wells in and near the outcrop generally is high in iron content, generally exceeding the limits established by the U. S. Public Health Service; at some places the water is referred to as red water. In 10 water samples, the hardness ranges from 4 to 264 ppm and the dissolved solids from 162 to 2,219 ppm; in 3 samples the dissolved solids exceeded 1,000 ppm. The bicarbonate content ranged from 23 to 750 ppm and averaged 423 ppm. The sodium-potassium content ranged from 144 to 822 ppm, exceeding 200 ppm in all but 3 samples.

The estimated volume of fresh to slightly saline water stored in the sands of the Woodbine Formation in the Brazos River Basin is about 4,000,000 acre-feet; only a small part of this, however, is recoverable by known methods at present costs. The amount of water stored in the sands was estimated by planimetering the areas of approximate average saturated thickness and computing the volume of saturated sand. The volume of saturated sand multiplied by 30 percent assumed porosity equals approximately 4,000,000 acre-feet of water.

Although the Woodbine Formation ranks as a primary aquifer in the basins of the Trinity and Red Rivers, it is not important in the Brazos River Basin because of its small areal extent and its relatively thin sand sections. More information, however, is needed to fully evaluate its potential as an aquifer in the Brazos River Basin.

Eagle Ford Shale, Austin Chalk, Rocks of Taylor Age, and Navarro Group, Undifferentiated

The Eagle Ford Shale, Austin Chalk, rocks of Taylor age, and the Navarro Group, undifferentiated, which are listed from oldest to youngest, are considered as a unit for the purposes of this report. The unit crops out in a northeast-trending belt ranging in width from 20 miles to as much as 40 miles (Plate 3).

The character of the formations of the unit are described briefly in the following discussion. The Eagle Ford Shale, which has a maximum thickness of about 200 feet, consists of shale and thinly-bedded sandstone and limestone. The Austin Chalk reaches a maximum thickness of about 600 feet. It consists of chalky and marly limestone and limy shale. The rocks of Taylor age, which have a maximum thickness of about 1,100 feet, consist of marl, sandy marl, chalky limestone, and calcareous sandstone. The Navarro Group, which has a maximum thickness of about 550 feet, consists of sandy marl and clay, locally gypsiferous, and glauconitic and fine sand, in places lime cemented.

In general, the Eagle Ford Shale, Austin Chalk, rocks of Taylor age, and the Navarro Group, undifferentiated, are not important sources of ground water in the Brazos River Basin. In some places in the outcrop, shallow wells generally less than 100 feet deep yield small quantities of fresh to moderately saline water from the individual formations that comprise the unit, except from the Eagle Ford Shale, which is not known to yield potable water to any wells in the Brazos River Basin. Most of the wells are shallow dug wells used only for domestic and livestock supplies, and they are not dependable during periods of drought. Available data show that only two major wells produce from rocks of Taylor age. These wells, which are reported to tap a localized deposit of sand and gravel in the Taylor, pumped an estimated 60,000 gpd in 1961 for the public supply of Thrall, 7 miles east of Taylor.

Tertiary System in the High Plains

Ogallala Formation

General

The Ogallala Formation is the only primary aquifer in the High Plains part of the Brazos River Basin. The aquifer is continuous throughout much of the area, although it is absent in some places, as in the vicinity of some of the larger lakes where the formation has been removed by wind action and in places where the underlying consolidated rocks are above the water table. Such areas are small, and because of the scale of the maps used in this report, it was not possible to show these and other small details.

In the Brazos River Basin, the Ogallala Formation covers an area of about 7,500 square miles. It has an average width of about 60 miles and extends in a general southeasterly direction across the central part of the Southern High Plains from the New Mexico-Texas State line to the escarpment of the High Plains, a distance of about 115 miles (Plate 1).

Physical Description

The Ogallala Formation consists chiefly of sediments deposited by streams that had their headwaters in the mountainous regions to the west and northwest, although some evidence indicates that a part, perhaps small, of the sediments were from a local source. At the time of deposition, the Ogallala Formation probably extended from the mountains of New Mexico eastward into Texas beyond the present escarpment of the High Plains. Following deposition of the sediments, erosion became the dominant force, resulting in the formation and retreat of bounding escarpments with consequent physiographic isolation of the Llano Estacado (Evans, 1956, p. 16). The water-bearing sands and gravels of the Ogallala are, therefore, cut off in all directions from any underground connection, except through the underlying older rocks which contain highly mineralized water entirely unlike the fresh water in the Ogallala (White, Broadhurst, and Lang, 1946, p. 386).

The Ogallala Formation consists of red and yellow clay, silt, fine to coarse, gray and buff colored sand, gravel, and caliche. From a study of 537 drillers' logs of wells in 5 counties of the High Plains, Barnes and others (1949, p. 12) concluded that 68 percent of the saturated material in the Ogallala Formation between 72 and 350 feet below the surface is sand. The sand, gravel, and silt are, in part, consolidated and, in part, cemented, chiefly by calcium carbonate. The cementation occurs irregularly throughout the formation and the degree of cementation ranges from well cemented to loosely cemented.

The individual beds or lenses of silt, sand, gravel, and clay are not continuous over wide areas. Instead, as illustrated by Leggat (1957, pl. 2), the individual beds or lenses generally pinch out or grade, perhaps imperceptibly, both laterally and vertically into the finer or coarser material of another bed or lens. A possible exception to the above might be the "Cap Rock Caliche," which occurs at or near the surface throughout much of the High Plains.

In the High Plains section of the Brazos River Basin, the Ogallala Formation rests unconformably on the eroded surfaces of Triassic and Cretaceous rocks. In general, the Cretaceous rocks are present in the subsurface in the area west and south of a line extending along the Double Mountain Fork of the Brazos River from the southern boundary of the sandhills area in central Lamb County to the escarpment of the High Plains (Plate 1). The Ogallala is underlain by Triassic rocks in the rest of the basin except in southern Hale County where outliers of Cretaceous rocks occur in the subsurface.

In general, the Ogallala Formation is thicker in the northern part of the Brazos River Basin than in the southern part. The thickness ranges from 400 or 500 feet to a knife edge where the formation wedges out against older rocks.

Occurrence of Ground Water

Ground water in the Ogallala Formation generally occurs under water-table conditions. Locally, however, a slight artesian pressure may exist where the water is confined beneath lenticular bodies of clay of limited areal extent. Relatively impermeable clay and shale strata of Triassic or Cretaceous age generally form the lower boundary of the aquifer. In some areas, however, for example in southeastern Hale County, the water in the Cretaceous rocks is hydrologically connected with the water in the Ogallala Formation and the Cretaceous rocks may be considered as part of the aquifer.

The zone of saturation occupies the space between the lower boundary of the aquifer and the water table. In this zone the pore spaces and voids in the rocks are filled with water. The pore spaces in clay and silt generally are very small, and although these rocks may store large quantities of water, they do not readily yield the water. Therefore, most of the water that is available to wells from the Ogallala Formation occurs in the voids of the sand and gravel.

The approximate depth to water below the land surface in the Ogallala Formation in 1958 is shown on Plate 6. The map shows that the depth to water ranges from less than 50 feet in the heavily pumped area near Muleshoe to more than 250 feet in the northwest corner of the basin and northeast of Crosbyton, where development of the ground-water resources has occurred only in recent years or where the saturated thickness in conjunction with the great depth to water has deterred development.

The thickness of the zone of saturation of the Ogallala Formation varies throughout the southern High Plains chiefly because of the unevenness of the bedrock surface. Plate 9 shows that the thickness of the saturated zone of the Ogallala Formation in the Brazos River Basin as of 1958 ranged from zero to more than 300 feet.

Recharge, Movement, and Discharge of Ground Water

The principal sources of ground-water recharge to the Ogallala Formation in the Brazos River Basin in Texas are precipitation that falls on the land surface in Texas and underflow from the Ogallala Formation in New Mexico. The amount of recharge, if any, that might result from the return of part of the water applied for irrigation is unknown. The amount of water moving into the Texas portion of the Brazos River Basin by underflow probably is small but relatively constant from year to year.

The north and south boundaries of the Brazos River Basin roughly parallel the direction of movement of the ground water. Therefore, recharge to the Ogallala Formation in the Brazos River Basin by underflow from the Red River Basin on the north probably would be small and probably would be negated by underflow out of the basin into the Colorado River Basin on the south.

Most of the precipitation that falls on the land surface is retained temporarily in depressional areas, which commonly occur throughout the High Plains, or in the soil close to the land surface from which it evaporates or is transpired by plants. A small part of the water percolates downward below the root zone and eventually reaches the water table.

Much of the surface of the High Plains is underlain by caliche. In some places, the caliche is indurated and relatively impermeable; however, in other places the caliche is absent or its character and composition may be different. Barnes and others (1949, p. 24) have indicated that in some localities the caliche probably prevents penetration of surface water, but more generally throughout much of the tight lands as in Castro, Swisher, Hale, and Floyd Counties, downward percolation is retarded by the clayey subsoils. Recharge is retarded also by relatively impermeable silt and clay deposits that form the bottoms of most of the depressional lakes and ponds; however, dessication cracks that develop when the ponds are dry may provide passageways for the downward movement of water for a time when the ponds are being filled. After the water has remained in the ponds for a period of time, the clay swells, thus sealing the cracks.

The effective drainage area of the Brazos River and its tributaries in the High Plains is small. During periods of normal rainfall, practically no runoff collects in the stream channels. However, after exceptionally heavy rains, the streams may, in some places, carry large quantities of water. Large flows, however, occur rather infrequently, and it is rare indeed that water flows over the eastern escarpment of the High Plains. Apparently, a large part of the water is absorbed by the soil and a part probably percolates downward to the water table.

A favorable area for recharge is in the sandhills extending east from the New Mexico-Texas State line eastward across the central part of Bailey and Lamb Counties into Hale County (Plate 1). Rain filters directly into the dune sands with little or no runoff. In places the downward movement of the water probably is retarded by less permeable layers of caliche which underlie the sandhills.

Recharge is greatest when rains are of sufficient intensity and duration to increase the soil moisture to a point where the capillary forces in the soil become small in comparison to gravitational forces.

Barnes and others (1949, p. 26-27) have suggested that studies made by White, Broadhurst, and Lang (1946) indicate that the average annual recharge would be only a fraction of an inch in an area of about 9,000 square miles in the High Plains of Texas. From studies made in New Mexico and Texas, Theis (1937, p. 564-568) suggested that the average annual recharge from precipitation in the High Plains is less than half an inch.

The approximate altitude of the water table in the Ogallala Formation of the High Plains section of the Brazos River Basin in 1958 is shown by contour lines in Plate 7. Ground water tends to move in the direction of the greatest slope of the water table, which is perpendicular to the contours. In general, the ground water moves southeastward through the basin area to an area of discharge along the escarpment of the High Plains. The average slope of the water table is about 10 to 11 feet per mile. The slope of the water table is roughly parallel with the slope of both the bedrock surface (Plate 8) and the land surface. The rate at which ground water moves is extremely slow. For example, Cronin and Wells (1960, p. 36) estimated a rate of about 2 inches per day in the vicinity of Plainview in Hale County.

Ground water in the Ogallala is discharged naturally by springs and seeps along the escarpment of the High Plains, by evapotranspiration in shallow water-table areas, and by evaporation from some of the larger playa lakes, and artificially by wells.

The total natural discharge from an area of about 9,000 square miles in 1938 was about 25,000 to 30,000 acre-feet per year (White, Broadhurst, and Lang, 1946, p. 391). The area for which this estimate was made included most of the Brazos River Basin.

Chemical Quality of Ground Water

The chemical analyses of 24 water samples from wells pumping from the Ogallala for public-supply, irrigation, industrial, and domestic and livestock uses are given in Table 8. The locations of the wells are shown on Plate 1 with a bar over the well symbol.

Water from the Ogallala typically is hard and has an objectionably high concentration of fluoride. The hardness, in addition to the high concentration of silica, makes it somewhat objectionable for domestic and many industrial uses. Except possibly in the vicinity of the playa lakes, the water is satisfactory for irrigation and only an excessive fluoride content makes it objectionable as a public supply.

Analyses of 2 samples of water from windmills near the playa lakes show that the water from the Ogallala has been contaminated probably by the movement of highly mineralized water from the lakes. For example, water from well RU-24-05-701 in southwestern Lamb County contained 1,680 ppm dissolved solids, 632 ppm sulfate, 350 ppm chloride, and 145 ppm magnesium; water from well SR-28-02-204 in south-central Lynn County contained 2,160 ppm dissolved solids, 743 ppm sulfate, 620 ppm chloride, and 200 ppm magnesium.

Utilization and Development of Ground Water

The total quantity of ground water pumped in 1959 from the Ogallala Formation in the Brazos River Basin was estimated to be about 2,200,000 acre-feet, or about 2,000 mgd (Table 9). Of this amount, 35,000 acre-feet was used for public supply and 7,000 acre-feet was used for industrial purposes.

Irrigation from wells in the High Plains part of the Brazos River Basin reportedly was started near Plainview, Hale County, in 1911. The fact that water was available at a shallow depth, 50 feet or less, undoubtedly was a controlling factor in the location of the first irrigation wells. Drilling subsequently was started in the vicinity of Muleshoe, Bailey County, where water was available also at shallow depths. Development of wells progressed very slowly until 1937. From that date to 1943, the drilling of new wells increased annually. Many of the new wells were drilled outside of the older more or less isolated areas, and by 1943-44, the areas were beginning to merge into one big irrigated area. Drilling of new wells continued at a rapid pace until 1951. New wells were drilled

Table 8.--Chemical analyses of water from selected wells in the Ogallala Formation, Brazos River Basin

[Analyses given are in parts per million except specific conductance, pH, percent sodium and sodium adsorption ratio (SAR).]

Well	Depth of well (ft.)	Date of collection	Silica (SiO_2)	Iron (Fe) (total)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3) [a]	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Boron (B)	Dissolved solids	Hardness as $CaCO_3$	Percent sodium	Sodium adsorption ratio (SAR)	Specific conductance (micromhos at 25°C)	pH
AR-10-41-901	140	June 17, 1955	46	0.00	62	46	35	8.6	211	140	70	2.4	4.9	--	551	344	18	0.8	824	7.8
AR-24-09-601	206	Apr. 11, 1961	30	--	43	25	55	6.4	222	80	42	3.0	7.5	0.20	403	210	35	1.6	653	7.6
DD-10-30-503	423	Oct. 18, 1960	60	.08	32	28	48	7.2	293	34	15	2.8	1.2	--	374	195	34	1.5	568	7.1
DP-24-12-701	217	Apr. 11, 1961	38	--	33	41	55	8.6	280	85	38	3.4	3.8	.22	444	251	31	1.5	723	7.5
DP-25-24-301	178	May 24, 1961	59	--	124	50	[b] 131		196	422	136	2.2	2.0	--	1,020	515	36	2.5	1,490	7.3
HK-23-20-605	--	Oct. 17, 1960	42	.22	41	35	37	11	330	34	15	2.5	3.8	--	383	246	24	1.0	622	7.0
HK-23-23-703	304	Oct. 17, 1960	39	.02	38	31	61	10	351	38	16	3.0	4.5	--	414	222	36	1.8	667	7.1
HK-23-31-401	325	May 16, 1961	40	--	39	31	74	9.1	382	43	20	3.6	5.9	.54	454	225	40	2.1	718	7.6
JW-11-53-401	268	June 16, 1955	60	.03	45	37	42	10	352	40	22	2.4	1.1	--	432	264	25	1.1	668	7.7
JW-23-06-501	368	Apr. 17, 1961	50	--	38	38	34	8.6	346	29	12	2.6	4.0	.13	391	252	22	.9	620	7.3
KJ-23-44-801	140	May 17, 1960	50	--	36	52	78	11	325	97	82	--	6.6	.19	582	304	35	1.9	917	7.3
KY-11-49-501	200	June 22, 1955	59	.20	48	32	19	7.7	307	21	16	2.6	4.3	--	366	252	14	.5	550	7.7
KY-23-10-101	267	Oct. 17, 1960	47	--	96	74	52	15	364	162	142	1.8	3.5	--	780	544	17	1.0	1,240	7.0
LX-24-21-801	241	Apr. 11, 1961	43	--	34	47	71	12	310	117	44	4.3	4.0	.50	533	278	34	1.9	835	7.5
LK-24-30-601	170	Aug. 15, 1956	52	.00	48	56	64	12	343	141	51	4.8	1.5	--	599	351	28	1.5	949	7.7
RU-10-53-301	200	Oct. 18, 1960	31	.04	41	28	30	7.0	276	28	16	1.8	8.4	--	334	218	22	.9	550	7.0
RU-10-63-601	250	June 21, 1955	58	.02	66	24	22	5.8	296	28	26	1.1	12	--	389	263	15	.6	601	7.7
RU-24-05-701	54	June 5, 1952	30	--	70	145	[b] 298		293	632	350	8.0	7.2	--	1,680	770	46	4.7	2,580	8.0
SP-23-17-101	170	Aug. 14, 1956	63	.00	95	98	140	17	298	464	165	1.6	.8	--	1,190	640	32	2.4	1,750	7.7
SP-24-32-902	207	Oct. 17, 1960	50	.04	28	44	93	12	357	89	49	5.8	3.0	--	550	251	43	2.5	869	7.2
SR-23-43-401	151	Oct. 17, 1960	52	.08	46	48	117	12	346	142	91	4.9	9.7	--	712	312	44	2.9	1,100	7.0
SR-28-02-204	40	Aug. 10, 1949	48	--	206	200	[b] 299		217	743	620	--	11	--	2,160	1,340	27	3.6	3,360	--
UR-09-40-901	318	Apr. 12, 1961	35	.03	30	26	30	6.6	226	28	19	2.9	9.8	.23	300	182	25	1.0	484	7.5
UR-10-35-901	400	June 17, 1955	33	.03	42	22	24	7.7	263	20	10	1.9	7.4	--	300	195	20	.7	476	7.8

[a] Includes the equivalent of any carbonate (CO_3) present.
[b] Sodium and potassium calculated as sodium (Na).

Table 9.--Pumpage from major wells tapping the Ogallala Formation in the Brazos River Basin, 1959

Major subdivision	Public supply		Industrial		Irrigation		Total*	
	mgd	acre-ft./yr.	mgd	acre-ft./yr.	mgd	acre-ft./yr.	mgd	acre-ft./yr.
BR- 1	9.58	10,740	3.89	4,355	250	280,000	260	300,000
3	1.86	2,080	.01	8	110	120,000	112	120,000
5	12.00	13,440	1.94	2,170	270	300,000	280	320,000
8	1.67	1,895	.32	354	130	150,000	130	150,000
10	.25	284	--	--	.98	1,100	1.2	1,400
13	.12	132	.05	56	300	330,000	300	330,000
14	3.68	4,127	.02	20	290	330,000	290	330,000
15	1.72	1,927	.01	16	480	530,000	480	530,000
17	.53	592	--	--	130	140,000	130	140,000
18	--	--	--	--	7.67	8,600	7.7	8,600
19	--	--	--	--	.71	800	.71	800
Total*	31	35,000	6.2	7,000	2,000	2,200,000	2,000	2,200,000

* Figures are approximate because some of the pumpage figures are estimated. Public-supply and industrial pumpage figures are shown to the nearest 0.01 mgd and to the nearest acre-foot. Irrigation figures and totals are rounded to two significant figures.

at an even greater pace from 1951 through 1955 when precipitation was below normal. In 1956, the drilling rate slackened and continued at a reduced rate during 1957-58. By 1959, an estimated 28,300 major wells were in use in the High Plains part of the Brazos River Basin. Of this number, about 28,000 were irrigation wells and about 275 were public-supply wells. The areas of greatest concentration of wells are shown in Plate 1.

Changes in Water Levels

The changes in water levels in wells in the Ogallala Formation in the Brazos River Basin are controlled principally by the changes in the rate of ground-water withdrawals. The fluctuations of water levels in five representative wells are shown in Figure 18; the locations of the wells are shown on Plate 1. Three of the wells have records extending from 1936 to 1961, one from 1937 to 1961, and one from 1952 to 1961.

The pattern of the fluctuations of the water table in the High Plains may be described generally as follows: Prior to 1941, the water table was lowered in what were then the heavily pumped areas at the average yearly rate of about 1 foot, or less. The water-level decline was interrupted by the above-normal precipitation of 1941, which reduced the need for pumping, and in some places contributed a substantial amount of recharge to the ground-water reservoir. The drawdown trend of the water table started again about 1943 or 1944 and has continued in most areas at varying rates to January 1961.

Well AR-10-49-501 is in the "sandhills" area in Bailey County, somewhat remote from areas of heavy pumping. The hydrograph (Figure 18) shows that the water table declined 2.7 feet from 1952 to 1961, as compared to a decline of 38.1 feet in well JW-11-61-203 in the heavily pumped part of the High Plains.

Availability and Potential Development of Ground Water

The volume of water stored in the Ogallala Formation in the High Plains part of the Brazos River Basin is the product of the volume of saturated material and the porosity. Such an estimate of volume of water in storage is of little value in itself because much of the water will not drain from the material and, therefore, will not be available to wells. The proportion of water in storage that will be available to wells is determined by the specific yield of the aquifer. The quantity of water in storage that would be available to wells is the product of the volume of saturated material and the specific yield.

The specific yield of the Ogallala Formation has been estimated by comparing the volume of water pumped with the volume of Ogallala deposits dewatered during the 3-year period 1938-41 (Alexander, Broadhurst, and White, 1943, p. 15-16). Estimates based on the assumption that there was no recharge during the period indicates the specific yield to be 14.5 percent for the "Plainview district" and 14.1 percent for the "Hereford district." By laboratory methods, Barnes and others (1949, p. 41) concluded that the average specific yield of the Ogallala Formation probably is greater than 15 but less than 20 percent. In 1954 and 1955, long-duration recharge tests of wells near Amarillo, Texas (Moulder and Frazor, 1957, p. 15) showed that the coefficient of transmissibility of the

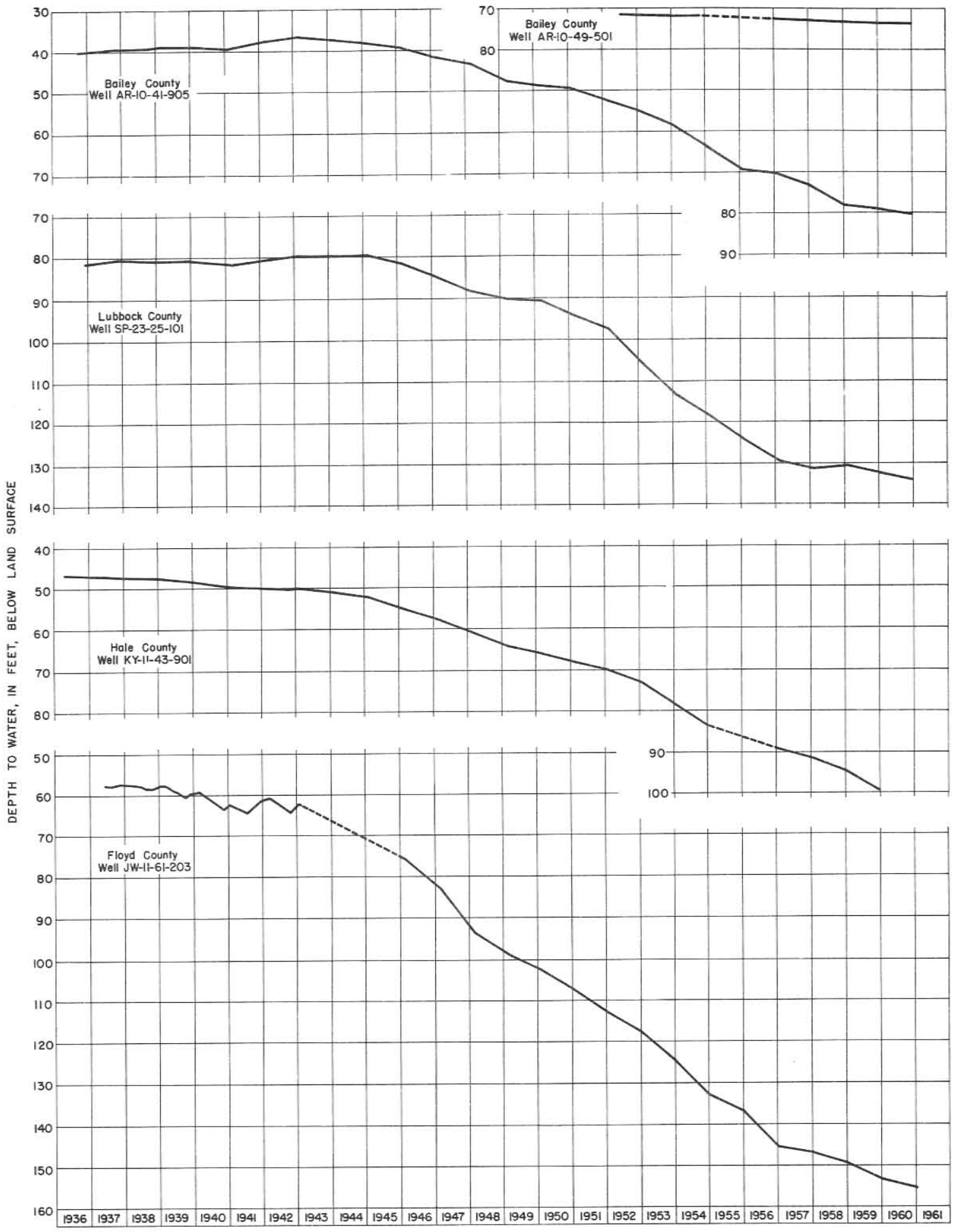

Figure 18

Changes in Water Levels in Wells in the Ogallala Formation

U. S. Geological Survey in cooperation with the Texas Water Commission

134

aquifer ranged from 6,000 to 7,000 gpd per foot and the specific yield from 9 to 16 percent. A 120-day pumping test of the Ogallala Formation at Plainview in Hale County indicated that the coefficient of transmissibility at the test site was between 24,000 and 38,000 gpd per foot, and was probably somewhat less than 38,000 but probably not less than 34,000 gpd per foot. The specific yield was determined to be between 11 and 14 percent but probably nearer 14 (Cronin and Wells, 1960, p. 35).

In 1957, a long-duration aquifer test of about 5 months was made at the city of Lubbock well field in Lamb and Bailey Counties. Results obtained from this test showed the specific yield of the Ogallala to be 12 percent (Moulder, E. A., written communication).

The volume of saturated material in the Ogallala was determined from Plate 9, which shows by means of contours the approximate thickness of the water-bearing material. Based on a specific yield of 15 percent, it is estimated that as of 1958 the Ogallala Formation in the High Plains part of the Brazos River Basin had on the order of 89,000,000 acre-feet of water in storage that would be available to wells. The following table shows a breakdown of the volume of water in storage by counties:

County	Water in storage (acre-feet)
Bailey	6,600,000
Castro	11,000,000
Cochran	2,700,000
Crobsy	7,900,000
Dawson	a/
Dickens	a/
Floyd	11,000,000
Garza	210,000
Hale	15,000,000
Hockley	5,100,000
Lamb	9,600,000
Lubbock	6,500,000
Lynn	800,000
Parmer	10,000,000
Swisher	1,900,000
Terry	260,000
Total	89,000,000

a/ Not estimated; quantity probably very small.

Problems

A problem of major concern in the High Plains section of the Brazos River Basin is the continued large-scale withdrawals of water with consequent reduction of the saturated thickness of water-bearing material. The amount of water withdrawn each year exceeds even the most optimistic estimates of recharge; thus, the ground-water supply is being depleted or mined. Continued large-scale withdrawals of water with consequent reduction of the saturated thickness will result also in a continued decrease in the yield of wells, which was recognized by Leggat (1954a, p. 16-17) as early as 1951.

Because the ground-water reserves are being depleted, methods of supplementing the water supply have been proposed. Facilities are now being constructed to divert water from the Canadian River near Amarillo and the White River for use by some municipalities in the Brazos River Basin area of the High Plains. The use of surface water by some cities will conserve some ground water for irrigation and other uses, but the quantity will be small. Artificially recharging the ground-water reservoir with water from the depression lakes and ponds involves hazards such as the clogging of the well screen or formation by suspended matter in the recharge water, the possible pollution of the ground water by the direct addition of contaminated water, and the possible clogging of the well screen or formation by chemical precipitates caused by the incompatability of the recharge water with the native ground water and the constituent parts of the formation being recharged. However, the amount of water available for recharge will vary from year to year, depending chiefly on the amount, intensity, and time of precipitation. The maximum amount available in any year will not equal the estimated present-day annual withdrawals. Other remedial measures such as the importation of water from other areas, although remotely possible, appear infeasible at this time.

Conservation of the present supply by using it in the most effective manner supplemented by the use of water from the lakes and ponds, either by direct application to the crops or stored in the ground for future use, and effective use of soil water are perhaps the best and only foreseeable means of extending the life of the ground-water reservoir.

A potentially serious problem connected with the development of ground water from the Ogallala is the possibility of contamination by oil-field brines. In some areas, oil operators dispose of the brine produced with the oil through surface disposal pits, which has resulted in some contamination of the ground-water supplies. Steps have been taken by the State and other groups to prohibit the use of surface pits for the disposal of oil-field brines.

Tertiary System in the West Gulf Coastal Plain

Midway Group

The Midway Group of Paleocene age crops out in a slightly rolling black-land belt from 2 to 10 miles wide in region III of the Brazos River Basin (Plate 3). The Midway Group consists of glauconitic sand, silt, calcareous and gypsiferous clay, and lentils of limestone. The thickness ranges from zero to about 900 feet and the group dips southeastward at about 60 to 75 feet to the mile, the dip probably increasing with depth.

The Midway is an aquifer of small importance. A few shallow dug wells yield small quantities of water on the outcrop; some of the water is fresh, but most is slightly to moderately saline water. The wells are undependable; many fail during droughts.

Drilled wells tapping fractures, cracks, or crevices in a limestone lentil in Limestone County yield moderate quantities of fresh water; the water generally is hard. The city of Mexia and the Mexia State School pumped 0.81 mgd (910 acre-feet) of water in 1959 from several wells tapping limestone (Table 20). At that time, the yield of the wells ranged from 60 to 300 gpm. The yield of each well was reported to decrease with time, eventually requiring abandonment and the drilling of new wells. The city began using a surface-water supply in 1961.

Carrizo Sand and Wilcox Formation, Undifferentiated

Physical Description

The Carrizo Sand and Wilcox Formation, undifferentiated, of Eocene age, crops out in a northeast-trending band ranging in width from about 10 to 24 miles in the Brazos River Basin. The outcrop is wider east of the river than west of it (Plate 3). The Carrizo Sand and Wilcox Formation, undifferentiated, consists principally of alternating beds of sand and clay containing layers of silt and lignite; many of the beds of sand grade laterally and vertically into clay, lignite, or silt in short distances. The Carrizo Sand and Wilcox Formation are treated as a hydrologic unit in this report because of their similar lithology and water-bearing properties.

The thickness of the Carrizo Sand and Wilcox Formation, undifferentiated, ranges from zero on the outcrop to 4,340 feet in an oil test in southeastern Washington County where the top of the unit is at a depth of 6,670 feet. The thickness is about 1,700 feet near Hearne and about 2,200 feet at the city of Bryan well field. The thickness of the Carrizo Sand differs from place to place, ranging from 50 to about 230 feet.

The Wilcox Formation consists principally of reddish-brown to light-gray, unconsolidated, ferruginous, fine to medium sand interbedded with light to dark-gray clay, lignite, and silt. The principal bed of sand in the Wilcox Formation in the Brazos River Basin is the Simsboro Sand Member of the Rockdale Formation of Plummer (Sellards, Adkins, and Plummer, 1932), which is about 450 feet thick in the Bryan area and is composed of medium-grained sand and thin layers of clay about an inch to 10 feet in thickness. The top of the Simsboro is at about the middle of the Wilcox Formation. Other sand beds lie above and below the Simsboro and the total thickness of sand in the Wilcox is 1,000 feet or more in some places. Both the total thickness of the Wilcox Formation and the combined thickness of sand generally increase downdip. Except for the massive Simsboro, the individual sand beds are lenticular and may grade laterally into clay, lignite, or silt in short distances. However, the lenticularity of the strata generally does not isolate water in one lens from that in another.

The Carrizo Sand consists of light gray to reddish-brown unconsolidated, cross-bedded, fine to medium sand and interbedded fine sand, silt, clay, and shale. Near Giddings, the Carrizo is about 90 percent sand, but the thickness generally decreases eastward and downdip in the Brazos River Basin. In the Bryan area, the Carrizo Sand is mostly sandy clay and shale and yields only small quantities of water to wells.

The dip of the Carrizo Sand and Wilcox Formation, undifferentiated, is southeastward toward the Gulf Coast (Figure 8 and Plate 5). From its outcrop, the average dip of the beds to 3,000 feet below sea level elevation is about 130 feet per mile on the west side of the basin, 90 feet per mile along the line of section C-C' (Figure 8), and 80 feet per mile on the east side of the basin. The dip generally increases with depth as does the total thickness of the unit.

Recharge, Movement, and Discharge of Ground Water

The principal source of recharge to the Carrizo Sand and Wilcox Formation, undifferentiated, is precipitation on the outcrop. In many places, the outcrop is loose, porous sand which offers ideal conditions for the infiltration of precipitation, which averages from 34 to 41 inches a year (Figure 3). Only a small percentage of the annual precipitation, however, is added to the ground water in storage. The presence of numerous springs, seeps, and marshes in the outcrop indicates that recharge is being rejected. Following heavy rains, the sands are nearly or completely saturated on the outcrop. Most of the small streams which flow across the outcrop ultimately to the Brazos River are effluent at least part of the time while on the Carrizo Sand and Wilcox Formation, undifferentiated. Although no seepage investigations have been made, some water is believed to discharge to the Brazos River, Little River, Little Brazos River, and to the overlying alluvium from the Carrizo Sand and Wilcox Formation, undifferentiated.

The movement of water in the Carrizo Sand and Wilcox Formation, undifferentiated, is chiefly southeastward downdip. The geologic structure may affect the downdip movement of the water to some extent along the Luling-Mexia-Talco fault zone in Lee and Milam Counties; however, it is likely that the displacement of the beds only partly restricts the movement of water across the faults. In the middle of the basin, the piezometric surface has a southeastward average slope of about 4 feet to the mile from the outcrop toward the Bryan well field.

The principal source of artificial discharge of ground water is by wells. In 1959, about 4,500 acre-feet (4 mgd) was discharged by major wells from the Carrizo Sand and Wilcox Formation, undifferentiated, in the Brazos River Basin (Table 10). For further discussion of the amounts of ground water discharged by wells, see the later section titled "Utilization and Development of Ground Water."

Significant amounts of ground water also are discharged naturally by springflow and seepage on the outcrop as rejected recharge. The amount of the effluent is not known, but the base flow of many creeks probably is sustained in large measure by ground water from the Carrizo Sand and Wilcox Formation, undifferentiated. Transpiration by plant growth is believed also to constitute a large part of the total water discharged.

Changes in Water Levels

The pumpage of water from the Carrizo Sand and Wilcox Formation, undifferentiated, in the Brazos River Basin increased gradually until 1952 when the Aluminum Company of America started pumping about 1,700 acre-feet a year near Rockdale. The total pumpage of 4,500 acre-feet in 1959 was well distributed throughout the basin. Based on the limited data available, the relatively small

Table 10.--Pumpage from major wells tapping the Carrizo Sand and Wilcox Formation, undifferentiated, in the Brazos River Basin, 1959

Major subdivision	Public supply		Industrial		Irrigation		Total*	
	mgd	acre-ft./yr.	mgd	acre-ft./yr.	mgd	acre-ft./yr.	mgd	acre-ft./yr.
BR-69	--	--	--	--	0.09	95	0.09	95
71	0.96	1,076	0.03	34	--	--	.99	1,100
73	.63	700	1.44	1,623	.06	66	2.1	2,400
75	.21	238	--	--	.12	130	.33	370
76	.03	28	--	--	--	--	.03	28
78	.42	466	--	--	--	--	.42	470
Total*	2.3	2,500	1.5	1,700	.27	290	4.0	4,500

* Figures are approximate because some of the pumpage is estimated. Public-supply and industrial pumpage figures are shown to the nearest 0.01 mgd and to the nearest acre-foot. Irrigation figures and totals are rounded to two significant figures.

pumpage compared to the large potential has caused little change in water levels. The railroad well (WK-59-11-314) 3 miles west of Hearne in Robertson County had a reported artesian pressure head of 53 feet above land surface in 1922, 56 feet above land surface in 1938, and 46 feet above land surface in 1960. On the outcrop at Rockdale in a city-owned dug well, the water level was measured at 28.7 feet below land surface in 1936 and 34.2 feet in 1960.

Chemical Quality of Ground Water

Fresh to slightly saline water may be obtained from the Carrizo Sand and Wilcox Formation, undifferentiated, from near the northwest edge of the outcrop to the approximate limit shown on Plate 5. Most of the water from wells less than 50 feet deep on the outcrop is fresh, but in general the quality of water from somewhat deeper wells is of better quality. In the artesian part of the aquifer, the dissolved-solids content gradually increases with depth, reaching the upper limit of slightly saline water where the top of the Carrizo Sand and Wilcox Formation, undifferentiated, is at 1,800 to 2,400 feet below sea-level elevation (Plate 5). The lower part of the Carrizo Sand and Wilcox Formation, undifferentiated, may contain moderately saline water while the upper part of the unit contains fresh to slightly saline water. Chemical analyses of water from 9 selected wells in the Carrizo Sand and Wilcox Formation, undifferentiated, in the Brazos River Basin are shown in Table 11. Locations of the wells are shown on the well map (Plate 3) by a bar over the well symbol. The water generally is high in sodium bicarbonate content. The hardness of 9 samples ranged from 8 to 454 ppm. The dissolved-solids content of the 9 samples ranged from 247 to 1,650 ppm. The boron content ranged from 0.01 to 1.6 ppm in the 3 samples that were analyzed for boron. The SAR (sodium adsorption ratio) of the 9 samples ranged from 1.0 to 76; 4 were in the low sodium hazard range (0-10), 1 in the high range (18-26), and the other 4 in the very high range (more than 26).

The quality of water in the Carrizo Sand and Wilcox Formation, undifferentiated, is acceptable for municipal use in the northwestern part of the aquifer. The concentrations of minerals generally are within the recommended limits as established for drinking water by the U. S. Public Health Service. Concentrations of iron in excess of 0.3 ppm may be expected in some places and treatment may be necessary. The dissolved-solids content normally increases with depth in the Carrizo Sand and Wilcox Formation, undifferentiated, but was only 770 ppm in well BJ-59-21-303 screened from 2,670 to 2,940 feet. In general, the best quality of water can be obtained by selectively screening the sand beds containing the less mineralized water.

The water in the Carrizo Sand and Wilcox Formation, undifferentiated, is suitable for many industrial needs or can be made suitable with minimum treatment.

Water from the northwestern half of the aquifer (between the outcrop and the line midway between the outcrop and the southeast limit of slightly saline water) probably is suitable for at least supplemental irrigation. The relatively high rainfall would tend to flush the undesirable minerals in the water from the soil; in some years little or no irrigation water would be used.

Table 11.--Chemical analyses of water from selected wells in the Carrizo Sand and Wilcox Formation, undifferentiated, Brazos River Basin

[Analyses given are in parts per million except specific conductance, pH, percent sodium, and sodium adsorption ratio (SAR).]

Well	Screened interval (feet)	Date of collection	Silica (SiO_2)	Iron (Fe) (total)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3) a/	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Boron (B)	Dissolved solids	Hardness as $CaCO_3$	Percent sodium	Sodium adsorption ratio (SAR)	Specific conductance (micromhos at 25°C)	pH
b/ BJ-59-21-303	2,670-2,940	May 8, 1954	25	0.5	3	2	c/ 322		714	28	71	0.7	--	--	770	16	--	35	--	8.1
BJ-59-21-714	d/ 2,741-2,989	July 31, 1956	24	.03	2.4	.5	c/ 235		536	.0	55	.5	0.0	--	581	8	98	36	950	8.2
BS-59-43-401	? -2,500	Nov. 11, 1959	18	--	4.5	.9	652	3.8	702	2.4	620	--	.2	1.6	1,650	14	99	76	2,880	8.0
RZ-58-40-603	475-518	Nov. 17, 1959	18	1.0	34	8.3	45	5.0	145	73	19	.1	.0	.17	275	119	44	1.8	441	7.1
RZ-59-33-701	d/ 168-486	Sept. 16, 1953	18	11	121	37	49	8.8	258	186	111	--	1.0	.01	694	454	19	1.0	1,090	7.0
TK-58-32-503	120-170	Aug. 15, 1952	--	.3	15	4.0	c/ 45		78	8.2	55	--	--	--	247	53	--	2.7	--	6.2
WK-39-51-801	190-254	Feb. --, 1943	19	.05	42	8.2	65	6.6	205	28	63	.2	1.0	--	334	138	49	2.4	--	8.3
WK-59-03-202	d/ 534-679	Feb. --, 1943	16	.02	6.3	1.5	321	6.0	692	1.6	111	.4	2.0	--	807	22	96	30	--	8.3
WK-59-04-701	d/ 1,221-1,426	Nov. 10, 1943	25	.02	3.4	1.8	c/ 187		427	3.9	48	.4	.0	--	480	16	96	20	--	8.5

a/ Includes the equivalent of any carbonate (CO_3) present.
b/ Analyzed by Texas State Department of Health.
c/ Sodium and potassium calculated as sodium (Na).
d/ Not screened throughout interval.

Utilization and Development of Ground Water

Water from the Carrizo Sand and Wilcox Formation, undifferentiated, in the Brazos River Basin is used for domestic purposes and livestock on the outcrop area and for a short distance downdip to a point where water from the Queen City Sand Member of the Mount Selman Formation is available from shallower wells.

Water from the Carrizo Sand and Wilcox Formation, undifferentiated, is used for public supply and industrial use on the outcrop and for several miles downdip. Of the 4,500 acre-feet of water pumped in 1959, 2,500 acre-feet was used for public supply, and 1,700 acre-feet by industries (Table 10, page 91). One industry, Aluminum Co. of America near Rockdale, and 3 cities, Hearne, Rockdale, and Bryan, used about 65 percent of the water pumped; the rest was used by several smaller cities, towns, and small industries. Few wells have been drilled to the Carrizo Sand and Wilcox Formation, undifferentiated, downdip from Bryan because fresh water is available from other aquifers at shallower depths. The city of Bryan and Texas A. & M. College use water from the Carrizo Sand and Wilcox Formation, undifferentiated, (wells screened between 2,600 and 2,974 feet) to supplement water from the Sparta Sand. Very little water from the Carrizo Sand and Wilcox Formation, undifferentiated, (290 acre-feet in 1959) is used for irrigation in the Brazos River Basin.

Availability and Potential Development of Ground Water

The coefficient of transmissibility measured in 3 wells on the outcrop of the Carrizo Sand and Wilcox Formation, undifferentiated, near Rockdale averaged about 24,000 gpd per foot, ranging from 15,000 to 30,000 gpd per foot; at the Bryan well field it was about 87,500 gpd per foot. The coefficient of transmissibility for the entire unit would have been greater at each place if all of the sands present had been screened. No coefficients of storage were obtained during the tests, but the average in the basin is estimated to be about 0.001.

Specific capacities of 7 wells ranged from 0.6 to 26 gpm per foot of drawdown. The yields of wells tapping the unit ranged from about 30 gpm from wells on the outcrop to 3,160 gpm from well BJ-51-21-723 in the Texas A. & M. College well field. Both the sand thickness and the yield generally increase with depth. The wells having the largest yields and specific capacities generally are screened opposite the greatest thicknesses of sand.

The saturated thickness of fresh to slightly saline water sands in the Carrizo Sand and Wilcox Formation, undifferentiated, ranges from about 400 to 1,170 feet except in the outcrop area where it ranges from zero to 600 feet (Plate 5). The greatest thickness of saturated sand is about 1,000 feet in well BJ-59-29-601 about 10 miles south of Bryan and 1,170 feet in a well near Giddings.

The altitude of the top of the Carrizo Sand and Wilcox Formation, undifferentiated, ranges from about 400 feet above sea level at the surface contact with the Mount Selman Formation in the Brazos River Basin to about 1,800 to 2,400 feet below sea level at the southeast margin of fresh to slightly saline water (Plate 5). The top of the Carrizo Sand and Wilcox Formation, undifferentiated, is at about 6,470 feet below sea level in well YY-59-56-101 in Washington County (Figure 8, well 52), but the unit contains saline water at this depth.

The estimated volume of fresh to slightly saline water stored in the sands in the Carrizo Sand and Wilcox Formation, undifferentiated, in the Brazos River Basin is about 380,000,000 acre-feet, assuming a porosity of 30 percent; however, only a small fraction of the water is economically recoverable by known methods at present costs.

For comparison purposes, the order of magnitude of the water available from the unit in the Brazos River Basin was computed using a number of assumptions, none of which are precisely true. A line of discharge was postulated extending from a point on the west basin boundary 4 miles west of Giddings to a point on the east basin boundary 4 miles south of the Leon-Madison County line. The line is about 78 miles long and generally parallels the trend of the outcrop, and is about the same location as the 1,000-foot below-sea-level contour on the top of the Carrizo Sand and Wilcox Formation, undifferentiated. The length of the centerline of outcrop (recharge line) was 114 miles. The assumed length of the section was 90 miles. The distance from the assumed line of discharge to the centerline of the outcrop ranged from 17 to 31 miles; however, the assumed distance from the line source is 24 miles and the line of discharge is assumed to be always equidistant from the line source or recharge line. The transmission capacity of the aquifer from the outcrop to the line of discharge was computed using the following assumptions:

1. Water levels will be lowered to a maximum depth of 400 feet below land surface along the line of discharge.

2. No water moves downward into the aquifer except in the outcrop area where all recharge is assumed to occur along the line in the outcrop parallel with the strike and in the middle of the outcrop (assumed effective line source of recharge).

3. The altitude of the water levels is the same and remains the same at all points along the centerline of the outcrop (assumed effective line source of recharge), and the altitude of the water levels is the same at all points along the line of discharge.

4. The slope of the water surface will be constant from the line source after the drawdown to 400 feet at the line of discharge.

5. The hydraulic gradient is the slope of a straight line from the water level at the line source of recharge to the water level along the line of discharge.

6. All the sands between the line source of recharge and the line of discharge transmit water from the outcrop areas to the line of discharge. The assumed average coefficient of transmissibility of the Carrizo Sand and Wilcox Formation, undifferentiated, is 50,000 gpd per foot.

7. The amount of recharge along the line source is sufficient to supply the water that can be transmitted to the line of discharge at the assumed gradients.

8. The average hydraulic gradient is the average of the present hydraulic gradient and the maximum hydraulic gradient that can be attained with a water level of 400 feet at the line of discharge.

The transmission capacity of the Carrizo Sand and Wilcox Formation, undifferentiated, from the assumed line source to the assumed line of discharge at the average hydraulic gradient during the time that the water level is being lowered to 400 feet would be about 70,000 acre-feet per year (62 mgd). The amount of water withdrawn from artesian storage as the water level was lowered to 400 feet along the line of discharge would be about 600,000 acre-feet, assuming no dewatering. If the 1959 discharge rate (4.0 mgd or 4,500 acre-feet) were continuously withdrawn from wells evenly spaced along the assumed line of discharge, the water levels would not be lowered to 400 feet. However, if the pumpage rate were increased to 100 mgd (112,000 acre-feet) per year from wells evenly spaced along the assumed line of discharge, the water level could be lowered to 400 feet in about 14 years at the average gradient. However, the transmission capacity at the maximum gradient after the water level had been lowered to 400 feet below land surface would be about 104 mgd (116,000 acre-feet) per year. Also, the proper distribution of pumpage throughout the area, leakage from overlying formations, locally much larger coefficients of transmissibility and storage, and other factors probably would increase the perennial potential discharge rate.

The amount of recharge on the outcrop necessary to replace the water moving downdip at the maximum transmission capacity (116,000 acre-feet per year) would be about 1.32 inches of rainfall per year or about 3.5 percent of the annual rainfall.

Problems

Data are insufficient to permit a complete evaluation of the potential of the Carrizo Sand and Wilcox Formation, undifferentiated. More information is needed on the hydraulic characteristics to determine more accurately the rate of movement of ground water in the aquifer and the ability of the sands to transmit and yield water to wells. Also, periodic measurements of water levels in selected observation wells are needed in order to evaluate the effects of ground-water development on available supply.

More data also are needed on the location of the southeastern limit of fresh to slightly saline water as the present limit was located approximately from limited data. The downdip rate of increase in salinity should be studied. The differences in salinity in different sand beds in the Carrizo Sand and Wilcox Formation, undifferentiated, also should be studied.

More water is wasted than used from flowing domestic and livestock wells tapping the unit.

Mount Selman Formation

The Mount Selman Formation, of Eocene age, crops out in a gently rolling, mostly sandy northeast-trending belt 5 to 10 miles wide across the Brazos River Basin (Plate 3). The maximum thickness is about 1,200 feet and it dips southeastward at about 80 feet per mile. The Mount Selman is a secondary aquifer in the Brazos River Basin.

The Mount Selman Formation is divided, in ascending order, into the Reklaw Member, the Queen City Sand Member, and the Weches Greensand Member. The Mount Selman consists of fine to medium sand, glauconite, clay, fine sandstone, lignite, greensand, glauconitic clay, and ironstone.

The Reklaw Member at the Base of the Mount Selman overlying the Carrizo Sand has a thickness of about 80 feet in the outcrop and consists mainly of clay or sandy clay in the Brazos River Basin. The Reklaw yields small quantities of slightly to moderately saline water to a few farm and ranch dug wells in the outcrop.

The Queen City Sand Member, about 225 feet thick in the outcrop in the Brazos River Basin, consists of about 70 percent sand, 22 percent fine to medium sandy-silty clay or shale, 1 percent lignite, 1 percent bentonite, and 5 percent glauconite (Sellards, 1932, p. 633). The Queen City Sand Member yields small quantities of fresh to slightly saline water to many farm and ranch wells in the outcrop area and downdip to the point where water from the Sparta Sand can be obtained.

The Weches Greensand Member, which underlies the Sparta Sand, has a thickness of about 70 feet in the outcrop, and consists of 55 percent glauconite, 30 percent glauconitic clay, 10 percent glauconitic sand, 4 percent clay, and 1 percent iron (Sellards, 1932, p. 642). The Weches yields small quantities of slightly to moderately saline water to a few farm and ranch dug wells in the outcrop.

There are no major wells in the Brazos River Basin which tap the Queen City Sand Member. The city of Giddings, which is on the topographic divide between the Colorado River and Brazos River Basins, obtains most of its supply from wells tapping the Queen City in the Colorado River Basin. One of the wells yields about 500 gpm, most of the water being from the Queen City Sand Member. Yields of 200 to 400 gpm of fresh to slightly saline water probably can be obtained from the Queen City Sand Member of the Mount Selman Formation in the Brazos River Basin for municipal supply, most industrial uses, and supplemental irrigation.

Chemical analyses of water from the city of Giddings wells show that the dissolved-solids content ranges from 772 to 1,080 ppm; water from a test well at Bryan (BJ-59-21-301, Table 12) had a dissolved-solids content of 1,150 ppm. In general, water in the Mount Selman decreases in mineralization toward the outcrop.

Data are insufficient in the Brazos River Basin to permit a complete evaluation of the potential development of the Mount Selman Formation. More information is needed on the hydraulic characteristics to determine accurately the rate of movement of ground water in the aquifer and the ability of the sands to transmit and yield water to wells. Periodic measurements of water levels in selected wells are needed to evaluate the effects of ground-water development on available supply. Chemical analyses of water samples will be required to outline the extent of fresh to slightly saline water in the Queen City Sand Member.

Table 12.--Chemical analyses of water from selected wells in the southeast half of region III, Brazos River Basin

[Analyses given are in parts per million except specific conductance, pH, percent sodium, and sodium adsorption ratio (SAR).]

Water-bearing unit: Tcm, Cook Mountain Formation; Tcol, Catahoula Sandstone, Oakville Sandstone, and Lagarto Clay, undifferentiated; Tj, Jackson Group; Tms, Mount Selman Formation; Ts, Sparta Sand; Ty, Yegua Formation.

Well	Water-bearing unit	Screened interval (feet)	Date of collection	Silica (SiO_2)	Iron (Fe) (total)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3) a/	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Boron (B)	Dissolved solids	Hardness as $CaCO_3$	Percent sodium	Sodium adsorption ratio (SAR)	Specific conductance (micromhos at 25°C)	pH
b/ YY-59-54-401	Tcol	105-135	1957	--	--	72	46	c/ 22		323	23	43	--	--	--	571	372	--	0.5	--	--
YY-59-53-909	Tcol	d/ 98-500	Oct. 14, 1959	30	0.05	148	3.1	24	1.2	387	8.2	76	0.2	5.6	0.08	499	382	12	.5	839	6.7
KW-59-40-702	Tcol	175-276	Sept.12, 1942	37	.40	23	3.4	c/ 238		556	2	93	.3	.0	--	671	72	88	12	--	7.8
KW-60-17-401	Tj	374-404	Dec. 15, 1942	--	--	19	2.2	c/ 313		238	294	164	0	4.0	--	913	56	92	18	--	--
BJ-59-22-601	Ty	? -300	May 22, 1961	42	--	8.5	1.6	128	4.1	140	30	118	.2	.0	.09	411	28	90	11	678	6.6
BS-59-44-303	Ty	178-198	Nov. 2, 1939	--	2.5	69	3.5	c/ 587		492	222	585	.5	3.6	--	1,710	187	87	19	--	7.9
BS-59-44-301	Tcm	775-815	do	--	e/ .02	19	2.3	c/ 635		644	98	570	1.4	.0	--	1,640	57	96	37	--	8.7
BJ-59-21-302	Ts	435-523	Nov. 10, 1942	18	.04	2.0	.3	c/ 67		156	5.7	12	.2	.0	--	184	6	96	12	--	8.2
BJ-59-21-718	Ts	d/ 411-482	June 22, 1943	31	.73	2.0	.4	c/ 84		172	20	18	.5	.0	--	265	6	96	15	--	8.1
f/ BJ-59-21-301	Tms	648-688	May --, 1938	--	--	4.8	2.1	c/ 485		1,070	6.9	72	1.6	.1	--	1,150	21	97	46	--	--

a/ Includes the equivalent of any carbonate (CO_3) present.
b/ Analyzed by Texas State Chemist.
c/ Sodium and potassium calculated as sodium (Na).
d/ Not screened throughout interval.
e/ Iron in solution.
f/ Drill-stem test at interval indicated.

Sparta Sand

Physical Description

The Sparta Sand overlies the Mount Selman Formation and crops out in a band 1 to 6 miles wide, extending northeastward from Bastrop County into the eastern part of Leon County (Plate 3). The Sparta Sand, which is a secondary aquifer in the Brazos River Basin, supplies moderate quantities of water to major wells only in the Bryan area. Artesian conditions prevail where the Sparta is overlain by the Cook Mountain Formation and in the outcrop where water-bearing sand beds are covered by layers of clay.

The Sparta Sand consists of about 70 percent sand, 25 percent sandy shale or clay, 3 percent glauconitic sand, 1 percent limonite, and 1 percent lignite (Sellards and others, 1932, p. 654). The sand is gray or buff colored and fine to medium grained. Generally, the clay and sandy clay are near the top of the formation. The sand beds often are separated by lenses of clay or sandy clay.

In the subsurface, the Sparta Sand has a fairly uniform thickness, ranging between 250 and 300 feet. Figure 8 indicates that the thickness of the Sparta actually decreases slightly downdip. The Sparta Sand dips southeastward at about 70 feet per mile from the outcrop to the Bryan area; south of Bryan, the rate of dip increases rapidly (Figure 8).

Recharge, Movement, and Discharge of Ground Water

Recharge to the Sparta Sand is from precipitation on the outcrop. The outcrop is favorable for ground-water recharge because it is covered with a sandy soil and has comparatively low relief. The average annual rainfall on the outcrop is probably on the order of about 35 to 41 inches, but only a small percentage of the rainfall becomes recharge.

The movement of the water in the Sparta Sand is southeastward except locally where it is toward the Brazos River or toward centers of large withdrawals such as at the Bryan well field.

Ground water is discharged from the Sparta Sand naturally by springs, seepage to streams, transpiration and evaporation, and artificially by wells. Significant amounts of ground water are discharged naturally by springflow and seepage to streams on the outcrop and to the alluvium along the Brazos River, by evaporation where the water table is near the land surface, and by plant transpiration. Data are not available to estimate the quantity of ground water discharged naturally from the Sparta Sand. Most of the discharge by wells is in the well fields of the city of Bryan and Texas A. & M. College, where 4.5 mgd was pumped in 1959 (Figure 19 and Table 13). Only 0.05 mgd was pumped from the Sparta Sand by major wells in the rest of the basin. An undetermined amount of water is wasted by flowing wells that are never shut in.

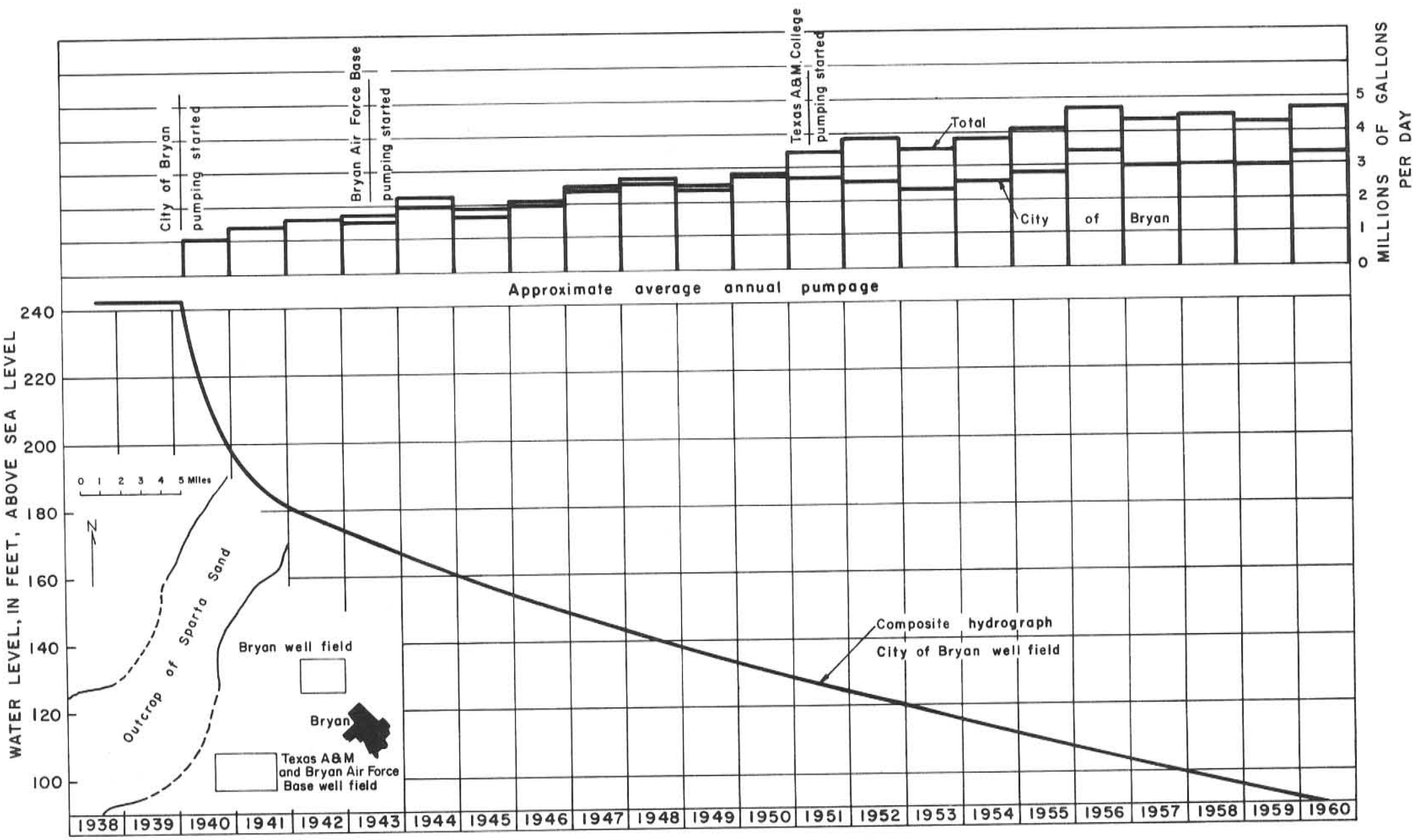

Figure 19

Composite Change in Water Level and Pumpage from Wells in the Sparta Sand, Brazos County

U. S. Geological Survey in cooperation with the Texas Water Commission

Table 13.--Pumpage from major wells tapping the Sparta Sand in region III, Brazos River Basin, 1959

Major subdivision	Public supply		Industrial		Irrigation		Total*	
	mgd	acre-ft./yr.	mgd	acre-ft./yr.	mgd	acre-ft./yr.	mgd	acre-ft./yr.
BR-71	1.49	1,660	--	--	--	--	1.5	1,700
73	.01	13	--	--	--	--	.01	13
75	--	--	--	--	0.01	10	.01	10
78	2.95	3,308	--	--	.04	47	3.0	3,400
Total*	4.5	5,000	--	--	0.05	57	4.5	5,100

* Figures are approximate because some pumpage is estimated. Public-supply and industrial pumpage figures are shown to the nearest 0.01 mgd and to the nearest acre-foot. Irrigation figures and totals are rounded to two significant figures.

Utilization and Development of Ground Water

In the Brazos River Basin, water from the Sparta Sand is used for domestic and livestock purposes in the outcrop area and for a short distance downdip to the point where the water is highly mineralized or water is available from the Cook Mountain Formation at shallower depths. Some wells in creek or river bottoms that tap the Sparta Sand will flow.

The city of Bryan and Texas A. & M. College obtain most of their water supply from the Sparta Sand. The Bryan Air Force Base also used water from the Sparta until about 1954 when a well tapping the Carrizo Sand and Wilcox Formation, undifferentiated, was completed. Prior to 1940, Bryan obtained part of the water from the Sparta Sand wells in downtown Bryan. In 1940, the city of Bryan completed a well field about 3-1/2 miles northwest of town and closer to the outcrop of the Sparta Sand. Bryan Air Force Base and Texas A. & M. College drilled wells to the Sparta Sand about 6 miles west of Bryan (Plate 3). Pumpage from the Sparta Sand in the Bryan area increased from about 1 mgd in 1940 to about 4.7 mgd in 1960.

Water from the Sparta Sand from wells in or near the outcrop has been used successfully for supplemental irrigation in the Brazos Basin. About 57 acre-feet of water from the Sparta Sand was used for irrigation in 1959.

Changes in Water Levels

Regular periodic water-level measurements have not been made in wells in the Sparta Sand in the Brazos River Basin. Measurements made in several wells in the Bryan well field at irregular intervals show a decline of about 150 feet between 1938 and 1960 (Figure 19). The static water level in 1960 was about 60 feet above the top of the Sparta Sand and about 170 feet above the top of the highest screen. The pumping levels probably were above the screens even when all the wells were pumping.

Evidence of significant changes in the water level in the Sparta Sand elsewhere in the Brazos River Basin is lacking.

Chemical Quality of Ground Water

Water from the Sparta Sand in the Brazos Basin generally is suitable for public supply, industrial use, and irrigation, although very little is used for irrigation and none by industry. Water from wells on the outcrop is generally of good quality.

Table 12 shows that the water in two wells (BJ-59-21-302 and BJ-59-21-718) in the Bryan city well field, is low in dissolved-solids content and soft; only the iron content in one of the wells exceeds the standards recommended by the U. S. Public Health Service. In other wells, which supply Texas A. & M. College and Bryan Air Force Base, the water contains as much as 600 ppm dissolved solids.

The water in the Sparta Sand apparently is fresh from the outcrop downdip to a point where the base of the formation is about 600 feet below land surface. Further downdip, the water becomes slightly saline. For example, water from a well in the abandoned well field at Bryan contained 1,600 ppm dissolved solids. Available data also show that in the well field that supplies Bryan, the water in the upper part of the Sparta is more mineralized than that in the lower part, but whether this condition exists elsewhere is not known.

Availability and Potential Development of Ground Water

The thickness of saturated sand containing fresh to slightly saline water in the Sparta Sand ranges between 50 and 150 feet in the vicinity of the well fields near Bryan. In a Giddings city well, only about 50 feet of sand was present in the Sparta Sand. Available data suggest that the aggregate thickness of saturated sand in the Sparta Sand is less than 100 feet over much of the area between the city of Bryan and Giddings.

Results of pumping tests in the Bryan city wells in June and July 1944 show that the coefficients of transmissibility ranged from about 9,300 to 15,000 and averaged 12,000 gpd per foot; the coefficients of storage ranged from 0.00015 to 0.00027 and averaged 0.00022 (Barnes and others, 1944, p. 19).

The coefficient of transmissibility in the Bryan Air Force Base ranged from about 11,000 to 14,000 and averaged 12,000 gpd per foot; the coefficients of storage ranged from 0.00015 to 0.00023 and averaged 0.00016.

The amount of water available in the Sparta Sand is dependent on both the total saturated thickness of sand and the hydraulic properties. The magnitude of the water available from the Sparta Sand cannot be determined accurately because of the following reasons: The sand thickness in the formation is not known throughout the basin; the coefficients of transmissibility and storage are known only in the Bryan area; and the approximate limit of the fresh to slightly saline water cannot be determined from available data. However, an approximation of the volume of water available is possibly based on the following assumptions: (1) The fresh to slightly saline water extends over an area of about 720 square miles; (2) the porosity of the sands is 30 percent; and (3) the thickness of the saturated sand averages about 75 feet. On this basis, the amount of fresh to slightly saline water in the Sparta Sand is approximately 11,000,000 acre-feet. Actually, this volume might be considered as conservative because the average saturated thickness may be more than 75 feet. Only a part of the ground water in storage can be recovered by present methods. Large withdrawals should be widely spaced to minimize interference between wells owing to the low transmissibilities. However, pumpage from the Sparta Sand in the Brazos River Basin could be increased to several times the 1960 rate and still maintain reasonable pumping levels for many years, providing the wells were properly spaced.

Problems

Data are insufficient to permit a complete evaluation of the potential of the Sparta Sand in the Brazos River Basin. More information is needed regarding the thickness of the saturated sand as well as the ability of the sands to transmit and yield water to wells.

Periodic measurements of water levels in selected observation wells are needed in order to evaluate the effects of ground-water development on available supply.

Chemical analyses are required to determine the extent of the fresh to slightly saline water in the Sparta Sand. The quality of water at different depths in the Sparta Sand should be studied.

A large but undetermined amount of water is wasted by uncontrolled flowing wells. As development occurs, however, the decline in artesian pressure head will ultimately reduce or eliminate the flow of these wells.

Cook Mountain Formation

The Cook Mountain Formation overlies the Sparta Sand and crops out in a slightly rolling, more or less sandy belt 1 to 7 miles wide, extending northeastward across the Brazos River Basin (Plate 3). The formation, which has a maximum thickness of about 700 feet, dips southeasterly; the slope generally increases with depth.

The Cook Mountain consists of about 90 percent clay, shale, and sandy shale, 9 percent sand and glauconite, and 1 percent limestone and ferruginous concretions (Sellards and others, 1932, p. 660).

The Cook Mountain is not an important aquifer in the Brazos River Basin. In general, the beds of sand yield small to moderate quantities of water to farm and ranch wells on the outcrop area and to wells as much as a few hundred feet in depth downdip from the outcrop where the Cook Mountain Formation is overlain by the Yegua Formation. In general, the water in the outcrop is fresh but increases in mineralization downdip. Well BS-59-44-301, approximately 16 miles downdip from the outcrop, yields water containing 1,640 ppm dissolved solids and 570 ppm chloride (Table 12). Further downdip the water becomes moderately saline.

Only one major well in the Brazos River Basin obtains water from the Cook Mountain Formation. An industrial well in south-central Burleson County yields about 0.29 mgd (323 acre-feet per year).

Yegua Formation

The Yegua Formation overlies the Cook Mountain Formation and crops out in a gently rolling, more or less sandy belt 4 to 22 miles wide, extending northeastward across the Brazos River Basin (Plate 3). The maximum thickness is about 1,000 feet in the subsurface in Washington County. The Yegua Formation dips southeastward at about 150 feet per mile (Figure 8).

In general, the formation is a heterogeneous complex of layers of sand, clay, lignite, sandy clay, and carbonaceous clay lentils. Individual beds or lenses cannot be correlated except for very short distances. The Yegua Formation consists of about 50 percent sand, 26 percent sandy clay, 22 percent compact clay, 1 percent lignite, and 1 percent bentonite (Sellards and others, 1932, p. 671). The sand is medium to fine grained.

The Yegua Formation is a secondary aquifer in the Brazos River Basin. In general, wells tapping the Yegua yield only small quantities of fresh to slightly saline water to many farm and ranch wells in the outcrop area to depths of about 700 feet; the water is slightly to moderately saline at depths greater than about

700 feet. Some of the water used for domestic purposes does not meet U. S. Public Health Service standards for public supplies.

Beds of sand in the Yegua Formation yield moderate quantities of potable water to a few wells for public supply, industrial use, and irrigation in the Brazos River Basin. The chemical analysis of water from an irrigation well (BJ-59-22-601, Table 12) in the outcrop east of Bryan shows that the dissolved-solids content was 411 ppm. The maximum reported yield was 300 gpm from another irrigation well in Brazos County; smaller yields usually can be expected.

In 1959, the city of Somerville on State Highway 36 in south-central Burleson County pumped about 0.13 mgd (144 acre-feet) of slightly saline water from wells in the Yegua Formation about 200 feet in depth (BS-59-44-303, Table 12). In Burleson County, 4 irrigation wells, which tap the Yegua, pumped about 55 acre-feet of water in 1959.

Until 1940, part of the Texas A. & M. College water supply came from wells drilled to about 800 feet in the Yegua Formation. The water contained about 1,500 ppm dissolved solids and had a disagreeable odor and, as a consequence, the well field was abandoned and the water supply was obtained from the Sparta Sand.

Jackson Group

The Jackson Group crops out in a band 7 to 9 miles wide, extending northeastward across the Brazos River Basin (Plate 3). In the Brazos River Basin, the dip ranges from 120 to 150 feet per mile on the outcrop. The maximum thickness of the group is about 1,200 feet, thickening downdip and toward the coast. The lower part of the Jackson Group is predominantly clay and silt; the upper part is composed of interbedded tuffaceous sand and bentonitic clay lenses. Some strata contain fossils, lignitized wood, and limestone concretions.

The Jackson Group is not an important aquifer in the Brazos River Basin. Generally, wells that tap sand beds in the Jackson yield only small to moderate quantities of water. The Jackson yields potable water to many shallow farm and ranch wells in the outcrop, but at depths greater than 400 feet, the water is slightly to moderately saline. Well KW-60-17-401 (Table 12) yields water containing 913 ppm dissolved solids, 294 ppm sulfate, and 164 ppm chloride.

Sand beds in the Jackson Group yield small to moderate quantities of water for public supply and irrigation in the Brazos River Basin (Table 20). The cities of Anderson, 10 miles northeast of Navasota, and Navasota in Grimes County obtain part of their municipal supply from sands in the Jackson; it is estimated that in 1959 about 0.12 mgd (129 acre-feet) per year was from the Jackson. About 15 acre-feet was pumped from one irrigation well in Grimes County in 1959. In Washington County, two irrigation wells obtain water from the Jackson Group but also from the Catahoula Sandstone and the Yegua Formation. However, most of the 310 acre-feet of water pumped in 1959 probably was from the Catahoula Sandstone and has been assigned to the Tertiary System and Pleistocene and Recent Series undifferentiated, in Table 20.

Tertiary System and Pleistocene and Recent Series, Undifferentiated

The Catahoula Sandstone, Oakville Sandstone, and Lagarto Clay, undifferentiated, which crops out in regions III and IV (Plates 3 and 4), is a primary aquifer in the Gulf Coast region (Wood, Gabrysch, and Marvin, 1963, p. 32). Region IV of this report is the part of the Brazos River Basin that was described in subregion III of that report.

In this report, the boundary between region III and region IV (the boundary of the Gulf Coast region) is based on the boundary of a major subdivision of the Brazos River Basin--that is, the boundary was based on topography and not on geology. Based on geology, the boundary of region IV quite properly would have included all of the outcrop area of the Catahoula Sandstone, Oakville Sandstone, and Lagarto Clay, undifferentiated.

This report reproduces the parts of the map showing the base of fresh to slightly saline water (Plate 10), the map showing the thickness of sands containing fresh to slightly saline water (Plate 11), and the section (Figure 9) that pertains to the Brazos River Basin from the report by Wood, Gabrysch, and Marvin (1963, Pls. 8 and 9 and Fig. 6). Because of the difficulty in differentiating the rocks of Miocene, Pliocene, and Pleistocene age in the subsurface and the relative unimportance to the occurrence of ground water, the fresh to slightly saline water zone in region IV was studied as a unit. This report extracts the discussion from the report by Wood, Gabrysch, and Marvin (1963) and combines with it the part of the Catahoula Sandstone, Oakville Sandstone, and Lagarto Clay, undifferentiated, that crops out in region III of the Brazos River Basin.

Aquifers in the fresh to slightly saline zone in the Gulf Coast are the Catahoula Sandstone, Oakville Sandstone, and Lagarto Clay, undifferentiated, a primary aquifer; the Goliad Sand, Willis Sand, and Lissie Formation, undifferentiated, a primary aquifer and the most important in the part of the Brazos River Basin underlain by the Catahoula Sandstone, Oakville Sandstone, and Lagarto Clay, undifferentiated; the Beaumont Clay, a secondary aquifer; and the Quaternary alluvium, a primary aquifer.

Physical Description

The Catahoula Sandstone, Oakville Sandstone, and Lagarto Clay, undifferentiated, crops out in the Brazos River Basin in Washington, Grimes, Austin, and Waller Counties (Plates 3 and 4). The aquifer consists of alternating series of clay and shale beds with layers of coarse sand and lime-cemented sandstone. The formations are difficult to separate in wells on the basis of drillers' logs or electric logs and the Oakville Sandstone and Lagarto Clay are not differentiated on the surface east of the Brazos River on the Geologic Map of Texas (1937).

The Catahoula Sandstone, Oakville Sandstone, and Lagarto Clay, undifferentiated, thickens downdip; its thickness is about 2,300 feet at the Washington-Austin County line and its maximum thickness is about 4,100 feet in the Brazos River Basin.

The Lagarto Clay, about 1,200 feet thick at the Austin-Fort Bend County line, consists of about 75 percent marl, 15 percent medium to coarse sand, and

10 percent silt (Sellards and others, 1932, p. 744). The sand is lenticular and often cemented with calcium. The Lagarto is very similar to the Oakville except that it has a greater proportion of clay.

The Oakville Sandstone, about 200 feet thick at the Brazos River in Washington County, consists of about 40 percent sand, 30 percent sandy and ashy or bentonitic clay, 20 percent marl, 5 percent redeposited Cretaceous shells, and 5 percent gravel (Sellards and others, 1932, p. 734).

The Catahoula Sandstone, about 200 feet thick in Washington County, consists of 60 percent pyroclastic material, 20 to 30 percent sandstone, 10 to 20 percent clay, and minor amounts of conglomerate (Sellards and others, 1932, p. 721). The sandstone beds consist of medium and coarse-grained quartz sandstone; in many places it is well cemented.

The Goliad Sand, Willis Sand, and Lissie Formation are difficult to differentiate in the subsurface with the available electric or drillers' logs. Because the sand beds in these three formations are hydraulically connected, they are grouped together as a single aquifer forming the thickest section of sand in the fresh to slightly saline water zone in region IV.

Although the Goliad Sand is not recognized in the outcrop in the Brazos River Basin because it is overlapped by the Willis Sand, the Goliad is present in the subsurface as a bentonitic clay interbedded with reddish-colored sand and gravel which are cemented with lime. The Goliad ranges in thickness from zero to 250 feet and dips toward the coast at 20 to 45 feet per mile. The Goliad is reported to be thickest near the coast (Sellards and others, 1932, p. 752).

The Willis Sand, which overlaps the Goliad Sand, is predominantly a fine to coarse sand containing gravel, silt, and clay intimately mixed with the sand or in lenses interbedded with the sand. The Willis ranges in thickness from zero to 350 feet and dips coastward about 25 feet per mile.

The Lissie Formation, dipping coastward at 10 to 20 feet per mile, is composed mainly of beds of fine to light-colored sand, grading into and interbedded with sandy clay, clay, and gravel. Most of the sand beds are in the lower part of the formation; some of the sand beds are massive, more than 80 feet thick. The Lissie increases in thickness toward the Gulf Coast, ranging from zero to about 1,100 feet.

The Goliad Sand, Willis Sand, and Lissie Formation, undifferentiated, crops out in Grimes, Waller, Austin, and Fort Bend Counties in the Brazos River Basin (Plates 3 and 4). The unit is overlain by the Beaumont Clay and the alluvium in much of region IV in the basin.

The Beaumont Clay, dipping coastward at an average of 20 feet per mile, is principally a poorly bedded, variegated, calcareous clay about 1,300 feet thick, containing thin stringers and beds of silt and fine sand. The formation consists of from 80 to 90 percent clay and silt and from 10 to 20 percent sand. The sand occurs in beds as much as 40 feet thick, although generally the sands are much thinner.

The Quaternary alluvium crops out along the Brazos River and overlies all of the older formations in the area. The alluvium consists of gravel, sand, silt, and clay; the beds of gravel and sand are lenticular and grade into silt or clay in very short distances. The alluvium is at least 80 to 100 feet thick near Richmond; it may be 200 or more feet thick below State Highway 35 in Brazoria County (Plate 4).

Occurrence of Ground Water

The base of the fresh to slightly saline water in the Tertiary System and Pleistocene and Recent Series, undifferentiated, in the Brazos River Basin ranges from above sea level near the Brazos-Washington County line (Plate 3 and Figure 8) to more than 3,000 feet below sea level in Fort Bend County (Plate 10). In most of the area, the base is between 600 and 2,400 feet below sea level.

The water-bearing sands attain their maximum thickness in Fort Bend County, where as much as 1,000 feet is present in the fresh to slightly saline water zone (Plate 11). The total thickness of sands is greatest through the central part of region IV, thinning in both a downstream and upstream direction as shown by section D-D' (Figure 9).

The range in transmissibility of the sands as determined by field tests is from 10,000 gpd per foot where only part of the Catahoula, Oakville, Lagarto is present to as much as 250,000 gpd per foot in the central part where all of the aquifers are present. The area between southern Waller County and northern Brazoria County is underlain by sands whose composite transmissibility is greater than 100,000 gpd per foot. North of Bellville and Hempstead and south of State Highway 35 in Brazoria County (Plate 4), the composite transmissibility generally is less than 50,000 gpd per foot.

Wells that obtain water from the aquifer in the Catahoula, Oakville, and Lagarto range in depth from 200 to 900 feet and yield from 100 to 500 gpm, or more. The average specific capacity of the wells is about 5 gpm per foot and yields of less than 500 gpm, causing drawdowns greater than 100 feet, are common.

In the central part, yields as great as 3,000 gpm are obtained from wells less than 1,000 feet deep in sands in the Goliad, Willis, Lissie, the Beaumont Clay, and the alluvium. Some wells that are less than 300 feet deep yield more than 1,000 gpm; however, most of the large wells are deeper than 300 feet and the average yield of the deeper wells is about 2,000 gpm. Yields of 2,000 gpm with drawdowns of about 50 feet are not unusual in the deeper wells, and pumping levels less than 150 feet are common. Specific capacities generally are less than 50 gpm per foot in wells less than 1,000 feet deep.

Chemical Quality of Ground Water

Fresh to slightly saline ground water can be obtained throughout the area of the Tertiary, Pleistocene, and Recent, undifferentiated. Selected chemical analyses of water from wells in region IV and from wells in the Catahoula, Oakville, Lagarto in region III are shown in Tables 14 and 12. Most of the water is moderately hard to very hard, although soft water generally can be obtained in the central part of the region by selectively screening wells in the 1,000 to 2,500 foot depth zone; however, the water from the deeper sands contains greater concentrations of bicarbonate than the water in the shallow sands.

Table 14.--Chemical analyses of water from selected wells in region IV, Brazos River Basin

[Analyses given are in parts per million except specific conductance, pH, and sodium adsorption ratio (SAR).]

Analyses no.	Screened interval (feet)	Silica (SiO_2)	Iron (Fe) (total)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3) [a]	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Boron (B)	Dissolved solids	Hardness as $CaCO_3$	Sodium adsorption ratio (SAR)	Specific conductance (micromhos at 25°C)	pH
AP-66-06-602	[b] 487-740	29	[c] 0.08	68	12	92	9.1	367	46	58	0.2	0.2	--	495	219	2.7	801	7.3
BH-65-43-901	192-837	18	--	36	8.1	[d] 128		324	2.8	93	.5	.0	--	445	124	5.0	769	7.0
JY-65-26-503	[b] 970 1,590	15	.13	22	6.1	87	2.1	253	.2	43	.4	.0	--	300	80	4.2	516	7.5
JY-65-42-303	234- 1,090	19	--	74	18	185	2.6	278	14	305	--	2.5	0.21	792	258	5.0	1,430	7.5
YW-59-64-201	[b] 476-724	21	.37	29	6.6	119	3.4	356	3.2	48	.6	.0	.18	406	100	5.2	674	7.5
YW-66-08-902	? - 1,602	22	--	37	14	[d] 145		269	118	86	--	.2	--	557	150	5.1	955	8.2

[a] Includes the equivalent of any carbonate (CO_3) present.
[b] Not screened throughout interval.
[c] Iron in solution at time of analysis.
[d] Sodium and potassium calculated as sodium (Na).

The ground water in region IV generally is suitable for public supplies, although some of it contains more than the 500 ppm dissolved solids recommended by the U. S. Public Health Service (Table 14). The water is suitable for most industrial purposes, but may require treatment for special uses.

Water being used for irrigation would be classified as low to medium for the alkali hazard and medium to high for the salinity hazard, according to standards used in arid regions. The water would be marginal or unsuitable for irrigation in arid regions because of the bicarbonate content. However, the climate is subhumid; rainfall and drainage seem to be adequate for use of the waters, irrigation having been practiced for many years with no apparent harm to the soil or plants.

Utilization and Development of Ground Water

Plate 4 shows the location of the major wells and Table 15 shows the 1959 pumpage from wells tapping the Tertiary, Pleistocene, and Recent, undifferentiated, in regions III and IV. In 1959, about 33,000 acre-feet of fresh to slightly saline water was pumped for major uses, 70 percent of it from wells in major subdivision BR-85.

Water for all public supplies in the area is obtained from wells. In 1959, 20 public-supply wells discharged 4.2 mgd. All the major industrial wells in the area were in BR-85, where about 8 mgd was pumped for industry in 1959. Most of the industrial water was used for sulphur mining.

More water was pumped for irrigation than any other use. Approximately 19,000 acre-feet was pumped in 1959, most of it to irrigate rice. About 16,000 acre-feet, or 85 percent, of the irrigation water was pumped from wells in BR-85 and BR-86.

Prior to 1955, very few wells were used primarily for row-crop irrigation. The period of subnormal rainfall from 1947 to 1957 pointed out the need for supplementary irrigation of some crops, and by 1959 many wells had been drilled for the irrigation of crops other than rice, such as cotton and corn. The development in region IV of the Brazos River Basin is principally for crops grown on the outcrop of the alluvium and irrigated by wells tapping the alluvium. During years of normal or above-normal rainfall, supplemental supplies of ground water for irrigation are unnecessary and consequently most of the wells are not used, as in 1959.

Changes in Water Levels

The most significant changes in water levels have occurred in the eastern part of Fort Bend County and at the mouth of the Brazos River in the vicinity of Freeport. Pumping in the Freeport area (Plate 4) caused local declines of as much as 95 feet during the period 1941 to 1956. Since 1956, pumpage in the Freeport area has decreased by about 2-1/2 mgd, resulting in a significant recovery of water levels, locally as much as 60 feet. Not enough information is available to determine the areal extent or amount of recovery.

Table 15.--Pumpage from major wells tapping the Tertiary System and Pleistocene and Recent Series, undifferentiated, in regions III and IV, Brazos River Basin, 1959

Major subdivision	Public supply		Industrial		Irrigation		Total*	
	mgd	acre-ft./yr.	mgd	acre-ft./yr.	mgd	acre-ft./yr.	mgd	acre-ft./yr.
BR-78	0.33	371	--	--	0.01	15	0.34	390
82	.72	807	--	--	.43	480	1.2	1,300
83	1.08	1,210	--	--	2.1	2,400	3.2	3,600
85	1.48	1,658	7.98	8,869	11	12,000	20	23,000
86	.58	650	--	--	3.6	4,000	4.2	4,700
Total*	4.2	4,700	8.0	8,900	17	19,000	29	33,000

* Figures are approximate because some of the pumpage is estimated. Public-supply and industrial pumpage figures are shown to the nearest 0.01 mgd and to the nearest acre-foot. Irrigation figures and totals are rounded to two significant figures.

In the eastern part of Fort Bend County in an area west of the Brazos River, approximately 15 miles southeast of Richmond, about 41 feet of decline was recorded during the period 1947 to 1961, more than 38 feet of the decline occurring between 1947 and 1957. The decline was caused by pumpage outside the area in the vicinity of Houston, 30 miles northeast of Richmond.

Elsewhere levels have declined at lesser rates, although seasonal declines of 50 feet or more may be expected in the rice irrigation areas.

Availability and Potential Development of Ground Water

The following is adapted from the discussion on availability of ground water by Wood, Gabrysch, and Marvin (1963, p. 97-102).

One of the chief objectives of the reconnaissance of the river basins of Texas was to determine the order of magnitude of ground-water supplies available in each river basin. A method was devised that will permit at least a comparison of one area with another and provide a preliminary estimate of the potential water available. A reliable estimate of the amount of water available and the proportion that might be recovered will have to await more detailed data and improved methods. Many undetermined factors have a great bearing on the availability of the ground water. Among these are the amount of recharge to the aquifers, the amount of natural discharge that can be salvaged, the effect of vertical leakage in areas of lowered artesian pressure, and the amount of water that will be released by compaction of the clays as the artesian pressures are lowered. Other undetermined factors are the effects of updip salt-water movement, effects of subsidence and other causes on pumpage distribution, and economic conditions that will determine the price that will be paid for water.

The calculations of availability in this report are for only the principal aquifer in the region (in the Goliad, Willis, and Lissie) because the data for the other aquifers are meager and the inclusion of the calculations for the other aquifers would add only relatively small amounts to the total availability figures.

The maps depicting the transmissibility of the aquifer (Wood, Gabrysch, and Marvin, 1963, Figure 13) and the thickness of the water-bearing sands (Plate 11) were used with the following assumptions to estimate the relative ground-water availability:

1. Water levels will be lowered to a maximum depth of 400 feet along a line of discharge approximately paralleling the outcrop area and lying approximately midway between the centerline of the outcrop and the salt-water interface, the line generally lying within the area of the greatest depth of fresh water.

2. No water moves downward into the aquifer except in the outcrop area where all recharge is assumed to occur along a line parallel with the strike of the outcrop and in the middle of the outcrop.

3. For computation of water available from storage:

    a. The altitude of the water levels is the same and remains the same at all points along the centerline of the outcrop (assumed effective line source of recharge); the altitude of the water levels is the same at all points along the salt-water interface; and the altitude of the water levels is the same at all points along the line of discharge.

b. The net coefficient of storage is 0.10 and includes those parts of the storage coefficient related to water released from storage as the result of draining, compaction, and depressurizing.

c. The slope of the water surface will be constant after drawdown to 400 feet at the line of discharge.

4. For computations of the average transmission capacity of the aquifer (defined here as the quantity of water which can be transmitted through a given width of an aquifer at a given hydraulic gradient):

a. No further decline in water levels will occur along the line source of recharge (assumed adequate recharge to maintain present water level).

b. The hydraulic gradient is the slope of a straight line from the water level at the line source of recharge to the water level along the line of discharge.

c. The average hydraulic gradient is the average of the present hydraulic gradient and the maximum hydraulic gradient that can be attained with a water level of 400 feet at the line of discharge.

d. All the sands between the line source of recharge and the line of discharge transmit water from the outcrop area to the line of discharge. The assumed average coefficient of transmissibility of these sands in region IV is 125,000 gpd per foot.

e. Where recharge is considered, the amount of recharge along the line source is sufficient to supply the water that can be transmitted to the line of discharge at the assumed gradients.

f. The only increment to the water moving toward the line of discharge from the coastal side is that water released from storage as a result of lowering water levels.

For purposes of computation, different rates of withdrawal include (1) the present rate of withdrawal (29 mgd or 33,000 acre-feet per year) and (2) a rate arbitrarily chosen based on reasonable estimates of potential development (100 mgd or 112,000 acre-feet per year). These rates of withdrawal, the amount of water in transient storage, and the average transmission capacity were used to determine the time required to meet the above assumptions. Only the amount of water in transient storage was used in computing the time required to meet the condition of no recharge.

Region IV of the Brazos River Basin is about 20 percent of subregion III of the Gulf Coast region (Wood, Gabrysch, and Marvin, 1963, Pl. 9 and Table 13). Apportionment of the data presented in Table 13 of that report on the basis of area shows that about 7.2 million acre-feet of fresh to slightly saline water is in storage, the transmission capacity at the average gradient is 39,000 acre-feet per year, and at the maximum gradient 67,000 acre-feet per year. At the present rate of withdrawal and assuming no recharge, it would take 220 years to lower the water level to 400 feet along the line of discharge. At a rate of withdrawal of 100 mgd, it would take 60 years to lower the water level to 400 feet along the line of discharge. With adequate recharge, the water level could not be lowered to 400 feet along the line of discharge at the present rate of withdrawal, because the transmission capacity at both the average and the maximum gradient exceeds the present rate of withdrawal. If the rate of withdrawal were 100 mgd, it would take about 100 years at the average gradient and 160 years at the maximum gradient to lower the water level to 400 feet along the line of discharge. The recharge necessary to equal the transmission capacity at the average and maximum gradients would be 1.6 and 2.7 inches, respectively.

Results of the calculations are presented with the warning that the figures can be changed by a factor of several times by a small change in any one of several of the above assumptions. Limited basic data analyzed on a regional basis under assumed development conditions provide a preliminary estimate of potential water available. Thus, these preliminary estimates, which are especially suited for comparative purposes, will need to be revised and kept current as development takes place and more data become available.

The amounts of water computed are conservative because the assumptions ignore water contributed by compaction of the fine-grained materials and by recharge and vertical movement of water throughout the cone of depression--that is, water is derived not only from the line source in the center of the outcrop. From the same aquifer in the Houston area, for example, the principal sources of water pumped to date appear to be from storage, from compaction, and from local recharge rather than being transmitted from the outcrop of the Lissie Formation and the Willis Sand.

Another factor that would increase the water available is the distribution of withdrawals throughout the region instead of along a line of discharge as assumed. By moving wells closer to the outcrop, steeper gradients could be established that would increase the flow of water through the aquifer.

A factor which might be overlooked is the extremely large quantity of water in storage. For example, about 7.2 million acre-feet of fresh to slightly saline water is in storage in region IV. Also, computations show that it would take 60 years of pumping 100 mgd (about three times the 1959 rate of pumping) to lower the water levels along the line of discharge to 400 feet. This is based on the assumption of no recharge--that is, all of the water is being taken from storage.

Continuing study as development continues plus the utilization of new techniques, such as the analog model of the aquifer in the Houston district under construction in 1962, will aid in the calculation of more reliable estimates than those presented.

Problems

Fresh-water sands could be contaminated in areas of extensive development of oil-field and sulphur-mining operations in the area if proper precautions are not taken to prevent leakage of saline water into the fresh-water sands. No extensive contamination from leaky casings, disposal pits, or other means of industrial contamination have been observed, but small areas may have been affected by this type of contamination.

Much additional information is needed to determine (1) the relation between fresh water and salt water and the rate of movement of salt water, (2) properties of aquifers, (3) details of present development and the availability of water to wells, (4) possible areas of land-surface subsidence, and (5) possible areas of contamination. More information on water levels is needed throughout the area.

Quaternary System

Quaternary Alluvium in the West Gulf Coastal Plain

Quaternary alluvium crops out along the Brazos River along a large part of its total length; the outcrop is about 1 to 7 miles wide between Whitney Dam in Bosque and Hill Counties and the Gulf of Mexico (Plates 3 and 4). The alluvium is classed as a primary aquifer. The principal development is in region III in Robertson, Brazos, and Burleson Counties (Plate 3).

Physical Description

The Quaternary alluvium consists of lenticular beds of sand, gravel, silt, and clay; beds of sand and gravel grade laterally and vertically into silt and clay. The thickness of the alluvium in region III ranges from a minimum of 16 feet in McLennan County to a maximum of 100 feet in Washington County. In region IV, the alluvium is probably more than 200 feet thick near the coast in Brazoria County. The known saturated thickness ranges from a minimum of 4 feet in McLennan County to 84 feet in Washington County, although the saturated thickness near the coast is probably nearly as great as the total thickness.

Recharge, Movement, and Discharge of Ground Water

Recharge to the alluvium principally is from precipitation on the outcrop, runoff from adjacent slopes, return water from irrigation, and from underflow from adjacent and underlying formations.

The flood plain and lowermost terraces, locally called the "Brazos bottoms," annually receives an average of about 34 to 48 inches of precipitation (Figure 3); part of the precipitation is added to the water in storage by direct infiltration.

Recharge to the alluvium adjacent to the Brazos River occurs in places during high water or flood stages when surface water moves from the stream into the alluvium as bank storage. However, much of this water drains back into the stream after the high river stages subside.

Some of the surface water pumped from the streams and the ground water pumped from wells for irrigation becomes recharge by direct infiltration.

The Brazos River is a discharge point for most of the formations that it crosses in the West Gulf Coastal Plain. Water moving from the formations toward the river passes through the alluvium, except where the formations crop out in the bed of the river. The quantity of underflow moving from the formations is unknown; it depends upon the permeability of the formations, the hydraulic gradients in the formations, width of outcrop, and many other factors. For example, the quantity of underflow from the Carrizo Sand and Wilcox Formation, undifferentiated, should be many times greater than that from the Mount Selman Formation. The amount of recharge to the alluvium in excess of the pumpage during the 1957-60 period, based on infrequent water-level measurements in scattered wells, was in the order of 250,000 acre-feet.

The movement of ground water in the alluvium is slightly downstream toward the Brazos River. In no areas along the river, as far as could be determined, is the reverse situation true during normal stages of the river. The rate of movement of the water is not known; it depends on the hydraulic gradient and permeability.

Discharge of ground water from the alluvium is by pumpage from wells and by natural means. All the approximately 950 major wells tapping the alluvium between Waco and Hempstead were drilled for irrigation. About 47,000 acre-feet of ground water was withdrawn for irrigation in 1958 to irrigate an estimated 58,000 acres (Table 16). Not all the irrigation wells were pumped in 1958. Pumpage for irrigation ranged from about 200,000 acre-feet a year from 1953 to 1956 to about 20,000 acre-feet a year in 1959 and 1960.

Large amounts of ground water are discharged naturally by springs and seeps along the banks of the Brazos River. Other natural means of discharge include evaporation from areas where the water table is at or near the surface and transpiration by vegetation. Although the quantity of ground water discharged by evapotranspiration and seepage is not known, it probably is much greater than the quantity pumped by wells except during periods of below-normal rainfall.

Chemical Quality of Ground Water

The chemical quality of the water from wells in the alluvium along the Brazos River differs from place to place, even in short distances. The water ranges from fresh to slightly saline; generally, it has a high bicarbonate content and is very hard. Chemical analyses of water from 13 selected wells in the alluvium along the Brazos River are shown in Table 17. The locations of the wells are shown on Plate 3 by means of a bar over the well symbol. The hardness of the 13 samples ranged from 227 to 1,630 ppm. The dissolved-solids content ranged from 407 to 2,790 ppm; it was less than 1,000 ppm in 9 samples and more than 2,300 ppm in 3. The boron content ranged from 0.14 to 1.8 ppm in 6 samples for which it was determined. The boron in 5 of the samples did not exceed 0.33 ppm, which is the upper limit for water classed as excellent for irrigation. The water containing 1.8 ppm of boron would be unsuitable for crops sensitive to boron; however, most of the crops grown in the Brazos bottoms are semitolerant to tolerant to boron. The SAR (sodium adsorption ratio) of the 13 samples ranged from 0.4 to 7.3; only 1 exceeded 4.5. According to the classification of water for irrigation (Figure 14), the water is low in sodium hazard.

Table 16.--Pumpage from irrigation wells tapping the Quaternary alluvium in the West Gulf Coastal Plain, region III, Brazos River Basin, 1958

Major subdivision	Irrigation	
	mgd	acre-ft./yr.
BR-50	0.03	36
53	.56	650
56	.75	840
71	30	34,000
78	9.7	11,000
82	.86	960
Total*	42	47,000

* Figures are approximate because some of the pumpage is estimated. Figures and totals are rounded to two significant figures.

Utilization and Development of Ground Water

The development of irrigation from the alluvium in the Brazos River bottoms began during the latter part of the 1948-57 drought. About 950 irrigation wells were drilled in the Brazos bottoms between Waco and Hempstead. The development of irrigation wells did not reach its full potential before the end of the drought because many tracts of land suited for irrigation do not have wells drilled on them and are in areas where successful wells can be drilled. Some tracts are irrigated with surface water pumped from the Brazos River and some are irrigated with both surface and ground water.

No public water supplies are obtained from the alluvium in the Brazos bottoms in region III. Very few permanent residences are on the outcrop of the alluvium because it has been subject to flooding in some years; consequently, few domestic wells obtain water from the alluvium. Local residents report that tenant farmers for the large plantations, which at one time occupied the valley, obtained their water supplies from dug wells in the alluvium. It also is reported that rudimentary sanitary facilities were often located near the dug wells and that waterborne diseases such as dysentary and typhoid caused much sickness and many deaths among the tenant farmers because the rapid infiltration of water from the surface to the water table did not allow sufficient time for purification. Normally, the disposal of domestic sewage by percolation is not a threat to the quality of the ground water unless the water table is close to the land surface or wells are near the area of percolation.

The typical irrigation well in the alluvium is drilled after test drilling to find the most favorable location. The well is drilled at the site of a test

Table 17.--Chemical analyses of water from selected wells in the Quaternary alluvium in the West Gulf Coastal Plain, region III, Brazos River Basin

[Analyses given are in parts per million except specific conductance, pH, percent sodium, and sodium adsorption ratio (SAR).]

Well	Screened interval (feet)	Date of collection	Silica (SiO_2)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3) [a]	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Boron (B)	Dissolved solids	Hardness as $CaCO_3$	Percent sodium	Sodium adsorption ratio (SAR)	Specific conductance (micromhos at 25°C)	pH
[b] BJ-59-20-503	? -70	Jan. 27, 1953	--	124	34	[c] 86		345	99	177	--	--	--	865	449	--	1.8	--	--
[b] BJ-59-38-903	? -73	June 21, 1956	--	121	33	[c] 120		475	71	167	--	--	--	957	438	--	2.5	--	--
[b] BJ-59-38-904	? -66	Sept.19, 1956	--	173	18	[c] 376		791	44	447	--	--	--	1,801	510	--	7.3	--	--
[b] BJ-59-21-721	30-70	Apr. 1, 1958	--	84	5	[c] 15		326	17	--	--	--	--	407	227	--	1.4	--	--
[b] BS-59-28-201	? -51	July 6, 1957	--	154	41	[c] 67		488	58	170	--	--	--	978	564	--	1.2	--	--
[b] BS-59-29-705	? -48	Aug. 9, 1954	--	233	119	[c] 325		828	445	443	--	--	--	2,394	1,074	40	4.3	--	--
JR-39-41-101	23-45	May 10, 1961	16	56	51	83	1.1	536	43	16	0.5	41	1.8	573	349	34	1.9	940	7.4
JR-39-58-202	? -42	Apr. 26, 1961	19	320	136	380	4.4	574	473	880	.3	.2	.30	2,500	1,360	38	4.5	4,020	7.0
ST-40-32-703	? -50	May 10, 1961	19	113	7.2	48	1.6	318	46	67	.1	25	.25	483	312	25	1.2	825	7.0
ST-40-40-601	? -28	do	18	142	26	116	2.6	428	151	107	.3	76	.31	849	462	35	2.3	1,340	7.7
WK-59-03-701	? -51	Apr. 26, 1961	18	115	24	51	2.8	520	43	22	0.3	1.0	0.33	546	386	22	1.1	892	6.9
WK-59-03-905	? -70	May 25, 1961	16	154	33	71	6.1	276	317	89	.4	.0	.14	902	520	23	1.4	1,230	7.0
WK-59-03-914	? -50	do	23	440	129	373	7.9	718	570	890	--	1.8	--	2,790	1,630	33	4.0	4,300	6.7

[a] Includes the equivalent of any carbonate (CO_3) present.
[b] Analyzed by Texas State Chemist.
[c] Sodium and potassium calculated as sodium (Na).

hole, using the test hole as a guide for the reamer. The hole is reamed out to a diameter of 36 to 42 inches to the base of the alluvium, using a locally fabricated bit and a reverse-circulation rotary rig. The casing, generally 18-inch corrugated-galvanized-culvert pipe with 1/2-inch mesh, woven wire screen placed opposite the coarser sand and gravel, extends to the base of the alluvium. Pea gravel is used to fill the annular space between the casing and the wall of the well. The well is then developed with a test pump; pea gravel is added to replace the drilling mud and the sand pumped from the annular space. Following development, a short test is run to determine the capacity of the well and the size pump and power plant needed. The typical pump is 6- or 8-inch diameter turbine pump, although there are some 4-, 5-, and 10-inch pumps. The pump generally is belt-driven by an internal combustion engine or is powered by an electric motor.

Other wells are cased with 12- to 20-inch diameter steel casing which is slotted opposite the coarser sand and gravel. In a few cases, the well is simply a large pit excavated by a dragline; a few wells are hand dug.

Some wells cave when large quantities of sand are pumped, but they are replaced with a new well drilled only a few feet away.

Changes in Water Levels

Water levels in the alluvium along the Brazos River fluctuate in response to changes in ground-water storage. During periods of adequate rainfall when irrigation wells are not used, water levels tend to rise. Conversely, during periods of drought when withdrawals of ground water for irrigation are large, water levels tend to decline. The fluctuations are small near the river, increasing in magnitude toward the edge of the alluvium. The water levels are very shallow, probably less than 15 feet below land surface near the edge of the outcrop, but are 35 to 45 feet below land surface near the Brazos River. The hydrographs of selected wells in Brazos, Burleson, and Robertson Counties show that water levels were higher in 1961 than in 1957 (Figure 20). The 1957 measurements were made near the end of a long drought, during which pumpage for irrigation was large. Since early 1957, rainfall has been near or above normal; consequently, pumpage decreased accompanied by an increase in recharge. Records of water levels in wells in the alluvium from McLennan County to Grimes County show similar fluctuations.

Availability and Potential Development of Ground Water

Available data indicate that about 1,800,000 acre-feet of water was in storage in the alluvium between the Hill-McLennan County line and Hempstead in the spring of 1961, assuming a specific yield of 0.15, or about 250,000 acre-feet more than was in storage in the spring of 1957. During the 4-year period 1957-61, an estimated 150,000 acre-feet was pumped by wells; the total recharge was about 400,000 acre-feet assuming no changes in natural discharge rates. Thus, the recharge in addition to that discharged by springs and seepage and by evapotranspiration and other natural losses must have been in the order of 100,000 acre-feet per year during the 4 wet years. The minimum long-term yield would be in the order of 100,000 acre-feet a year and would be sufficient to irrigate

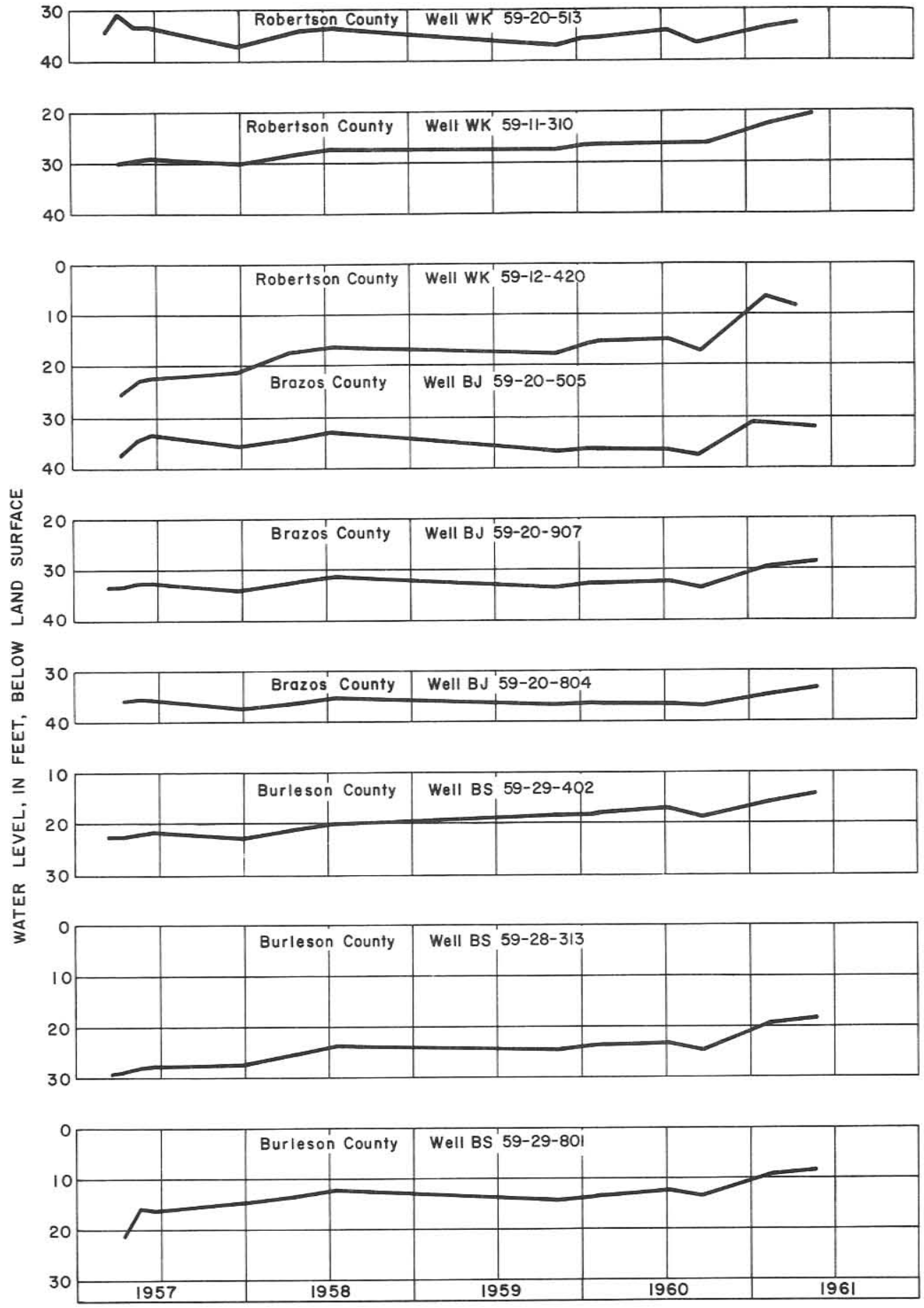

Figure 20

Changes in Water Levels in Wells in the Alluvium in Robertson, Brazos, and Burleson Counties

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134

100,000 acres or more, except during extended periods of drought. Additional withdrawals would probably salvage a large amount of the natural discharge, increasing the amount of water available to wells.

According to the Brazos River Authority (1955, p. 9) about 200,000 acres of land in the Brazos River bottoms between Waco and Richmond could be irrigated profitably from surface water or ground water, or both. Irrigation wells could be drilled to serve most of the land suitable for irrigation.

The yields of the irrigation wells in the alluvium range from about 100 to at least 1,350 gpm. A pumping test on well WK-59-03-905, 3-1/2 miles west of Hearne, indicated a transmissibility of about 130,000 gpd per foot and a specific capacity of 37 gpm per foot. The specific capacities of 39 wells in Brazos, Burleson, and Robertson Counties ranged from 4 to 89 gpm per foot and averaged 29 gpm per foot (Frank Hughes, personal communication).

Problems

Before full utilization of the water resources in the Brazos River Valley can be accomplished, additional information is needed regarding the wide range in quality of the water in the alluvium downstream from Waco, the areal extent of the aquifer as well as the total thickness and saturated thickness, the volume of natural recharge to and discharge from the aquifer, and the relation between ground water and surface water and water quality.

Quaternary Alluvium in the Osage Plains

The Quaternary alluvium, which for purposes of this report includes all of the sediments of Quaternary age, including remnants of the Seymour Formation (Pleistocene) and windblown deposits, constitutes a primary aquifer in the Osage Plains section of the Brazos River Basin. Remnants of the Seymour Formation and other alluvial deposits have similar hydrologic and lithologic characteristics and, in places, the sediments are intimately associated and hydrologically connected. Because it would be difficult, if at all possible, to divide the sediments into separate water-bearing formations, they are discussed together in this report as the Quaternary alluvium.

Physical Description

The Quaternary alluvium was deposited by streams and by wind action, the former being the principal agent. The deposits occur chiefly as terraces or flood-plain deposits along the principal streams and as remnants of earlier deposits on the upland areas. In certain areas, accumulations of sand of greater or lesser extent were caused by the action of the wind.

The alluvial deposits in the Osage Plains are mainly in the area underlain by Permian and Triassic rocks (Plate 2). Many of the deposits are small and unimportant hydrologically except as a source of meager quantities of water for domestic or livestock uses. In other places, the deposits are thick and cover large areas. In such places the deposits are capable of storing and yielding large quantities of water. The thickness of the Quaternary alluvium in the Osage Plains ranges from zero to about 165 feet.

The alluvial deposits consist, in general, of coarse-grained sand and gravel, fine-grained sand and silt, and clay that is commonly red or gray. Caliche and volcanic ash are present in some places. The upper part of the deposits commonly consists of beds of fine-grained sand and silt, whereas the lower part consists of coarser materials containing beds of sand and gravel, interstratified in places with lenses of clay. The composition of the sediments varies from place to place; the beds are not continuous over wide areas but rather they tend to grade laterally into beds of finer or coarser materials.

Source and Occurrence of Ground Water

The source of water to the Quaternary alluvium in the Osage Plains is chiefly precipitation on its outcrop area. However, the flood-plain and terrace deposits also receive recharge from the rivers, especially after heavy rains when the streams are in flood. Sandhills and areas of sandy soil are considered to be important recharge areas. A part of the water that accumulates in topographic lows during periods of heavy precipitation probably percolates downward to the water table.

Ground water is discharged naturally from the Quaternary alluvium by springs and seeps, where the land surface intersects the water table along the drainageways. Ground water also is discharged by evaporation and transpiration in areas where the water table is at or near the land surface. The total quantity of ground water discharged from the alluvium by natural means has not been measured. The artificial discharge by wells probably is greater than the natural discharge.

The ground water in the Quaternary alluvial deposits occurs chiefly under water-table conditions--that is, the upper surface of the zone of saturation is unconfined and the water does not rise in wells above the level at which it is found in the alluvium. Locally, however, a slight artesian pressure may exist where the water is confined beneath lenticular bodies of clay of limited areal extent.

Principal Areas of Development

Most of the major wells are drilled through the entire thickness of the Quaternary alluvium to the underlying Permian or, in some places, Triassic rocks. The locations of the major wells or areas in which major wells are concentrated are shown on Plates 1 and 2. The principal areas in which the Quaternary alluvium is significant hydrologically are Haskell and Knox Counties, Baylor County, Fisher County, Jones County, and Kent and Dickens Counties.

Haskell and Knox Counties

In Haskell and Knox Counties, the aquifer in the Quaternary alluvim occupies an area of about 430 square miles, of which 185 is in Knox County and 245 is in Haskell County. It is the largest and most heavily developed area of Quaternary alluvium in the Osage Plains.

Figures 21 and 22 show the altitude of the water table in the Quaternary alluvium in Haskell and Knox Counties during the winter of 1956-57 and the approximate altitude of the base of the alluvium. Figure 21 shows that the water table slopes generally toward the north and northeast at an average rate of about 10 feet per mile. The slope of the water table conforms generally to the slope of the land surface and to the slope of the surface of Permian rocks underlying the Quaternary alluvium as shown in Figure 22.

Ground water was first used for irrigation in Haskell and Knox Counties in 1938; however, until 1951, all of the supplies for irrigation were obtained from three dug wells. The number of irrigation wells increased from 115 in 1952 to 1,100 in 1956 (Ogilbee and Osborne, 1962, p. 31) and by 1960 the number of irrigation wells had increased to about 1,250.

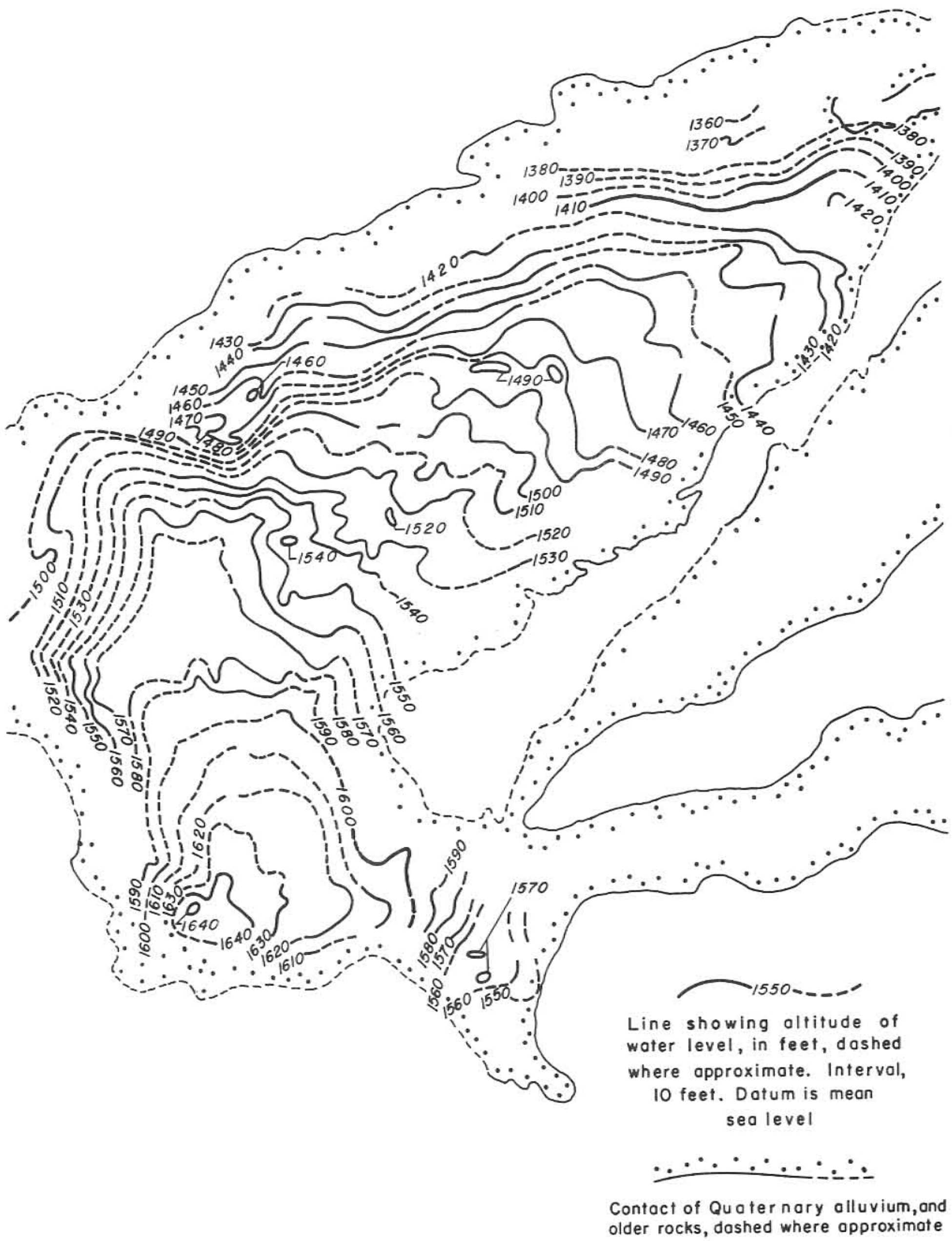
Approximately 76,500 acre-feet of water was pumped to irrigate about 50,000 acres of land in Haskell and Knox Counties in 1956, according to Ogilbee and Osborne (1962, p. 32). They indicated that the average irrigation requirement over a long period of time may be less than was pumped in 1956 because during that year the rainfall was below normal.

Prior to 1900, the Quaternary alluvium in the Haskell-Knox County area was practically dry, according to Ogilbee and Osborne (1962, p. 35). The water level rose somewhat irregularly starting about 1900 and reached a maximum altitude in the 1930's when some of the low-lying lands became waterlogged. During that period of time, large areas of land had been put into cultivation. The rise of the water level during that period is related in part to a change in land use and in part to a cyclic increase in precipitation, the former probably being the most important factor. The water table continued at near-maximum height until about 1951 when drought conditions and withdrawals for irrigation started a decline that continued to 1957 (Figure 23). Above-normal rainfall in 1957 and near normal in 1958 combined with a decrease in withdrawals caused the water table to rise slightly as shown on the hydrographs in Figure 23. Following this rise, the water table again started to decline in most wells.

Short duration recovery-type pumping tests made on several wells in Haskell and Knox Counties indicate that the calculated coefficients of transmissibility of the alluvium ranged from 23,000 to 220,000 gpd per foot and field permeability ranged from 1,000 to 14,000 gpd per square foot. Specific capacities as indicated from several 1-hour tests ranged from 18 to 178 gpd per foot. The field conditions at the test sites in Haskell and Knox Counties were far from ideal and the calculated values of transmissibility and permeability are subject to considerable error and should be used with extreme caution. Yields of wells in the Haskell-Knox County area ranged from a few gallons per minute to as much as 1,300 gpm.

The coefficient of storage of the Quaternary alluvium in Haskell and Knox Counties was estimated by Ogilbee and Osborne (1962, p. 31) by comparing the volume of water pumped with the volume of alluvium dewatered during 1956. The estimate, based on the assumption that there was no recharge during the test period, indicated that the coefficient of storage of the Quaternary alluvium in Haskell and Knox Counties was about 0.14.

Figure 24 shows the approximate saturated thickness of Quaternary alluvium in Haskell and Knox Counties in the winter of 1956-57. Using a specific yield



After Ogilbee and Osborne (1962, Plate 2)

Figure 21

Altitude of Water Level in Wells in the Quaternary Alluvium in Haskell and Knox Counties, Winter of 1956-57

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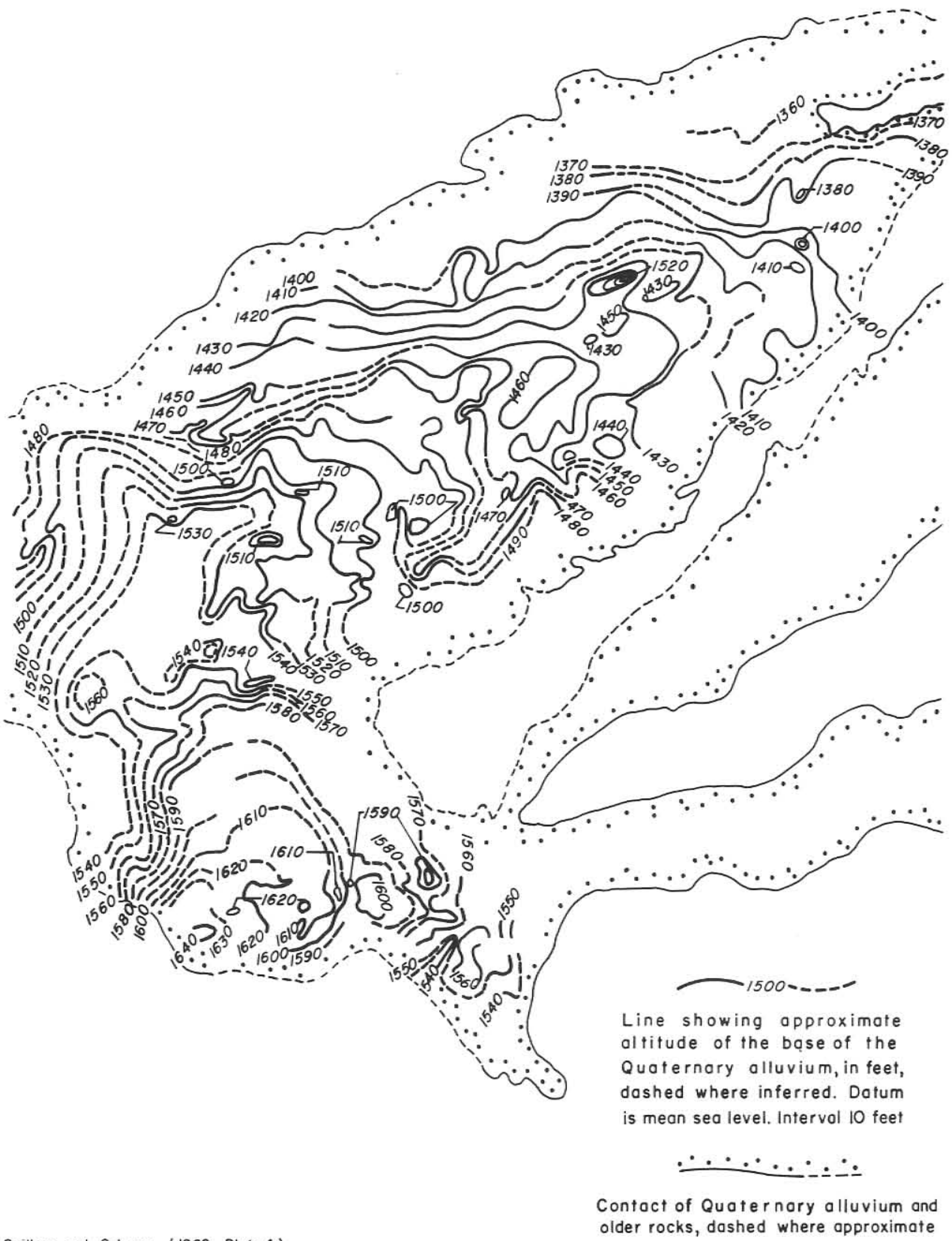

After Ogilbee and Osborne (1962, Plate 4)

Figure 22

Approximate Altitude of the Base of the Quaternary Alluvium, Haskell and Knox Counties

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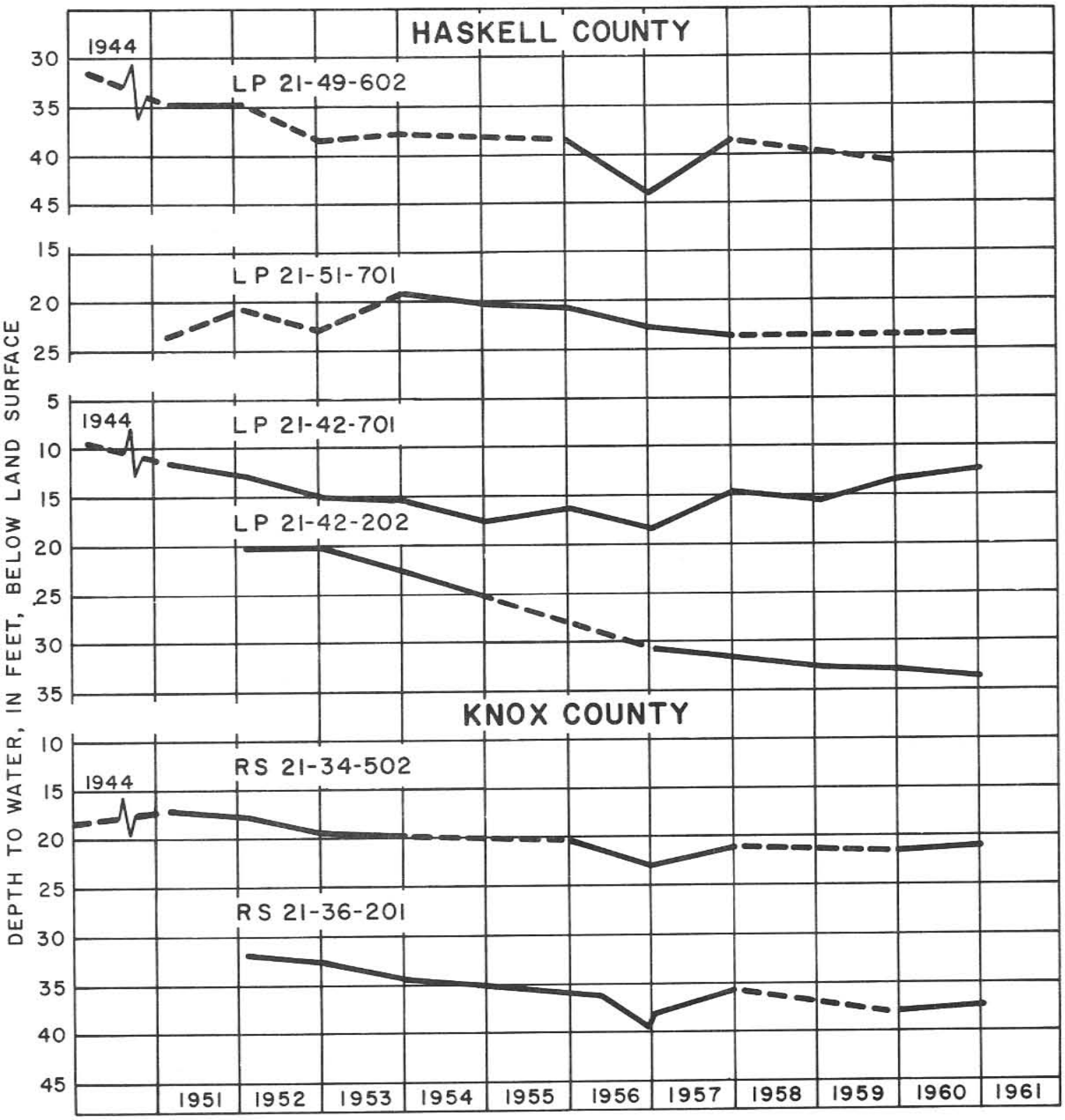

Figure 23

Changes in Water Levels in Wells in the Alluvium in Haskell and Knox Counties

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134

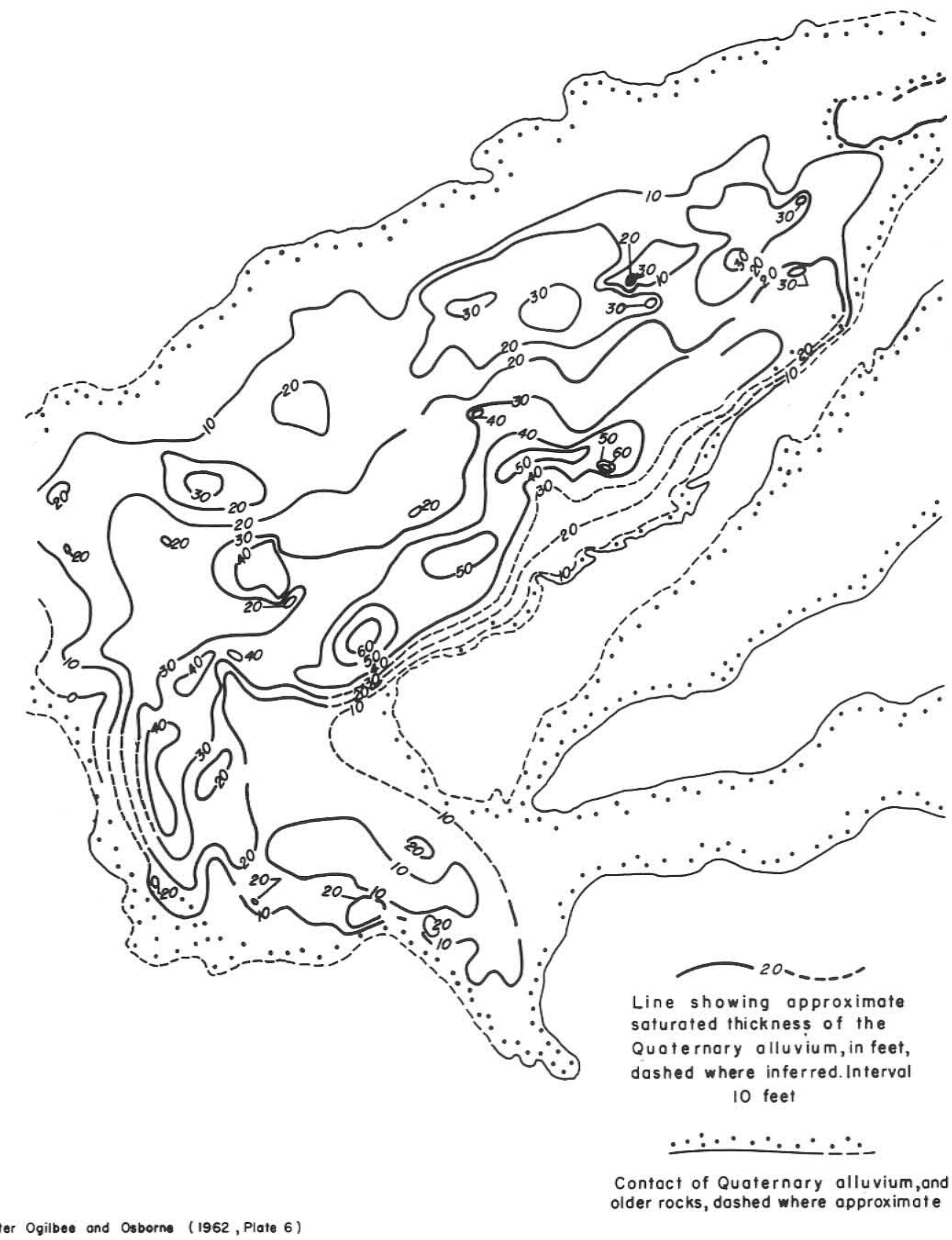

Figure 24

Approximate Saturated Thickness of the Quaternary Alluvium, Haskell and Knox Counties, Winter of 1956-57

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(coefficient of storage) of 14 percent, Ogilbee and Osborne (1962, p. 35) calculated that the amount of water in storage in 1956 was approximately 740,000 acre-feet.

Ogilbee and Osborne (1962, p. 35) estimated that the average rate of recharge to the Quaternary alluvium in Haskell and Knox Counties was about 20,000 acre-feet per year. This estimate was based on the assumption that the aquifer was essentially dry in 1900 and in 1935 contained an estimated 740,000 acre-feet of water in storage, the same amount in storage in 1956 when the aquifer was slightly less than full. The rate of recharge probably would be somewhat greater, the amount depending upon the amount of discharge during the 35-year period.

Baylor County

In the vicinity of Seymour in Baylor County, ground water is pumped from the Quaternary alluvium for irrigation and public-supply use in an area of about 30 square miles (Plate 2). The depth of the wells ranges from 10 to 41 feet. Depth to water below land surface, as indicated by measurements made in 1960 and 1961, ranged from about 4 feet to about 22 feet. The yields of the major wells in the Baylor County area ranged from 33 to 800 gpm.

Jones County

In Jones County, deposits of Quaternary alluvium occur in the vicinity of Stamford and east and south of Anson (Plate 2). In the vicinity of Stamford, a few domestic and livestock wells yield small amounts of potable water, but in these wells the saturated part of the alluvium is thin, ranging from a few inches to possibly 3 or 4 feet (Broadhurst and Follett, 1944, p. 3). In the south-central part of the county, extending to the Clear Fork of the Brazos River, the alluvial deposits range in thickness from a knife edge to approximately 150 feet, and average about 50 feet, according to Winslow, Doyel, and Guam (1954, p. 8). The thickness of the water-bearing material ranged from about 25 feet to about 58 feet in this area. In 1960, about 25 wells were pumping water from the Quaternary alluvium in this area for irrigation and industrial use. The reported yields of the wells range from small to moderate.

Fisher County

In Fisher County water is pumped from the Quaternary alluvial deposits to irrigate land in the vicinity of Rotan (Plate 1) and in a strip of land extending along the Clear Fork of the Brazos River, almost across the entire width of the county. The wells, ranging in depth from about 30 to 80 feet, yield small to moderate quantities of water. The depth to water below land surface in wells as indicated by measurements made in 1959 and 1960 ranged from about 17 to about 31 feet. The relation between streamflow in the Clear Fork of the Brazos River and the ground water in the Quaternary alluvium has not been determined. Bordering the irrigated area on the north is a rather large sandy area which may be the source of recharge to the alluvium in the irrigated area.

Dickens and Kent Counties

In Dickens and Kent Counties, the main deposit of Quaternary alluvium from which wells pump small to moderate quantities of water for irrigation and public supply borders Duck Creek (Plate 1). In this area the wells range in depth from 26 to 165 feet, the deeper wells being in Kent County. The depth to water below land surface, as indicated by measurements made in 1960 and 1961, ranged from about 5 to about 73 feet.

Duck Creek is hydrologically connected with the Quaternary alluvium in places. It is possible that at times, depending on the position of the water table, the creek may provide some recharge to the alluvium, but it is also possible that at times it may receive water from the alluvium.

Other Areas

Small isolated areas of Quaternary alluvium (Plates 1 and 2) provide some water for irrigation--for example, in the northeastern part of Nolan County along the southern boundary of the Brazos River Basin and in the northeastern part of Garza County, small quantities of water are pumped from wells in the alluvium where the saturated thickness is only about 10 to 15 feet. Other areas of flood-plain and terrace deposits along the principal drainageways have not been adequately mapped and are not shown on Plates 1 and 2; however, in a few places where wells for industrial or irrigation use have been developed, the presence of some Quaternary alluvium has been shown.

Chemical Quality of Ground Water

The chemical analyses of 46 water samples from selected wells in the Quaternary alluvium in the Osage Plains are given in Table 18. The wells from which these samples were obtained pump water for irrigation, public supply, and industrial use. The locations of the wells are shown by a bar over the well symbol on Plates 1 and 2.

The results of the analyses show that all the water is very hard and that the chemical composition of the water varies between wide limits. Eleven of the samples shown in Table 18 are from public-supply wells. A comparison of the results of the analyses of these 11 wells with the limits suggested by the U. S. Public Health Service shows that the dissolved-solids content exceeded the limit in 9 of the samples. The nitrate content was above the standard in 7 samples and the fluoride content was above 1.5 ppm in 3 samples. The limits for chloride and sulfate were exceeded in 3 and 5 samples, respectively. The comparison indicates that the water being used for public supply, from which the 11 samples were taken, did not meet all of the suggested limits of mineral composition for drinking water. However, the average person can become adjusted to drinking water having higher concentrations than the suggested limits, especially in an area where the availability of water is an important factor.

A comparison of the specific conductance of the 46 samples shown in Table 18 with the diagram for classification of irrigation waters shown in Figure 14 indicates that most of the samples had a high or very high salinity hazard and that in a few samples the SAR was also high. This is an indication that the water

Table 18.--Chemical analyses of water from selected wells in the Quaternary alluvium in the Osage Plains, Brazos River Basin

[Analyses given are in parts per million except specific conductance, pH, percent sodium, and sodium adsorption ratio (SAR).]

Well	Depth of well (ft.)	Date of collection	Silica (SiO_2)	Iron (Fe) (total)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3) a/	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Boron (B)	Dissolved solids	Hardness as $CaCO_3$	Percent sodium	Sodium adsorption ratio (SAR)	Specific conductance (micromhos at 25°C)	pH
AU-21-22-804	41	Aug. 8, 1961	31	--	45	58	b/ 269		540	164	205	--	42	--	1,080	351	63	6.2	1,760	7.3
21-29-302	27	do	24	--	70	33	125	5.2	424	101	62	1.1	51	0.46	681	310	46	3.1	1,090	7.1
21-30-302	45	Jan. 13, 1961	30	c/ 0.01	71	62	431	5.2	540	394	350	--	42	--	1,650	432	68	9.0	2,580	7.7
d/ HY-22-25-302	83	June 4, 1960	27	.03	74	22	81	1.7	312	86	68	1.0	17	.20	538	275	39	2.1	866	7.3
22-25-902	63	May 16, 1961	19	--	80	125	712	5.5	566	932	560	--	84	1.9	2,800	714	68	12	4,190	7.4
d/ 22-34-105	46	June 9, 1961	27	c/ .02	80	45	270	1.1	300	366	218	3.6	56	.95	1,220	384	60	6.0	1,880	7.3
JU-29-13-101	25	Aug. 4, 1960	25	--	585	33	b/ 39		120	1,390	16	--	139	.21	2,290	1,600	5	.4	2,400	6.5
29-13-601	50	do	36	--	675	161	b/ 752		220	2,040	1,140	--	86	.72	5,000	2,350	41	6.7	6,350	6.5
29-14-901	36	do	22	--	94	29	b/ 336		332	446	225	--	37	.64	1,350	354	67	7.8	2,070	7.0
29-23-102	30	Aug. 8, 1960	23	--	530	146	b/ 743		322	1,940	870	.7	32	--	4,440	1,920	46	7.4	5,370	6.8
29-23-603	34	do	24	--	228	59	b/ 420		322	734	460	.8	58	--	2,140	812	53	6.4	3,130	6.9
KJ-23-46-201	24	May 29, 1961	37	--	72	56	879	3.3	664	724	650	2.6	131	1.1	2,880	410	82	19	4,320	7.5
23-55-801	22	do	13	--	64	31	b/ 684		254	212	950	2.0	.0	--	2,080	287	84	18	3,650	7.5
LP-21-35-701	70	Sept. 1, 1956	26	--	81	27	120	5.9	336	99	103	1.0	54	.44	684	312	45	3.0	1,110	7.5
21-42-101	60	Aug. 16, 1956	32	--	71	38	202	--	215	248	200	--	68	.50	1,020	334	57	4.8	1,550	8.0
d/ 21-42-401	54	Mar. 24, 1944	21	.14	75	17	109	5.2	333	59	43	.6	129	--	623	257	47	3.0	888	7.6
e/ 21-49-101	48	Aug. 9, 1961	14	--	715	188	871	11	238	2,300	1,320	.6	46	1.3	5,580	2,560	42	7.5	7,160	7.3
d/ LP-21-49-601	45	Mar. 21, 1944	21	.05	91	24	114	6.6	362	57	73	.4	152	--	627	326	43	2.7	1,060	7.8
21-50-601	50	Aug. 16, 1956	30	--	130	61	217	--	311	255	322	--	75	.40	1,240	575	45	3.9	2,070	7.5
d/ 21-51-701	32	Mar. 17, 1944	21	.02	151	92	221	10	399	251	365	1.2	177	--	1,490	756	38	3.5	2,290	7.6
PY-30-17-101	32	July 9, 1953	38	c/ .00	90	16	b/ 13		298	20	12	1.8	40	--	374	290	9	.3	710	8.1
30-18-401	69	June 22, 1953	42	--	140	25	109	--	552	80	100	.6	8.2	.12	776	452	34	2.2	1,280	7.1
30-19-401	46	July 6, 1953	30	--	144	34	176	--	576	109	215	1.0	2.0	.16	994	500	43	3.4	1,680	7.3

See footnotes at end of table.

Table 18.--Chemical analyses of water from selected wells in the Quaternary alluvium in the Osage Plains, Brazos River Basin--Continued

Well	Depth of well (ft.)	Date of collection	Silica (SiO_2)	Iron (Fe) (total)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3) a/	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Boron (B)	Dissolved solids	Hardness as $CaCO_3$	Percent sodium	Sodium adsorption ratio (SAR)	Specific conductance (micromhos at 25°C)	pH
PY-30-19-402	60	June 18, 1953	47	--	146	27	176	4.9	545	130	200	0.2	22	0.08	1,020	476	44	3.5	1,680	7.2
RH-22-41-801	72	May 16, 1961	23	--	525	162	530	7.9	234	2,390	345	--	2.5	1.8	4,100	1,980	37	5.2	4,720	7.2
22-43-203	102	June 21, 1960	45	--	358	60	b/ 44		194	898	88	.8	19	--	1,610	1,140	78	.6	1,920	7.0
22-43-503	98	do	47	--	301	53	b/ 132		344	590	225	.7	51	--	1,570	970	23	1.8	2,150	7.0
22-43-504	136	June 22, 1960	--	--	--	--	--	--	--	344	88	--	40	--	--	--	--	--	1,510	--
22-43-505	126	June 21, 1960	52	--	288	44	b/ 121		308	610	168	.5	47	--	1,480	900	23	1.8	1,970	7.0
22-43-508	110	do	24	--	203	45	b/ 85		236	514	88	.7	26	--	1,100	692	21	1.4	1,500	7.2
22-51-104	44	May 16, 1961	21	--	655	217	1,280	11	158	2,760	1,680	--	40	6.3	6,750	2,530	52	11	8,680	7.0
d/ 22-52-102	52	June 21, 1960	25	--	252	42	b/ 85		249	578	112	.6	25	--	1,240	800	19	1.3	1,680	7.0
d/ 22-52-103	52	do	20	--	104	12	b/ 21		229	113	20	.5	25	--	436	309	13	.5	649	7.5
22-52-104	62	do	21	--	96	8.9	3.0	5.9	214	86	5.2	.5	24	--	356	276	2	.1	550	7.3
e/ 22-59-702	--	June 1, 1961	17	--	432	91	b/ 423		181	1,430	520	.8	.0	--	3,000	1,450	39	4.8	3,880	6.9
RS-21-33-901	50	Aug. 30, 1956	24	--	170	128	528	5.8	342	1,120	460	--	45	1.8	2,650	950	55	7.5	3,750	7.5
21-34-201	31	Aug. 15, 1956	34	--	59	35	97	--	323	106	50	--	63	.33	618	292	42	2.5	959	7.6
d/ 21-34-501	35	Apr. 24, 1957	36	--	109	43	b/ 180		350	211	185	1.4	84	--	1,020	448	47	3.7	1,570	7.4
d/ 21-36-401	37	Mar. 22, 1944	21	0.12	112	99	372	15	481	469	340	1.9	183	--	1,780	686	53	6.2	2,660	7.6
d/ 21-36-401	37	Apr. 25, 1957	35	--	113	98	b/ 334		485	411	360	2.4	90	--	1,680	685	51	5.6	2,640	7.6
e/ 21-34-401	40	Aug. 30, 1956	19	--	229	53	628	6.4	322	853	740	--	1.9	.93	2,690	790	63	9.7	4,080	7.5
XR-21-49-102	58	Aug. 9, 1961	24	--	46	16	b/ 86		321	43	16	.5	44	--	434	181	51	2.8	680	7.0
XR-22-45-801	59	May 22, 1961	17	--	695	176	b/ 605		84	2,020	1,130	.5	7.5	--	4,690	2,460	35	5.3	5,930	6.8
22-46-801	52	June 14, 1961	34	--	85	16	b/ 190		356	154	135	.2	58	--	854	278	60	5.0	1,340	7.2
e/ XR-29-06-104	51	Aug. 10, 1961	18	--	525	138	933	9.0	190	1,600	1,480	1.1	7.5	.94	4,810	1,880	52	9.3	6,900	6.9
XW-30-50-102	21	Aug. 4, 1960	24	--	100	36	b/ 94		282	114	115	--	111	.27	796	398	34	2.0	1,200	7.2

a/ Includes the equivalent of any carbonate (CO_3) present.
b/ Sodium and potassium calculated as sodium (Na).
c/ Iron in solution.
d/ Well used for public supply.
e/ Well on river terrace or flood plain.

should not be used on soils with restricted drainage. Where such water is used for irrigation, close observation should be maintained to observe the effects of the use of the water, if any, on either the crops or the soil.

Water from the Quaternary alluvium in the Osage Plains was used for some industrial purposes in 1960. As indicated above, the chemical composition of the water in the Quaternary alluvium ranges widely and the suitability of the water for industrial uses would depend on the source of water and specific use for which the water is intended.

Utilization of Ground Water

The estimated total amount of ground water pumped from the Quaternary alluvium in the Osage Plains in 1959 is shown by major subdivisions in Table 19 to be 95,000 acre-feet or about 85 mgd. Of this amount, an estimated 90,000 acre-feet, or about 95 percent, was used for irrigation. The remainder was used for public supply and industry.

Availability and Potential Development of Ground Water

The occurrence of ground water in the Quaternary alluvium in the Osage Plains has not been studied in detail, except in Haskell and Knox Counties. In this area, Ogilbee and Osborne (1962, p. 35) estimated that more than 20,000 acre-feet can be withdrawn annually without permanently depleting the water in storage. They estimated that about 740,000 acre-feet of water was in storage. Information is lacking on the areal extent of the other deposits that contain considerable quantities of water, nor are reliable estimates of the annual recharge and natural discharge and hydraulic properties of the aquifer available. Because of the lack of reliable information, it is not practical to attempt to estimate the total quantity of water available to wells from the Quaternary alluvium in the Osage Plains of the Brazos River Basin.

Problems

Problems regarding the development of ground water from the Quaternary alluvium in the Osage Plains are chiefly those resulting from insufficient data. The areal extent of the deposits is not well known and the thickness and character of the water-bearing materials is poorly known in many places. Much information is needed concerning the hydraulic properties of the alluvium and the amount of natural recharge.

Another major problem is that of the poor chemical quality of much of the water. Some of the poor-quality water is probably related to the use of surface pits for the disposal of oil-field brines.

SUMMARY OF GROUND-WATER WITHDRAWALS IN THE BRAZOS RIVER BASIN

A summary of the ground-water withdrawals from major wells in the Brazos River Basin in 1959 is shown in Table 20. The withdrawals have been tabulated by

Table 19.--Pumpage from major wells tapping the Quaternary alluvium in the Osage Plains, Brazos River Basin, 1959

Major subdivision	Public supply		Industrial		Irrigation		Total*	
	mgd	acre-ft./yr.	mgd	acre-ft./yr.	mgd	acre-ft./yr.	mgd	acre-ft./yr.
BR-11	--	--	1.77	1,985	0.27	300	2.1	2,300
12	0.16	184	--	--	.98	a/ 1,100	1.1	a/ 1,300
18	--	--	--	--	.45	500	.45	500
19	.51	571	--	--	6.7	7,500	7.2	8,100
21	--	--	--	--	.09	100	.09	100
22	.08	85	--	--	12	a/ 13,000	12	a/ 13,000
23	.68	762	.01	5	51	a/ 57,000	52	a/ 58,000
27	--	--	--	--	1.3	1,500	1.3	1,500
28	--	--	--	--	.62	700	.62	700
29	--	--	--	--	.18	200	.18	200
30	--	--	.01	10	.27	300	.27	310
31	.49	552	--	--	7.1	a/ 7,900	7.6	a/ 8,500
33	--	--	.02	20	.27	300	.27	320
Total*	1.9	2,200	1.8	2,000	81	90,000	85	95,000

* Figures are approximate because some of the pumpage figures are estimated. Public-supply and industrial pumpage figures are shown to the nearest 0.01 mgd and to the nearest acre-foot. Irrigation figures and totals are rounded to two significant figures.

a/ Based on estimate of pumpage for irrigation in Haskell and Knox Counties in 1956.

principal use, aquifer, and major subdivision. The table shows that about 2,400,000 acre-feet of ground water was pumped from major wells in the Brazos River Basin in 1959. Of the total amount of ground water pumped, about 2,200,000 acre-feet, or 90 percent, was from the Ogallala Formation in the High Plains (major subdivisions 1, 3, 5, 8, 10, 13, 14, 15, 17, 18, and 19, Plates 1 and 2). In addition to the ground water pumped for irrigation, about 30 percent of the amount pumped for industrial use and slightly more than 50 percent of the amount pumped for public supply in the basin were from the Ogallala Formation in the High Plains.

In 1959, about 140,000 acre-feet of ground water was pumped from the Quaternary alluvium, principally for irrigation. Of this amount, almost 70 percent was from wells in the Osage Plains (major subdivisions 11, 12, 18, 19, 21, 22, 23, 27, 28, 29, 30, and 31, Plates 1 and 2). The remainder of the pumpage from the Quaternary alluvium was withdrawn from wells in the West Gulf Coastal Plain (Plates 3 and 4).

The meager amounts of ground water withdrawn from major wells tapping the rocks of Permian and Pennsylvanian age, which crop out over a large area in the Osage Plains, indicates the poor chemical quality of the water, which ranges from slightly to moderately saline.

About 90 percent of the ground water pumped in the Brazos River Basin was from wells in region I (Plate 1) owing to the semiarid climate and to the availability of water from the Ogallala Formation. Large-scale withdrawals of ground water have resulted in a marked decrease in the quantity of ground water in storage in the Ogallala Formation; the decrease has been smaller in other aquifers in regions I and II. In regions III and IV, where the potential ground water available is much greater, the climate is more humid, and thus the need for irrigation is considerably less than in regions I and II. Moreover, surface-water supplies generally are more available in regions III and IV.

Table 20.--Summary of ground-water withdrawals from major wells in the Brazos River Basin, 1959, in acre-feet

Major subdi-vision	Use: Public supply	Use: Industrial	Use: Irrigation	Ogallala Formation	Rocks of Triassic age	Quaternary alluvium	Clear Fork Group	White-horse Group	Cisco Group	Canyon Group	Trinity Group and equivalents	Woodbine Formation	Edwards Lime-stone and equivalents	Rocks of Taylor Age	Midway Group	Carrizo Sand and Wilcox Formation, undifferentiated	Sparta Sand	Cook Mountain Formation	Yegua Formation	Jackson Group	Tertiary System and Pleistocene and Recent Series, undifferentiated	Total*
BR- 1	10,740	4,355	280,000	300,000	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	300,000
3	2,080	8	120,000	120,000	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	120,000
5	13,440	2,170	300,000	320,000	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	320,000
8	1,895	354	151,000	150,000	--	--	--	--	--	--	--	--	900	--	--	--	--	--	--	--	--	151,000
10	284	--	1,100	1,400	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	1,400
11	--	2,172	1,000	--	890	2,300	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	3,200
12	184	--	a/ 1,100	--	--	1,300	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	a/ 1,300
13	132	56	330,000	330,000	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	330,000
14	4,127	20	330,000	330,000	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	330,000
15	1,927	16	530,000	530,000	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	530,000
17	592	--	140,000	140,000	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	140,000
18	--	--	9,100	8,600	--	500	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	9,100
19	571	--	8,300	800	--	8,100	--	35	--	--	--	--	--	--	--	--	--	--	--	--	--	8,900
21	--	100	--	--	--	100	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	100
22	85	--	a/ 13,000	--	--	a/ 13,000	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	a/ 13,000
23	762	5	a/ 57,000	--	--	a/ 58,000	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	a/ 58,000
24	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	0
26	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	0
27	239	--	3,000	--	1,700	1,500	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	3,200
28	132	145	1,500	--	830	700	100	--	--	--	150	--	--	--	--	--	--	--	--	--	--	1,800
29	30	--	200	--	--	200	--	--	--	--	30	--	--	--	--	--	--	--	--	--	--	230
30	15	60	350	--	--	310	100	--	--	--	15	--	--	--	--	--	--	--	--	--	--	430
31	552	20	a/ 8,100	--	--	8,400	220	--	--	--	--	--	--	--	--	--	--	--	--	--	--	a/ 8,600
33	--	20	300	--	--	320	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	320
34	100	--	--	--	--	--	--	--	--	--	100	--	--	--	--	--	--	--	--	--	--	100
36	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	0
37	27	22	--	--	--	--	--	--	49	--	--	--	--	--	--	--	--	--	--	--	--	49
40	26	--	--	--	--	--	--	--	--	26	--	--	--	--	--	--	--	--	--	--	--	26
42	--	5	--	--	--	--	--	--	--	5	--	--	--	--	--	--	--	--	--	--	--	5
44	356	6	2	--	--	--	--	--	--	--	360	--	--	--	--	--	--	--	--	--	--	360
46	90	22	240	--	--	--	--	--	--	--	350	--	--	--	--	--	--	--	--	--	--	350
48	2,520	151	--	--	--	--	--	--	--	--	2,700	--	--	--	--	--	--	--	--	--	--	2,700
50	1,250	47	b/ 110	--	--	b/ 36	--	--	--	--	1,100	240	--	--	--	--	--	--	--	--	--	1,400
51	1,810	8	250	--	--	--	--	--	--	--	2,100	--	--	--	--	--	--	--	--	--	--	b/ 2,100
52	189	--	--	--	--	--	--	--	--	--	190	--	--	--	--	--	--	--	--	--	--	190
53	3,541	2,374	b/ 900	--	--	b/ 650	--	--	--	--	6,200	--	--	--	--	--	--	--	--	--	--	b/ 6,900
56	312	--	b/ 840	--	--	b/ 840	--	--	--	--	310	--	--	--	--	--	--	--	--	--	--	b/ 1,200
57	462	33	1,800	--	--	--	--	--	--	--	2,300	--	--	--	--	--	--	--	--	--	--	2,300
59	403	45	530	--	--	--	--	--	--	--	980	--	--	--	--	--	--	--	--	--	--	980
60	958	--	120	--	--	8	--	--	--	--	1,100	--	--	--	--	--	--	--	--	--	--	1,100
61	37	6	--	--	--	--	--	--	--	--	43	--	--	--	--	--	--	--	--	--	--	43
62	171	--	10	--	--	10	--	--	--	--	170	--	--	--	--	--	--	--	--	--	--	180
63	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	0
65	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	0
66	1,048	--	42	--	--	--	--	--	--	--	250	--	840	69	--	--	--	--	--	--	--	1,100
68	1,230	346	34	--	--	--	--	--	--	--	1,200	--	310	--	--	--	--	--	--	--	--	1,600
69	1,868	213	410	--	--	63	--	--	--	--	2,300	--	11	--	--	95	--	--	--	--	--	2,500
71	3,386	34	b/ 34,000	--	--	b/ 34,000	--	--	--	--	650	--	--	--	--	1,100	1,700	--	--	--	--	b/ 37,000
73	213	1,623	66	--	--	--	--	--	--	--	--	--	--	--	--	2,400	13	--	--	--	--	2,400
75	382	324	140	--	--	--	--	--	--	--	--	--	--	--	--	370	10	320	150	--	--	850
76	938	--	--	--	--	--	--	--	--	--	--	--	--	--	910	28	--	--	--	--	--	940
78	4,274	--	b/ 11,000	--	--	b/ 11,000	--	--	--	--	--	--	--	--	--	470	3,400	--	55	130	390	b/ 15,000
82	807	--	b/ 1,400	--	--	960	--	--	--	--	--	--	--	--	--	--	--	--	--	--	1,300	b/ 2,300
83	1,210	--	2,400	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	3,600	3,600
85	1,658	8,869	12,000	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	23,000	23,000
86	650	--	4,000	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	4,700	4,700
Total*	68,000	24,000	2,400,000	2,200,000	3,400	140,000	420	35	49	31	23,000	240	2,100	69	910	4,500	5,100	320	210	130	33,000	2,400,000

* Figures are approximate because some of the pumpage is estimated. Irrigation figures are shown to no more than two significant figures. Public-supply, industrial, or other pumpage figures are shown to the nearest acre-foot. Totals are rounded to two significant figures.

a/ Based on estimate of pumpage for irrigation in Haskell and Knox Counties in 1956.

b/ Based on estimate of pumpage for irrigation in 1958.

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(Please note that the name of the Texas Board of Water Engineers was changed to Texas Water Commission January 30, 1962.)

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Year	Water-Supply Paper No.	Year	Water-Supply Paper No.	Year	Water-Supply Paper No.
1935	777	1942	947	1949	1159
1936	817	1943	989	1950	1168
1937	840	1944	1019	1951	1194
1938	845	1945	1026	1952	1224
1939	886	1946	1074	1953	1268
1940	909	1947	1099	1954	1324
1941	939	1948	1129	1955	1407