GEOLOGY AND GROUND-WATER RESOURCES OF HARDIN COUNTY, TEXAS

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GEOLOGY AND GROUND-WATER RESOURCES OF HARDIN COUNTY, TEXAS

ABSTRACT

Hardin County, having an area of 895 square miles, is in the West Gulf Coastal Plain of southeastern Texas and is in the second tier of counties north of the Gulf of Mexico. The county had a population of 24,629 in 1960. Kountze, the county seat, had a population of 1,768 in 1960, and is 25 miles northwest of Beaumont and 75 miles northeast of Houston. The county has a humid climate and an average precipitation of about 54 inches per year. Almost all of Hardin County is in the Neches River drainage basin.

The economy is dependent largely upon the availability of ground water for industry and agriculture. Irrigation is practiced in the southern part of the county where rice is the principal crop. A large part of the industrial development is associated closely with lumbering and the production of petroleum and natural gas.

Deposits of gravel, sand, silt, and clay of Miocene, Pliocene, Pleistocene, and Recent age underlie Hardin County. The deposits (except those of Recent age) crop out in belts parallel to the coastline and dip gently southeastward at an angle greater than the slope of the land, thereby creating artesian aquifers. The deposits of Recent age are exposed along the Neches River and transgress the older formations.

The formations that yield fresh to slightly saline water to wells are the Lagarto Clay (Miocene(?)) and the Oakville Sandstone (Miocene), Goliad Sand (Pliocene), the Willis Sand (Pliocene(?)), Lissie Formation and Beaumont Clay (Pleistocene), and alluvium of Recent age along the Neches River. Only the Lissie Formation, Beaumont Clay, and alluvium are exposed in Hardin County.

The surface geology of Hardin County is represented by alluvial sequences of sediments deposited by streams as deltaic plains during periods of rising sea level as glaciers waned. Each alluvial sequence of sediments is typically stratified and grades from basal gravelly sand upward into finer sand, silt, and clay. The upper limit of each alluvial sequence is represented physiographically by a terraced depositional surface, except for the youngest, which is represented by the Neches River flood plain. The Pleistocene surface in Hardin County consists of two terraced, coastwise plains, which merge inland with contemporaneous fluviatile terraces along the Neches River. The Recent surface is the modern flood plain of the Neches River.

The term "Gulf Coast" aquifer, when used in this report, includes collectively all the geologic formations that contain fresh to slightly saline water in Hardin County.

Ground water in Hardin County moves southeastward from areas of recharge to areas of discharge. An average rate of movement in the Gulf Coast aquifer is perhaps 20 feet per year. Precipitation on the outcrop is the primary source of recharge to the aquifer. The outcrop is saturated in most places and rejects additional rainfall at the rate of about 54,000 acre-feet per year after evapotranspiration needs are fulfilled.

The use of ground water in Hardin County has increased significantly over the last two decades. In 1943, the total withdrawal of water was about 1,000,000 gpd (gallons per day). By 1962, ground-water withdrawal had increased almost 10 times to 9.8 million gpd. Of this amount, 50 percent was used for public supply, 19 percent was used for industry, 25 percent was used for irrigation, and 6 percent was used for domestic and livestock purposes. Thirty-eight percent of the county's total pumpage was from the city of Beaumont's two large-capacity wells at Loeb.

Ground-water levels have declined only slightly because the aquifers have been only partly developed. Declines in some industrial and public-supply wells have averaged 0.6 foot per year. This is not a significant rate of decline as the artesian pressure is sufficient to maintain water levels close to the surface. A significant decline in artesian pressure, however, has occurred at Loeb since 1959 as a result of heavy withdrawals in that area. Water levels in some observation wells in this vicinity of heavy pumping have been declining at the rate of about 1.5 to 2 feet per year. The rate of decline may be expected to increase as additional wells are put in production.

Ground water in the Gulf Coast aquifer is good to excellent and is suitable for most public supply, industrial, and irrigation purposes. Results of chemical analyses indicate that ground water in most of the county is a sodium bicarbonate water, low in dissolved-solids content, which generally does not exceed the maximum concentrations of chemical constituents as recommended by the U. S. Public Health Service. Mineralized water commonly occurs in the salt-dome areas, however.

Pumping tests in wells that tap the Gulf Coast aquifer gave an average coefficient of transmissibility of 83,000 gpd per foot. An estimated coefficient of transmissibility, based on the total thickness of water-bearing materials in the fresh to slightly saline water section, is between 100,000 and 200,000 gpd per foot in most of the county. Yields of 4,000 to 6,000 gpm (gallons per minute) and specific capacities of 40 to 50 gpm per foot are possible with properly constructed wells in favorable locations.

Fresh ground water is being contaminated by salt water in places, although on a regional scale it is not a serious problem. Most of the contamination is encroachment of salt water by lateral movement in salt-dome areas or in southeastern Hardin County. Of greatest concern is the gradual northward movement of the salt water from northern Jefferson County into southeastern Hardin County. The rate of encroachment is expected to increase as artesian pressure is lowered by large withdrawals of water in the Loeb area.

Land subsidence from withdrawals of ground water may be occurring in southeastern Hardin County. However, additional land subsidence is an expected consequence of large ground-water pumpage and probably will occur in the Loeb area.

The vast ground-water resources of Hardin County are only partly developed. The fresh to slightly saline water section has a maximum thickness of almost 2,300 feet, and the sand beds containing fresh to slightly saline water attain a composite maximum thickness of 1,500 feet. The volume of fresh to slightly saline water in transient storage in the Gulf Coast aquifer in Hardin County is estimated to be 170,000,000 acre-feet. Most of the water is not recoverable for development by known methods at present costs partly because of the depth at which it occurs, but high artesian heads and high specific capacities are favorable to future development within economic limits of pumping lifts.

An estimate of the potential quantity of ground water perennially available from the Gulf Coast aquifer in Hardin County, without exceeding various pumping levels, required many assumptions, chiefly because of the lack of sufficient hydrologic data. Hardin County, for instance, could support a ground-water development of 100 mgd (million gallons per day) indefinitely with pumping levels not exceeding 400 feet along a line of discharge of about 71 wells equally spaced across the county and each well pumping 1,000 gpm. Under the assumed conditions, it would require 173 years of pumping 200 mgd to lower the water levels to 400 feet. The water thus produced would have a quality suitable for public supplies, most industries, and irrigation.

Before large developments of ground-water supplies are planned, the area should be explored by test drilling. The problems of well spacing and pumping rates should be studied thoroughly in order to determine the optimum conditions of development permitted by the available ground-water supply. Current periodic observations should be continued with special emphasis on the progress of salt-water encroachment.

GEOLOGY AND GROUND-WATER RESOURCES

OF HARDIN COUNTY, TEXAS

INTRODUCTION

Location and Extent of Area

Hardin County is in southeastern Texas between latitudes 30°05' and 30°35' N and longitudes 94°00' and 94°45' W. It is bordered on the north by Polk and Tyler Counties, on the west by Liberty County, on the south by Liberty and Jefferson Counties, and on the east by Orange and Jasper Counties (Figure 1). Kountze, the county seat, is 25 miles northwest of Beaumont and 75 miles northeast of Houston. The area of the county is 895 square miles.

Purpose and Scope of Investigation

The Hardin County investigation was started in January 1962 as a cooperative project of the Lower Neches Valley Authority, the Texas Water Commission, and the U. S. Geological Survey. Its purpose was to determine and describe the ground-water resources of Hardin County. The results of the investigation include an analytical discussion of the geology and hydrology as it relates to the occurrence and availability of ground water. The report presents information and data obtained during the investigation that can be used in obtaining optimum benefits from available ground-water supplies.

The investigation included a determination of the location and extent of sands containing fresh to slightly saline water (less than 3,000 parts per million dissolved solids), the chemical quality of the water they contain, the quantity of water being withdrawn and the effect the withdrawals have had on water levels, the hydraulic characteristics of the water-bearing sand, and the quantity of ground water available for development.

The investigation was made under the immediate supervision of A. G. Winslow, district geologist of the U. S. Geological Survey in charge of ground-water investigations in Texas.

Methods of Investigation

To accomplish the investigation of the ground-water resources of Hardin County, the following items of work were done:

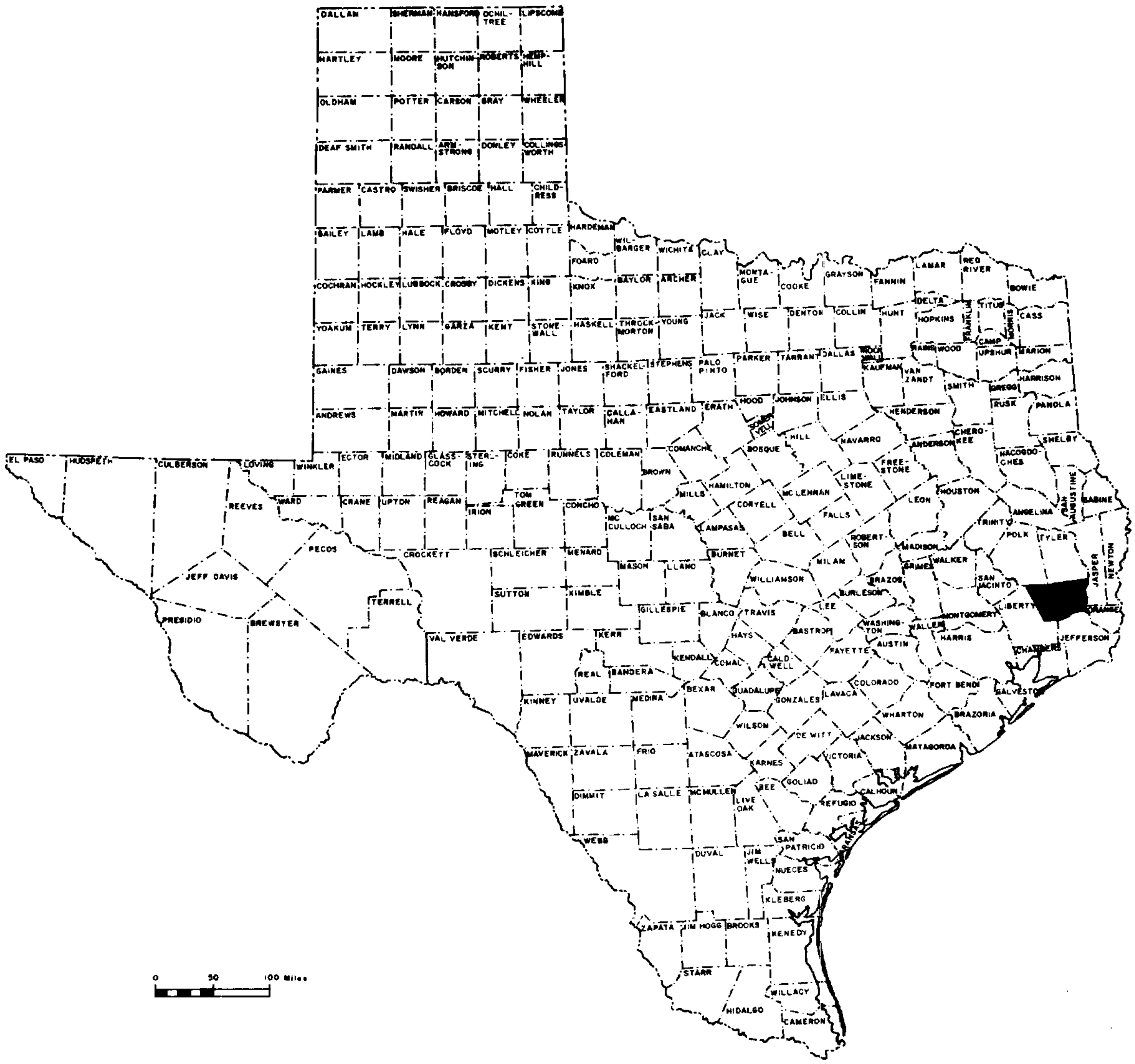

Figure 1

Map of Texas Showing Location of Hardin County

U. S. Geological Survey in cooperation with the Texas Water Commission and the Lower Neches Valley Authority

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1. An inventory was made of 296 wells, including all municipal, industrial, and irrigation wells, and a representative number of livestock and domestic wells (Table 8). The locations of the wells inventoried are shown on Plates 1 through 4.

2. The electric logs of 273 oil tests were used for correlation and evaluation of subsurface characteristics of the water-bearing units. In addition to the electric logs, 65 drillers' logs of water wells (Table 9) were used as an aid in determining the total thickness of sand containing fresh to slightly saline water.

3. An inventory was made of municipal, industrial, and irrigation pumpage.

4. Pumping tests were run in 20 wells to determine the hydraulic characteristics of the water-bearing sands (Table 2).

5. Elevations of water wells were determined from topographic maps.

6. Measurements of water levels were made in wells and available records of past fluctuations of water levels were compiled (Table 10).

7. Climatological and streamflow records were collected and compiled (Figures 2, 3, and 5).

8. The areas of recharge and natural discharge were determined.

9. Samples of water were collected from 144 wells to determine the quality of the water (Table 11).

10. Maps, cross sections, charts, and graphs were prepared correlating and illustrating geologic, hydrologic, and quality-of-water data.

11. The hydrologic data were analyzed to determine the quantity and quality of water available for development from the water-bearing units.

12. Problems related to development of ground-water supplies in Hardin County were studied.

Well-Numbering System

The well-numbering system used in this report is one adopted by the Texas Water Commission for use throughout the State and is based on latitude and longitude. Under this system, each 1-degree quadrangle in the State is given a number consisting of two digits. These are the first 2 digits appearing in the well number. Each 1-degree quadrangle is divided into 7-1/2 minute quadrangles which are also given 2-digit numbers from 01 to 64. These are the third and fourth digits of the well number. Each 7-1/2 minute quadrangle is subdivided into 2-1/2 minute quadrangles and given a single-digit number from 1 to 9. This is the fifth digit of the well number. Finally, each well within a 2-1/2 minute quadrangle is given a 2-digit number in the order in which it is inventoried, starting with 01. These are the last two digits of the well number. In addition to the 7-digit well number, a 2-letter prefix is used to identify the county. The prefixes for Hardin County and adjacent counties are as follows:

County	Prefix	County	Prefix
Hardin	LH	Orange	UJ
Jasper	PR	Polk	UT
Jefferson	PT	Tyler	YJ
Liberty	SB		

Previous Investigations

Prior to this investigation, little detailed study had been made of the ground-water resources of Hardin County. Among the first investigations was that by Taylor (1907, p. 47-48), who included in his study the whole coastal plain of Texas, discussing briefly the wells in Hardin County. Deussen (1914, p. 186-219), in a reconnaissance investigation of the southeastern part of the Texas coastal plain, discussed in more detail than did Taylor the geology and hydrology of Hardin County, and included a list of wells and springs and drillers' logs of wells.

The next work was done in 1942 when Cromack (1942) inventoried more than 100 wells and included chemical analyses and drillers' logs in his report. These records served as a guide to landowners, officials of industrial plants, well drillers, and others who needed information regarding wells, the depth to ground water in various parts of the county, and the quantity and chemical character of water yielded by the wells.

Rose (1945) conducted an investigation of ground water in the Beaumont area with special reference to southeastern Hardin County and southwestern Jasper County. This report discussed the possibilities of developing a ground-water supply possibly as great as 20 mgd (million gallons per day) in southeastern Hardin County or southern Jasper County.

Sundstrom, Hastings, and Broadhurst (1948, p. 124-126) presented a summarized description of the public water supplies of eastern Texas, including in Hardin County basic data on the public-supply wells of Honey Island, Kountze, Silsbee, and Sour Lake.

In 1956, Wood reported on the availability of ground water in the Gulf Coast region of Texas, describing the potentialities for development of large ground-water supplies suitable for industrial or irrigation use.

A report by Wood, Gabrysch, and Marvin (1963) discussed the order of magnitude of the ground-water supplies potentially available from the principal water-bearing formations in the Gulf Coast region, which includes Hardin County.

Economic Development

A large supply of easily obtainable fresh ground water is one of the most important natural resources of Hardin County. The ground water is widely used throughout the county for public supply, industrial, irrigation, and domestic and livestock purposes. The water is basic to both the present and future welfare and economy of the county.

Hardin County derives its income principally from timber, oil and gas, and agriculture, principally rice farming. The raising of beef cattle, poultry, and dairying also add to the economy of the area. The cities of Silsbee, Kountze, and Sour Lake are the industrial centers of the county. Silsbee, the largest city, is a commercial center for lumbering, oil, and livestock. Kountze, the county seat, is the center of the lumber industry, having three sawmills in operation, where pine, gum, ash, and some hardwoods are processed. Sour Lake derives its principal income from oil production, the Sour Lake oil field being in and around the center of the city. Rice farming is practiced successfully on the nearly level plains around Sour Lake.

Dense forests, largely pine trees with an undergrowth of hardwood trees, mainly oak, gum, elm, ash, and some hickory, occupy 89 percent of the county. The region of dense forests is part of the "Big Thicket" of southeastern Texas. Systematic logging and reforestation programs are practiced as conservation measures for this important source of income.

The production of oil and gas in Hardin County is an important source of revenue (about $28,000,000 in 1958). Oil was first discovered in Hardin County at Saratoga in 1893; about 272 million barrels of oil was produced to January 1, 1962. Production of oil in 1961 was about 6 million barrels, according to records of the Railroad Commission of Texas (1962). The Commission recognized 87 oil fields (including multiple pay zones in any one locality) in Hardin County in 1961.

Hardin County had a population of 24,629 in 1960, an increase of 21 percent over 1950. Seventy-five percent of the population lives in rural areas. The population of Silsbee increased from 3,179 in 1950 to 6,277 in 1960; during the same period, the population of Kountze increased from 1,651 to 1,768; the population of Sour Lake (1,602) remained essentially unchanged from 1950 to 1960. Other towns in the county include Saratoga, estimated population 350; Honey Island, 300; Batson, 200; Village Mills, 200; Votaw, 100; Grayburg, 75; and Thicket, 50.

Hardin County is served by two major railroads, the Missouri Pacific and Santa Fe, and by a network of hard-surfaced Federal and State highways.

Physiography and Drainage

Hardin County is in the West Gulf Coastal Plain physiographic province. The topographic configuration of the county can be divided naturally on the basis of geology and age into three prominent land surfaces--the Recent alluvial flood plains of the Neches River and two terraced Pleistocene deltaic coastwise plains, the outcrops of the Beaumont Clay and the Lissie Formation, which slope seaward and form belts parallel to the coastline. These two coastwise plains merge inland with their contemporaneous fluviatile terraces flanking the Neches River.

The alluvial valley of the Neches River, consisting of Recent alluvial deposits, is a broad, generally flat-bottom flood plain bounded by well-defined valley walls. The major tributaries of the river exhibit the same physiographic features on a smaller scale. The low-lying Recent flood plains, ranging in elevation from about 5 feet in southeastern Hardin County to about 40 feet in the northeast, slope seaward at an average rate of 1.3 feet per mile.

Bernard (1950, p. 61-62) recognized an early Recent terrace along the Sabine and Neches Rivers, which he named the Deweyville terrace. This terrace along the Neches River has a large areal extent and a width of 4 miles or more. Swamps, marshes, abandoned river channels, and oxbow lakes characterize this sandy Recent terrace. Barton (1930a, p. 382) first noted these fluviatile features of the Deweyville terrace and stated, "The ancient Neches and Sabine Rivers, therefore, must have been very large rivers. The rainfall in the Gulf Coast must have been greater in late Pleistocene and early Recent times than it is at present."

The alluvial valley of the Neches River is covered by a dense growth of hardwood trees and relatively few pine trees, the pines being restricted to the Deweyville terrace. The alluvial valley extends inland, traversing other contrasting physiographic features. When viewed from the air, the Recent flood plains of the valley are the most distinctive physiographic features of the area (Bernard, 1950, p. 11).

The Recent flood plains and terraces of the Neches River are bounded by valley walls or scarps about 10 to 40 feet high and are as much as 10 to 12 miles wide on either side of the Neches River. The valley walls or scarps are the terraced remnants of older depositional surfaces or ancestral flood plains that have since been uplifted and eroded and, in many places, considerably dissected. Each valley terrace merges downstream with a contemporaneous seaward-facing deltaic coastwise plain.

The plain formed by the outcrop of the Beaumont Clay consists of a fluviatile upstream terrace along the valley walls of the Neches River and a coastwise deltaic plain which occupies the interstream divides. The deltaic plain, which has been relatively uneroded, has a gentle slope seaward of about 1.5 feet per mile and ranges in elevation from about 25 feet near Pine Island Bayou in southeastern Hardin County to about 50 feet at its contact with the plain formed by the outcrop of the Lissie Formation. The deltaic plain is about 10 to 15 feet higher than the Recent bottomlands along the Neches River. It occupies roughly the southern half of Hardin County. Its surface is characterized by grass-covered prairies where typical backswamp interlevee clays were deposited, although where sandy, the surface supports a dense growth of pine and hardwood trees.

The plain formed by the outcrop of the Lissie Formation consists of a coastwise deltaic plain, which occupies the interstream divides, and a fluviatile upstream terrace, which according to Bernard (1950, p. 86-94), extends along the Neches River Valley scarp for about 50 miles. The deltaic plain occupies roughly the northern half of Hardin County. The plain is characterized by isolated grass-covered surfaces and in many places by a dense growth of pine trees and an undergrowth of hardwood trees. The deltaic plain is separated from the adjoining deltaic plain formed by the outcrop of the Beaumont Clay by a seaward-facing escarpment. The regional strikes of the two plains are almost parallel. The slope of the upper plain ranges from about 3 feet per mile along its inland margin to as much as about 8 feet per mile near the contact with the adjacent lower plain. The seaward-facing escarpment of the surface generally is dissected but is represented by a line of low hills about 10 feet above the lower plain. Most of the original depositional forms of the higher plain, such as meanders, channels, and natural levees, have been obliterated. The elevation of uneroded remnants of the plain ranges from about 60 feet at its seaward-facing escarpment to about 200 feet at the base of the scarp of the next higher plain in Tyler and Polk Counties.

Various depositional and erosional features such as pimple mounds, baygalls, pock marks, or prairie ponds are found on the Pleistocene surfaces in Hardin County. Baygalls and pock marks or prairie ponds are small depressions, which probably are the remains of incompletely filled ancestral stream channels. Bernard (1950, p. 86) reported that pimple mounds are more common on the upper part of the outcrop of the Lissie Formation than on any other surface, and generally are aligned in rows along the divides of concentrated sheetwash. Bernard, Le Blanc, and Major (1962, p. 188) agreed that the mounds are in alignment with the slope of the land and the drainage. These pimple mounds are very low, 1 to 4 feet high, generally circular although a few are oblong, and range in diameter from about 10 to 60 feet. They occur only on silty or sandy terrains having gentle slopes, and probably are either erosional or accumulational (erolian) in origin (Saul Aronow, 1962, oral communication).

Some of the piercement-type salt domes have an effect on the topography in Hardin County; slight relief of a few feet is apparent at the Sour Lake and Batson salt domes. Sellards (1930, p. 11) stated that the 44-foot topographic contour encircles the Sour Lake dome and the high point of the surface of 56 feet is slightly south of the structural high point of the dome. Sawtelle (1925, p. 1279) reported that the elevation of the land surface at Batson is not more than 10 feet above the surrounding country. The topography at Saratoga, in contrast to that at Batson and Sour Lake, apparently has little relation to the salt dome.

All of Hardin County is drained by the Neches River and its tributaries, with the exception of about 8 square miles in the extreme northwestern part of the county which is drained by a tributary of the Trinity River. Pine Island Bayou and Little Pine Island Bayou drain the western part of the county, while Village Creek and Cypress Creek drain most of the northern and eastern parts. Because much of the surface of the county consists of young depositional plains of low elevation and gentle seaward slopes, the drainage is consequent to the maximum slope of the plains and the depositional morphology of the sediments.

Numerous small tributaries head near the contacts of the Beaumont Clay and Lissie Formation and the Lissie Formation and Willis Sand where there is a change in slope of the coastwise plains. Depositional features such as natural levees and abandoned channels control the minor drainage on the outcrop of the Beaumont Clay in the southern part of the county, whereas the major drainage is dendritic and controlled by the regional slope of the plain. Drainage on the more dissected outcrop of the Lissie Formation is controlled largely by the regional slope of the plain.

The Neches River heads in Van Zandt, Smith, and Henderson Counties in the northeastern part of Texas and flows southeast to the northwest corner of Jasper County, whence it continues in a south-southeast direction and empties into Sabine Lake, where the river has its greatest width of about 1,200 feet. A minimum width of about 500 feet is maintained upstream to Beaumont from which point upstream to its confluence with Pine Island Bayou, the Neches River is not less than about 400 feet wide. From Pine Island Bayou upstream to the northeastern part of Hardin County, the width ranges from about 100 to 300 feet.

Meander belts characterize the Neches River where it nears the coast. From northeastern Hardin County to Pine Island Bayou, its meander belt does not exceed 0.6 mile in width; from Pine Island Bayou to Beaumont, the meander belt increases to 0.8 mile in width and the belt widens even more in the marshland south of Beaumont.

Data issued by the U. S. Corps of Engineers office in Galveston indicate an average gradient of 0.7 foot per mile in the Neches River from north-central Tyler County to Sabine Lake. South of Beaumont in the tidal section, its gradient is zero for average bank stage and less than 0.4 foot per mile for high-water stage (Bernard, 1950, p. 27).

Climate

Hardin County has a humid climate as indicated by Figures 2 and 3 which show graphically the precipitation, temperature, and evaporation at Beaumont. Precipitation averaging 54.28 inches annually is fairly well distributed throughout the year, being greatest from May through September and least from January through April. Droughts occur infrequently and generally are not prolonged. Because rice, the principal crop in Hardin County, is irrigated with ground water, no damage to the crop results from periods of deficient rainfall.

The average annual temperature in Hardin County is about 70°F (Figure 2), the average January temperature being about 55°F and the average July temperature about 84°F. Freezing weather may be expected in the winter, but is usually of short duration. The approximate dates for the last killing frost in spring and the first killing frost in the fall are March 1 and December 2. The long growing season of 277 days is favorable to agriculture.

The average monthly evaporation from a free-water surface, as determined at the Agricultural Experimental Station near Beaumont, is shown in Figure 2. The adjusted potential average annual evaporation of 47.42 inches is 87 percent of the average annual precipitation. Evaporation is greatest during the hot summer when the soil-moisture demand to sustain plant life also is large. However, evaporation from soil areas is less than from a free-water surface, and the amount of evaporation increases as the soil becomes drier (Rich, 1951, p. 6). Vegetation, because it decreases the wind velocity at the land surface, also decreases evaporation. Thus, the 47.42 inches of annual evaporation determined from a free-water surface near Beaumont is considerably greater than the actual evaporation from the soil in Hardin County where 89 percent of the area is forested.

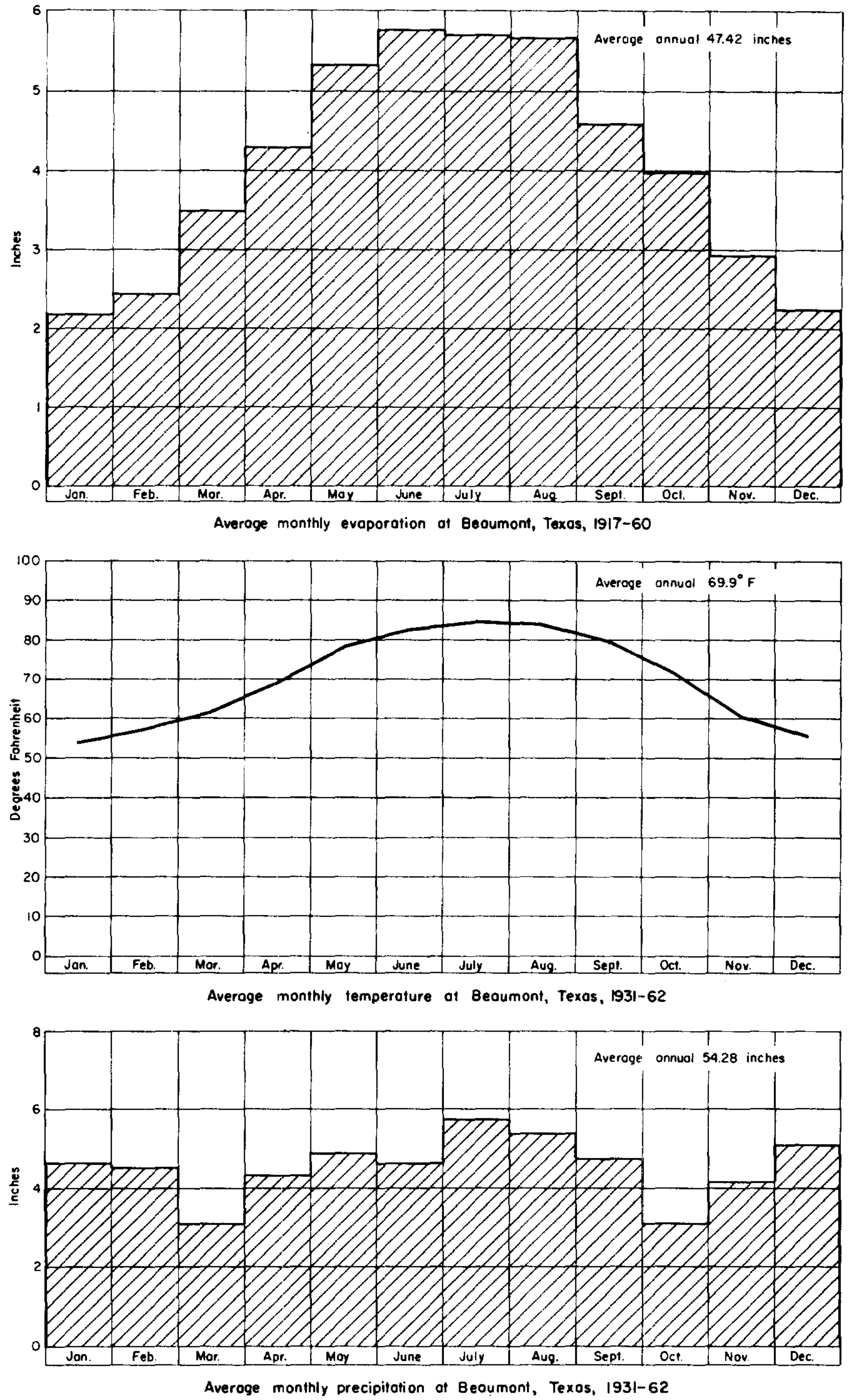

Figure 2

Monthly Precipitation, Temperature, and Evaporation at Beaumont, Jefferson County

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

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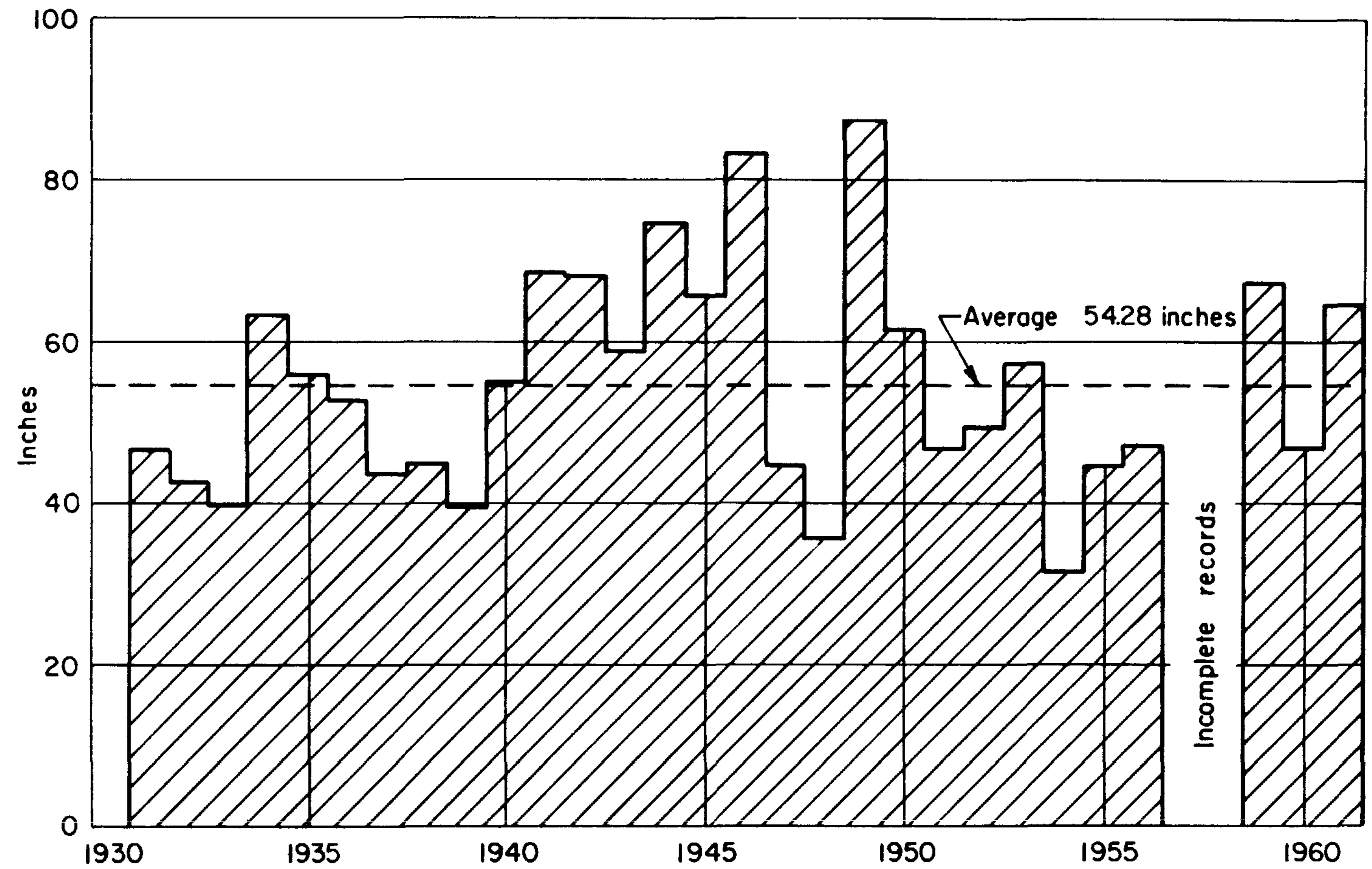

Figure 3

Annual Precipitation at Beaumont, Jefferson County

(From records of U. S. Weather Bureau)

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Acknowledgments

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GEOLOGY AS RELATED TO THE OCCURRENCE OF GROUND WATER

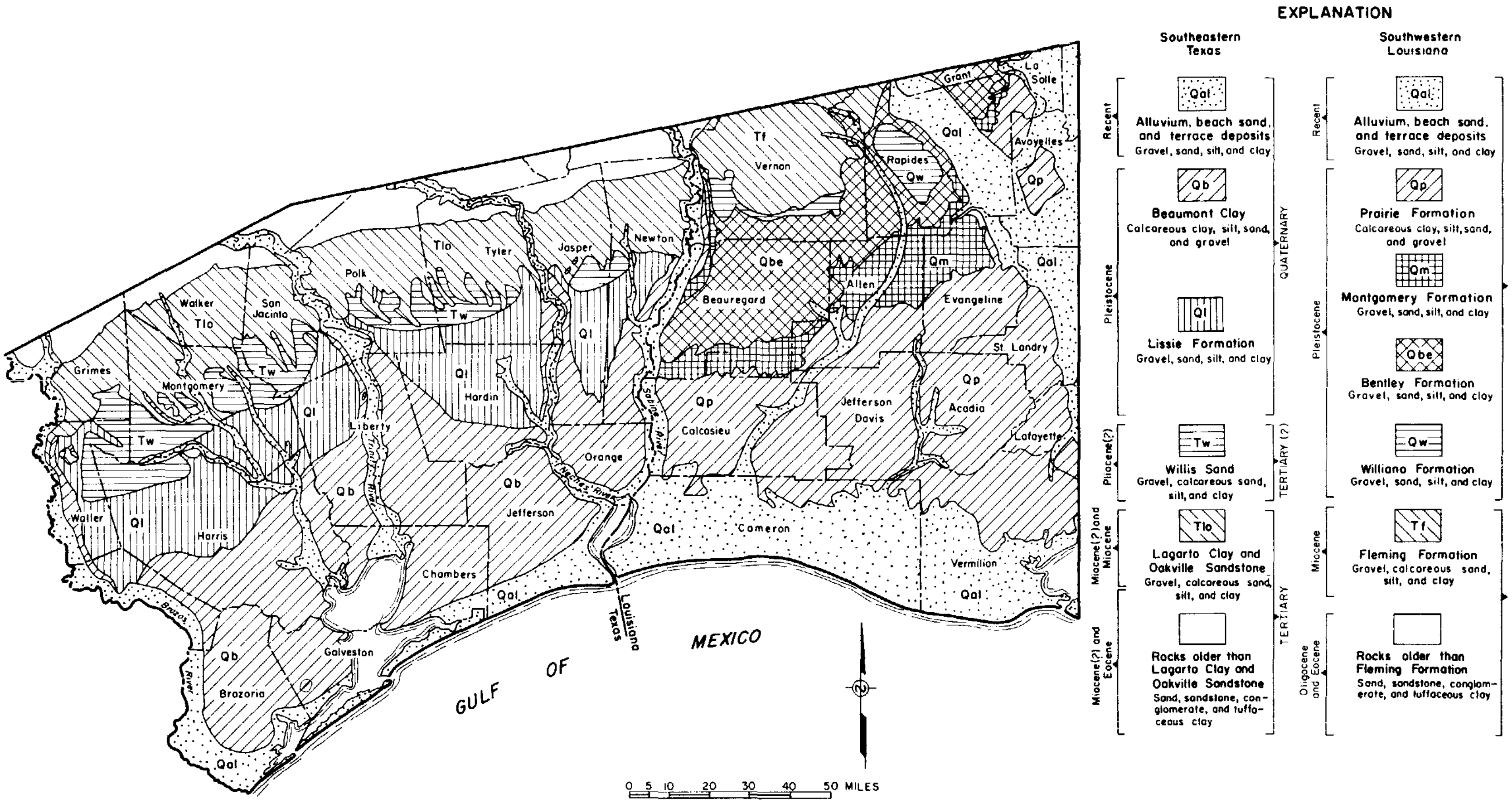
General Stratigraphy and Structure

The geologic formations that contain fresh to slightly saline water in Hardin County are, in order of decreasing age, the Oakville Sandstone and the Lagarto Clay of Miocene age and Miocene(?) age, the Goliad Sand of Pliocene age, the Willis Sand of Pliocene(?) age, the Lissie Formation and Beaumont Clay of Pleistocene age, and the alluvium of Recent age. Only the upper part of the Lissie Formation, lower part of the Beaumont Clay, and alluvium in the Neches River Valley are exposed in Hardin County. The Lagarto Clay and Oakville Sandstone, Willis Sand, and lower part of the Lissie Formation crop out north of Hardin County and are present in the subsurface in Hardin County. The upper part of the Beaumont Clay crops out south of the county. Table 1 is a correlation of nomenclature of the Miocene through the Recent Series in the Gulf Coast region of southeastern Texas and southwestern Louisiana. It is presented as an aid in reconciling different geologic names and ages for the same formation when used in discussing the geology pertaining to this report.

The geologic formations in Hardin County crop out in belts that are nearly parallel to the Gulf Coast (Figure 4). The younger formations crop out close to the coast and successively older ones farther inland. Because of the different ages of the geologic formations, the outcrops are progressively more eroded and

Table 1.--Correlation of nomenclature of Miocene to Recent Series in the Gulf Coast region of southeastern Texas and southwestern Louisiana

Hays and Kennedy (1903)	Deussen (1914)	Plummer (1932)	Doering (1935)	Fisk (1940)	Bernard (1950)	Doering (1956)	Bernard, Le Blanc, and Major (1962)	This paper	Series	System
Port Hudson Clays	Flood plain, marsh, and beach deposits	Flood plain, beach, marsh, and windblown deposits	Flood plain and beach deposits and Post-Beaumont terrace deposits	Flood plain deposits	Modern flood plain deposit Deweyville beds(?)	Flood plain and beach deposits Sicily Island Formation Holloway Prairie Formation	Flood plain, beach, and marsh deposits	Flood plain and terrace deposits	Recent	Quaternary
Beaumont Clays	Beaumont Clay	Houston Group: Beaumont Clay	Beaumont Formation	Prairie Formation	Prairie Formation	Eunice Formation Oberlin Formation	Beaumont	Beaumont Clay	Pleistocene	Quaternary
Columbia Sands	Lissie Gravel	Houston Group: Lissie Formation	Lissie Formation	Montgomery Formation Bentley Formation	Montgomery Formation Bentley Formation	Lissie Formation	Unnamed 2nd Terrace Lissie	Lissie Formation	Pleistocene	Quaternary
Lafayette Sands	Lissie Gravel	Citronelle Group: Unnamed upper sands	Willis Formation	Williana Formation	Williana Formation	Citronelle Formation	Willis	Willis Sand	Pliocene(?)	Tertiary
Lafayette Sands	Dewitt Formation and Fleming Clay	Citronelle Group: Goliad Formation	Goliad(?) Sand	(not given)	(not given)	Goliad Formation	Goliad Formation	Goliad Sand	Pliocene	Tertiary
	Dewitt Formation and Fleming Clay	Fleming Group: Lagarto Clay	Fleming Formation	Grand Gulf Group: Fleming Formation	Fleming Formation	Fleming Formation	Fleming Formation	Lagarto Clay and	Miocene(?)	Tertiary
	Dewitt Formation and Fleming Clay	Fleming Group: Oakville Sandstone	Fleming Formation	Grand Gulf Group: Fleming Formation	Fleming Formation	Fleming Formation	Fleming Formation	Oakville Sandstone	Miocene	Tertiary
			(not given)	Grand Gulf Group: Catahoula Formation	Catahoula Formation	(not given)	Catahoula Formation	Catahoula Sandstone	Miocene(?)	Tertiary



Geology of Texas except Hardin County from Geologic Map of Texas (Darton, Stephenson, and Gardner, 1937)
Geology of Hardin County modified from Geologic Map of Texas
Geology of Louisiana from Louisiana Geological Survey; Fisk (1940), and Welch (1942)

Figure 4

Geologic Map of Southeastern Texas and Southwestern Louisiana

U. S. Geological Survey in cooperation with the Texas Water Commission
and the Lower Neches Valley Authority

dissected inland. The outcrops of the upper part of the Pleistocene and Recent formations are comparatively uneroded and retain much of their depositional surfaces.

The geologic formations change in lithology, dip, and thickness in the direction of the dip and commonly change in lithology and thickness laterally along the strike. The dip and thickness increase gulfward and the clastic sediments comprising the formations grade from fluviatile and deltaic gravel, sand, silt, and clay in inland areas to predominantly finer materials that interfinger with brackish and marine deposits near the Gulf Coast and offshore.

Because of variations in lithology, dip, and thickness in short distances, subsurface mapping of individual geologic formations is extremely difficult. However, accurate delineation of the units is relatively unimportant because all are aquifers in Hardin County and are, in most places, hydraulically connected. Thus, the entire sequence of sediments from Miocene through Recent may be treated as a single aquifer.

The relatively simple geologic structure of Hardin County is shown in the geologic sections in Plates 5 through 8. The formations underlying the county form a monocline that dips gently toward the coast.

The monoclinal structure is indicated by a structural map of Texas by Sellards and Hendricks (1946), which shows structural contours on the top of the Textularia hockleyensis zone and the top of the Heterostegina antillea zone (faunal zones in the deeply buried Tertiary formations in Hardin County). The contours show that the formations dip Gulfward at 100 to 135 feet per mile in Hardin County. Only upthrusts caused by salt domes interrupt the monoclinal structure. The structure of the younger and more shallow geologic formations in Hardin County generally conforms to the structure of the deeper faunal zones. However, the younger formations generally have lower dips than the older formations; the water-bearing units in Hardin County have dips ranging from about 85 to less than 25 feet per mile. These dips are not constant; the dip of each formation increases near the surface contact with the next younger formation. For example, the position of increase in dip of the Lissie Formation is near its surface contact with the overlying Beaumont Clay.

Piercement-type salt domes, structural features influencing the occurrence of ground water at least locally in Hardin County, underlie the towns of Batson, Saratoga, and Sour Lake. The salt domes rise to within a few hundred feet of the land surface, causing a general deformation of the adjacent water-bearing formations. The availability and quality of ground water over and around the salt domes are affected substantially.

Faults are common in the subsurface of Hardin County. They are particularly numerous around the salt domes, but generally the faults have little or no surface expression. Bernard (1950, p. 135-136), however, reported a prominent set of strike faults averaging N. 80° E. on the Montgomery surface (in part, outcrop of the Lissie Formation) in Jasper County and a throw of 17 feet was noted on one fault. Several of the oil fields of southeast Tyler County and northern Hardin County occur in alignment with the strike of several faults observed at the surface in Jasper and Newton Counties by Bernard (1950, p. 138). The majority of the faults are normal faults downthrown to the south, and they probably have little effect on the movement of ground water in the county.

Physical Characteristics and Water-Bearing Properties of the Geologic Formations

The following descriptions of the geologic formations that collectively comprise the principal aquifer in Hardin County and adjacent areas are restricted to the outcrop and the downdip part of the section containing fresh to slightly saline water. Because little detailed stratigraphic information is available regarding the Miocene and younger formations in Hardin County, the physical descriptions are based largely on the detailed work of Bernard (1950) in Jasper, Newton, and Orange Counties, and supplemented by descriptions of formations in other areas of Texas and Louisiana where detailed stratigraphic work has been done.

Lagarto Clay and Oakville Sandstone

The Oakville Sandstone of Miocene age and the Lagarto Clay of Miocene(?) age are not differentiated on the surface in southeast Texas, and are, thus, shown as one unit on the "Geologic Map of Texas" (Darton, Stephenson, and Gardner, 1937) east of the Brazos River. Plummer (1933, p. 730), Doering (1935, p. 658-659), and others conclude that east of the Brazos River the Oakville Sandstone grades laterally into clay and merges with the lower part of the Lagarto Clay.

The Lagarto Clay and Oakville Sandstone crop out as a band about 10 to 25 miles wide across central Polk and Tyler Counties and northern Jasper and Newton Counties (Figure 4). The width of the outcrop varies greatly in places, depending on the extent of dissection of the overlapping Willis Sand. Where the Willis Sand is comparatively uneroded and has a large inland extent, the outcrop of the Lagarto and Oakville is narrow. In northern Jasper and Newton Counties, the Willis Sand overlaps the outcrop of the Lagarto and Oakville and lies directly on the Catahoula Sandstone (Bernard, 1950, p. 111). In places along the Neches River and its tributaries, the Willis Sand has been completely eroded and the outcrop of the Lagarto and Oakville extends Gulfward until it is overlapped by the Lissie Formation.

The Lagarto Clay and Oakville Sandstone constitute a thick sequence of light-colored, massive calcareous marl and silt interbedded with sand, which is, in places, cemented with lime. The bedding is nearly continuous. Sand in the lower part is typically light gray, medium, friable, cross bedded, calcareous, and, in places, indurated. The clay is gray to yellowish gray, massive, and calcareous. Redeposited Cretaceous shells incorporated in the sediments indicate uplift and erosion of Cretaceous strata far inland (Smith, 1962, p. 140). The sand in the upper part is brown, reddish gray, gray, or mottled, medium to coarse, friable, cross bedded, calcareous, and, in places, massive. In some places lenticular sand beds grade into conglomerate. Yellow, gray, and green marl is typically common; upon weathering, it produces a thick black soil. Based on electric logs near the outcrop, the average sand content is about 50 percent. Massive beds of sand 40 to 100 feet thick occur in places in the upper part; however, some of the sand beds are relatively thin and interbedded with marl.

The thickness of the Lagarto and Oakville is estimated to be 1,500 feet near the outcrop in Tyler County. This thickness is based on an average width of outcrop of 18 miles and a dip of 85 feet per mile for the base. Welch (1942, Pl. 3) also reports a dip of 85 feet per mile for the base of the Fleming of Fisk, 1940 (maybe equivalent to Lagarto and Oakville) across Vernon Parish, Louisiana. The dip of the top of the Lagarto and Oakville at its contact with the overlying Goliad Sand and Willis Sand is about 45 feet per mile; thus, the thickness of the Lagarto and Oakville increases downdip about 40 feet per mile. These rates of dip and thickness are based on the generalized stratigraphic section by Hamner (1939, p. 1642) at the Amelia oil field in Jefferson County.

Reported thicknesses of the Lagarto Clay and Oakville Sandstone and equivalents vary depending on the location. At Saratoga, Suman (1925, p. 267) reported a thickness of 700 to 1,200 feet. This is a conservative figure because of thinning of strata commonly observed adjacent to salt domes. At Batson, Deussen (1914, p. 186) reported uppermost Miocene fauna at 323 and 333 feet below land surface, and Sawtelle (1925, p. 1279) reported a thickness of 1,200 to 1,800 feet for the Lagarto and Oakville in wells off the dome. At the Hull salt dome 8 miles south-southwest of Batson, Applin, Ellisor, and Kniker (1925, p. 91) reported 2,000 feet of the unit as an average section. In San Jacinto County, Alexander (1947, p. 6) reported a thickness of 1,200 feet near the outcrop, and in Liberty County, the unit is reported to be 1,100 to 1,500 feet thick (Alexander, 1950, p. 9-10).

The Lagarto Clay and Oakville Sandstone is an aquifer of major importance in parts of Hardin County, containing fresh to slightly saline water throughout most of the county. The upper 1,300 to 1,500 feet of the aquifer contains fresh to slightly saline water at the Hardin-Polk-Tyler county line. The section containing fresh to slightly saline water decreases in thickness southeastward with increasing depth of occurrence to nearly zero in places along the southeastern boundary of Hardin County. In most of Jefferson County to the south, the aquifer contains moderately to very saline water (3,000 to 35,000 parts per million dissolved solids).

Goliad Sand

The Goliad Sand as shown on the "Geologic Map of Texas" (Darton, Stephenson, and Gardner, 1937) crops out extensively in south Texas; however, in most places in southeastern Texas, it is overlapped by younger formations.

The nearest outcrop to Hardin County is about 12 miles north of the county line where Doering (1935, p. 660) questionably correlated as the featheredge of the overlapped Goliad Sand some thin bedded, well indurated, gray, sandy siltstone, which forms shoals in the Neches River.

Although the Goliad Sand generally is not recognized in the outcrop in southeastern Texas, excepting a few local exposures, it is believed to be present in the subsurface as an overlapped wedge consisting of chalky white and pink bentonitic clay streaked with red and purple and gravelly beds and lenses of lime-cemented sandstone. The sand is pinkish or whitish gray and contains many black grains of chert, giving a salt and pepper effect. The beds may grade into and may be represented by the basal part of the Willis Sand, but cannot be positively separated from the Willis Sand (Lang, Winslow, and White, 1950, p. 34). The base of the Goliad Sand dips Gulfward at a rate computed to be about 45 feet per mile through a 44-mile span from the contact of the Lagarto and Oakville with the overlying Willis Sand in Tyler County to the base of the Goliad Sand, 1,850 feet deep at the Amelia oil field in Jefferson County. Hamner (1939, p. 1641-1645), in describing the section at the Amelia field, states, "This zone consists of several thick, loosely consolidated sand bodies separated by breaks of sandy clay and with a few zones of what is probably marine clay. The sand bodies comprise about 60 percent of the section and grade in content from fresh water at the top of the zone to salt water at the bottom. The formation undoubtedly contains several loose gravel beds as evidenced by the fact that drilling mud returns were often lost."

According to Plummer (1932, p. 752), the average thickness of the Goliad Sand is estimated to be about 250 feet, and it is known to be thicker in east Texas than in southwest Texas and thicker in well sections near the coast. Its exact thickness in well sections is not known definitely because of the difficulty in separating it from the overlying Willis Sand and underlying Lagarto and Oakville.

Applin, Ellisor, and Kniker (1925, p. 92) assign a thickness of 350 feet to the Pliocene Goliad, and Pliocene(?) Willis(?) Sand on the Saratoga dome. In the Houston district, the Goliad Sand is reported to range in thickness from zero to 250 feet (Lang, Winslow, and White, 1950, p. 34).

Sand and gravel beds in the Goliad Sand supply moderate (100 to 1,000 gallons per minute) to large (more than 1,000 gallons per minute) quantities of fresh water (less than 1,000 parts per million dissolved solids) in Hardin County. South of Hardin County, the water becomes saline. Because of difficulty in differentiating the Goliad Sand in the subsurface, more information is needed regarding thickness and lithology before this aquifer can be appraised accurately hydrologically.

Collectively, the Goliad Sand, Willis Sand, and Lissie Formation constitute the most prolific part of the Gulf Coast aquifer in Hardin County.

Willis Sand

The age of the Willis Sand, accepted as Pliocene(?) by the U. S. Geological Survey, has been a controversial issue for many years. Plummer (1933, p. 750), Doering (1935, p. 662), and others believed the Willis to be Pliocene or Pliocene(?) in age. Some of the more recent geological reports by Weeks (1945), Doering (1956), Bernard (1950), Bernard, Le Blanc, and Major (1962), and others consider the Willis Sand to be basal Pleistocene in age.

The Willis Sand is shown on the "Geologic Map of Texas" (Darton, Stephenson, and Gardner, 1937) as cropping out only east of the Colorado River. It is exposed as a hilly dissected belt 15 to 20 miles wide, paralleling and just south of the outcrop of the Lagarto Clay and Oakville Sandstone (Figure 4). It uncomformably overlies the Lagarto and Oakville, and in northern Jasper and Newton Counties, it completely overlaps the Lagarto and Oakville and laps onto the Catahoula Sandstone (Bernard, 1950, p. 115).

The Willis Sand in southeastern Texas exhibits a greater degree of dissection than any of the adjacent formations (Figure 4). It caps the divides between creeks and streams which have cut through the sand. The regional strike is consistent with the adjacent formations, and the average slope of the outcrop of the Willis Sand is about 15 feet per mile. In Jasper and Newton Counties, the Willis is represented only by its coastwise equivalent, which probably is deltaic in origin (Bernard, 1950, p. 100), and the maximum elevations of the uneroded parts of the Willis Sand are reported to be about 550 feet at its landward margin and about 250 feet at the contact with the Lissie Formation (Bernard, 1950, Pl. 2). Bernard, Le Blanc, and Major (1962, p. 210) state that southwest of Hardin County in the Houston area, the highest part of the outcrop of the Willis Sand is 350 to 420 feet above sea level and the elevation at its coastal margin at the Lissie contact is about 200 feet. The seaward slope of the outcrop in this area is about 10 feet per mile.

Doering (1935, p. 660-662) divided the Willis Sand in southeastern Texas into three members--a basal "Willis gravelly sand" (30 feet thick), a "Willis ferruginous sand" (30 feet thick), and a "Hockley Mound sand" (20 to 25 feet thick). Fisk (1938, p. 155) divided the Williana Formation (may be equivalent to Willis Sand) into three transitional phases in central Louisiana--a coarse basal phase, consisting of lenticular masses of sand and gravel; a central, predominantly sandy phase with local lenses of gravel; and an upper silty clay phase having local sand lenses. The total thickness ranges from 50 to 95 feet in Grant and La Salle Parishes 145 miles northeast of Hardin County. Welch (1942, p. 62-70) in a detailed study of Vernon Parish, Louisiana, 75 miles northeast of Hardin County, also recognized three phases of the Williana Formation from a description of 99 geophysical borings--a "coarse phase" consisting of coarse sand and chert gravel 30 feet thick, a "sandy phase" 30 to 60 feet thick, and a "silty clay phase" about 35 feet thick. The maximum known thickness recorded by Welch in Vernon Parish was 142 feet.

Bernard (1950, p. 117-119) in mapping Jasper, Newton, and Orange Counties, found Welch's description of the Willis Sand consistent with that in southeastern Texas excepting the percentage of gravel is less and the upper clayey phase generally is absent. Bernard's description of the Willis Sand is believed to be consistent with that of the outcrop area north of Hardin County. Bernard noted that gravel in the Willis Sand is common in its inland margin and is rare at its seaward margin where sand predominates. Locally, lenses of well-indurated conglomerate occur, but they are rarely more than 10 feet thick. Gravel lenses are rarely more than a few inches thick, and near the base of the formation, they usually contain gray to bluish-gray clay balls derived from the underlying strata. The basal sands also contain material from the underlying strata, mostly bentonitic material.

Near the seaward margin of the outcrop of the Willis Sand in Jasper and Newton Counties, the weathered surface of sand and silt generally is covered with small ferruginous concretions. Ferruginous nodules also occur as residual concentrations at or near the surface of the Willis west of Houston on hilltops where it is mined for road metal. Most of the gravel, rarely more than 1 inch in diameter, is composed of yellow chert, and fragments of quartzite pebbles are numerous. Pertrified wood occurs throughout the formation, the smaller fragments being in the basal gravel and larger pieces of logs and stumps being in the upper sandy phase. Reworked Cretaceous fossils are rare. The Willis Sand is typically cross bedded, thick and massive in places, reddish brown, yellow-brown, orange-brown, and brown. Mottling is common. Purple sediments generally are present at the contact with the underlying strata.

The Willis Sand is unconformable to the underlying Miocene and Pliocene strata, which were eroded to a generally level plane before being overlapped by the Willis. However, local erratic thicknesses of the Willis Sand may be due to a locally dissected pre-Willis surface. Bernard (1950, p. 115) noted that on the Tertiary divides, the Willis Sand is about 40 feet thick; the maximum thickness measured on the surface is about 150 feet in Jasper and Newton Counties.

This thickness is consistent with that of the Willis in the Houston area where Lang, Winslow, and White (1950, p. 34) reported a thickness of 80 to 150 feet, and in Vernon Parish, Louisiana, where Jones, Turcan, and Skibitzke (1945, p. 65) reported a thickness of 142 feet for the Williana. Subsurface data derived by logging a water well near Votaw in northwestern Hardin County revealed a total thickness of 90 feet for the Willis Sand, and logs of 8 additional water wells that penetrated the entire section of the Willis Sand near its outcrop west of Hardin County revealed an average thickness of 80 feet (Bernard, Le Blanc, and Major, 1962, Fig. 14).

The dip of the base of the Goliad Sand and that part of the Willis Sand that laps onto the Lagarto and Oakville is about 45 feet per mile through a span of 44 miles from the Lagarto-Willis contact in Tyler County to the Amelia oil field in northern Jefferson County. Assuming a straight-line slope between these two locations, the base of the Goliad Sand should be at a depth of 1,290 feet below land surface at Loeb. This compares favorably with a determination of 1,275 feet below land surface for the top of the Lagarto in well LH-61-55-205 at Loeb. The dip of the base of the Willis Sand overlying the Goliad Sand, of course, would be much less than 45 feet per mile. Lang, Winslow, and White (1950, Pl. 1) show a dip of 45 feet per mile for the Goliad and Willis Sand in the Houston district through a span of 70 miles from the surface outcrop of the Lagarto Clay and Oakville Sandstone. Bernard, Le Blanc, and Major (1962, p. 218) show a dip of 15 feet per mile for the base of the Willis through a span of 48 miles from the outcrop of the base of the Willis downdip to the city of Houston. Jones, Turcan, and Skibitzke (1954, Pl. 6) show a dip of the base of the Williana of 24 feet per mile from northern Beauregard to southern Calcasieu Parishes, Louisiana.

The thick sand and gravel deposits in the Willis Sand are highly permeable and favorable for development of large quantities of water. The Goliad Sand, Willis Sand, and the Lissie Formation form the most prolific aquifer and together supply most of the ground water for municipal, industrial, and rice irrigation in Hardin County. South of Hardin County in Jefferson and Orange Counties, the water becomes saline.

Lissie Formation

The Lissie Formation of Pleistocene age is shown on the "Geologic Map of Texas" (Darton, Stephenson, and Gardner, 1937) cropping out the length of the State and paralleling the Gulf Coast in most places. In southeastern Texas (Figure 4), it crops out in an irregularly-shaped pattern continuous in places and in isolated patches in other places where stream erosion has breached the outcrop. On interstream divides and near the coast, the Lissie Formation dips beneath younger strata.

In Tyler and Polk Counties, the Lissie Formation unconformably overlies the Willis Sand, in places lapping upon the Lagarto and Oakville, and occupies the southern parts of the counties. The outcrop of the Lissie Formation extends southward into Hardin County, covering roughly the northern half of the county before it dips beneath the Beaumont Clay. The Neches River breaches the outcrop of the Lissie, thus separating the outcrop in Hardin and Tyler Counties from the outcrop in Jasper County. The outcrop of the Lissie Formation is more highly dissected than that of the overlying Beaumont Clay, but appears relatively undissected when compared to the outcrop of the older and underlying

Willis Sand. The surface of the Lissie Formation, very sandy in the northern part of Hardin County and southern parts of Tyler and Polk Counties, is conducive to infiltration of water, and thus is a major area of recharge.

The elevation of the relatively uneroded remnants of the surface of the Lissie Formation ranges from about 50 feet at its contact with the overlying Beaumont Clay to about 230 feet at its contact with the underlying Willis Sand. Elevations determined by Bernard (1950, Pl. 2) for the terraces of Montgomery and Bentley (equivalents of the Lissie Formation) in Jasper and Newton Counties roughly conform with those in Hardin, Tyler, and Polk Counties.

Bernard's determinations of the dip slope of the terraces of Montgomery and Bentley in Jasper and Newton Counties, which are assumed to conform to the dip slope of the Lissie Formation in Hardin County, were about 3 to 5 feet per mile near the inland margin of the Lissie Formation and about 7 to 8 feet per mile near the contact with the Beaumont Clay.

The Lissie Formation consists of a deltaic coastwise plain, which overlies the Willis Sand, and a fluviatile inland terrace, which is well developed in places in Tyler, Jasper, and Hardin Counties along the Neches River. The Neches River has cut its valley through the Willis Sand, and the Lissie Formation unconformably overlies the Lagarto and Oakville near the stream valleys.

Fisk (1938, p. 157-163), in describing the Bentley and Montgomery Formations in Grant and LaSalle Parishes, Louisiana, recognized three phases of the Bentley--a "coarse phase" consisting of about 10 feet of basal gravelly sand, lenses of sand and chert gravel, and a few large boulders; the middle "sandy phase" consisting of 25 to 40 feet either entirely of thick sand bodies or a sequence that grades upward from sand to clay; and the top "silty clay phase" ranging in thickness from 5 to 25 feet of typical dark-red clay and interbedded silty clay. Fisk's Montgomery Formation consists of as much as 115 feet of clay, sand, and marly gravel.

Welch (1942, p. 70-72) described the Bentley and Montgomery Formations in Vernon Parish, Louisiana, about 75 miles northeast of Hardin County, where the Bentley consists of 50 to 65 feet of dominantly red argillaceous silt and sand with lesser amounts of clay and gravel. The Montgomery Formation, from 5 to 40 feet thick, consists predominantly of finer materials and is thinner than either the Bentley or Williana. In both the Bentley and Montgomery, the coarser materials are at the base and grade upward into finer materials.

In Allen Parish, Louisiana, about 80 miles east of Hardin County, Jones, Turcan, and Skibitzke (1954, p. 73, 74) record a thickness of 145 feet for the Bentley and Montgomery Formations.

The lithology of the Bentley and Montgomery Formations in Jasper and Newton Counties, as described by Bernard (1950, p. 122-125), probably is consistent for the most part with the Lissie Formation in Hardin County. Bernard describes the Bentley and Montgomery Formations as consisting of a basal gravelly sand which grades upward into finer sand, silt, and clay. Gravel may not always occur at the base but may be in lenses in an upper sandy phase. Coarser sediments are more common in the fluviatile terrace and finer materials predominate in the coastwise deltaic plain where little or no gravel occurs.

The outcrop of the Lissie generally consists of fine sand, silt, and silty clay, the coarser sediments being more common near its landward margin than near its seaward margin. Limonite nodules are common in the weathered zone on the surface. Much of the sediments of the Lissie Formation are similar to those of the Willis Sand from which the Lissie, at least partially, was derived; the two formations are easily differentiated by the difference in slope. The Lissie Formation is typically cross-bedded, particularly in the fluviatile facies, and colored various shades of brown. The coarser materials generally weather reddish brown, whereas the finer materials weather brown, yellowish brown, buff, and gray. Mottling is common.

The thickness of the Lissie Formation in Hardin County ranges from 0 to about 300 feet. Frink (1941, Pl. 5) shows that the Montgomery and Bentley are 1,000 feet thick in northern Jefferson Davis Parish, Louisiana (85 miles due east of Kountze) at its contact with the Prairie Formation (equivalent to the Beaumont Clay). The thicknesses of the Bentley and Montgomery, as indicated by Frink, are highly variable within short distances. Hecker (1949, Pl. 2) shows that the Montgomery and Bentley are 725 feet thick at the Prairie-Montgomery contact in northern East Baton Rouge Parish, Louisiana, and that the base of the Bentley dips 46 feet per mile in a span of 13 miles. Holland, Hough, and Murray (1952, p. 89-90) state that the thickness of the Bentley Formation ranges from a minimum of a few hundred feet along the northern margin of Beauregard Parish, Louisiana, to a maximum of about 1,500 feet on the western side of the parish in a distance of about 30 to 35 miles. Lang, Winslow, and White (1950, p. 134, Pl. 1) state that the thickness of the Lissie in the Houston district ranges from 0 to 1,600 feet, and in a dip section from northern Montgomery County to Galveston County, the thickness of the Lissie Formation at its contact with the overlying Beaumont Clay is estimated to be about 750 feet.

The thick sand and gravel beds in the Lissie Formation yield large supplies of water to wells for public supply, industry, and irrigation in Hardin County. Wells 100 feet deep, or less, generally yield very hard water; deeper wells yield softer water and the water becomes saline in Jefferson County.

Collectively, the Goliad Sand, Willis Sand, and Lissie Formation constitute the most prolific aquifer in Hardin County.

Beaumont Clay

The Beaumont Clay of Pleistocene age unconformably overlies the Lissie Formation. The Beaumont has the most extensive outcrop of the Pleistocene formations in southeast Texas. It crops out in a belt extending across Texas nearly parallel to the coastline (Figure 4).

In Hardin County, the deltaic coastwise plain of the Beaumont Clay covers roughly the southern half of the county. Along the Neches River, the fluviatile facies extends northward and rests unconformably on the Lagarto and Oakville and possibly on the Goliad Sand. Paired river terraces, in places more than a mile wide, are exposed along the Neches River. In the areas between streams, the Beaumont Clay laps upon the Lissie Formation. The outcrop of the Beaumont Clay has undergone relatively little erosion, retaining, for the most part, the features of a depositional plain. Much of the outcrop of the Beaumont near its contact with the Lissie Formation is covered by a fine sandy loam because of the greater proportion of sand near the base. In a coastwise direction, the Beaumont becomes progressively more clayey and the soils are heavy and dark in Jefferson County and the southern part of Orange County.

The elevation of the outcrop of the Beaumont Clay in Hardin County ranges from about 50 feet at its deltaic coastwise contact with the Lissie Formation to about 25 feet in the southeastern part of the county, indicating a southeastward dip of about 1.5 feet per mile. The dip slope in Hardin County compares with the 1.35 feet per mile dip in Jasper, Newton, and Orange Counties as calculated by Bernard. In the Houston area, Bernard, Le Blanc, and Major (1962, p. 176) showed that the dip slope of the Beaumont is 2 feet per mile.

The Beaumont Clay generally is described as consisting predominantly of clay; however, it also contains much sandy material. A general description from top to bottom would list clay, limy clay, sandy clay, clayey sand, and fine sand. The lime is present as calcareous concretions like those that occur in backswamp clay. Also included in the clay are small limonite concretions. Good descriptions of shallow test holes in the upper part of the Beaumont Clay by Livingston and Cromack (1942, p. 42-44) in the northern part of Jefferson County reveal dark-colored surface clay in the weathered zone and various shades of yellow, brown, and gray clay, silty clay, and sand. The distribution of the sandy areas on the outcrop of the Beaumont has been shown by Barton (1930b, p. 1303) to be related to the system of distributary ridges in which deltaic sediments are deposited. The coarse materials are on or near the ridges, while the finer materials are at a distance or between the ridges. The sediments of the Beaumont Clay are significantly finer than those in the older Pleistocene formations. In conformance with the older Pleistocene formations, the coarser materials are at the base of the formation and grade upward into finer sand, silt, and clay. Bernard (1950, p. 127, 128) observed that gravelly sands in the Beaumont Clay were common in the fluviatile remnants which parallel the Neches River and its tributaries. He also stated that clay becomes more common downdip in the coastwise facies in southern Orange County where clay beds more than 200 feet thick overlie gravelly sand.

The maximum thickness and dip of the Beaumont Clay in Hardin County is not known pending the determination of the age of the basal part, the "Alta Loma sand" of Rose (1943b). Based on the assumption that the base of the "Alta Loma sand" is the base of the Beaumont Clay, the Beaumont in Hardin County probably does not exceed about 550 feet. This is based on the occurrence of the "Alta Loma sand" in well LH-61-55-205 (Figure 18), the base of the sand being about 530 feet below land surface. In cross section A-A' (Plate 5), the base of the "Alta Loma sand" in well PT-61-63-304 is about 700 feet below sea level. The depth to the base of the "Alta Loma sand," determined from an electric log 10 miles due south of Beaumont, is 1,000 feet. The dip of the base of the Beaumont over a span of 27 miles from the Beaumont-Lissie contact in Hardin County to the point of control 10 miles south of Beaumont is 38 feet per mile. Hecker (1949, Pl. 2) shows that the Prairie Formation (equivalent to the Beaumont Clay) in East Baton Rouge Parish, Louisiana, is about 450 feet thick 12 miles downdip from the featheredge of the Prairie Formation, indicating a dip of the base of the formation of about 38 feet per mile. Bernard (1950, p. 131) estimates that the maximum thickness of the Prairie Formation is 250 feet in southwestern Jasper County. This thickness was based on the occurrence of basal gravel in wells in this area. Bernard also stated that the average depth of basal gravels (probably "Alta Loma sand") is 700 feet in southern Orange County, and if the correlation of the basal gravels in southwestern Jasper County and southern Orange

County (a span of 20 miles) is correct, the dip of the basal gravels is about 35 feet per mile. Hecker's and Bernard's calculations of the dip of the base of the Beaumont Clay are in approximate agreement with the author's calculation in Hardin and Jefferson Counties using the "Alta Loma sand" at the base of the Beaumont Clay. Lang, Winslow, and White (1950, Pl. 1) indicate a dip of about 26 feet per mile for the base of the Beaumont Clay in the Houston district and a thickness of about 1,000 feet in Galveston County. This was calculated in a span of 38 miles downdip from the surface contact of the Lissie Formation and Beaumont Clay.

In the coastal section through the southern parts of Brazoria, Galveston, Chambers, and Jefferson Counties, Petitt and Winslow (1957, Pl. 2) correlate the "Alta Loma sand" as the base of the Beaumont Clay. The deepest occurrence of the "Alta Loma sand" in this section is 1,300 feet in southern Galveston and Chambers Counties. Frink (1941, Pl. 4), in his study of the subsurface Pleistocene of Louisiana, shows that the Prairie (equivalent to the Beaumont Clay) is as much as 2,800 feet thick just offshore about 30 miles east of the Texas-Louisiana state line. This thickness is about twice as much as the 1,430 feet of Beaumont Clay about 8 miles offshore from Galveston Island (Petitt and Winslow, 1957, p. 13).

Sand beds in the Beaumont Clay yield small to moderate amounts of fresh to moderately saline water to domestic and livestock wells in southern Hardin County. Because the Beaumont Clay is relatively thin and contains a small percentage of sand in Hardin County, it is not considered an aquifer of major importance.

Wells that tap the "Alta Loma sand" in parts of Harris, Galveston, Chambers, Jefferson, and Orange Counties yield large quantities of fresh to slightly saline water.

Alluvium

Alluvium of Recent age is exposed along the Neches River in Hardin County as a flood plain and terrace trending in a south-southeast direction. The elevation of the alluvial surface ranges from about 65 feet in northeastern Hardin County to less than 5 feet in the coastal marshes in the southeastern part of the county at the confluence of Pine Island Bayou and the Neches River. The average dip slope of the surface of the alluvium is 1.9 feet per mile.

The width of the alluvium varies, depending on the ancestral meandering of the river. The combined flood plain and terrace in Hardin County ranges in width from 2.2 miles, 6 miles north of Silsbee, to as much as 5.6 miles at the latitude of Loeb in southeastern Hardin County. The Recent terrace and flood-plain surfaces are bordered on both sides of the river by well-defined scarps 20 to 50 feet high.

Barnard (1950, p. 59) recognized and mapped an alluvial terrace, in places well defined and in other places obscure, along the Neches River above the flood plain. Numerous borings by the U. S. Corps of Engineers across the Sabine River near Orange revealed two Recent alluvial sequences of basal gravel grading upward into finer materials. Borings across the Neches River, 4.7 miles north of

Hardin County near the site of the Town Bluff Dam (Dam B), also revealed two Recent alluvial sequences. The Neches River is thus flowing on a bed of its own alluvium the length of Hardin County.

The Recent alluvium consists of two sequences of basal, generally gravelly sand grading upward into finer sand, silt, and clay. The upper sequence contains much organic clay and driftwood and was deposited during the last rise of sea level. The beds are lenticular and generally less than 30 feet thick. According to Kane (1959, p. 228), the base of the Recent alluvium is 120 feet below sea level where the Neches River empties into Sabine Lake, indicating a considerable thickness of alluvium at that point. Upstream from the mouth of the Neches River, the upper sequence of alluvium (late Recent) averages 40 feet in thickness (Bernard, 1950, p. 134). The thickness of the lower sequence of alluvium (early Recent) upstream from the mouth of the Neches River is not known.

The alluvium is a minor aquifer in Hardin County. Its narrow outcrop, relative thinness, and the availability of other aquifers that contain larger quantities of water have discouraged large-scale development of ground water from the alluvium.

Origin and Mode of Deposition of the Aquifers

The importance of geologic events of the late Tertiary and Quaternary Periods to the ground-water geology of Hardin County cannot be stressed too greatly. The depth of occurrence, the distribution, and the textural changes of the beds of gravel, sand, silt, and clay that form the aquifers are all related to their mode of deposition and the geologic history of the area.

The origin and mode of deposition of the aquifers of Hardin County and adjacent regions follows a simple repetitious pattern. The sediments were produced by the action of streams, principally the ancestral Sabine, Neches, and Trinity Rivers in southeastern Texas. During a series of cycles of deposition and erosion, several sequences of coalescing deltas built depostional plains, which formed the Lagarto Clay and Oakville Sandstone, Goliad Sand, Willis Sand, Lissie Formation, Beaumont Clay, and alluvium. Each of these formations had an original profile corresponding to that of its depositing streams; each now has a fairly distinctive slope reflecting events subsequent to deposition.

According to Doering (1956, p. 1817-1818) during the Quaternary Period and during the preceding Miocene and Pliocene Epochs, the general physiography of the Gulf Coast region probably did not differ greatly from that of today. The Gulf Coast region, then, as now, was the locus toward which much of the drainage of the interior highlands was directed and toward which sediment was transported by streams and deposited as broad coalescing deltas which were to become massive aquifers. Sedimentation followed by subsidence and inland uplift followed by erosion have been a relatively continuous cycle since the beginning of Tertiary time.

The Lagarto and Oakville were deposited by streams on a gently inclined coastal plain along the border of the sea and the deposits merged seaward with marine deposits. Conditions probably favored rapid deposition of material derived from Cretaceous and older Tertiary formations. This material was deposited in great quantities in the form of broad coalescing alluvial fans or sheets. The finer-grained upper part was deposited probably on a lower-lying coastal plain where the rivers were nearer the base level and were carrying finer sediments. The shoreline with its deltas and bays was not far from the present Beaumont-Lissie contact (Plummer, 1933, p. 744).

Later, erosion of the thick section of Lagarto and Oakville provided material for much of the thick Pliocene Goliad Sand section found in wells near the coast. Uplift of the land mass or possibly subsidence of the sea, because of early glaciation and interglaciation, caused the streams to increase their gradients and eventually deposit sediment comprising the Willis Sand on the erosional plain of the Lagarto and Oakville and the Goliad Sand. Still older formations contributed a considerable part of the coarse sand and chert gravels at or near the base of the Willis Sand. The ferruginous Eocene formations of eastern Texas and western Louisiana contributed most of the iron found in the Willis Sand and younger formations.

Although the Gulf Coast area was not glaciated during the Pleistocene Epoch or Ice Age, glaciation and interglaciation in other parts of the earth have had an indirect but profound influence on the geologic history of the Gulf Coast area. The events, as recorded in the Gulf Coast sediments, are divided logically into cycles resulting from sea-level fluctuations which are related to the advances and retreats of the glaciers.

The sediments associated with the Pleistocene Epoch were deposited during glacial retreats when the sea level was rising and eventually high standing. The rise of the sea resulted in progressively lower stream gradients, which caused the deposition of progressively finer materials. The sediments typically grade from basal gravelly sand upward into finer sand, silt, and clay. Glacial advances lowered sea level at least 450 feet below its present level (McFarlan, 1961, p. 132) and rejuvenated the streams which entrenched the preceding alluvial sequence. Erosion of the land was prevalent; thus unconformities and weathered surfaces underlie each alluvial sequence. Later, rising of the sea level during the following glacial retreat accompanied by deposition completed a cycle. Howe and others (1935, p. 37-38) have shown by the occurrence of oxidized terrace materials at increasing depths in bore holes that the level of the sea was not materially higher during the Pleistocene Epoch than now. As erosional and depositional processes became adjusted to the high-standing sea level, sediments transgressed seaward causing a regression of the shore line, thus forming an offlap or a regressive sequence of sediments. These transgressions and regressions produced major changes in the character of the sediments both vertically and laterally.

The upper limit of each alluvial sequence was represented physiographically by a terraced depositional surface or coastwise plain which paralleled the coastline. Each surface merged with a contemporaneous fluviatile terrace upstream in the major valleys. The variations in elevation and seaward slope of the alluvial deposits reflect coastal subsidence and compensating inland uplift since early in the Tertiary Period (Fisk, 1940, p. 61).

At some undetermined time, salt from deep-seated salt beds began to rise up through thousands of feet of overlying sediments. This upward rising of the salt was a gradual process extending over a long period. Some of the salt plugs or domes, as much as 2 to 4 miles in diameter, rose nearly to the land surface. Batson, Saratoga, and Sour Lake overlie some of these shallow piercement-type salt domes.

Recent history began about 25,000 years ago with the last rising sea level. Early Recent ended 3,000 to 5,000 years ago when the sea reached its present high-standing level. During the Recent Epoch, alluvium was deposited along the Neches River as flood-plain deposits. However, coastal sedimentation by the Neches and Sabine Rivers did not keep pace during the last rise of sea level because of the relatively small volume of sediment transported by the streams. As a consequence, the Sabine and Neches River valleys were drowned for several miles inland from the coast line and Sabine Lake was formed. According to Le Blanc and Bernard (1954, p. 193), no significant sea-level changes have occurred during the past 5,000 years.

Gulf Coast Aquifer

Owing to a similar mode of deposition, the geologic formations in Hardin County are similar in lithology and origin and do not have persistent individual features that can be easily traced in the subsurface. Efforts to classify the sediments by lithology and correlate the formations in the subsurface by means of electric and drillers' logs are difficult and unassuring. Thus, for the purpose of this report and because the formations in Hardin County are, for the most part, hydrologically connected, the term "Gulf Coast" aquifer is hereby applied, and when used in this report, includes collectively all the formations that contain fresh or slightly saline water.

GROUND-WATER HYDROLOGY

The following discussion concerns the general principles of ground-water hydrology as they apply to Hardin County. For a more comprehensive discussion of these and other hydrologic principles, the reader is referred to Meinzer (1923a, 1923b, and 1932), Meinzer and others (1942), Tolman (1937), and Wisler and Brater (1959).

Source and Occurrence of Ground Water

The principal source of ground water in Hardin County is precipitation on the land surface in the county and in adjoining areas which drain into the county. Water from precipitation, which is not evaporated at the land surface, transpired by plants, or retained by capillary forces in the soil, migrates downward by gravity through the zone of aeration or essentially dry sediments until it reaches the zone of saturation, where the sediments are saturated with water. Open spaces in the sediments--interstices or pore spaces between grains in rocks, such as sand and gravel, the dominant type of sediments composing the aquifers in Hardin County--contain the water in the zone of saturation. The upper surface of the zone of saturation is the water table.

The aquifers in Hardin County may be divided into two types--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 or under water-table conditions wherever the upper surface of the zone of saturation is under atmospheric pressure only and is free to rise or fall in response to changes in the volume of water stored. Such water-table conditions occur in the outcrop of the aquifers in and around Hardin County and in the flood plains along the Neches River. A well penetrating an aquifer under water-table conditions becomes filled with water to the level of the water table.

Confined water occurs in artesian aquifers or under artesian conditions wherever the aquifers are separated from the zone of aeration or from other overlying permeable sediments saturated with water by sediments of lower permeability. Under these conditions, the ground water is confined and under pressure. Such artesian conditions occur downdip from the outcrop of the aquifers in Hardin County. A well penetrating sands under artesian conditions becomes filled with water to a level above the point where the water was first encountered. Water levels in various sand beds in the Gulf Coast aquifer (Figure 18, page 66) illustrate the artesian conditions that prevail downdip from the outcrop. The level or surface to which the water will rise in artesian wells is called the piezometric surface. Although the terms water table and piezometric surface are synonomous in the outcrop area, the term piezometric surface as used in this report is applicable only in artesian areas. If the artesian pressure is sufficient to cause the water to rise above the land surface, the well will flow as indicated by the water levels in the screened sand sections between 900-1,000 feet and 1,200-1,300 feet in the well shown in Figure 18.

Recharge, Movement, and Discharge of Ground Water

Aquifers may be recharged either by natural or artificial processes. Natural recharge comes from rain, either where it falls or by runoff en route to a water course, melting snow or ice, water in streams, lakes, or other natural bodies of water, or subsequent transfers of water from one saturated zone of sediments to another (not a primary source of recharge but only an incident to underground water movement). Artificial processes include infiltration of irrigation water and improper disposal of industrial wastes and sewage, which may contaminate the fresh ground-water supply.

The natural and principal source of water for recharge of the aquifers in Hardin County is precipitation. In general, the greater the precipitation on the intake area of the aquifer, the greater the recharge. Also, a given amount of rainfall in a short period generally produces less recharge than the same amount of rainfall over a longer period, although there are exceptions. A larger proportion of the precipitation infiltrating during the dormant or non-growing season will reach the zone of saturation than during the season of active plant growth. The sandy and loamy sand soils that cover much of northern Hardin County are highly receptive to infiltration of rainfall.

Ground water in Hardin County moves from areas of recharge to areas of discharge, gravity being the motivating force in the movement of the 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 or velocity. ing head or pressure. The movement is rarely uniform in direction or velocity. The water may be impeded by structural barriers, such as faults, fractures, and folds, by masses of sediment having relatively low permeability, such as well-cemented sandstone or clay, or the water may follow a devious path along courses of sediment affording the least resistance to flow, such as unconsolidated sand and gravel.

The quantity of water available as recharge in Hardin County is difficult to determine accurately without extensive research, and only a few scientists in Texas have collected and studied data helpful in estimating this quantity. White, Livingston, and Turner (1939, p. 7-8) measured infiltration rates using lysimeters, and they collected water-level data in about 70 shallow wells in the outcrops of the Lissie Formation and Willis Sand north of Houston. The experiments with the lysimeters indicated that water from infiltration moves downward in considerable quantities to depths exceeding 10 feet below the surface in places. It is estimated that the penetration of 1 inch of water to the water table in Hardin County in 1962 would provide recharge amounting to more than six times the quantity of ground water pumped for all uses in the county in that year.

The rate of movement of ground water is a direct function of the size of the open spaces and interconnecting passages in the sediments and the hydraulic gradient of the water. The rate of movement of ground water may range from velocities approaching zero to those of rapidly flowing streams. In Hardin County, where the type of sediment ranges from clay and silt to sand and gravel, the velocity of ground water, based on a natural undisturbed gradient, might be about 10 to 20 feet per year. Velocities vary, however, depending on the hydraulic gradient, the permeability and porosity, and the temperature of the water at any locality.

Fresh to slightly saline water in the aquifers underlying Hardin County is in transient storage--that is, it is in a constant state of movement, and the volume of water moving out of the county or being discharged within the county is essentially offset by replenishment of water moving into the county from updip areas to the north. The general direction of movement of ground water in Hardin County is normal to the strike of the outcrop of the aquifers--that is, southeastward toward the Gulf of Mexico. Locally, however, in areas of withdrawals of water by pumping, the direction of movement of ground water is toward these sites from all directions.

Water in the aquifers of Hardin County is discharged both naturally and artificially. The most obvious methods of natural discharge are seepage to streams and marshes that intersect the water table, transpiration by vegetation, evaporation through the soil, and movement out of the county into adjacent counties to the south and southeast.

A large amount of ground water is transpired by about 800 square miles of pine and hardwood forests in Hardin County. The consumptive use of water by forests depends on the amount and distribution of rainfall, climate, topography, and the storage capacity of the soils of the watershed as well as the type of trees (Rich, 1951, p. 14). As reported by Raber (1937, p. 81-82), the maximum seasonal transpiration rate of pine and hickory is about 8 to 10 inches per acre based on 60-year old, even-aged, full-stocked stands. Assuming these figures apply to the forests and climatic conditions in Hardin County, 384,000 acre-feet of water per year, or about 340 mgd (million gallons per day), is transpired by the forests in the county. This is 34 times more water than is used in Hardin County for all purposes. If the root systems of varieties of hardwood and pine trees extend from 5 to 20 feet below land surface, as reported by Raber (1937, p. 3-4), then much of the pine and hardwood trees are taking water from the zone of saturation. This represents a loss of water from storage in the outcrop of the aquifers and a decrease in the amount of available recharge. Even so, in most places in Hardin County, the aquifers are filled to capacity and are rejecting recharge to streams.

The amount of ground water in Hardin County discharged naturally beneath the land surface by transfer of ground water from one zone to another because of different artesian pressures in different zones is not known but may be large. For example, water may be added to a heavily-pumped zone from another overlying or underlying zone because the latter is being pumped relatively little or not at all and hence has a greater artesian pressure. Because of the difference in pressure between the sand and clay, water may move to a heavily-pumped sand from an adjacent clay bed as a result of compaction of the clay. Such compaction of clay beds may be large enough to cause the land surface to subside.

Discharge of ground water to streams by seepage and spring flow in the outcrop of the aquifers represents a major loss of ground water in Hardin County. This discharge can be considered rejected recharge--that is, water that enters the outcrop but cannot move down the dip under present hydraulic gradients and thus moves toward topographic lows in the outcrop and runs off. Seepage is common along many of the more deeply incised creeks and streams in Hardin County, thereby sustaining their flow even during periods of below-normal rainfall. The quantity of water thus rejected as potential recharge is difficult to determine accurately. According to Wood (1956, p. 30) in the Gulf Coast region within the rainfall belts of 40 to 50 inches per year (annual precipitation in Hardin County is about 54 inches), probably 1 inch or more of the water that enters the outcrop of the aquifers updip from heavily-pumped areas is discharge to the streams in the outcrop areas as base flow or rejected recharge.

Village Creek north of the gaging station near Kountze drains 837 square miles of Hardin, Polk, and Tyler Counties, and has an average base flow (rejected recharge) of about 54,000 acre-feet per year calculated over the non-growing season during a period of 8 non-consecutive years (Figure 5). The base flow (rejected recharge) of 54,000 acre-feet represents about 1.2 inches of precipitation that enters the outcrop of the aquifers but is discharged to the streams as rejected recharge. Assuming that the same rate of rejection is true for all of Hardin County, about 58,000 acre-feet per year would be rejected from the 895 square miles in the county. This is about six times as much ground water as was used for all purposes in Hardin County in 1962. The rejected recharge of 1.2 inches compares favorably with the calculations of rejected recharge in different rainfall belts by Wood (1956, p. 30).

Considering the 384,000 acre-feet of water per year that is transpired by the pine and hardwood forests, plus the 58,000 acre-feet discharged to streams as rejected recharge, a total of about 440,000 acre-feet, or about 9 inches, of precipitation annually could be considered as potential recharge to Hardin County, if the water table in the outcrops of the aquifer was maintained at a level low enough so that no recharge was rejected and the vegetation could not reach it. Heavy withdrawals and the attendant lowering of water levels will salvage part of the water used by vegetation and rejected to streams.

The exchange of water between different sands within well casings is common in many of the older oil fields, especially those at Batson, Saratoga, and Sour Lake. Suman (1925, p. 279), in discussing the Saratoga oil field, states:

> "The ground waters of this field are fresh to a much greater depth than those of the other Hardin County fields. The strong flow usually met at a depth of about 500 feet in the southwestern part of the field is always reported as fresh. It appears that, by ill fortune or carelessness, this water was not properly cased off in certain wells. When the wells were drilled through the underlying clay, this water was

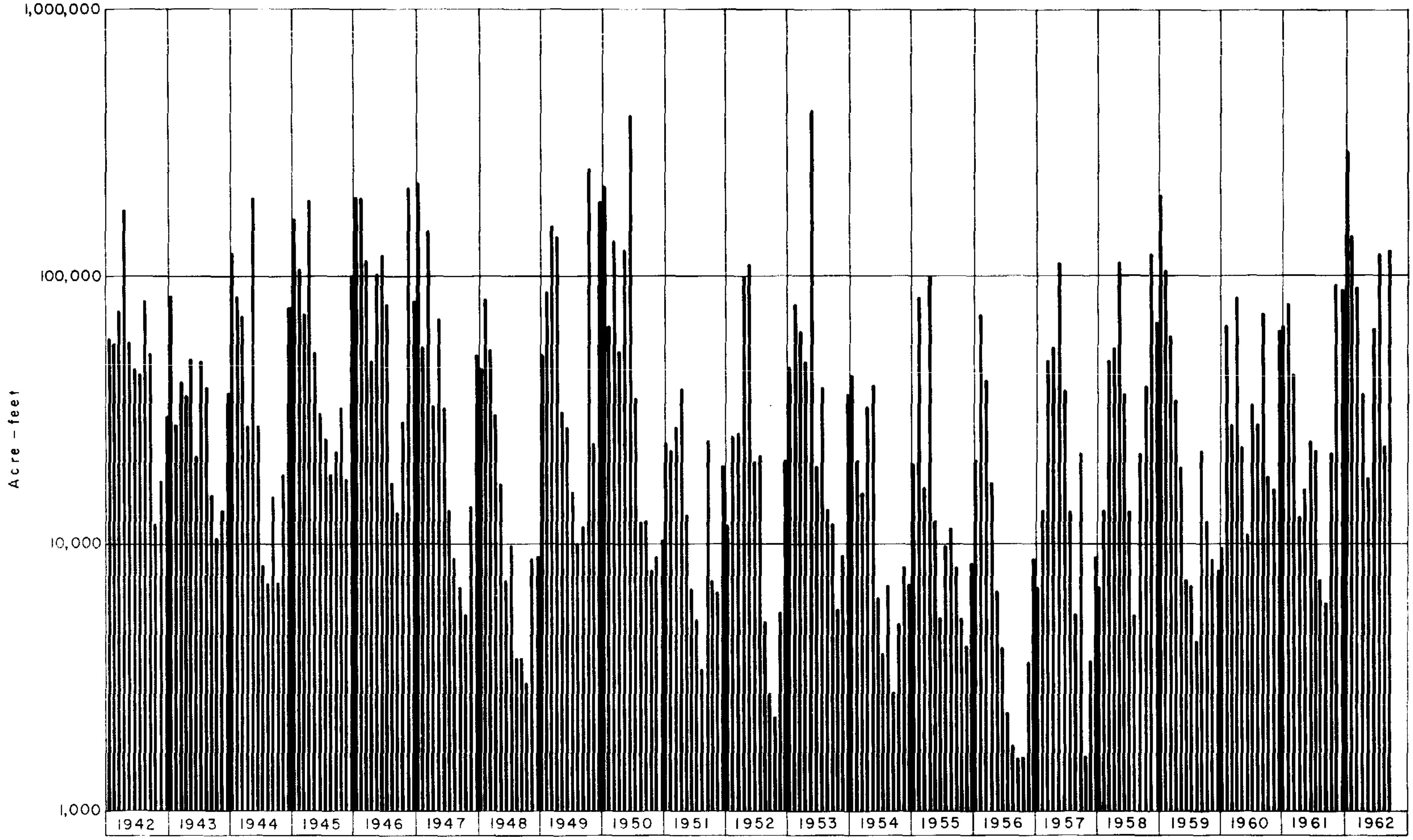


Figure 5

Monthly Flow of Village Creek near Kountze, Hardin County

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given access to the sandy zones containing the oil and soon appeared in other wells, which had been pumping oil alone."

Other similar incidences in the Saratoga field were reported to the author. Corrosion of the casing opposite the relatively high-pressure fresh-water zone in many old wells allows the water to enter the casing and circulate down the hole and into the lower pressure oil and salt-water-sand zones, which are heavily pumped. This process probably has been occurring for many years, and thus an immense quantity of fresh water has been lost to low-pressure saline-water sands.

The practice of screening multiple sand zones in large-capacity water wells allows a circulation of water among the sand zones, the water flowing from the high-pressure sand zone up or down the well and entering the lower-pressure sand zones. This situation probably is prevalent in most irrigation wells where the casing is slotted almost the entire depth of the well. This interchange of water in the well has been noted in the Houston district by Lang, Winslow, and White (1950, p. 10-11). The condition probably exists in Hardin County as indicated by the various water levels in different sand zones in well LH-61-55-205 (Figure 18).

Hydraulic Characteristics of the Aquifers

When water is discharged from an aquifer by a well, a hydraulic gradient in the water table or piezometric surface is established toward the well. If a well is pumped or flows, the level of the water table or piezometric surface is lowered; the difference between the discharging level and the static level (water level before pumping started) is the drawdown. The water table or piezometric surface surrounding a discharging well assumes more or less the shape of an inverted cone which is called the cone of depression. Theis (1938, p. 893) considers the cone of depression as "...a pirating agent created by the well to procure water for it, first robbing the aquifer of stored water and finally robbing surface water or areas of transpiration in the localities of recharge or natural discharge."

The rate at which water is transmitted by aquifers depends on the ability of the aquifer to transmit water and the hydraulic gradient. The amount of water released from storage where artesian conditions prevail depends chiefly on the elasticity and compressibility of the sands and their associated confining clays, and of the contained water.

Formulas have been developed to show the relationship among the yield of a well, the shape and extent of the cone of depression, and properties of the aquifer such as specific yield, porosity, and the coefficients of permeability, transmissibility, and storage. The specific yield is the quantity of water that an aquifer will yield by gravity if it is first saturated and then allowed to drain. The porosity is the ratio, in percent, of the aggregate volume of interstices in a rock to its total volume. The permeability of an aquifer is the capacity for transmitting water under pressure; quantitatively its coefficient is expressed as the rate of discharge of water in gallons per day through a cross section of 1 square foot at a unit hydraulic gradient. 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 a hydraulic gradient of 1 foot per foot and at the prevailing temperature of the water. It may be expressed, also, as the number of gallons a day moving across a vertical section of the aquifer 1 mile wide and having a hydraulic gradient of 1 foot per mile. The transmission capacity of an aquifer is 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 head normal to that surface. When artesian conditions prevail, 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 in artesian aquifers is small compared to that in water-table aquifers; consequently, when an artesian well starts discharging, a cone of depression is developed over a wide area in a short time. Where water-table conditions prevail, 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 approaches the specific yield.

Formulas based on the hydraulic characteristics of an aquifer indicate that within limits the discharge from a well varies directly 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.

The yield of a well usually is measured in gallons per minute or gallons per hour. Yield depends upon the ability of the aquifer to transmit water, the thickness of the water-bearing material, the efficiency of the well, and the allowable drawdown.

Many wells have smaller specific capacities than expected because of incomplete development or unfavorable local geologic conditions. Some wells, however, actually have greater specific capacities than expected because the sands are cleaned and developed so that the effective diameter of the well is larger than the original drilled hole.

Pumping tests were conducted on 20 wells in the Gulf Coast aquifer in Hardin and Jasper Counties to determine the coefficients of transmissibility and storage (Table 2). The results of the tests were anlayzed either by the basic nonequilibrium formula or the recovery formula (Theis, 1935).

The coefficients of transmissibility determined from the tests ranged from a low of 6,800 gpd (gallons per day) per foot at well LH-61-53-928 to a high of 111,000 gpd per foot at well PR-61-48-301. The coefficient of transmissibility increases toward the east and the increase can be attributed, at least in part, to an increase in the thickness of sand in the Gulf Coast aquifer in that direction, in part to increased permeability, and in part to an increase in the amount of sand screened in the wells. Average values of the coefficients of transmissibility and storage determined in wells that tap the Gulf Coast aquifer in Hardin and Jasper Counties are approximately 83,000 gpd per foot and 1×10^{-3}, respectively.

The coefficients of transmissibility and storage may be used to predict future drawdowns in water levels in wells caused by pumping. Figure 6 shows the theoretical relation between drawdown and the distance from the center of pumping for different coefficients of transmissibility. The calculations of

Table 2.--Coefficients of transmissibility, permeability, and storage determined from pumping tests of selected wells that tap the Gulf Coast aquifer in Hardin and Jasper Counties

Well number	Date	Coefficient of transmissibility (gpd per ft.)	Coefficient of permeability (gpd per ft.^{2})	Coefficient of storage	Remarks
LH-61-46-201	6- 4-62	29,000	296	--	
47-201	12-52	18,000	156	--	
202	12- 6/ 7-52	16,000	131	--	
206	5- 6-62	53,000	616	--	
207	6- 5-62	56,000	810	2.0×10^{-3}	
208	6- 6-62	38,000	304	--	
52-601	6- 1-60	75,000	250	--	
53-907	6- 1-62	45,000	150	--	
928	6- 7-62	6,800	174	--	Not used in computing averages.
929	6- 8-62	9,000	180	--	Do.
55-203	2-16/19-62	63,000	181	--	
204	5- 5-58	65,000	188	--	
PR-61-48-202	2-23-54	50,000	213	--	Recovery test.
203	2-22-54	83,000	332	8.9×10^{-4}	Interference test.
204	2-22-54	111,000	300	6.3×10^{-4}	Do.
205	2-22-54	90,000	290	8.3×10^{-4}	Do.
206	4-14-53	26,000	124	--	Recovery test; shallow well. Not used in computing averages.
207	11-16-53	42,000	257	1.5×10^{-3}	Recovery test.
208	2-22-54	94,000	362	1.3×10^{-3}	Interference test.
301	2-22-54	111,000	411	7.9×10^{-4}	Do.
Average		83,000	309	1×10^{-3}	

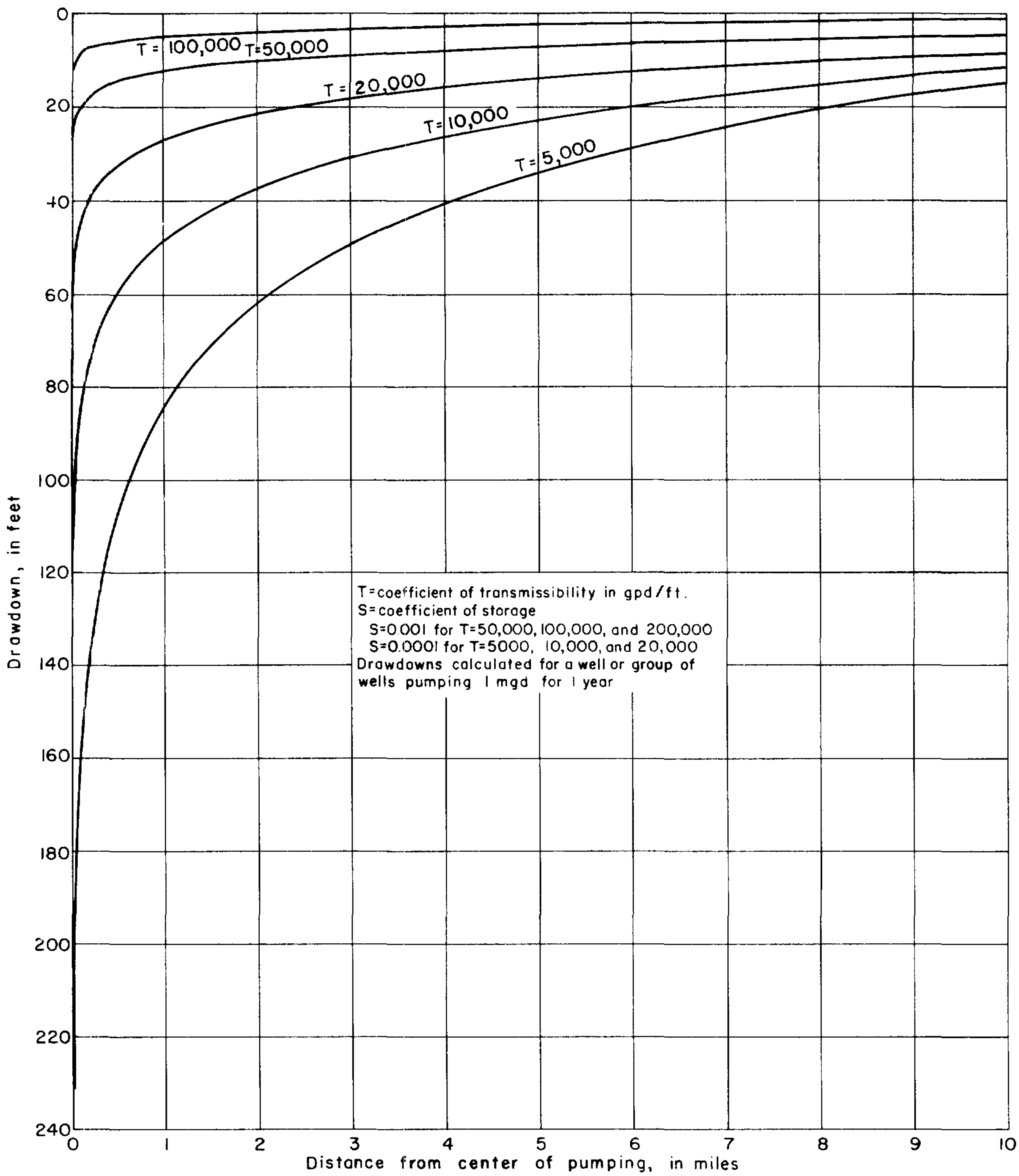

Figure 6

Graph Showing Relation of Drawdown to Transmissibility

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drawdown are based on a withdrawal of 1 mgd (million gallons per day) for 1 year from the Gulf Coast aquifer having coefficients of transmissibility and storage as shown. For example, if the coefficients of transmissibility and storage are 50,000 gpd per foot and 0.001, respectively, the drawdown or decline in the water level would be 12 feet at a distance of 1 mile from a well or group of wells discharging 1 mgd for 1 year. If the coefficients of transmissibility and storage are 5,000 gpd per foot and 0.0001, respectively, the same pumping rate for the same time would cause 84 feet of decline at the same distance.

Figure 7 shows the relation of drawdown to time as a result of pumping from the Gulf Coast aquifer where artesian conditions prevail and assuming infinite areal extent. It shows that the rate of drawdown decreases with time, and that the drawdown caused by pumping is proportional to the time of pumping. For example, if the drawdown 100 feet from a well is 11 feet after 1 mgd has been pumped for 1 year, the drawdown would be about 15 feet after 1 mgd has been pumped for 100 years. The total drawdown at any one place within the cone of depression or influence of several wells would be the sum of the influences of the several wells. The equilibrium curve shows the time-drawdown relation when a line source of recharge is 25 miles from the point of discharge.

Figure 8 shows the relation of drawdown to time as a result of pumping from the Gulf Coast aquifer, assuming infinite areal extent where water-table conditions prevail. The drawdown is less than that in an artesian aquifer because of the larger coefficient of storage, other factors being equal. These curves might apply to the outcrop area of the aquifer in Hardin County.

Wells drilled close together may create cones of depression that intersect, thereby causing additional lowering of 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. As long as the pumping level is not below the top of the screen, or screens, in a multi-screened well, the effective part of the aquifer from which the well draws water is still full of water. However, when the pumping level declines below the top of the screen, the saturated thickness of the aquifer decreases, in turn causing a decrease in the coefficient of transmissibility and, consequently, a decrease in the yield and efficiency of the well.

The specific capacities of 19 wells in the Gulf Coast aquifer in Hardin County and near Evadale in Jasper County ranged from 3.8 to 46.4 gpm (gallons per minute) per foot, averaging 25.0 gpm per foot. The yields and specific capacities of selected wells are shown in Table 3. Very few wells in Hardin County are screened through the entire thickness of the water-bearing sands; therefore, the yields of the wells, in general, are less than the maximum that could be developed if the wells penetrated to the bottom of the aquifer and were screened opposite all water-bearing sands.

Development of Ground Water

Table 4 shows the amount of ground water used for public supply, industrial, irrigation, and domestic and livestock purposes in Hardin County in 1962. In that year, about 9.8 mgd, or about 11,000 acre-feet, of water was used.

Records of 296 water wells were obtained during the ground-water investigation of Hardin County (Table 8). Of these, 173 wells were used for domestic and livestock purposes, 23 wells for public supply, 18 wells for industrial

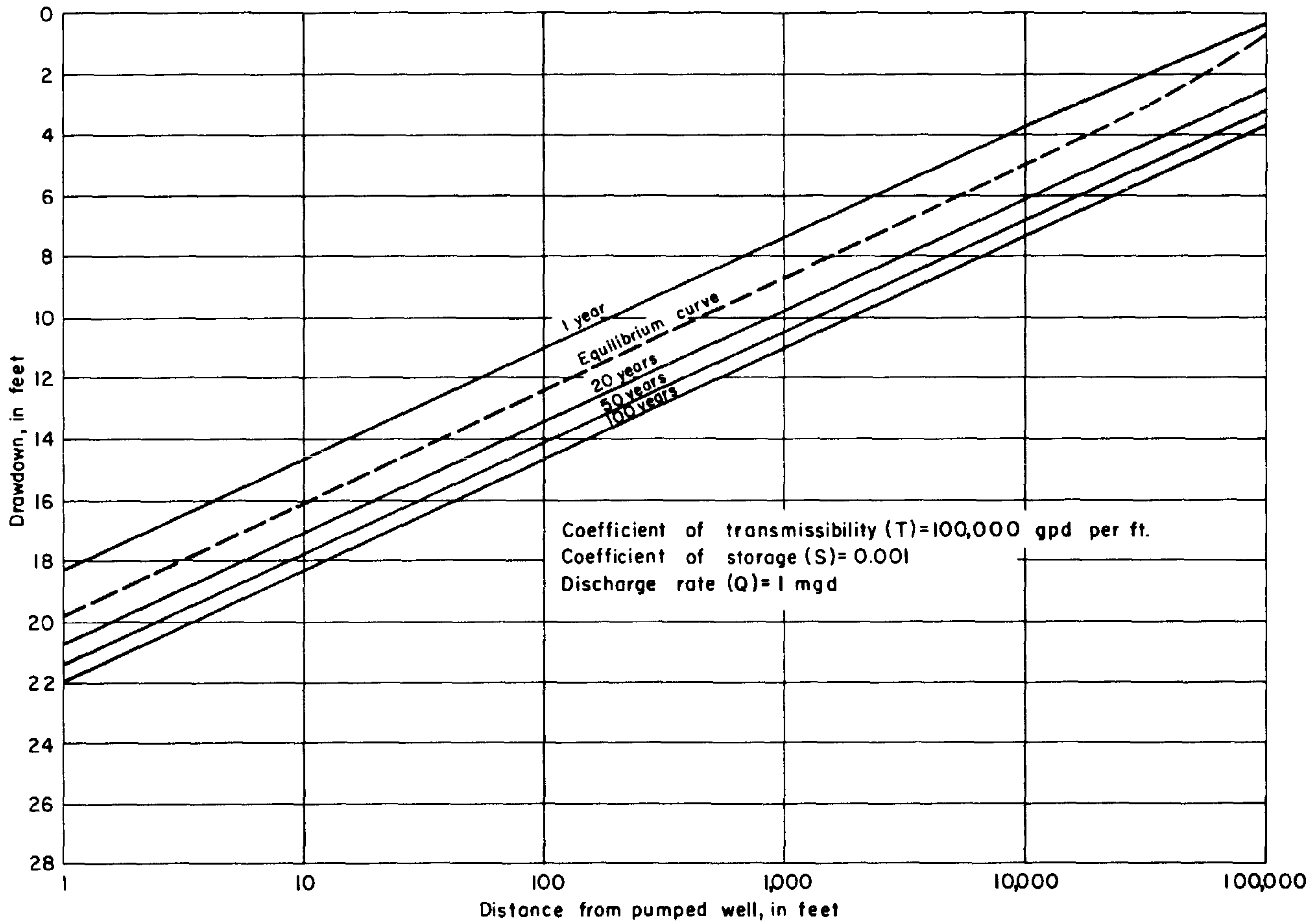

Figure 7

Graph Showing Relation of Drawdown to Time as a Result of Pumping Under Artesian Conditions

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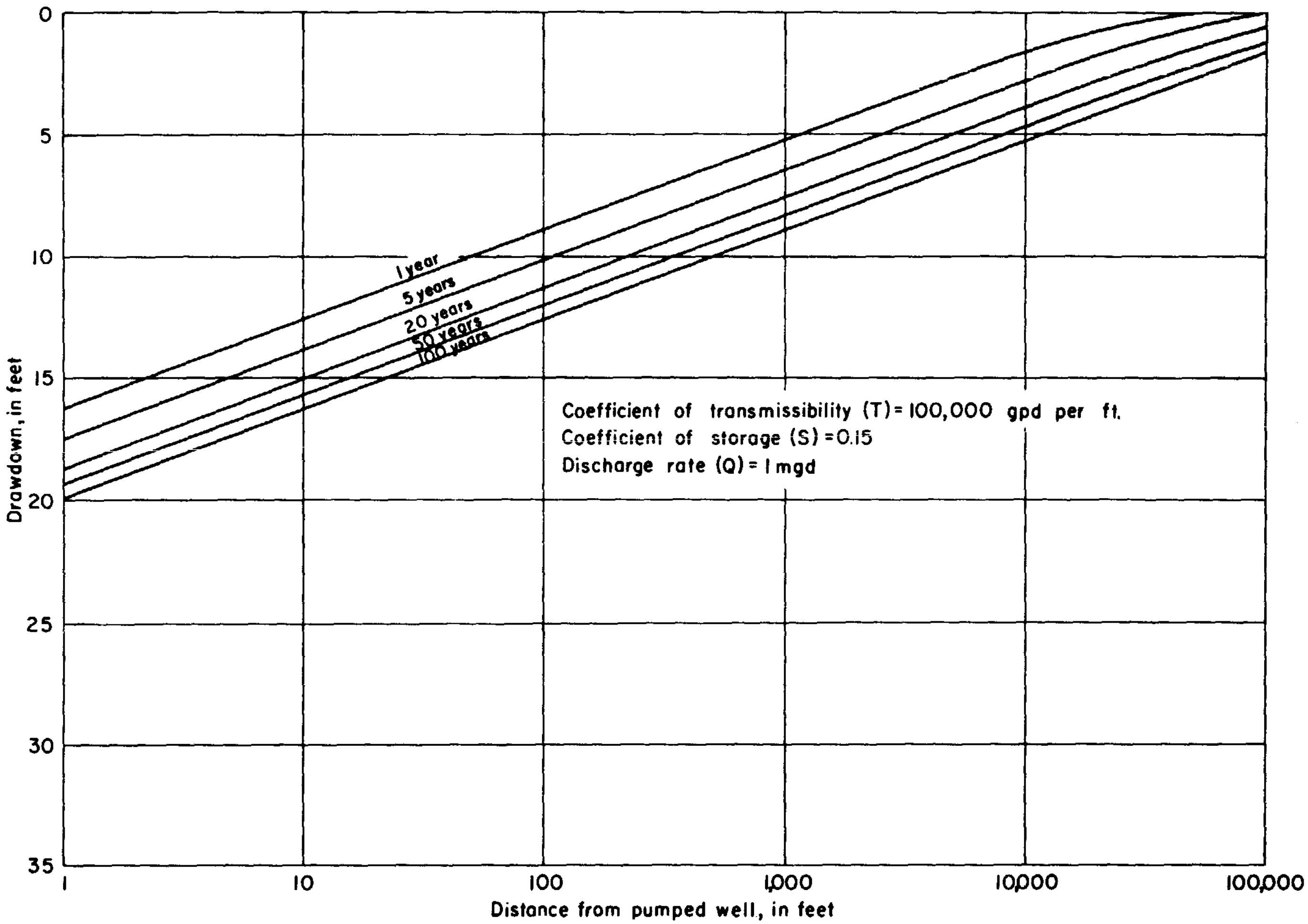

Figure 8

Graph Showing Relation of Drawdown to Time as a Result of Pumping Under Water-Table Conditions

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Table 3.--Yields and specific capacities of selected wells that tap the Gulf Coast aquifer in Hardin and Jasper Counties

Well number	Diameter of screen (inches)	Yield (gpm)	Drawdown (ft.)	Specific capacity (gpm per ft.)
LH-61-46-201	8	297	36.4	8.2
47-201	10	1,000	64	15.6
202	10	1,000	78	12.8
206	6	209	19.1	10.9
208	12	877	50.1	17.5
52-601	12	2,100	68	29.9
53-907	12	1,975	91.7	21.5
928	5	156	40.8	3.8
929	8	180	26.4	6.8
55-203	14 to 12	3,530	77.5	45.5
204	12	4,530	120	37.7
PR-61-48-202	12	2,510	56.8	44.2
203	12	2,510	92.0	27.2
204	12	2,510	54.0	46.4
205	12	2,510	67.2	37.3
206	12	2,000	106	18.8
207	12	2,400	132	18.2
208	12	2,510	65.6	38.2
301	12	2,460	69.5	35.4

purposes, 12 wells for irrigation, and 70 wells were not being used. The inventory included only a small part of the total number of wells in the county; however, records of all the public supply, industrial, and irrigation wells were obtained. Locations of the wells inventoried are shown on Plates 1 through 4.

Public Supply

Ground water used for public supply in Hardin County in 1962 amounted to 4.86 mgd, or 5,460 acre-feet per year. This represents about 50 percent of the ground water used for all purposes in the county.

The use of ground water for public supply in Hardin County has increased substantially in the past 20 years (Figure 9). The increasing population of cities and modernization of homes has created the need for additional supplies of water. Additional wells have been drilled to keep up with the increasing demand, and most of the newer municipal wells now in use were drilled within the past 10 years when the cities had substantial increases in population. The use of ground water for public supply increased from about 285 million gallons (0.78 mgd) in 1943 to 1,775 million gallons (4.86 mgd) in 1962, an increase of more than 520 percent. The largest increase was in 1960 when the city of Beaumont placed in operation a large-capacity well (LH-61-55-203).

The city of Beaumont in 1962 was the largest single user of ground water in Hardin County. Prior to March 1960, the city depended entirely on surface water. However, by 1962, the city's ground-water pumpage was 3.76 mgd; this is 38 percent of the county's total pumpage. Water from wells in Hardin County, however, is only a small part of Beaumont's total supply, most of which is still surface water from the Neches River. To keep up with the constantly growing demand for water, the city drilled a second well (LH-61-55-502) near Loeb in January 1962; the second well began serving the city after January 1, 1963.

Table 4.--Use of ground water in Hardin County, 1962

Use	Million gallons per day	Acre-feet per year
Public supply	4.86	5,460
Industrial	1.83	2,050
Irrigation	2.57	2,880
Domestic and livestock	.54	605
Totals*	9.8	11,000

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

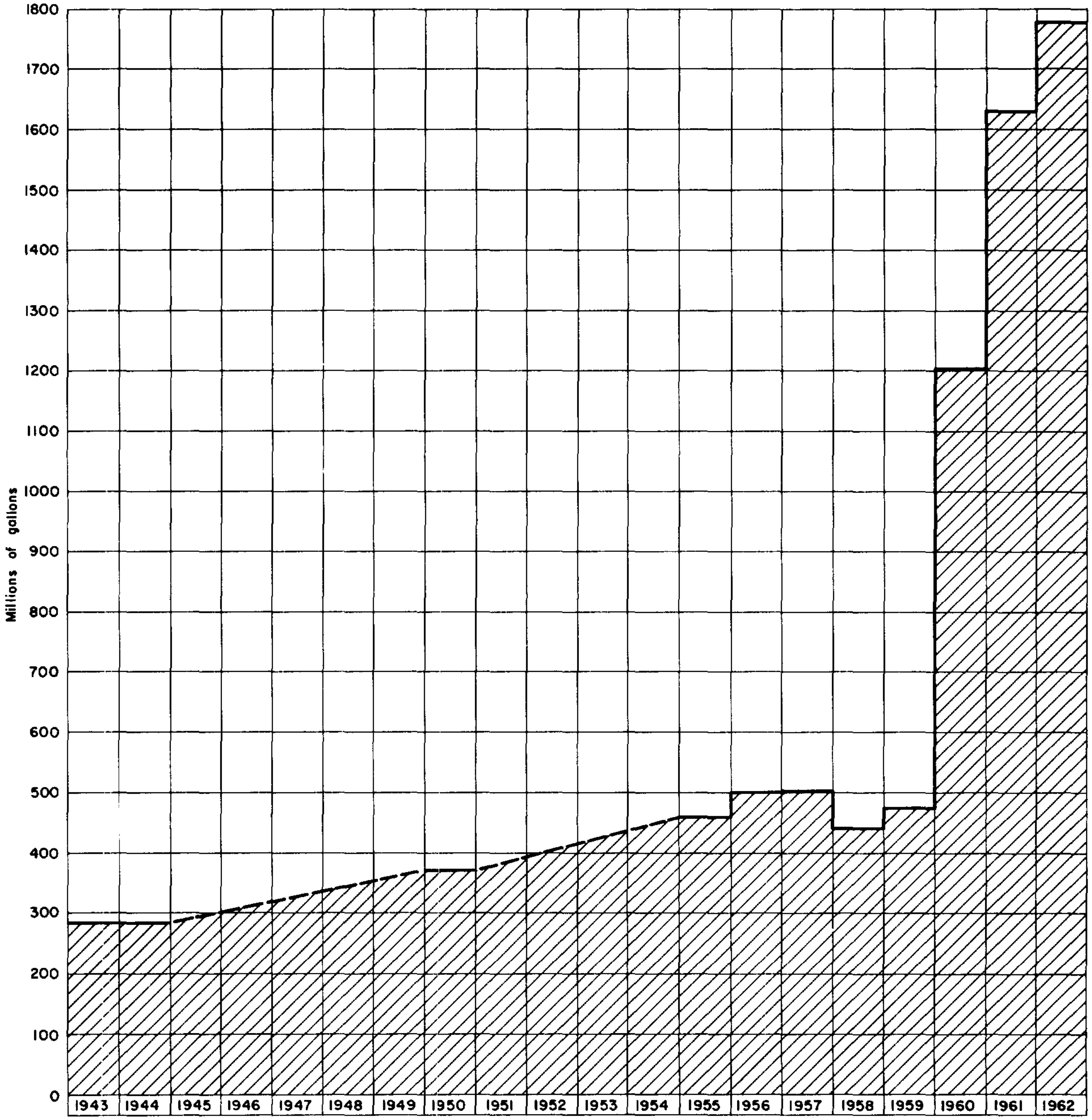

Figure 9

Use of Ground Water for Public Supply in Hardin County, 1943-62

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The city of Silsbee is the second largest consumer of ground water in Hardin County. In 1940, the city depended on a single well 357 feet deep to supply its water needs of about 0.15 mgd. In 1945, the city drilled a second well 405 feet deep to supplement the supply. In 1958, a third well was drilled to 853 feet and yielded 877 gpm. By 1960, the water consumption rose to about 0.5 mgd, and by 1962, it had declined to about 0.4 mgd.

The city of Kountze depended upon a privately owned well plus individual domestic wells prior to incorporation about 1945. In 1951, the city drilled a well 400 feet deep to keep up with increasing demands for city water. Early in 1958, the city drilled another well 497 feet deep having a yield of 297 gpm. Production from the two wells adequately supplies the needs of the city estimated at 160,000 gpd in 1962.

The city of Sour Lake drilled its first two municipal wells in October 1941. Both wells, about 50 feet apart, were 177 feet deep and together produced an adequate amount of fresh water. Gradually the water became increasingly mineralized until in 1950 the wells were abandoned. Two new wells, about 1 mile to the south, were drilled in 1950. One well was 812 feet deep, the other 224 feet. The wells, a few feet apart, produce between 250 and 300 gpm of water each. The water from the deeper well is becoming increasingly mineralized; however, the water from the shallow well has not changed appreciably in mineral content.

The town of Saratoga is partially supplied by three privately owned public-supply wells. Individual domestic wells supply the rest of the town.

The community of Honey Island was supplied by two public supply and industrial wells owned by the Kirby Lumber Corp. from about 1937 to 1958. The community's use ranged from an estimated 0.015 mgd in 1940 to an estimated 0.02 mgd in 1957. The Kirby Lumber Corp. consolidated its operations in the plant near Silsbee in 1958, and the Honey Island wells were abandoned. Individual domestic wells now supply the community.

The privately owned Honey Island swimming pool, about 2 miles south of Honey Island, obtains its water from a large-capacity flowing well 1,953 feet deep. The well was drilled in 1912 and in 1962 was flowing about 250 to 300 gpm although its potential flow capacity has been estimated at about 500 gpm.

Industrial Use

The withdrawal of ground water for industry in 1962 in Hardin County was 1.83 mgd, or 2,050 acre-feet per year. This is 19 percent of the total withdrawals for all purposes in the county.

The use of ground water for industrial purposes has increased significantly from 1943 to 1962 (Figure 10). Ground water for boiler feed in sawmills is the dominant use. This use has remained nearly constant from 1943 to 1954. In 1955, an expansion of lumbering operations north of Silsbee increased water usage to a large extent. The increasing oil and gas production in Hardin County has resulted in the establishment of liquified petroleum gas plants and gas pipeline booster or compressor stations, causing a considerable increase in water consumption. Wells for boiler feed and cooling purposes have been drilled periodically by these expanding industries whenever more water was needed.

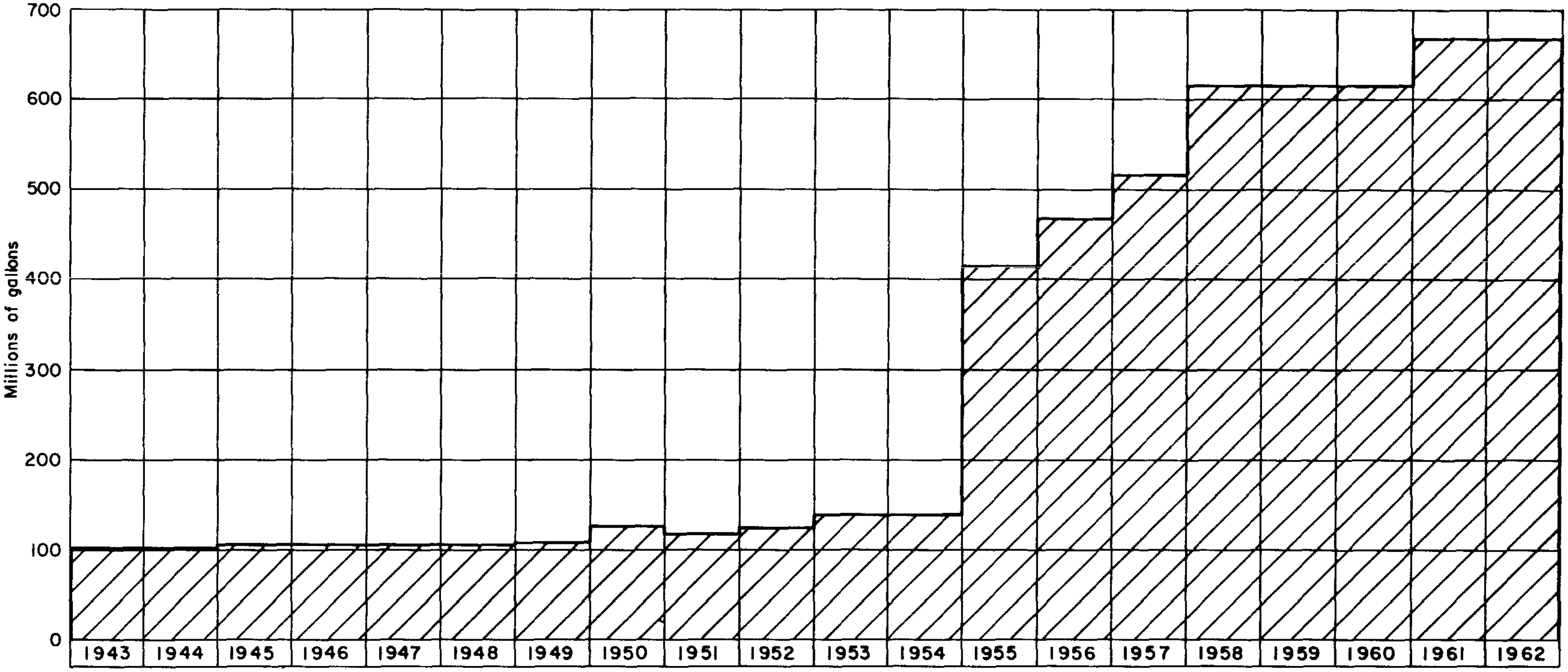

Figure 10

Use of Ground Water for Industry in Hardin County, 1943-62

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The industrial use of ground water increased from about 100 million gallons (0.27 mgd) in 1943 to about 670 million gallons (1.84 mgd) in 1962, an increase of 570 percent. Slightly more than 300 percent of this increase was during the period 1955-62 when the lumber and petroleum industries expanded.

Kirby Lumber Corp. is the largest single user of ground water for industrial purposes in Hardin County. In the late 1930's, the company was operating sawmills at two locations in the county--one at Honey Island where three wells were in operation and the other near the present location 1 mile north of Silsbee where three wells also were used. The annual ground-water use by the two sawmills from about 1937 to 1954 is an estimated 80 million gallons (0.22 mgd). In late 1952, two large-capacity wells, 615 and 625 feet deep, were drilled at the present plant site; each of the wells was test pumped at more than 1,000 gpm. Records of water use indicate that the plant used 350 million gallons (0.96 mgd) of water in 1955. Since 1955, the pumpage has increased steadily, and in 1962, 600 million gallons (1.65 mgd) was used, an increase of 71 percent in 7 years. Kirby Lumber Corp. in 1962 pumped 90 percent of the ground water used for industrial purposes in Hardin County.

Three other saw mills in Hardin County, all near Kountze, were using a total of about 30 million gallons (0.08 mgd) of ground water annually in 1962, or about 5 percent of the total industrial pumpage. Each plant had a single well which adequately supplies the mill's needs.

The petroleum industry used about 34 million gallons (0.09 mgd) of water, or about 5 percent of the total industrial pumpage in the county in 1962.

Sinclair Oil and Gas Co. operates liquified petroleum gas products plants at two locations 5 to 6 miles north and northwest of Silsbee. Five wells, ranging in depth from 165 to 442 feet, supplied 21 million gallons (0.06 mgd) of water in 1962 to the two plants, an increase of 77 percent since 1948. Boiler feed and cooling are the principal uses for the water.

Compressor stations operated by Atlantic Refining Co., Transcontinental Gas Pipeline Co., and Trunkline Gas Co. used more than 13 million gallons (0.04 mgd) of ground water in 1962. The Atlantic Refining Co. compressor station, 1 mile east of Village Mills, has used 11 million gallons (0.030 mgd) of water annually from two wells 440 to 480 feet deep since the station was constructed in 1950. Transcontinental Gas Pipeline Co., 6 miles west of Sour Lake, used 2.4 million gallons (0.007 mgd) of ground water in 1962. Two wells drilled in 1950 supply adequate amounts of water used for boiler feed and cooling. The pumpage has not increased significantly since the plant was constructed in 1950. Trunkline Gas Co., about 6 miles southwest of Kountze, uses two wells principally for public supply to company houses. Only a relatively small amount is used for boiler feed and cooling.

The Gulf, Colorado, and Santa Fe Railroad was among the first industrial users of ground water in Hardin County. At least 5 wells were drilled, ranging in depth from 355 to 900 feet at various places along the railway during the early part of the 20th century, to supply water to locomotive boilers. Deussen (1914, p. 188-190) described many of these old wells which are now abandoned. The more recently drilled wells include one 7 miles east of Votaw drilled in 1930 and plugged and abandoned in 1961 or 1962, and one at Silsbee drilled in 1942. The well at Silsbee, 365 feet deep, was one of 4 railroad wells at this site and was the only well still being used in 1962. The use of ground water by the railroad in Silsbee dropped from about 8 million gallons annually (0.02 mgd) in 1918 to about 4 million gallons (0.01 mgd) in 1962, the production being reduced in 1951 because of the transition from steam to diesel engines.

Irrigation

The use of ground water for irrigation in Hardin County in 1962 was about 2.57 mgd, or 2,880 acre-feet per year. This is 25 percent of the pumpage for all purposes in the county in 1962. The water for irrigation is supplied exclusively by wells and rice is the only irrigated crop.

Since irrigation began in 1947, the use of water has increased in proportion to the increase in acreage (Figure 11). In 1947, about 600 acres was irrigated, the acreage increasing significantly until the peak year 1954 when 2,800 acres was irrigated in Hardin County. The pumpage in 1954 was about 1,820 million gallons (5.0 mgd), exceeding all other uses by about 270 percent. From 1954 to 1957, the acreage irrigated, and consequently the pumpage, decreased. From 1957 to 1963, the number of irrigated acres was nearly constant, ranging from about 1,000 to 1,100 acres.

In 1962, five irrigation wells were in use in Hardin County in the vicinity of Sour Lake. In the vicinity of Batson, as many as five additional irrigation wells were not in production in 1962 because of the "rice-pasture" system of growing rice one or two years followed by two or more years of pasture improvement when rice is not planted.

The irrigation wells in Hardin County are large-capacity wells. Surface-casing diameters range from 8 to 30 inches; depths range from 100 to 952 feet (the deepest wells are in the vicinity of Sour Lake where shallow ground water is inadequate or of poor quality), and yields range from about 700 to 2,400 gpm. All the wells are equipped with turbine pumps powered by large internal combustion engines using liquified petroleum gas, diesel fuel, or natural gas.

Domestic and Livestock Needs

The use of ground water in 1962 for domestic and livestock purposes in Hardin County was about 0.54 mgd, or about 605 acre-feet. This is only 6 percent of the ground-water withdrawals for all purposes in the county in 1962.

Changes in Water Levels in Wells

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

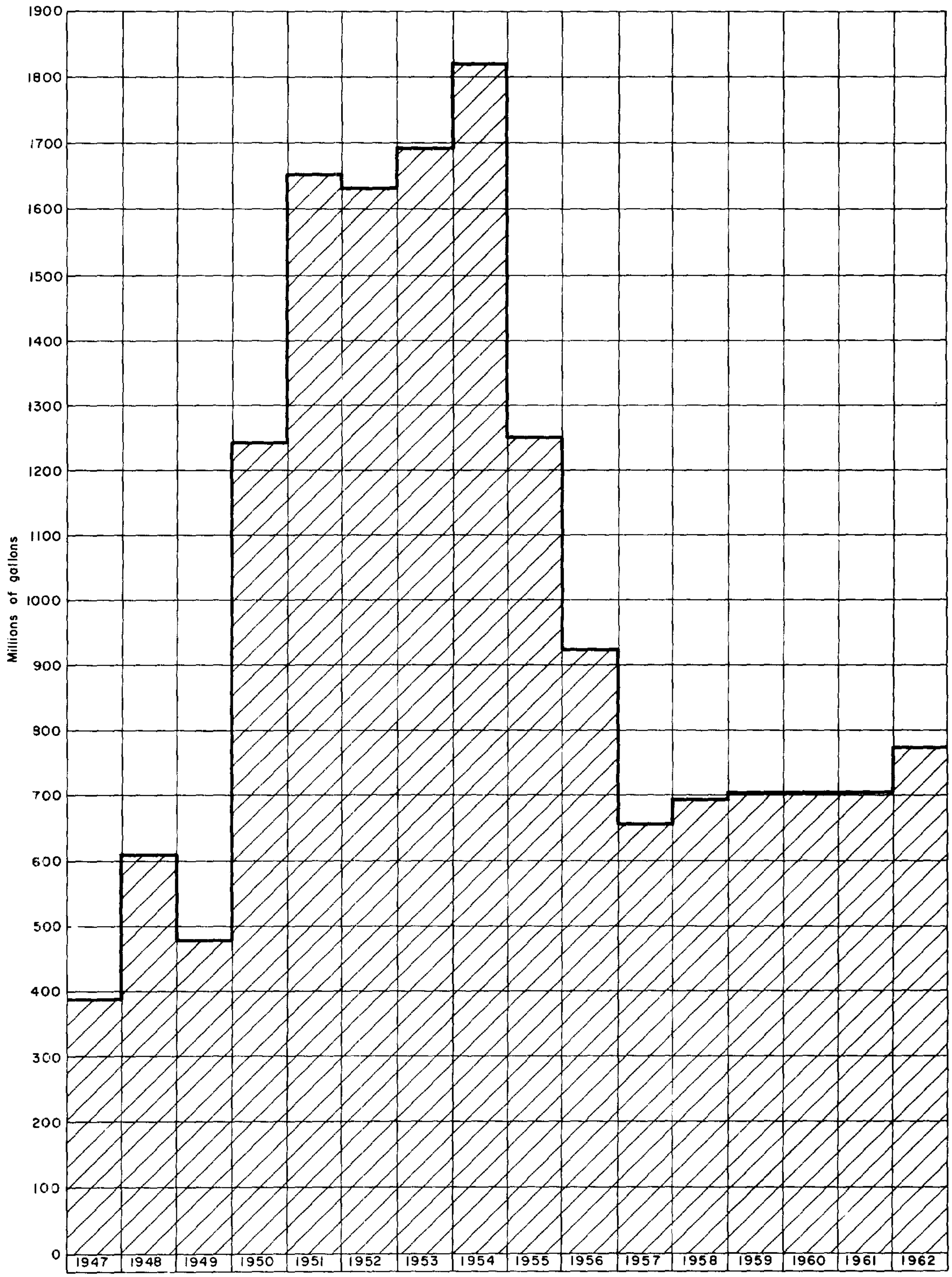

Figure 11

Use of Ground Water for Irrigation in Hardin County, 1947–62

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

Water-level declines of considerable magnitude may result from the withdrawal of water from wells. Where water-table conditions prevail, declines of levels due to pumping are less pronounced generally than where artesian conditions prevail, the decline of level being the result of a decrease in the storage of water. Pressure-type fluctuations have been observed even in water-table wells, suggesting that variations in permeability create a degree of confinement even in strata at shallow depth, in some places less than 20 feet (Thomas, 1951, p. 145). Where artesian conditions prevail, levels fluctuate primarily from an increase or decrease in pressure; the change in the amount of water in storage may be small.

Normally, in Hardin County in areas remote from pumping, the water level is highest in late spring or early summer of each year after the recharge from winter rains and at the end of the season when withdrawals are the smallest. It is lowest in the fall and early winter after the high evapotranspiration of the summer. During the growing season, much of the rainfall is captured and used by vegetation or is evaporated directly from the soil because of the higher summer temperature, and apparently very little rain recharges the sediments except after exceptionally heavy rains. The fall months of October and November receive less rainfall than any other period, and the water is used largely to restore the summer-depleted soil moisture, but when winter rains begin, the water table ceases to decline, and it rises until the beginning of a new growing season.

Prior to development of wells in Hardin County, the aquifers were essentially in a state of equilibrium--that is, the amount of recharge equaled the amount of discharge. The water table or internal pressure in the artesian parts of the reservoir fluctuated from changes in load imposed on the aquifers. The water levels would respond accordingly--that is, either rise or decline. The drilling of wells and discharge of water were artificial conditions imposed on the previously nearby stable system. Thus, the aquifers had to adjust to this unstable condition by (1) salvaging rejected recharge, (2) increasing the recharge to balance the discharge, (3) decreasing the amount of natural discharge, (4) losing ground water from storage, or (5) a combination of these.

The first report on the ground water of Hardin County was by Taylor (1907, p. 47-48). At the beginning of the 20th century, Hardin County had not really begun to develop its vast underground water supply. Taylor states, "The shallow wells of Hardin County vary in depth from 15 to 30 feet. In this county there is little need for artesian water and consequently no artesian wells have been drilled. Deep wells are owned by the Santa Fe Railroad at Silsbee, Dies (Kountze post office), and Votaw."

Deussen (1914, p. 186-219), during the summers of 1907 and 1908, studied the geology and ground water of Hardin County. The earliest known records of water level are recorded in his report. Deussen reported a water level of 30 feet in 1907 in a well owned by the Gulf, Colorado, and Santa Fe Railroad in

Silsbee. The well, LH-61-47-203, 476 feet deep, is still in existence, and because it no longer is being used, it makes an excellent observation well. In August 1962, the well had a water level of 63.42 feet below land surface. This represents a decline in water level of about 33 feet over a span of 55 years, or an average decline of 0.6 foot per year.

Hydrographs of water levels in selected wells in Hardin County are shown in Figure 12. Well LH-61-37-201, 156 feet deep, is 3 miles west of Village Mills and probably bottoms in either the Lissie Formation or Willis Sand. From 1942 to 1962, the water level declined almost 6 feet. Fluctuations of the level are chiefly the result of response to rainfall. The low for the period of record was 11.21 feet in April 1957 and was the response of the level to below-normal rainfall or recharge during the period 1954-56, when widespread drought prevailed. After the drought, the water level began to rise. This well is a typical example of a water level responding to rainfall. The long-time trend, however, is one of decline, which may be due partly to pumpage of water for nearby oil-field operations.

Wells LH-61-53-913 and LH-61-53-914, both 177 feet deep, are the old city of Sour Lake public-supply wells drilled in October 1941. Because of a lack of yearly measurements between 1942 and 1953, the true record of fluctuations between these dates is not known. A low for the period of record probably was reached in the summer of 1950 just before the wells were abandoned because of salt-water encroachment (Figure 21). Thus, much of the early decline is due to a decrease in artesian pressure because of an increase in pumpage. After the old wells were replaced by new wells 1 mile south of Sour Lake, the levels in the old wells recovered somewhat and, thereafter, began fluctuating largely in response to rainfall. The net decline in the level of well LH-61-53-913 from 1942 to 1962 was 12.11 feet, or 0.6 foot per year. The level in well LH-61-53-914 from 1942 to 1962 declined 6.28 feet, or 0.3 foot per year.

Well LH-61-38-701, having a depth of 113 feet, is 3 miles northwest of Kountze. The date that the well was drilled is not known, but the well is presumed to be an old industrial well that supplied boiler-feed water to a sawmill formerly at this site. The well probably bottoms in the Lissie Formation. From 1942 to 1959, the water level in the well had a net decline of about 1 foot, the peak in December 1959 probably reflecting recharge during 1959, an abnormally wet year of about 68 inches of rainfall. The decline of about 4 feet in 1960 probably reflects the deficiency of rainfall in 1960 when the precipitation was about 46 inches.

Well LH-61-39-202, 8.5 miles north of Silsbee, has a depth of 225 feet. The well, drilled in 1951 to supply water to an oil drilling rig, probably has not been used since 1951, and thus is an excellent observation well. The well has had a net decline in water level of about 3 feet during the period 1953-62, the level fluctuating primarily in response to rainfall.

Well LH-61-36-501, about 7 miles east of Votaw, is 868 feet deep. The well was drilled in 1930 to supply water to locomotive boilers. Because the well is screened in intervals from 227 to 867 feet, it taps a major part of the Gulf Coast aquifer. After the use of the well was discontinued, the water level responded chiefly to changes in the rate of recharge. The net decline from 1942-60 was 8.19 feet, or about 0.5 foot per year.

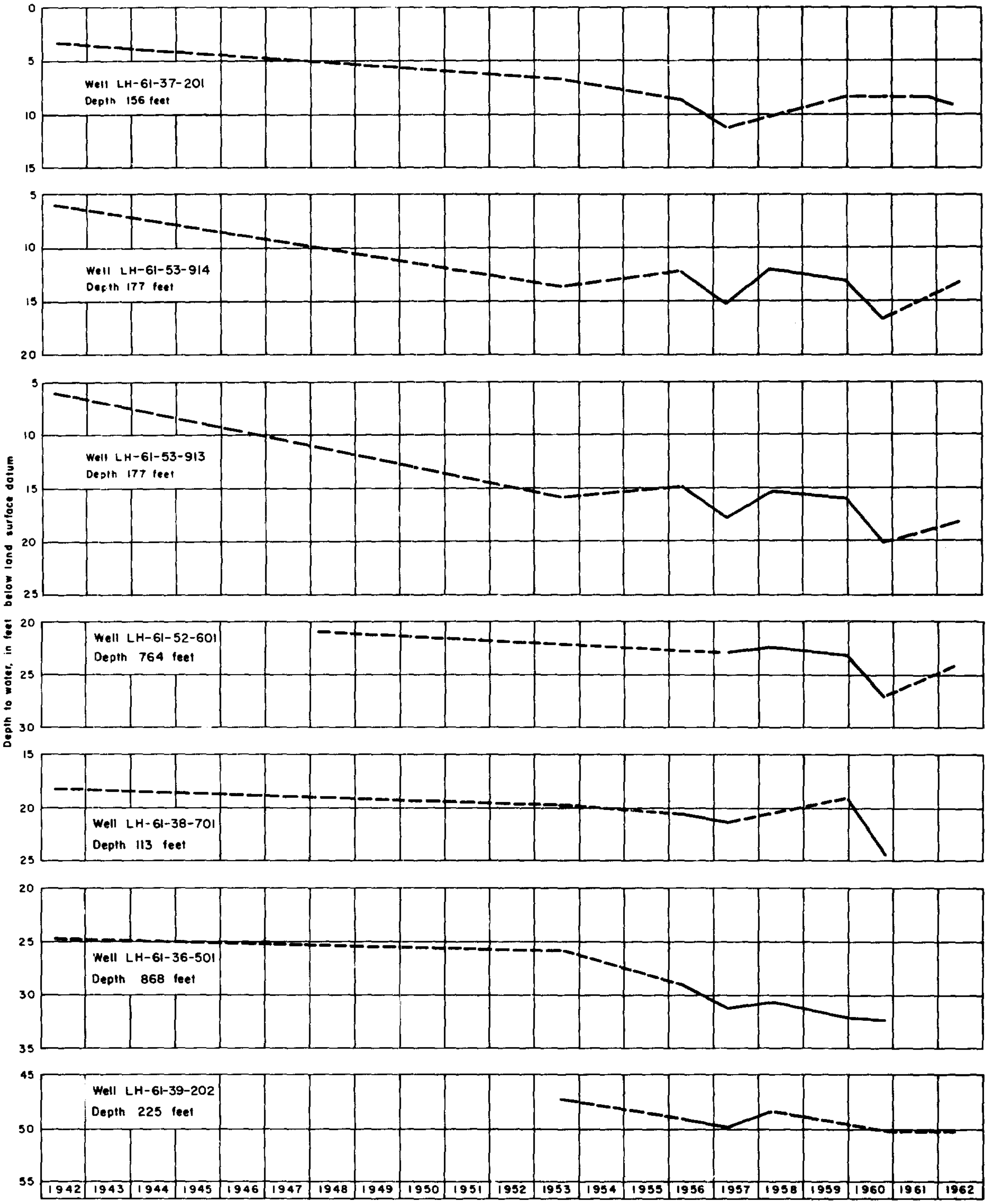

Figure 12

Hydrographs of Water Levels in Wells in Hardin County

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Well LH-61-52-601, 6.5 miles northwest of Sour Lake and used for irrigation, is 764 feet deep. Periodic water-level measurements were made on the well beginning in 1957, 9 years after the well was drilled. From 1948 to 1962, the water level declined about 3 feet, or about 0.2 foot per year.

Other irrigation wells in the Sour Lake area have declining water levels. Well LH-61-54-701, 2.6 miles east of Sour Lake, is 903 feet deep. This well, drilled in 1947, flowed a reported 3 gpm until the winter of 1954-55, and the water level in the well in 1962 was 5.2 feet below the land surface. Well LH-61-53-907, 2.1 miles northeast of Sour Lake, is 1.5 miles northwest of LH-61-54-701. Both wells are screened approximately opposite the same sand beds and interfere with each other to the extent that one well would cease flowing if the other well was pumping. Both are large-capacity wells capable of yielding more than 2,000 gpm each.

Eight wells on the outcrop of the Lissie Formation inventoried in April 1942 by Cromack (1942) were revisited in February 1962. A comparison of water levels in all the wells over the 20-year span revealed declines ranging from 0.86 foot to 10.81 feet. Six of the wells are less than 50 feet deep and are presumed to be water-table wells. The other are deeper than 150 feet and are probably artesian wells. The water levels in all the wells probably fluctuate in response to precipitation or transpiration, or both. Little significance can be attributed to the declines of water levels over the 20-year span as no water-level trend can be inferred from only the two sets of measurements.

QUALITY OF GROUND WATER

Chemical Quality

The chemical constituents in ground water originate principally from the soil and rocks through which the water has passed; consequently, the differences in chemical character of the water reflect in a general way the nature of the geologic formations that have been in contact with the water. Generally, ground water is free from contamination by organic matter, but the chemical content increases with depth.

The suitability of a water supply depends upon the chemical quality of the water and the limitations imposed by the contemplated use of the water. Various criteria of water-quality requirements have been developed, including most categories of water quality: bacterial content; physical characteristics, such as turbidity, color, odor, and temperature; chemical constituents; and radioactivity. 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 dissolved-solids content is a major limitation on the use of the water. A general classification of water based on dissolved-solids content, in ppm (parts per million), is as follows (Winslow and Kister, 1956, p. 5):

Description	Dissolved-solids content (ppm)
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 periodically 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 whenever more suitable supplies are or can be made available at reasonable cost. These limits should apply to the water at the free-flowing outlet of the ultimate consumer. Some of the major chemical standards adopted by the U. S. Public Health Service (1962, p. 7-8) are as follows:

Substance	Concentration (ppm)
Chloride	250
Fluoride	*
Iron	0.3
Manganese	.05
Nitrate	45
Sulfate	250
Total dissolved solids	500

*When fluoride is present naturally in drinking water, the concentration should not average more than the appropriate 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

The optimum fluoride level for a given community depends on climatic conditions because the amount of water (and consequently the amount of fluoride) ingested by children is influenced primarily by air temperature. Presence of fluoride in average concentrations greater than twice the optimum values as indicated by the table may constitute grounds for rejection of the supply. Excessive concentrations of fluoride in water may cause teeth to become mottled. Optimum fluoride concentrations may reduce the incidence of tooth decay in children with no ill effects, and caries rates may be 60 to 65 percent below the rates in communities using water supplies with little or no fluoride (Dean, Arnold, and Elvove, 1942, p. 1155-1179; Dean and others, 1941, p. 761-792).

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 the water is in excess of 45 ppm, the public should be warned of the potential dangers of using the water for infant feeding. Concentrations of nitrate in excess of 45 ppm in water used for infant feeding have been related to the incidence of infant cyanosis (methemoglobinemia or "blue baby" disease), a reduction of the oxygen content in the blood constituting a form of asphyxia (Maxcy, 1950, p. 271). Nitrate is considered the final oxidation product of nitrogenous matter and its presence in water in concentrations of more than several parts per million may indicate previous contamination by sewage or other organic matter (Lohr and Love, 1954, p. 10). Excessive concentrations of iron and manganese in water cause reddish-brown or dark-gray precipitates that discolor clothes and stain plumbing fixtures. Such high iron-bearing water on exposure to air becomes turbid with ferric hydroxide as a result of oxidation, but the water will become clear if it is quiescent. 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; however, persons evidently become acclimated to use of these waters in a relatively short time if the concentrations are not too excessive.

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. Commonly accepted standards and classifications of water hardness are shown in the following table:

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

Ground water that contains moderate quantities of dissolved material may change from hard water to soft water by ion exchange reactions in passage through sediments. In the Gulf Coast aquifer, water which contains calcium and magnesium in the outcrop moves downdip and may contain practically no calcium or magnesium at depth. Sodium and bicarbonate are the principal constituents of the deeper fresh water.

The quality of water for industry does not depend necessarily on whether or not it is acceptable for human consumption. The quality of water requirements for miscellaneous industries vary widely with each type of processing presenting individual requirements. According to Horner (1952, p. 57), the quantity of water required for unit value of product varies widely. In those industries requiring relatively large volumes of water per unit value of product, the cost of supply and treatment are of predominant importance. These industries must consider water supply to be a major limiting factor in their planning and development. In industries where the relation of water consumption to value of product is small, more elaborate treatment can be justified.

Ground water used for industry may be classified into three principal use categories--cooling, boiler, and process. Of these uses, the quantity used for cooling water far exceeds all others. Cooling water usually is selected for its temperature and source of supply, although its chemical quality also is significant. Any characteristic that may affect adversely heat-exchange surfaces is undesirable. Calcium, magnesium, aluminum, iron, and silica may cause scale. Corrosiveness is another objectionable feature. Calcium and magnesium chloride, sodium chloride in the presence of magnesium, acids, oxygen, and carbon dioxide are among substances that make water corrosive.

Boiler water for the production of steam must meet rigid chemical-quality 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 evaluate the water source for suitability of the water for treatment rather than for direct use as raw water. The calcium and magnesium content greatly affect the industrial value of the water by contributing to the formation of boiler scale. Silica in boiler water is undesirable because it forms a hard scale, the scale-forming tendency increasing with pressure in the boiler.

The following table shows the maximum suggested concentrations of silica for water used in boilers (Moore, 1940, p. 263):

Concentration of silica (ppm)	Boiler pressure (pounds per square inch)
40	Less than 150
20	150 to 250
5	251 to 400
1	More than 400

Process water 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 iron and manganese. However, treatment of the raw water is justified in the textile industry because the ratio of water consumption to value of product is relatively small. The paper industry, especially where high-grade paper is made, requires water in which heavy metals such as iron and manganese are either absent or in small concentrations because of the staining properties of these substances. 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 and becomes a part of the product or undergoes a change in quality in the manufacturing process and is not available generally for reuse.

The suitability of water for irrigation depends on the chemical quality of the water and other factors such as soil texture and composition, types of crops, irrigation practices, and climate. Chemical analyses of irrigation water identify the more important substances that are present and show their concentration. From such analyses it is possible to classify water in terms of suitability for irrigation and to anticipate with some assurance the effect of the water on crops and soils. Many classifications of irrigation water express the suitability of water in terms of one or more variables and offer 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 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, soil 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 SAR (sodium-adsorption ratio). This classification of irrigation water is diagrammed in Figure 13.

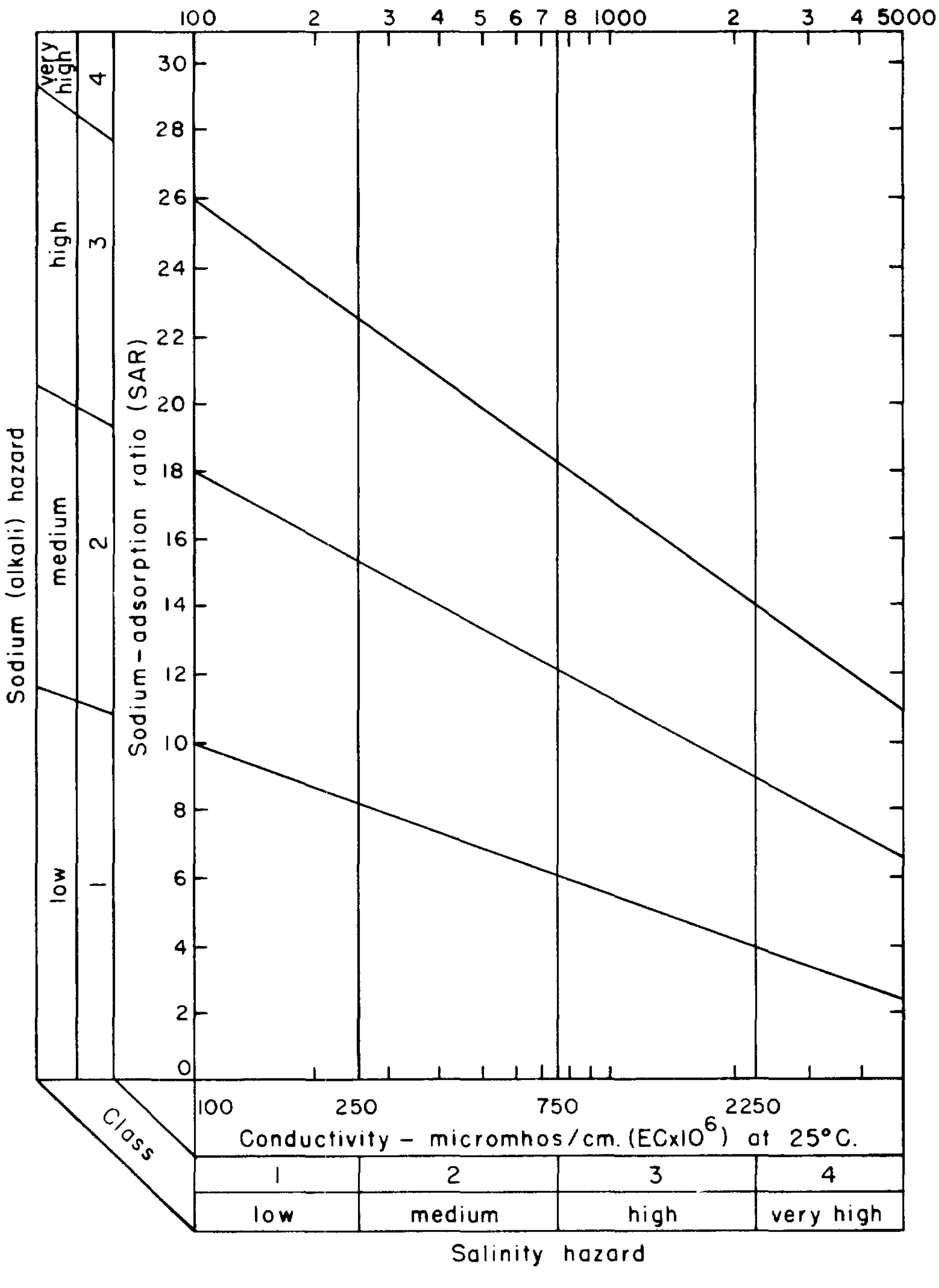

Figure 13

Diagram for the Classification of Irrigation Waters

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

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Wilcox (1955, p. 15) stated that the system of classification used by the U. S. Salinity Laboratory Staff "...is not directly applicable to supplemental waters used in areas of relatively high rainfall." Thus, in Hardin County and southeastern Texas, the system may not be directly applicable.

An excessive concentration of boron renders a water unsuitable for irrigation. Scofield (1936, p. 286) indicated that boron concentrations of as much as 1 ppm are permissible for irrigating most boron-sensitive crops and concentrations as much as 3 ppm are permissible for the more boron-tolerant crops. The permissible limits of boron are shown in the following table:

Classes of water		Sensitive crops (ppm)	Semitolerant crops (ppm)	Tolerant crops (ppm)
Rating	Grade			
1	Excellent	Less than 0.33	Less than 0.67	Less than 1.000
2	Good	0.33 to 0.67	0.67 to 1.33	1.00 to 2.00
3	Permissible	.67 to 1.00	1.33 to 2.00	2.00 to 3.00
4	Doubtful	1.00 to 1.25	2.00 to 2.50	3.00 to 3.75
5	Unsuitable	More than 1.25	More than 2.50	More than 3.75

Another factor used in assessing the quality of water for irrigation is the RSC (residual sodium carbonate) in the water. Excessive RSC will cause the water to be alkaline, and the organic content of the soil will tend to dissolve. The soil may become a grayish black and the land areas affected are referred to as "black alkali." Wilcox (1955, p. 11) states that laboratory and field studies have resulted in the conclusion that water containing more than 2.5 epm (equivalents per million) RSC is not suitable for irrigation. Water containing from 1.25 to 2.5 epm is marginal, and water containing less than 1.25 epm RSC probably is safe. However, it is believed that good irrigation practices and proper use of amendments might make it possible to use the marginal water successfully for irrigation. Furthermore, the degree of leaching will modify the permissible limit to some extent (Wilcox, Blair, and Bower, 1954, p. 265).

Quality limits of water 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. Concentrations as high as 15,000 ppm dissolved-solids content are safe for limited periods but not for continuous use (California State Water Pollution Control Board, 1952, p. 155).

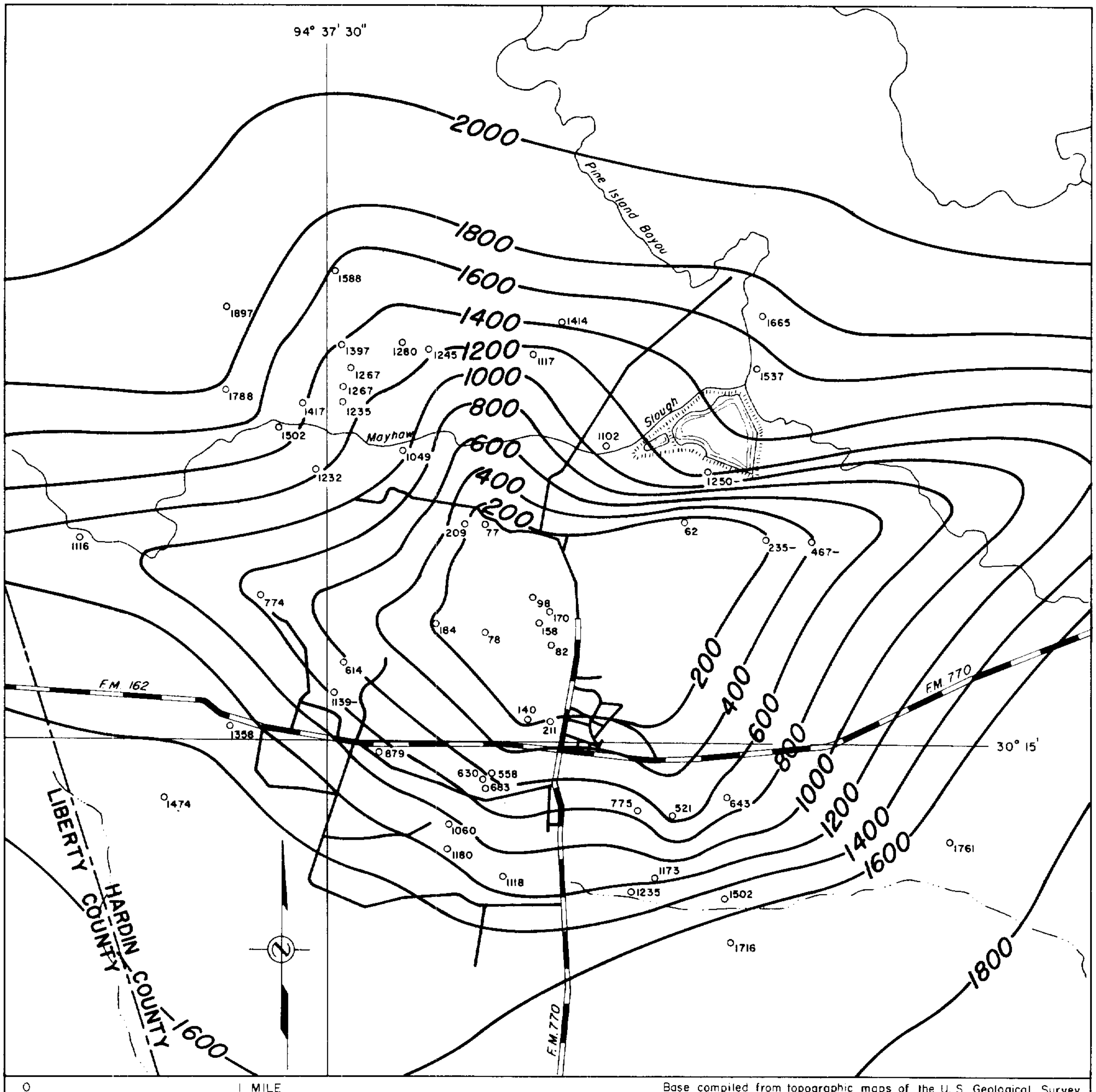
All of Hardin County is underlain by sands containing fresh to slightly saline water and extending to various depths (Figures 14 through 17). Most of the water in the zone of fresh to slightly saline water is fresh, containing dissolved solids of less than 1,000 ppm. The slightly saline water zone (1,000 to 3,000 ppm dissolved solids) is relatively thin compared to the fresh-water zone. Zones containing moderately saline water to brine underlie the fresh to slightly saline water.

A combination of electric logs and chemical analyses was used to determine the base of the fresh to slightly saline water in Hardin County. A study of the comparison of the resistivities of water-bearing sands on electric logs with the quality of the water in the sands indicates that the apparent resistivity of sand beds containing slightly saline water (3,000 ppm dissolved solids) based on the long normal and lateral curves is about 8 to 10 ohms m^2/m. The apparent resistivity of sand beds containing fresh water (less than 1,000 ppm dissolved solids) is about 15 to 20 ohms m^2/m in Hardin County. The correlation of chemical quality of ground water to resistivity is only approximate. This is partly because sands in different areas contain water that may be of different dominent type (sodium chloride water or sodium bicarbonate water), and partly because the apparent resistivities shown on the logs vary somewhat from the true resistivity of the sand beds (Figure 18). Rose, White, and Livingston (1944, p. 309-311) in correlating resistivity with quality, permeability, and sand size in 13 test wells in the Houston district, concluded also that resistivity of sand beds varied with permeability, the higher resistance being associated with higher permeability.

Table 11 shows 144 chemical analyses of water from wells that tap the Gulf Coast aquifer and the analyses of water from Sour Lake. The wells sampled are identified in Plates 1 through 4 by means of bars over the well numbers. The analyses shown are about half of the total number on record, but they may be considered representative of the quality of ground water in the Gulf Coast aquifer at the general depth and vicinity of the wells. Most of the analyses of the water sampled by Cromack (1942) are not shown because many of the wells were not relocated during the present investigation or have been destroyed. Wells that were relocated were resampled and the water was analyzed; the resample analyses are listed in the table with the older analyses for comparison. Figure 19 shows graphically the chemical composition of ground water from representative wells in Hardin County. A comparison of the quality of ground water in Hardin County with standards recommended by the U. S. Public Health Service and others is shown in Table 5.

In general, the ground water underlying Hardin County is of good chemical quality and suitable for most purposes, except in localized areas, particularly in the vicinity of the shallow salt domes at Batson, Saratoga, and Sour Lake. The water near the outcrop generally is less mineralized than that at greater depths and the shallow water is generally of a calcium bicarbonate type, being rather hard. The deeper water below about 500 feet is a sodium bicarbonate type of water, or locally a sodium chloride type water. The deeper water is generally considerably softer than the shallow water. The deeper water may exceed 500 ppm dissolved solids, but in most instances is less than 1,000 ppm. A typical analysis of water from a shallow well near the outcrop is illustrated on Figure 19 (well LH-61-46-201). A typical deep-well anlysis is that shown on Figure 19 for well LH-61-39-601.

Water suitable for public supply and most industrial uses can be found in most places in Hardin County. If water of a particular quality is needed, it can generally be obtained by a careful program of exploration and testing and selective screening of the wells. The high iron content found in many places is probably the water-quality characteristic that might cause the greatest concern.



EXPLANATION

——1200——

Line showing approximate altitude of base of fresh to slightly saline water, in feet below sea level

Contour interval 200 feet

○235-

Well used for control. Number indicates altitude of base of fresh to slightly saline water, in feet below sea level

Minus sign indicates altitude is less than number shown

Figure 15

Approximate Altitude of the Base of Fresh to Slightly Saline Water in the Batson Area, Hardin County

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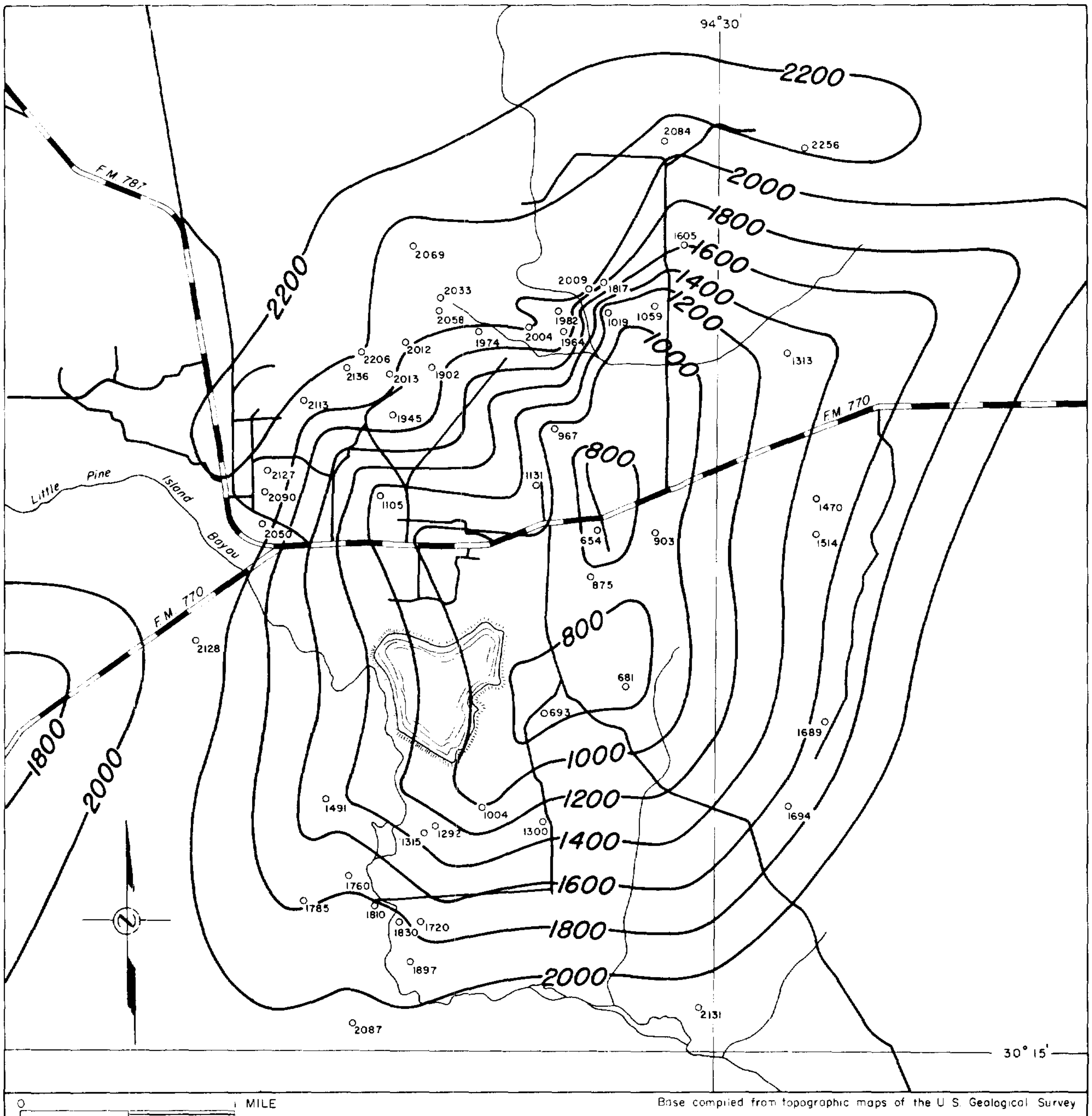

EXPLANATION

——1200——

Line showing approximate altitude of base of fresh to slightly saline water, in feet below sea level

Contour interval 200 feet

○ 2087

Well used for control. Number indicates altitude of base of fresh to slightly saline water, in feet below sea level.

Figure 16

Approximate Altitude of the Base of Fresh to Slightly Saline Water in the Saratoga Area, Hardin County

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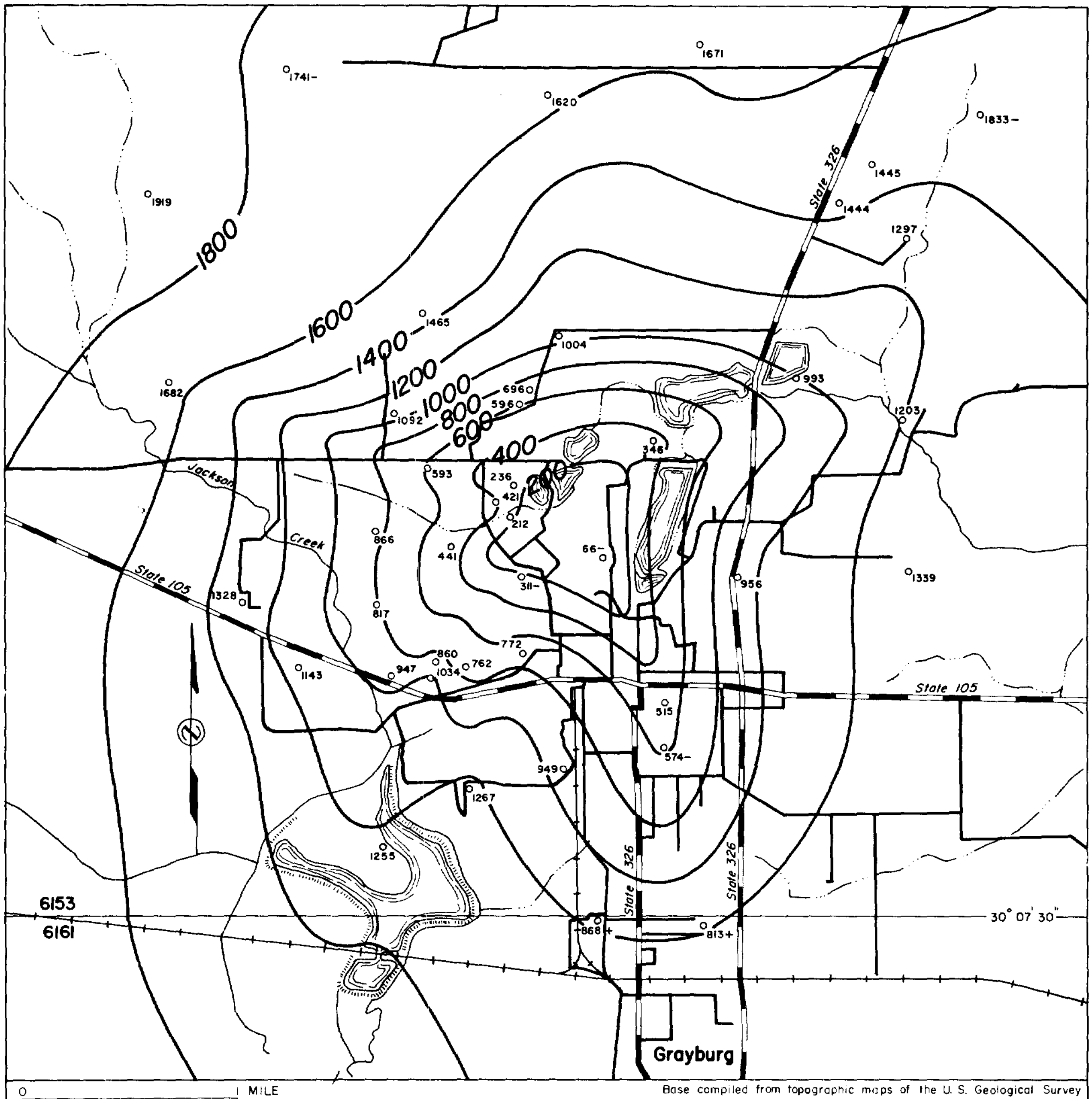

EXPLANATION

1200

Line showing approximate altitude of base of fresh to slightly saline water, in feet below sea level

Contour interval 200 feet

868±

Well used for control. Number indicates altitude of base of fresh to slightly saline water, in feet below sea level. Plus sign indicates altitude is greater than number shown. Minus sign indicates altitude is less than number shown

Figure 17

Approximate Altitude of the Base of Fresh to Slightly Saline Water in the Sour Lake Area, Hardin County

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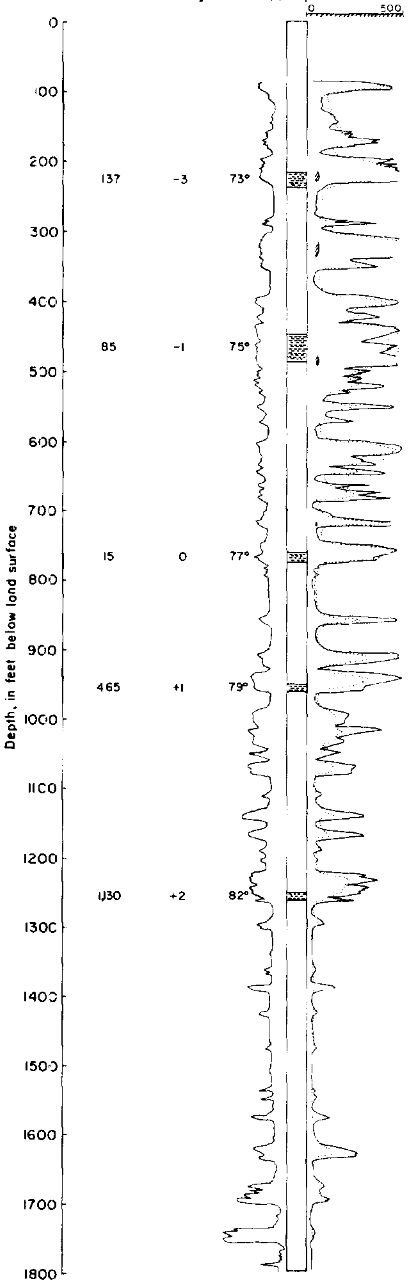
Chemical Analyses

(Parts per million except specific conductance, pH, sodium adsorption ratio, and residual sodium carbonate)

Coef. of permeability (gpd/ft²)	Water level, feet (-) below or (+) above ground	Temp. (°F)	Silca (SiO_2)	Total iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium and Potassium Na+K	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Dissolved solids	Hardness as $CaCO_3$	Sodium adsorption ratio (SAR)	Residual sodium carbonate (RSC)	Specific conductance (micromhos at 25° C)	pH	Date of collection
137	-3	73°	13	0.22	7	1	102	264	7	14	265	22	9.5	3.9	415	8.0	Nov. 7, 1957
85	-1	75°	14	.11	2	.7	151	316	0	32	378	8	23	5.0	610	8.6	Nov. 16, 1957
15	0	77°	12	* 12.0	9.5	2.3	101	266	0	10	281	33	7.6	3.7	466	9.0	Nov. 11, 1957
465	+1	79°	12	.10	2.5	.2	217	366	0	105	538	7	3.6	5.9	925	8.5	Nov. 10, 1957
1130	+2	82°	10	.05	2.0	.7	307	427	1	194	761	8	47	6.8	1340	8.5	Nov. 12, 1957



Screen

* Iron concentration, in filtered sample less than 0.05 ppm

Data from The Layne-Texas Company Ltd.

Figure 18

Chemical Quality and Temperature, Permeability, and Water Levels Measured in Various Water-Bearing Sands and the Electric Log of Well LH-61-55-205, Hardin County

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Table 5.--Comparison of quality of ground water in Hardin County with standards recommended by the U. S. Public Health Service and others

(Chemical constituents in parts per million except sodium adsorption ratio, residual sodium carbonate, and specific conductance)

	Silica (SiO_2)		Iron (Fe) (total) and Manganese (Mn)		Magnesium (Mg)		Sulfate (SO_4)		Chloride (Cl)		Fluoride (F)		Nitrate (NO_3)		Boron (B)		Dissolved solids			Hardness as $CaCO_3$		Sodium adsorption ratio (SAR)		Residual sodium carbonate (RSC)		Specific conductance (micromhos at 25°C)	
Maximum recommended	20[a]		0.3		125		250		250		1.5		45		1.0[b]		500			60[c]		14[d]		2.5[e]		2,250[d]	
	Number of determinations	Number exceeding 20 ppm	Number of determinations	Number exceeding 0.3 ppm	Number of determinations	Number exceeding 125 ppm	Number of determinations	Number exceeding 250 ppm	Number of determinations	Number exceeding 250 ppm	Number of determinations	Number exceeding 1.5 ppm	Number of determinations	Number exceeding 45 ppm	Number of determinations	Number exceeding 1.0 ppm	Number of determinations	Number exceeding 500 ppm	Number exceeding 1,000 ppm	Number of determinations	Number exceeding 60 ppm	Number of determinations	Number exceeding 14	Number of determinations	Number exceeding 2.5 epm	Number of determinations	Number exceeding 2,250 micromhos
Hardin County (excluding salt dome areas)	20	6	50	17	24	0	61	0	59	2	16	3	27	1	5	0	26	7	0	58	33	19	6	8	5	54	1
Batson Area	0	0	25	17	1	0	29	0	29	1	1	0	12	0	0	0	1	0	0	29	12	1	1	1	1	28	0
Saratoga Area	0	0	8	4	1	0	19	0	19	5	1	0	4	0	0	0	1	0	0	19	4	1	0	1	1	18	1
Sour Lake Area	17	5	28	9	18	0	37	0	37	15	18	5	18	0	3	0	20	20	8	36	28	4	2	1	0	25	4

a/ Moore (1940, p. 263).
b/ Scofield (1936, p. 286).
c/ Upper limit of soft water.
d/ Wilcox (1955, p. 16).
e/ Wilcox (1955, p. 11).

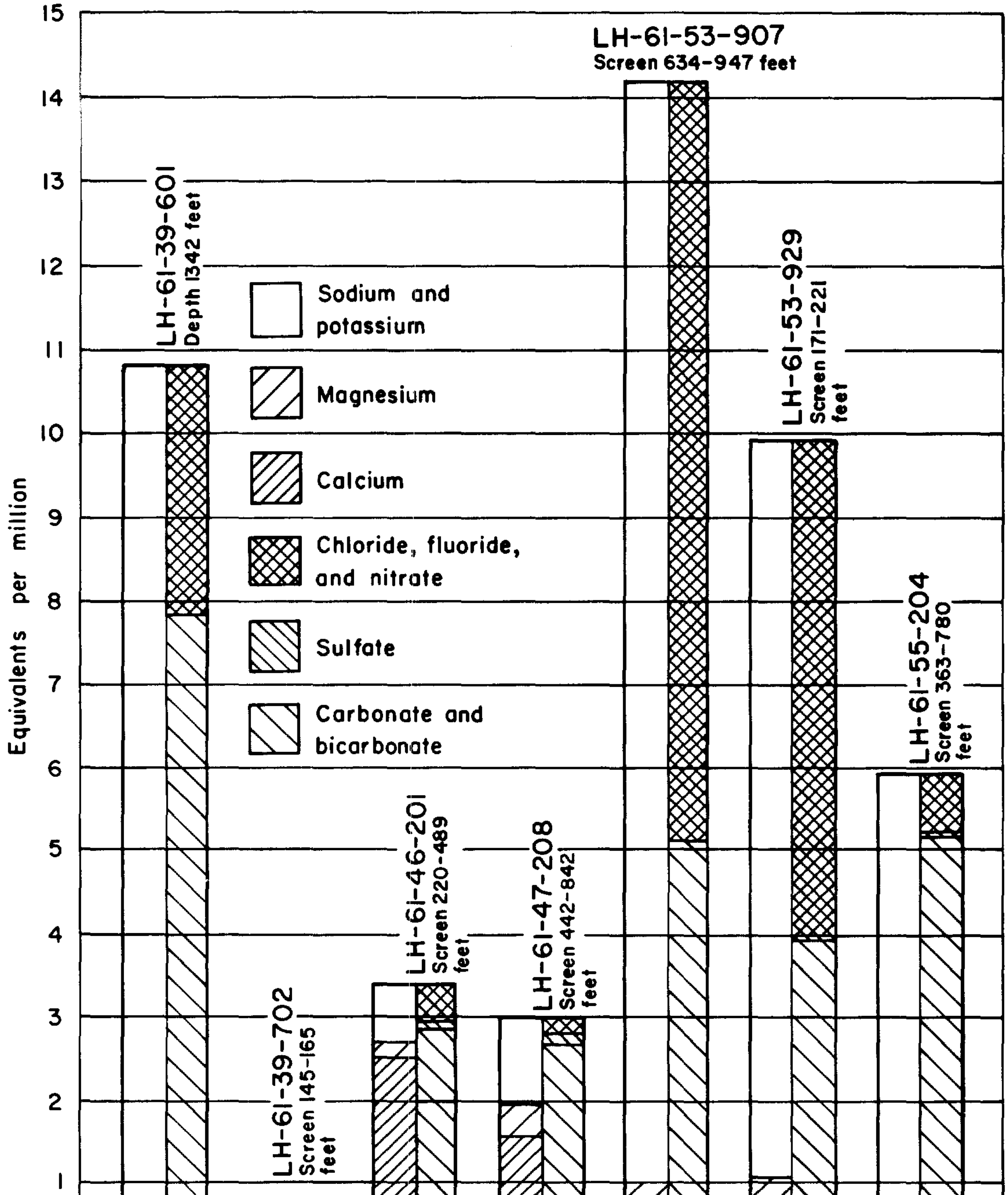

Figure 19

Chemical Composition of Water from Representative Wells, Hardin County

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Ample supplies of water of a quality suitable for irrigation are available from the Gulf Coast aquifer in Hardin County. The chemical analyses indicate that the sodium and salinity hazards range from low to very high, and in most areas the quality appears to be somewhat dependent on the depth of the well, particularly as pertains to the sodium hazard. Water from wells more than about 500 feet deep tend to have a high sodium hazard, whereas water from the shallow wells has a low hazard. The salinity hazard generally increases with depth. The classification shown on Figure 13 is useful in a general way for evaluating the water in Hardin County for irrigation use. However, the classification should not be used rigidly because in a high rainfall area such as that in the county, a considerable amount of leaching takes place, which will no doubt lessen the harmful effects of water that might be considered as doubtful or unsuitable.

Much study has been devoted to the determination of the quality requirements for rice irrigation, rice being the only irrigated crop in Hardin County. Young rice is particularly sensitive to high sodium chloride content in the water, but the rice develops resistance as the plant matures.

According to Shutts (1953, p. 871-884), the commonly accepted tolerances of rice to sodium chloride content are as follows:

Concentration of salts as sodium chloride (ppm)	Tolerance
600	Tolerable at all stages
1,300	Rarely harmful and only to seedlings in dry, hard soil
1,700	Harmful before tillering; tolerable from jointing to heading
3,400	Harmful before booting; tolerable from booting to heading
5,100	Harmful at all stages

The analyses of water from three of the deeper rice irrigation wells in Hardin County, wells LH-61-52-601 (764 feet deep), LH-61-53-907 (952 feet deep), and LH-61-54-701 (903 feet deep), indicate that the sodium chloride content is 152, 498, and 528 ppm respectively, and is, thus, tolerable by rice at all stages of growth. The analyses of the water from the three irrigation wells, when plotted on the diagram for the classification of irrigation water (Figure 13) indicate that water from well LH-61-52-601 is medium and low in salinity and sodium hazards, whereas the water from wells LH-61-53-907 and LH-61-54-701 is high and very high in salinity and sodium hazards. However, the large degree of leaching from flooding in rice irrigation probably tends to lessen the accumulation and effect of salts in the soil.

Boron probably is not an excessive constituent of ground water in Hardin County. Of eight samples tested, all contained less than 1.0 ppm.

Residual sodium carbonate (RSC) in excess of 2.5 epm, the upper limit of concentration in marginal irrigation water, was present in 31 water samples of a total of 129. The higher concentrations of RSC were generally in water from wells 500 to more than 1,000 feet deep. Exceptions to the relation of higher RSC to increasing depth were noted in the Saratoga area where wells as shallow as 97 feet had RSC in excess of 2.5 epm. RSC values for water from irrigation wells LH-61-52-601, LH-61-53-907, and LH-61-54-701 are 2.44, 4.10, and 4.26 epm, respectively. The latter two values are much higher than the upper limit of 2.5 epm; however, here again the large degree of leaching from flooding when irrigating rice probably will tend to lessen the undesirable effects of excess RSC in the water.

Ground water in the vicinity of the shallow salt domes ranges widely in chemical quality. At Batson, the presence of the salt mass a few hundred feet below the land surface affects the quality of the water in a large degree either directly or indirectly. The water that is being used in the area just off the flanks of the dome is a sodium bicarbonate type; sands near the crest of the dome contain a sodium chloride type water.

The iron content is the major quality problem in the Batson area. Almost 70 percent of the wells sampled had iron in excess of the recommended maximum of 0.3 ppm. Staining of plumbing fixtures is common in the area, and many of the private water systems have iron filtering devices. Chloride is not a problem in small wells on the flanks of the Batson dome, although near the crest, chloride in excess of 250 ppm may be expected.

At the Saratoga dome, the troublesome constituents are iron and chloride. Iron concentrations are not as great as at Batson; however, iron in excess of 0.3 ppm was found in water from half the wells tested. Chloride concentrations are relatively high at Saratoga, much more than at Batson.

The presence of hydrogen sulfide in many of the water sands in the immediate vicinity of the Saratoga salt dome renders the water objectionable because of the strong odor; however, the "sulfur" water is not everywhere present in the Saratoga area. Water from the north side of the dome has little if any hydrogen sulfide odor, but an area of a few square miles west and southwest of the crest of the dome yields water containing high concentrations of hydrogen sulfide. The hydrogen sulfide probably is the result of reaction between sulfate in the ground water with hydrocarbons associated with the salt dome. Such local occurrences of hydrogen sulfide over salt domes have been reported by Henninger (1925, p. 36). Extensive fracturing of the strata overlying the caprock probably was responsible for the escape of the hydrogen sulfide gas contaminating the fresh-water zone as postulated by Feely and Kulp (1957, p. 1850).

The quality of ground water in the Sour Lake area appears to have been affected more severely by the dome than at either Batson or Saratoga. In general, the quality of the water becomes progressively mineralized toward the dome, the top of which is a few hundred feet below the surface. The water may be classed as a sodium bicarbonate or sodium chloride type water, depending mainly on the depth of the water sand and its proximity to the dome. Wells LH-61-53-907 and LH-61-53-929, 952 and 224 feet deep, produce a sodium chloride type water (Figure 19).

Evidence of salt-water contamination in the Sour Lake area is noted in wells LH-61-53-913 and LH-61-53-914, 117 feet deep, which produced a sodium bicarbonate water when drilled in 1941. Three years later, the wells produced a sodium chloride water. A similar situation occurred in well LH-61-53-928, 812 feet deep, which produced a sodium bicarbonate water when drilled in 1950. Five years later, the well produced a sodium chloride water.

In general, chloride and hardness are the most objectionable constituents in the water in the Sour Lake area. Almost one-half of the samples had chloride in excess of the recommended maximum concentration and almost 80 percent of the samples exceeded the soft-water limit.

Temperature

The fresh to slightly saline ground water in Hardin County increases in temperature about 1°F for about every 100 feet in depth. The temperature near the land surface approximates the mean annual air temperature (about 70°F in Hardin County). Temperatures measured in single-screen wells revealed the following gradients: Well LH-61-45-201, 7 miles west of Kountze, 1°F per 89 feet; well LH-61-44-101, 7.5 miles northwest of Saratoga, 1°F per 105 feet; and well LH-61-55-205 at Loeb (Figure 18), 1°F per 114 feet (this gradient may be in error because temperatures were taken while jetting the well with air). Temperature gradients of 1°F per 66 feet of depth were observed in wells LH-61-53-928 and LH-61-53-929, both 1 mile south of Sour Lake. The proximity of these wells to the Sour Lake salt dome probably accounts for the high gradients.

PROBLEMS

Salt-Water Contamination

Lateral Movement through the Aquifers

Lateral movement of salt water is the most likely source of contamination of fresh ground water in Hardin County. The lateral movement of salt water up the dip of coastal aquifers is occurring at several localities in Texas near the coastline. The problem has become increasingly serious in recent years as demands for water from underground sources have expanded.

The salt water is in the aquifers because either the aquifers were deposited in brackish or salt water or after they were deposited in fresh water, they became saturated with salt water during inundations by the Gulf. After the sea withdrew, meteoric water entering the outcrop of the aquifers moved down the sand and gravel beds, displacing the salt water. The salt water was flushed from the aquifers by upward circulation through the overlying finer-grained beds (Winslow and others, 1957, p. 387). The downdip movement of the salt water-fresh water interface continued until the pressure on the fresh-water side of the interface equalled the pressure on the salt-water side. As long as the pressures throughout the aquifer remained in equilibrium, no further movement of the interface occurred. Before large-scale withdrawals began, the salt water-fresh water interface was essentially in a state of dynamic equilibrium, and the piezometric surface or water table sloped gently toward the Gulf--that is, the hydraulic gradient was southeastward toward the coast and the fresh water was moving through the aquifer in that direction.

Large withdrawals of ground water in eastern Jefferson County created cones of depression reversing the hydraulic gradient, and water began moving toward the centers of pumpage from all directions, thus initiating the landward movement of salt water. Prior to 1939, industrial and municipal wells in eastern Jefferson County were reported to have become salty (White, 1945, p. 1), and other wells updip became progressively more salty as the salt water continued to move inland. Figure 20 shows the increase in chloride content in water from industrial wells in eastern Jefferson County. Many of the wells shown are used for cooling and are still in use. The slight decrease in chloride content in wells PT-63-01-101 and PT-63-01-102 from 1948 to 1962 is probably due to the decrease in pumping in the area. Intrusion of salt water in eastern Jefferson County has occurred to such an extent that pumping has been reduced to about 5 percent of its maximum.

In some areas, a sand bed that contains saline water lies between sand beds that contain fresh water. White (1945, p. 3) reported such an occurrence in eastern Jefferson County, and it probably occurs in Hardin County. At the salt water-fresh water interface in southeastern Hardin County and northeastern Jefferson County (Figure 14), it is probable that tongues of salt water extend farther inland, forming an irregular front to the interface rather than the smooth one shown. The irregular front is the result of different hydraulic gradients and permeabilities of individual sands.

The mass of saline water is in the form of a wedge increasing in thickness southward. The configuration of the wedge is shown by the relatively closely spaced contours in southeastern Hardin County (Figure 14). The profile of the wedge of saline water is shown in Plate 5.

The saline water may be expected to advance into Hardin County because of current large withdrawals of fresh water in the city of Beaumont well field near Loeb. A new hydraulic gradient thus has been established, and water is moving toward the wells from all directions. The increase in gradient is indicated by the reduction in head of well LH-61-55-502, 1,017 feet deep, about 1 mile south of the city of Beaumont well LH-61-55-204, which was placed in production in March 1960. Sometime after December 21, 1959, presumably after March 1960, well LH-61-55-502, originally a flowing well, stopped flowing, and in August 1962, the water level was 2.49 feet below the land surface. Also, the chloride content in well LH-61-55-502 increased from 65 ppm on April 8, 1942, to 83 ppm on August 23, 1962. On August 5, 1953, the chloride content was 69 ppm. The 4 ppm increase in chloride from 1942 to 1953 probably is not significant. The large increase from 1953 to 1962, however, probably is related to the heavy withdrawal of water in the city of Beaumont well field, and thus to an actual updip movement of the saline water.

Upward Movement Through Underlying Sediments

The possibility of serious salt-water contamination by upward movement through the sediments underlying the fresh to sightly saline water is remote in Hardin County at the present stage of development. One reason is that very few water wells are drilled deep enough to be screened near the base of the fresh to slightly saline water. However, the possibility for upward movement of salt

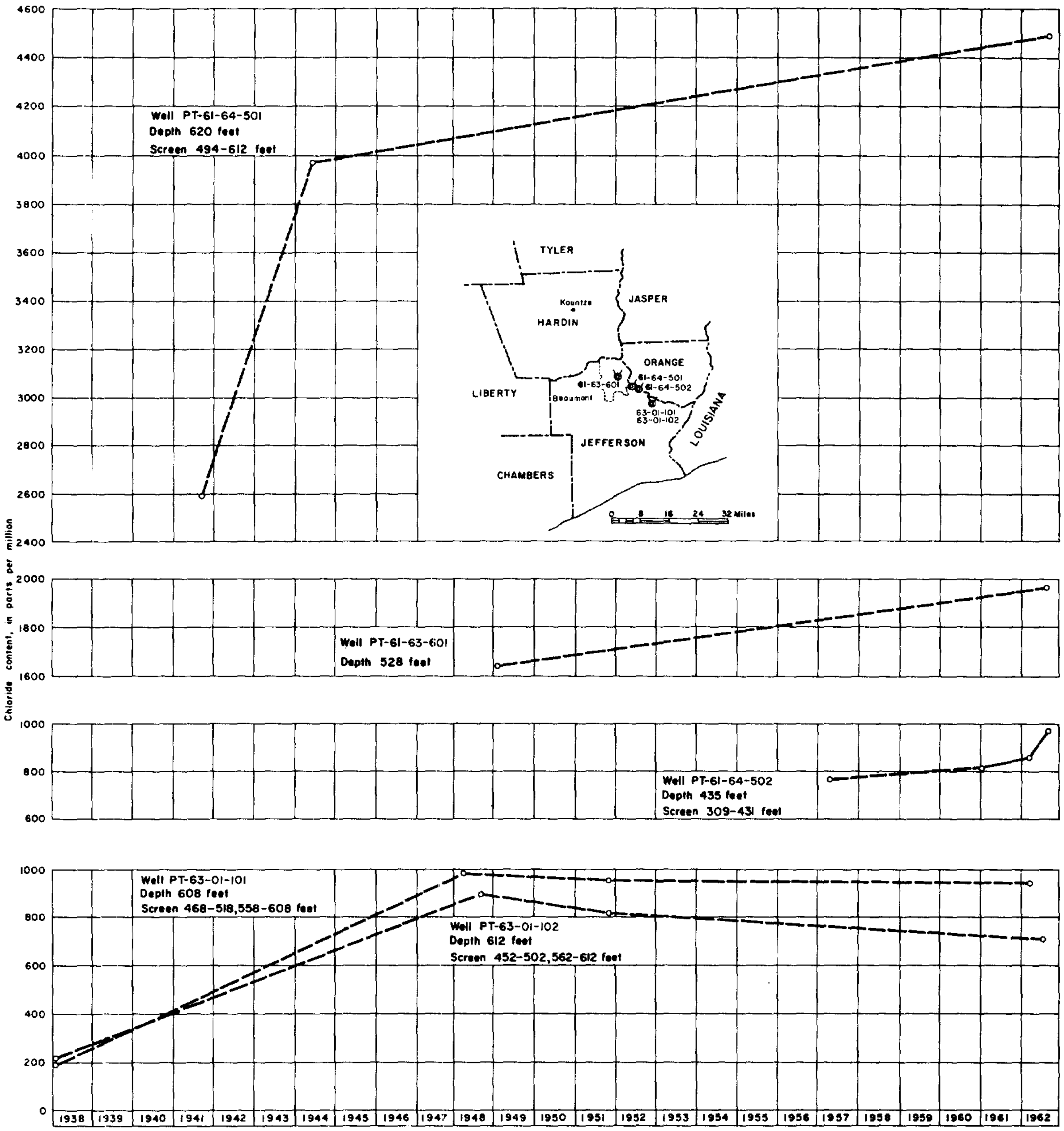

Figure 20

Changes in Chloride Content of Water from Industrial Wells, Jefferson County

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water would be increased greatly if water wells were drilled and screened deep enough to cause the underlying salt water to "cone upward" as a result of steep vertical hydraulic gradients. This has not happened, however, in the deepest known water well in Hardin County. Well LH-61-45-201, 1,953 feet deep, was drilled in 1912 and has a potential natural flow of about 500 gpm. The well is producing from a gravelly sand estimated to be from 100 to 150 feet above the base of the fresh to slightly saline water. Analyses of the water from the well show little change in quality from 1942 to 1953.

The geologic sections (Plates 5 through 8) reveal that as much as 200 feet of relatively impermeable sediments underlie the base of the fresh to slightly saline water in Hardin County. In some places, however, lesser amounts or none at all protect the fresh to slightly saline water from the underlying water. The zone of slightly saline water is noticeably absent in most places on cross sections C-C' and D-D' (Plates 7 and 8), fresh water directly overlying the sediments containing moderately to highly saline water.

Salt Domes

Shallow salt domes--Batson, Saratoga, and Sour Lake--are possible sources of contamination of fresh ground water in Hardin County. Possible avenues of conduits for upward migration of salt water from deep-seated formations exist in the deformed strata adjacent to the domes.

The strata may be arched gently or steeply; they may be ruptured and pierced by the salt; they may be faulted either radially, tangentially, or across the dome; or they may be deformed by various combinations of these. Normally the strata are upwarped adjacent to the salt core; the strata may be vertical or overturned. Thinning is commonly associated with arching of strata close to and around the domes; in some instances, it may amount to more than half the thickness of an individual sequence some distance away. Suman (1925, p. 272) states that "the Columbia and Lafayette" (Lissie Formation, Willis Sand, and Goliad Sand) sand and gravel covering and surrounding the Saratoga salt dome lap up on the edge of it and thicken markedly away from the center of the dome. Suman states also that the Fleming Formation is about 700 feet thick in the center of the field but appears to thicken to about 1,200 feet on the flanks. In the Batson area, Sawtelle (1925, p. 1279-1280) states that the wells off the dome show 1,000 feet of Lafayette and under this from 1,200 to 1,800 feet of Fleming. On top of the dome, the units are thinned and compressed. Compression of the beds over the domes may result in a reduction in porosity and permeability, and, hence, inhibit the circulation of water.

Although faulting is a common associate of salt domes, the unconsolidated sediments probably would respond to faulting in a manner approximating plastic flow, and it seems unlikely that openings large enough to permit passage of appreciable quantities of ground water could exist in the fault planes. Jones, Turcan, and Skilbitzke (1954, p. 97-99) state, "The salt mass of a piercement-type dome generally is tightly sealed from ground water in the beds penetrated. Fault gouge and crushed and altered rock blanket the plug. Steeply upturned pinched off beds abut it. Therefore, the principal hydrologic effect of the salt domes is a function of the thinning of the overlying beds and the faulting and folding they produce, rather than an effect on the quality of the water in the adjacent beds." They also point out as an example that the displacement of beds in the fresh-water section of the Hackberry dome in northern Cameron

Parish, Louisiana, has exceeded 800 feet, and there has been a marked effect on the movement of ground water.

Ground water, however, is directly involved in the shaping of the salt mass and principally in the formation of the caprock. The sequence of events that probably takes place is best summarized by Taylor (1938, p. 108-112). He says, in part:

> "1. Intrusion of the salt plug into a zone of active water circulation, probably up to within a few hundred feet of, but not to the surface, ...where intrusion did not bring the salt into the zone of active water circulation, caprock would be thin or wanting...." [This is apparently what has happened at the Arriola salt dome 4 miles northwest of Loeb where the top of this intermediate-depth dome is 3,800 feet below sea level, well below the base of actively circulating fresh ground water. The Arriola salt dome, thus has no caprock (Murray, 1961, p. 271).] "2. Rapid solution of the salt taking place with the greatest rapidity at the apex of the cone-shaped salt plug. Cementation of the surrounding sediments would take place at this stage. Anhydrite sand would begin to accumulate in irregular pockets or solution cavities in the salt surface. Waters moving up the sides of the salt plug would effect some solution and residue would also accumulate on the flanks; false caprock would also begin to form at this time." [Anhydrite and calcite zones have been reported to extend as much as 5,000 feet down the flanks of the salt stock, thus acting as a shield that retards solution of the salt mass by ground water.] "3. Gradual truncation of the top of the salt plug, decapitating the folds in the salt and forming a solution table, with the anhydrite sand derived from the salt accumulating on it,.... 4. Beginning of the compaction of the caprock as a result of occasional collapse of the false caprock and upthrust of the salt.... 5. Continued solution of the salt [by ground water] with the upthrust of the salt plug compensating for the salt removal, or with upthrust lagging behind solution. The upper part of the caprock and that along the flanks would be repeatedly broken and re-cemented. 6. Entrance of altering solutions and inauguration of the transition zone in which anhydrite alters to gypsum and both in turn alter to calcite and sulphur, with the relict anhydrite structure retained. 7. Transgression of the transition zone downward, escape of hydrogen sulphide or its oxidation to sulphur in place or within the overlying caprock, and deposition of calcite." [Hydrogen sulfide is common in much of the fresh water at Saratoga, being in greatest concentrations in the southwest quadrant of the salt-dome area. Suman (1925, p. 279) reported the occurrence of hot black sulfur in the caprock.] "Caverns develop in the upper calcite zone owing to active circulation of ground water and possibly as a result of removal of sulfur and collapse of the lower part because of the solution of salt." [The original subsidence at Sour Lake could have been caused at this stage of development.] "8. Cessation of caprock growth due to quiescence of the salt plug and the development of a seal that retards circulation of water."

It thus appears that circulating fresh ground water dissolves a portion of the salt after the salt mass reaches the zone of circulating fresh water. In the incipient stages of the formation of the caprock by the dissolving action of fresh ground water, salt domes are a source of contamination of ground water. However, by the very action of the ground water that forms the caprock, it ultimately becomes a seal retarding the solution of additional salt by the circulating ground water.

Although there is little direct evidence of the salt stock presently contaminating the ground water in the salt-dome areas, the ground water overlying the Batson, Saratoga, and Sour Lake domes, nevertheless, is more highly mineralized than ground water at greater distances from the domes.

Abnormally high temperatures of ground water commonly occur in the vicinity of salt domes. This greater-than-normal temperature gradient is not clearly understood, but could be the result of an upward migration of deep-seated water along upturned or vertical strata. Such upward migration of deep-seated water, if saline, could be a source of contamination to the fresh-water sands. The high temperatures of ground water around salt domes also may be explained by the relatively high heat conductivity of salt as suggested by A. G. Winslow (oral communication, 1963). Thus, the salt mass may be conducting heat from deep-seated sources and dissipating the heat to the surrounding sediments.

Examples of deteriorating quality of ground water near salt domes are revealed by the following analyses: Well LH-61-44-702, 1,500 feet deep, 1.3 miles northeast of Batson townside and on the northeast flank of the dome, showed an increase in chloride content from 110 ppm on April 16, 1942, to 135 ppm on April 19, 1962. This is an increase of 1.25 ppm per year. At Saratoga, well LH-61-44-918, 384 feet deep near the top of the dome, had a chloride content of 108 ppm on April 30, 1942, and 20 years later on May 10, 1962, had a chloride content of 135 ppm. This represents an increase of 1.35 ppm per year. At Sour Lake, well LH-61-53-915, 60 feet deep, 0.8 mile east of Sour Lake, is on the southeast flank of the dome; the chloride content in this well on May 2, 1942 was 439 ppm and on August 17, 1962 was 508 ppm. This is an increase of 3.45 ppm per year.

The change in chloride content of the city of Sour Lake wells from 1941 to 1962 is shown graphically in Figure 21. The two old city wells, 117 feet deep, showed an increase in chloride content from 209 ppm in September 1941 to 830 ppm in September 1949, an increase of 77.6 ppm per year. After the abandonment of the wells, two more wells of different depths were drilled about 1 mile south of Sour Lake. Water from well LH-61-53-928, 812 feet deep, increased in chloride content from 188 ppm in January 1952 to 645 ppm in August 1962, an increase of 45.7 ppm per year. Water from well LH-61-53-929, 224 feet deep, showed a slight increase in chloride content from 181 ppm in January 1952 to 212 ppm in August 1962, an increase of 3.1 ppm per year.

In general, the changes in quality and movement of ground water around salt domes are not clearly understood and some of the apparent contamination may be the result of a lack of adequate circulation or inadequate protection of fresh water from oil-field operations rather than direct contamination from the salt mass or underlying salt-water sands.

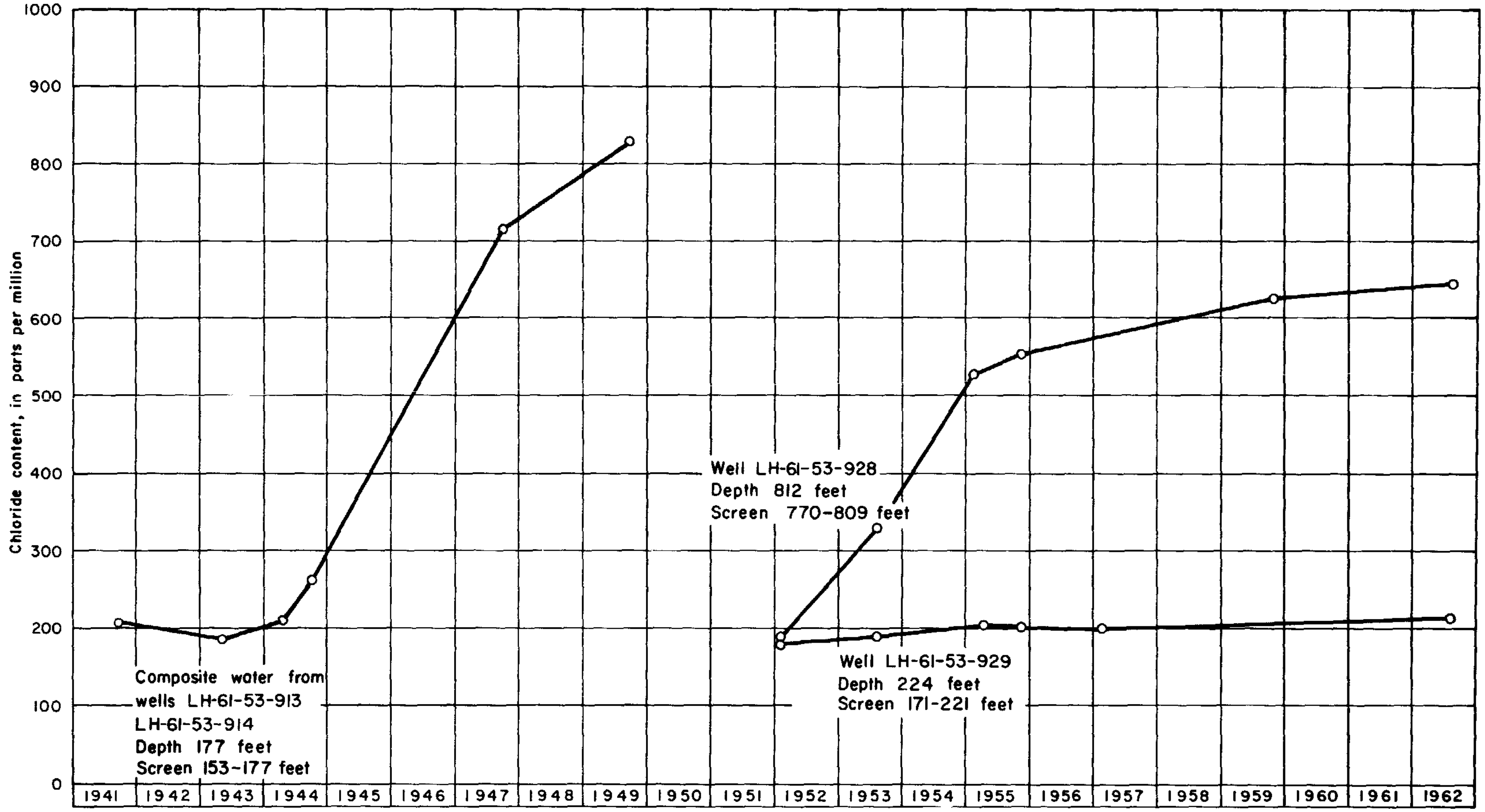

Figure 21

Changes in Chloride Content of Water from City of Sour Lake Wells, 1941-62

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Oil-Field Operations

The disposal of oil-field brines is another possible source of contamination of the ground water in Hardin County. Sundstrom (1941, p. 2) stated that the contamination of the water supply at Beaumont was from that part of the East Texas oil field within the Neches River drainage basin. At that time, a considerable number of oil wells were producing salt water that was draining into a tributary of the Neches River to such an extent that it had caused the waters of the river at the diversion plant of the city of Beaumont to become salty.

According to the East Texas Salt Water Disposal Co. (1958, p. 5), in 1939 an injuction suit was brought against many oil operators in the East Texas oil field to prevent salt-water pollution of the Neches River watershed. This suit foretold the end of haphazard disposal of salt water or any disposal that would contaminate fresh water. Bigger salt-water pits were constructed and other methods of disposal were attempted, but none of them were successful except, perhaps, as a temporary method, other than injecting into an underground formation. The subsurface disposal of the salt water offered the greatest possibility of an effective solution of the problem of contamination.

Brine placed in surface pits in Hardin County, at least in part, seeps into the ground and may contaminate the shallow aquifers. The average yearly potential evaporation rate of about 47 inches is offset by an average annual precipitation of about 52 inches and cannot be depended upon to dispose of the large quantities of brine continuously being produced. When the brine percolates downward to the water table, it may be diluted in somewhat the same manner as it would in a lake or stream. Lateral mixing, however, is different from that in surface waters, because ground-water flow is laminar whereas surface-water flow is generally turbulent. Thus, a slug of brine reaching a water-bearing sand may move in a well-defined streamline with a minimum of lateral or vertical diffusion and dilution (California State Water Pollution Control Board, 1952, p. 47).

The low velocity of movement of ground water causes two significant conditions in the aquifer. First, the brine that is being added to the ground at one point may not affect the quality of the water in wells nearby for many years; consequently, no complaints may be registered and no one may be aware of the damage being done. Second, when the contamination is finally discovered or when the quality of water supplies is degraded, the damage cannot be immediately rectified merely by stopping the contamination at its source, because purification by leaching and dilution will require a longer time than the period of original pollution.

An efficient means of retaining brines in salt-water reservoirs was noted in the Sour Lake oil field. The reservoirs were constructed on a clay foundation 15 to 19 feet thick, which is underlain by 1 to 6 feet of sand containing ground water. In order to prevent any seepage of brine into the water-bearing sands, the reservoirs were lined with impervious plank-like material consisting of asphalt-saturated paper. The joints were covered with heavy asphalt-saturated paper or felt bonded to the planks with asphalt. After construction and preliminary use, the lining was covered with about 1 foot of soil. This was found necessary because of melting of the asphalt over the seams apparently due to concentration of the sun's rays by the brine acting as a prism, the resulting heat loosening the seams to such an extent that the planks rose to the surface of the brine. The layer of soil may be considered an essential part of the construction. Gravel conduits beneath the reservoirs lead to a sump equipped with a pump, which, if there should be leakage, would automatically return the brine to the reservoir. The pumps have not been used as there has been no seepage since construction in 1954. This type of construction and installation has made the reservoirs 100 percent effective in retaining the brine and, thus, is an efficient and adequate means of preventing salt water in open reservoirs from contaminating shallow ground-water sands. The brine retained in the reservoirs is later used in an industrial process.

Fresh-water beds may be contaminated through defective wells. In some areas, it is necessary to drill through salt-water sands in order to penetrate fresh-water aquifers. If the wells are not properly constructed, or if the casings develop holes because of corrosion, salt water under greater pressure may enter the casing and circulate into the aquifers. This type of contamination is common and has been noted in many areas (Sayre, 1937, p. 77). It has not been observed in Hardin County, but it may be the cause of some of the contamination in some of the old oil fields.

Aquifers also may be contaminated by improperly cased oil wells. The oil and Gas Division of the Railroad Commission of Texas is responsible for the proper construction of oil wells and in the last few years the Texas Water Commission has furnished ground-water data to oil operators and to the Railroad Commission in order that all fresh to slightly saline water sands may be protected. The Railroad Commission requires fresh-water strata to be protected by casing and cement.

Figure 22 illustrates the approximate depth of the fresh to slightly saline water sands in some of the oil fields in Hardin County, and the amount of cemented casing required, according to published field rules of the Railroad Commission. No cases have been determined definitely where salt-water contamination has resulted from inadequately cased oil wells in Hardin County. Such contamination, however, is suspected in the salt dome oil fields, which were extensively developed before casing regulations went into effect. Figure 22 indicates that at least in some of the fields the fresh to slightly saline water sands are not adequately protected.

Land Subsidence

Poland and Davis (1956, p. 294-295) have summarized 10 possible causes of land subsidence. The major ones that apply to the Hardin County area are decline of pressure head in artesian aquifers and decline of pressure in oil zones due to removal of oil and gas. As the pressure head declines in the sand beds of an aquifer, the load of the overlying beds is increased because a part of the load is supported by the artesian pressure head, although most of it is supported by the skeleton of the aquifer (Meinzer, 1925, p. 90-93). The land surface subsides because the beds are not competent to carry the increased load and are thus compacted. Such subsidence generally is small, perhaps only a few tenths of a foot for each several hundred feet of decline of pressure head. However, the intervening clay beds in the aquifer also contain water under artesian pressure that, before pumping, was nearly in equilibrium with the artesian pressure in the sand beds. As artesian pressure declines in the sand beds, some of the water is forced out of the clay into the sands. As the pressure head in the clay is lowered and more of the load is transmitted to the particles comprising the clay beds, plastic deformation and subsidence takes place.

When the fine-grained materials such as clay compact, the volume of pore space lost by compaction is equal to the volume of subsidence. Thus, the volume

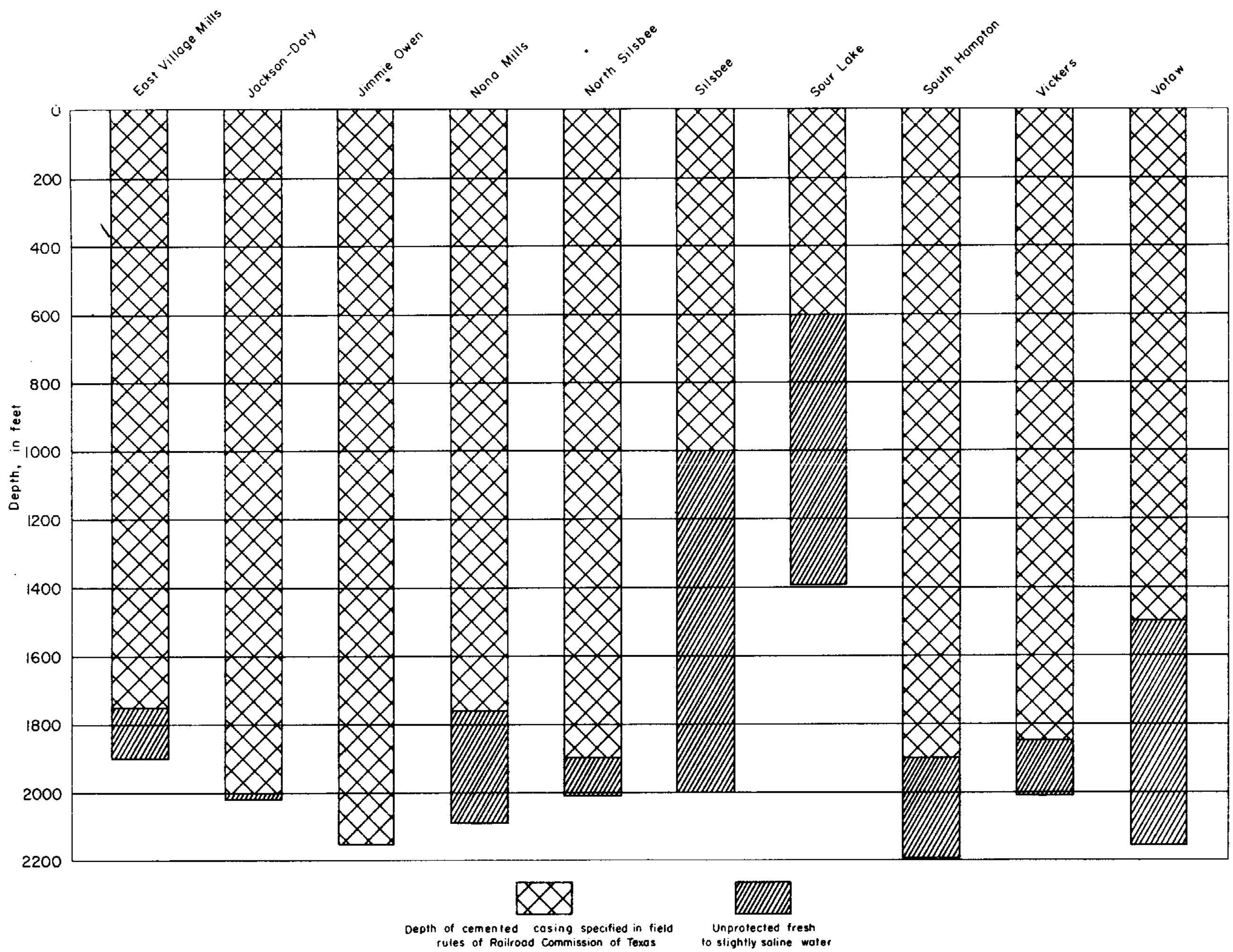

Figure 22

Comparison Between Depth to Base of Fresh to Slightly Saline Water Sands and Amount of Surface Casing Required in Oil Fields in Hardin County

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of water yielded from storage in the clay can be determined by computing the volume of subsidence. For example, 1 foot of subsidence yields 1 foot of water. Based on computations relating subsidence to ground-water withdrawals in the Houston district, an area similar hydrologically to Hardin County, (Winslow and Wood, 1959, p. 1034), about 22 percent of the total ground water pumped from an active area of subsidence came from the clay beds.

Major subsidence of the land surface related to ground-water withdrawal has been reported in recent years at several places in the United States and in other parts of the world. The most extensive areas of subsidence in the United States are in California and in the upper Gulf Coast region of Texas. In California, Poland (1960, p. 324) reported a maximum subsidence of 20 feet affecting 2,000 square miles in an irrigated district. The region referred to in Texas comprises about 7,200 square miles and embraces the most heavily populated and industrialized parts of Texas where much of the industrial and municipal water is obtained from wells. Subsidence is reported in all or parts of the following counties: Harris, Fort Bend, Waller, Brazoria, Galveston, Liberty, Chambers, Orange, and Jefferson. According to Winslow and Doyel (1954, p. 419-420) in the northern part of the Houston-Galveston region where the aquifers are mainly sand, the ratio between the subsidence of the land surface and the decline of artesian pressure head is about 1 foot of subsidence to 100 feet of decline. In the southern part of the region, where the fresh water-bearing formations contain a larger percentage of clay, the ratio is greater.

Another center of land subsidence is in eastern Jefferson County and parts of Orange County, where there is a concentration of industry. The total subsidence here is not as great as in the Houston-Galveston area; however, a rather large area has subsided at least 0.25 foot during the period 1918-54. According to Winslow and Wood (1959, Fig. 3), some land subsidence possibly has occurred or is still occurring in the irrigated district in the southwest corner of Hardin County.

The land surface is subsiding in Jasper County at the East Texas Pulp and Paper Co. plant site, 7 to 8 miles due east of Silsbee, where the well field consists of 8 wells about 700 to 1,400 feet deep. These large-capacity wells drilled in 1953 and 1954, yield a total of about 20 mgd. Bench marks and precise instrumental leveling have shown in April 1960 a maximum subsidence of 1.02 inches at a site north-northeast of the plant, 0.73 inch inside the plant, and 0.42 inch at a site south-southwest of the plant (written communication, Louis Freeman, East Texas Pulp and Paper Co., 1962).

The city of Beaumont well field at Loeb at the end of 1962 consisted of two large-capacity wells about 800 feet deep. Each well is expected to pump about 3,500 gpm, or 5 mgd, or a total withdrawal of about 10 mgd. The wells were drilled in 1958 and 1962 and no noticeable effects of subsidence in the Loeb area have been reported.

Land-surface subsidence should be expected in Hardin County following large-scale ground-water development. The rate of subsidence might be similar to that in the Houston-Galveston area as the two areas are similar hydrologically. Undesirable local effects of subsidence such as have been experienced at Texas City in Galveston County might be avoided by spacing centers of withdrawal through as wide an area as possible. In this way, the subsidence might be kept on a regional basis with little or no appreciable difficulties.

The decline of pressure in oil zones due to removal of oil and gas is another cause of land subsidence. This type of land subsidence has been observed at Sour Lake, where a depression was formed on October 9, 1929, and enlarged on October 12, 1929 by a second smaller depression. The circular depression was about 1,500 feet in circumference and about 37 feet deep in 1929. The lake filling the depression in 1962 was estimated at about 200 feet in diameter; the maximum depth of the water was reported to be in excess of 50 feet. The lake is reported to have never been dry since its formation and the water surface may represent the water table.

Sellards (1930, p. 12-13) described the Sour Lake subsidence, as follows:

> "As already stated the sink formed on October 9. That underground disturbance, however, had begun earlier is shown by the behavior of two wells. On October 8, Terry Oil Co. well no. 1, which was then producing from 90 to 100 barrels of oil per day, was found at 8:30 a.m. to be pumping water. At that time, the Texas Co. No. 150, offsetting the Terry well, was producing oil, but at 9:00 o'clock of the same day, the Texas Co. well was found to be producing water. In the afternoon of this day, the piping in both wells was raised 5 feet without, however, restoring the flow of oil. It is reported also that late Tuesday afternoon, a salt water ditch, which crosses the area where the sink formed, was seen to be spilling water over the sides. These observations indicate that as early as the morning of the 8th, earth was subsiding into an underground cavity sufficient to raise the underground water level near the sink, and late on that day to effect the surface elevation. Almost one week previous to the formation of the sink, the flow of gas increased in Texas Co. well No. 260. This well is located 1,000 feet south and 200 feet east of the sink."

The cause of the formation of the sink will, perhaps, remain to a degree a matter of speculation. It seems probable that the cause of the formation of the sink was the removal of large quantities of oil (73 million barrels) and brine from the caprock from 1902 to 1929. The most logical explanation is that a cavity developed in the salt body which continued enlarging until a thin porous and cavernous caprock collapsed, permitting subsidence of the overlying sediments (Sellards, 1930, p. 28).

Subsidence also may be caused naturally. The presence of the original sour lake at the crest of the salt dome is an example of natural subsidence. Springs and oil seeps were present in the old original sour lake as early as Pleistocene time as shown by the fossil bones and teeth of Pleistocene animals found in asphalt pits around the lake. The natural subsidence probably was caused by sagging of the caprock following solution of salt along the surface of the salt stock and salt table.

The sour lake, only a few feet deep, is supplied by springs of saline water, presumably affording an outlet for soluble salts and gas originating in the caprock. Emission of gas, probably hydrogen sulfide, was observed in the lake. Two chemical analyses were obtained of the lake water at different times and different stage levels. A field determination of chloride was made on June 16, 1962 when the lake level was near normal stage and showed a concentration of 2,360 ppm.

On August 27, 1962, when the lake was about 1 foot lower than in June and nearly dry because of an extended period of deficient rainfall and high evaporation, a sample was taken and a complete analysis was made (Table 11). This analysis indicated a chloride content of 4,090 ppm, an increase of 1,730 ppm. Both samples were taken at the bottom of the lake and at the same place to avoid a possible density stratification. The increase in chloride is believed to be due to a concentration of soluble salts by evaporation or an absence of dilution by rainfall, or both. No artificially produced salt water has access to the lake; the only increment to the water in the lake (excepting the springs) is rainfall.

A water well, LH-61-53-814, 2,100 feet southwest of the lake and 57 feet deep, showed from an analysis of the water a chloride content of 1,320 ppm, the water having a strong odor of hydrogen sulfide. Because the elevation of the water level in the well is lower than the lake level, the saline water in the lake probably is contaminating the water sand from which the well produces and may be a source of contamination to the water sands northeast of the lake in the direction of the drainage.

Subsidence can have both undesirable and beneficial effects. The undesirable effects may include protruding well casings, broken pipelines, reversed flow in sewage lines, cracked foundations of buildings, and possibly failure of wells, damaged highways, and subjection of land to possible flooding. The threat to structures in an area of subsidence is a matter of concern to industry and plans for construction should be modified accordingly.

The effect of subsidence that may be considered beneficial is that perhaps more than one-fifth of the water made available to wells is derived from compaction of the fine sediments as the land subsides. This increment of water tends to stabilize water levels and eliminate, at least temporarily, the necessity of lowering pumps and, thus, avoiding greater water-lifting costs.

AVAILABILITY OF GROUND WATER FOR FUTURE DEVELOPMENT

Water is universally classed as a renewable resource. Renewability is inherent in the hydrologic cycle, and is obvious in the continuous replenishment of soil moisture and streamflow by precipitation. Ground water also is recognized as generally renewable because practically all the usable supplies are of meteoric origin. Detailed studies of many areas have traced ground-water supplies to the source areas where there is conclusive evidence of recharge by precipitation or streamflow, or both, and no good examples can be cited of fresh ground-water resources that are truly isolated and shut off from any possible replenishment.

In terms, however, of actual quantities of water, most of our ground-water resources are only renewable over long periods of time. If the aquifers in Hardin County could be drained completely, it would require centuries for them to be refilled as only a fraction of the annual precipitation would go toward their replenishment. Thus, the renewable ground water for practical purposes perhaps should not be considered the accumulated resource but only the recharge plus the rejected recharge on the outcrop and the amount that could be salvaged from evapotranspiration. For practical purposes, the tremendous quantity of water in storage is available for one-time use only.

Perennial supply of ground water, or ground water that is available on a continuous basis without excessively lowering the water levels, is that which does not exceed the capabilities of replenishment. Sound ground-water management and planning recognize the consequences of overdevelopment and do not count on more water than is available.

The availability of water for future development in Hardin County is treated separately by areas--namely, the area excluding the salt domes and the areas of the salt domes. Availability of water in salt-dome areas though relatively insignificant regionally is complex and unique and will be given special treatment.

Hardin County (Excluding Salt-Dome Areas)

The surface of the saturated zone of fresh water is everywhere less than 50 feet below land surface in Hardin County. In many places, the water table is at the surface or from 10 to 20 feet below the land surface. The approximate altitude of the base of the fresh to slightly saline water differs from place to place within the county (Figure 14).

The base of the fresh to sightly saline water ranges in depth below sea level from less than 1,000 feet in the southwest part of the county to at least 2,272 feet, being deepest in the Kountze and Silsbee areas where -2,200-foot contours enclose areas of 4 to 6 square miles. The -1,800 to -2,100-foot contours enclose perhaps the largest area of the county, mostly the central part extending in a northeast-southwest direction.

When viewed on a regional scale (Wood, 1956, Fig. 18), this trough of deep fresh to slightly saline water in the central part of the county is bordered on the northwest and southeast by generally decreasing depths below sea level of fresh to slightly saline water. The existence of this trough of deep water, conforming roughly to the strike of the geologic formations, is related to the regional geology and to the flushing of the aquifers. The Miocene, Pliocene, and Pleistocene deposits underlying Hardin County are favorable reservoirs for the deep occurrence of fresh to slightly saline water because of their thickness, lithology, and permeability, which allow relatively good circulation of water to great depths. The trough of deep water is favorable for the development of relatively large yields of water from wells because of the relatively high permeability of the sand and gravel beds and because great thicknesses of sand and gravel beds are available for screening in wells. Northwest of the trough, the Miocene, Pliocene, and Pleistocene deposits thin to extinction and the older formations, because of their lithology and hydraulic characteristics, are not so favorable for the deep occurrence of fresh to slightly saline water. Southeast of the trough in central Hardin County, the wedge of saline water thins the zone of fresh to slightly saline water in that direction. Thus, Hardin County, particularly the central part, is favorably located for the availability of large volumes of fresh to slightly saline water.

The isopachous map (Figure 23), which shows the actual thickness of sand and gravel containing fresh to slightly saline water, may be used in computing the amount of ground water in transient storage and is useful also in showing the areas that are most favorable for ground-water development. The 600-foot isopachous line encloses less than 2 square miles in the extreme northwestern part of the county north of Votaw, less than 1 square mile south of the Sour Lake inset, and less than 1 square mile southeast of Loeb. The 1,500-foot isopachous line includes less than 1 square mile in the extreme northeastern part of the county. The largest area is enclosed by the 1,000 to 1,100-foot isopachous lines, this area trending roughly northeast and southwest through the central part of the county. The 1,000-foot thickness is about average for the county. In similarity to the regional trends of the approximate altitude of the base of the fresh to slightly saline water, the approximate thickness of sand decreases northwestward and southeastward on a regional scale (Wood, 1956, Fig. 19).

The ratio of sand to clay in the fresh to slightly saline water zone increases eastward. Thirty-five to 65 percent sand is present near the Hardin-Liberty county line, while 50 to 80 percent sand is present near the Hardin-Jasper-Orange county line.

The volume of fresh to slightly saline water in transient storage in the Gulf Coast aquifer in Hardin County is computed to be 160,000,000 acre-feet. However, only a small fraction of the water stored in the aquifer is recoverable or available for development by known methods at present costs.

A principal factor affecting the availability of large ground-water supplies is the ability of the aquifer to transmit water to wells. The transmissibility of the aquifer is not constant throughout Hardin County, but varies from place to place with changes in the lithology and thickness of the aquifer. An analysis of 20 pumping tests in Hardin and extreme western Jasper County (Table 2), when used in conjuction with maps showing the approximate base and thickness of the fresh to slightly saline water sands (Figures 14 and 23), indicate that the transmissibility of the full thickness of the Gulf Coast aquifer is between 100,000 and 200,000 gpd per foot in most of Hardin County. This relatively large transmissibility is comparable to that in the heavily pumped Houston district and indicates that the Hardin County area could support a development similar to that at Houston.

To compute the amount of ground water available from the Gulf Coast aquifer, several assumptions were made. For the purpose of this report, the amount of ground water available for development is construed to mean water of a quality suitable for municipal use and for use by most industries and irrigators that can be obtained on a continuous basis with pumping levels not to exceed the following depths below land surface: 100, 200, 300, or 400 feet. In a broader sense, water available for development, or safe yield of an aquifer, is considered by Stringfield and Cooper (1951, p. 803) as the maximum rate at which ground water may be withdrawn without depleting the supply or harming either the aquifer or the quality of the water. Meinzer (1932, p. 99, 119-120) referred to the safe yield of an aquifer as the practicable rate of withdrawing water from it perennially for human use. He goes on to say that the safe yield "...may be either greater or less than the rate of natural recharge or discharge determined before heavy withdrawals are begun. It may be less because natural discharge cannot be wholly prevented, even by heavy withdrawals through wells. On the other hand, it may be greater because of artificial increase of the rate of recharge."

For purposes of computation in this report, an east-west line of discharge was postulated more or less parallel to the outcropping formations. The line of discharge was 33 miles long, the average width of the county, and was about 4 miles north of Kountze. The line averages 25 miles from an assumed line source of recharge. The line source of recharge was assumed the same length as the line of discharge and was parallel to the outcropping formations in central Tyler County. The quantity of water available from storage as the aquifer is dewatered from the line source of recharge and the fresh water-salt water interface in northern Jefferson County to various water levels along the line of discharge was computed based on the following assumptions:

1. Water levels will be lowered to the 100, 200, 300, and 400-foot depths below land surface along the line of discharge.

2. While the aquifer is being dewatered, recharge is only along the effective line source of recharge parallel to the outcrop.

3. The altitude of the water levels is the same at all points along the effective line source of recharge; the altitude of the water levels is the same at all points along the fresh water-salt water interface in northern Jefferson County; and the altitude of the water levels is the same at all points along the line of discharge.

4. The coefficient of storage is 0.15.

5. The average width of Hardin County is the effective width of the storage area.

The transmission capacity of the Gulf Coast aquifer from the line source recharge to the line of discharge was computed based on the following assumptions:

1. Water levels will be lowered to the 100, 200, 300, and 400-foot depths below land surface along the line of discharge.

2. Recharge to the aquifer is only along the effective line source of recharge parallel to the outcrop.

3. The altitude of the water levels is the same and remains the same at all points along the 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 after dewatering to the 100, 200, 300, and 400-foot depths below land surface at the line of discharge.

5. The hydraulic gradient is a straight-line slope 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. The average coefficient of transmissibility of the Gulf Coast aquifer is 150,000 gpd per foot.

7. 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 predetermined gradients.

8. The rate of transmission of water through the aquifer is the average of the rate based on the present hydraulic gradient and the rate based on the maximum hydraulic gradients that can be attained with water levels at 100, 200, 300, and 400 feet below land surface at the line of discharge.

9. The average width of Hardin County is the effective width of the aquifer through which water is transmitted.

The time taken to dewater the Gulf Coast aquifer from the line source of recharge and the fresh water-salt water interface in northern Jefferson County to various water levels along the line of discharge is based on the following assumptions:

1. The quantity of ground water in storage from land surface to the depths below land surface of 100, 200, 300, and 400 feet is as previously computed.

2. The rates of withdrawal are arbitrarily assigned and range from 10 to 1,000 mgd.

3. The amount of recharge is sufficient to supply the water that can be transmitted to the line of discharge at the predetermined gradients.

4. The rate of transmission of water through the aquifer is the average of the rate based on the present hydraulic gradient and the rate based on the maximum hydraulic gradients that can be attained with water levels of 100, 200, 300, and 400 feet below land surface at the line of discharge.

Table 6 indicates the time, in years, at various pumping rates to dewater the Gulf Coast aquifer from the line source of recharge to depths of 100, 200, 300, and 400 feet below land surface at the line of discharge. Table 7 indicates the quantity of ground water that can be obtained on a continuous basis without exceeding pumping levels of 100, 200, 300, and 400 feet below land surface.

Table 6, for instance, indicates that at least 40 mgd could be pumped indefinitely without dewatering the aquifer to 100 feet below land surface along the assumed line of discharge. The total pumpage in 1962 in Hardin County for all uses was 9.8 mgd, which is the equivalent discharge of 68 wells equally spaced along the assumed line of discharge and each pumping 100 gpm continuously. By increasing the pumpage to 50 mgd, 474 years would be required to dewater the aquifer to a pumping level of 100 feet; the same results could be attained in 66 years if the pumpage was increased to 100 mgd, approximately 10 times the present pumpage.

At least 60 mgd could be pumped indefinitely without dewatering the aquifer to 200 feet below land surface along the assumed line of discharge. Pumpage in excess of about 60 mgd would dewater the aquifer to the 200-foot level only in the course of many years.

The 400-foot pumping level could be attained only by pumping in excess of about 100 mgd. One hundred and seventy-three years would be required to lower the pumping level to 400 feet at 200 mgd, an equivalent of 139 wells equally spaced along the assumed line of discharge and each pumping 1,000 gpm.

Table 6 should be used in conjunction with Table 7, which is useful in the mature or highly developed stage of development of the Gulf Coast aquifer. Table 6 shows the amount of water that can be pumped from storage in dewatering the aquifer to certain levels along the assumed line of discharge. Table 7 shows the rate of discharge that may be maintained indefinitely after the various levels have been reached along the line of discharge (transmission capacity).

A mature or highly developed stage of ground-water development may be reached after an aquifer has been pumped heavily for a long period of time. As pumping continues, the water levels continue to lower and the cone of depression extends farther and farther from the line of discharge, until it ultimately reaches

Table 6.--Approximate time and pumping rates to dewater the Gulf Coast aquifer from line source of recharge to various pumping levels at line of discharge

Pumping rate		Time in years to reach pumping level			
Million gallons per day	Acre-feet per year	Pumping level 100 feet	Pumping level 200 feet	Pumping level 300 feet	Pumping level 400 feet
10	11,200	∞ [1]	∞	∞	∞
20	22,400	∞	∞	∞	∞
30	33,600	∞	∞	∞	∞
40	44,800	∞	∞	∞	∞
50	56,000	474	∞	∞	∞
60	67,200	211	∞	∞	∞
70	78,500	135	1,060	∞	∞
80	89,700	100	468	∞	∞
90	99,200	82	318	1,840	∞
100	112,000	66	222	690	∞
200	224,000	24	62	107	173
400	448,000	11	25	40	99
600	672,000	7	16	24	34
800	896,000	5	12	18	24
1,000	1,120,000	4	9	14	19

[1] ∞ Infinity (water may be pumped indefinitely without dewatering aquifer from line source of recharge to pumping level at line of discharge).

Table 7.--Approximate quantity of ground water that can be obtained continuously after dewatering the aquifer without exceeding various pumping levels at line of discharge

Pumping rate		Pumping level
Million gallons per day	Acre-feet per year	feet
45	50,000	100
62	70,000	200
80	90,000	300
102	115,000	400

the outcrop or effective line source of recharge. When the hydraulic gradient has steepened sufficiently between the discharge area and the line source of recharge to cause enough water to move to the discharge area to replace the water that is pumped, the water level along the line of discharge ceases to decline and reaches a state of dynamic equilibrium. After the water levels have reached this state of dynamic equilibrium at, for instance, any of the 100, 200, 300, or 400-foot levels, any increased pumping would exceed the transmission capacity of the aquifer at that level and result in immediate declines of pumping levels. For example, the 100-foot pumping level would be exceeded quickly if pumpage was increased above 45 mgd (Table 7).

Of course, the use of Tables 6 and 7 is predicated on the assumptions given on pages 88 and 89 and it is obvious that some of the assumptions could not be met. However, it is believed that the figures given in the tables are of the correct order of magnitude and that the tables can be used in planning long-range, large-scale ground-water developments in Hardin County.

Salt-Dome Areas

The salt-dome areas in Hardin County--Batson, Saratoga, and Sour Lake--are treated separately from the remainder of the county, partly because these areas, though small, are not representative of the availability of ground water for future development for the whole of the county. Nevertheless, the salt-dome areas are important because they are population centers and because the salt domes influence the quality, movement, occurrence, and availability of ground water in their vicinity. The salt-dome areas presented in this report are arbitrarily restricted to 25 square miles; the center of the areas shown on the inset maps are approximately the structural high points on the domes.

Batson

Fresh to slightly saline water in the Batson area is underlain by a mound of more highly saline water and an anhydrite-capped salt stock which is elliptical, the major axis trending in a west-northwest direction. The top of the salt dome is gently undulating and has an area of about 400 acres. The highest point on the caprock is 1,081 feet below the surface. At the -4,000-foot contour on the caprock, the dome is 2 miles long and 1-1/2 miles wide (Sawtelle, 1925, p. 1279).

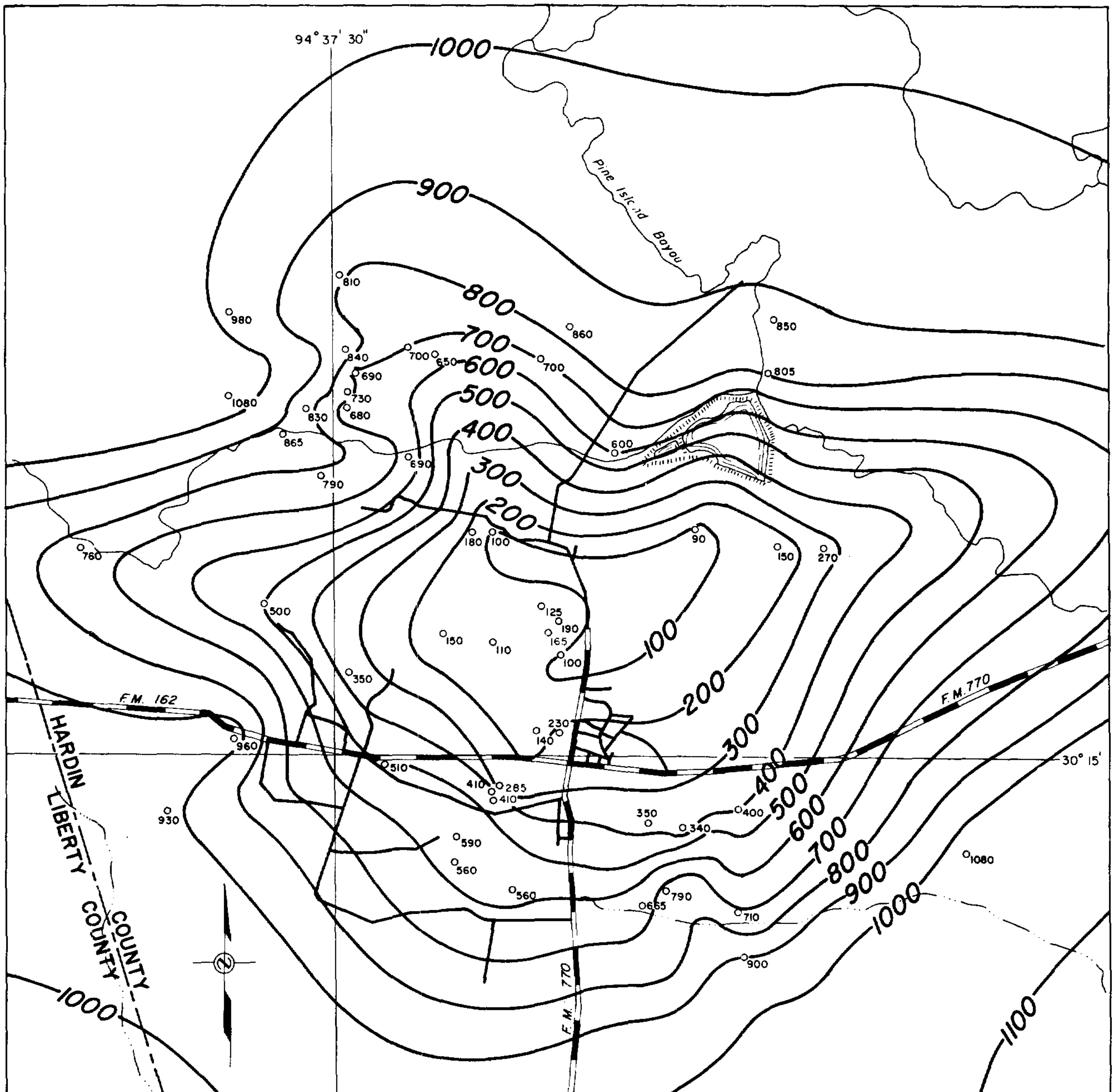
The base of the fresh to slightly saline water ranges from less than 100 feet below sea level at the crest of the dome to more than 2,000 feet on the north flank (Figure 15). The configuration of the base of the fresh to slightly saline water is shown in profile in Plate 7. The interval between the base of the fresh to slightly saline water and the top of the caprock is not constant but ranges from about 1,000 feet at the crest of the dome to about 2,600 to 2,800 feet at the -1,200-foot contour on the top of the caprock. The dip of the base of fresh to slightly saline water is steepest between the -200 and the -1,600 to -1,800-foot contours and is steeper on the north and south flanks than on the east and west flanks. At -1,800 to -2,000 feet, the dip is nearly flat and merges with the regional configuration of the base of fresh to slightly saline water. No evidence of a trough of fresh to slightly saline water, or rim syncline, was noted at Batson.

The approximate thickness of sand containing fresh to slightly saline water ranges from less than 100 to about 1,100 feet (Figure 24). The 100-foot isopachous line encloses about one-third square mile over the crest of the dome. From the crest of the dome, the thickness of sand increases progressively in all directions in a concentric pattern. The 1,100-foot isopachous line is at the extreme southeast corner of the area and includes about a one-quarter square mile area of thickness between 1,100 and 1,200 feet. The 900 to 1,000 isopachous lines enclose about 6 square miles, the largest area. The isopachous map generally corresponds in configuration to the map of the base of the fresh to slightly saline water.

The ratio of sand to clay varies only slightly within the Batson area; 50 to 60 percent sand is about average for the entire area. This ratio of sand to clay is slightly larger than the 35 to 60 percent sand which is typical of the western side of Hardin County, excluding the area of the Batson dome.

Little hydraulic information is available in the Batson area as conditions were unfavorable for pumping tests. Thus, the permeability of the sand and the coefficients of transmissibility and storage are matters of conjecture. Thick zones of sand, however, occur in wells LH-61-51-303 and LH-61-52-135 in cross section C-C' on the west side of the Batson dome from the land surface to 600 feet below sea level (Plate 7).

No large ground-water development exists in the area; most of the withdrawal of water is through small-diameter domestic wells averaging 165 feet in depth. The only large-capacity well is LH-61-44-702, 1.3 miles northeast of the townsite near the salt-water disposal reservoir (Plate 2). The well is reported to be 1,500 feet deep and is shut in by a valve at the well head. The flowing potential of the well in not known but is presumed to be several hundred gallons per minute. A temperature of 97°F was measured at the well head, the highest recorded in Hardin County. The abnormal temperature gradient of 1°F per 54 feet is due to the proximity of the salt dome. A comparison of analyses of the water from this well in April 14, 1942, and April 19, 1962, shows an increase in chloride content from 110 to 135 ppm, an increase or 1.25 ppm per year.



0 1 MILE

Base compiled from topographic maps of the U. S. Geological Survey

EXPLANATION

1200

Line showing approximate thickness of sand containing fresh to slightly saline water, in feet

Contour interval 100 feet

o 790

Well used for control. Number indicates thickness of saturated sand, in feet

Figure 24

Approximate Thickness of Sand Containing Fresh to Slightly Saline Water in the Batson Area, Hardin County

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The volume of fresh to slightly saline water in storage in the sands of the Gulf Coast aquifer in the Batson area is computed to be about 3,600,000 acre-feet. However, only a small fraction of the water stored in the aquifer is recoverable by known methods at present costs. The amount of water in storage per square mile averages 167,000 acre-feet compared to an average of 195,000 acre-feet per square mile for Hardin County (excluding salt-dome areas).

Planning a large development of fresh ground water in the Batson area should proceed with caution. Even though a large amount of fresh to slightly saline ground water is in storage and even though the base of the fresh to slightly saline water extends to more than 2,000 feet below sea level, the presence of saline-water sands a few miles from any proposed well location in the area would present the threat of salt-water contamination.

Any future development of ground water of a considerable magnitude in the Batson area should be based on the following:

1. Exploratory holes should be drilled to determine optimum sand thickness and samples of water should be taken to indicate the quality at each location.

2. The wells should be as far removed from the crest of the salt dome as possible, preferably on the north side in order to intercept the natural southeast flow of fresh water before it reaches the salt dome.

3. The wells should be as shallow as possible in order to increase the distance of the screened portion of the well from the base of the fresh to slightly saline water.

4. Pumping tests should be made upon completion of each production well to determine optimum pumping rates, pump settings, and to indicate the possible presence of hydrologic boundaries nearby such as faults which impede the movement or circulation of water. These data also will determine the correct spacing of future wells.

A moderate to large ground-water supply should be possible without the threat of salt-water contamination for many years if the water supply is properly developed.

Saratoga

Fresh to slightly saline water in the Saratoga area is underlain by a mound of more highly saline water and an anhydrite and gypsum capped salt stock, the highest point on the caprock being about 1,500 feet below the surface. The dome is rather flat and broad, having gently dipping flanks, and is roughly elliptical, its longer axis extending in a general northeast direction. At a depth of 2,000 feet, the dome is 1-1/2 miles across the longer axis. The dip on the caprock from the center of the dome to the -2,700-foot contour on the caprock is gentle, about 10° northeast and about 9° southwest. At the -2,700-foot contour on the caprock about 2 miles from the crest along the long axis, the dip becomes much steeper (Suman, 1925, p. 268).

The base of the fresh to slightly saline water ranges from less than 700 feet below sea level at and near the crest of the dome to between 2,200 and 2,300 feet on the north flank (Figure 16). The configuration of the base of the fresh to slightly saline water is shown in profile on cross section C-C' (Plate 7). The interval between the base of the fresh to slightly saline water and the top of the caprock is not constant but ranges from about 800 feet at the crest of the dome to about 1,100 feet at the -2,300-foot contour on the caprock. The dip of the base of the fresh to slightly saline water is steepest between the -1,000 and -2,000-foot contours and is steepest on the north flank where the base steepens from -1,000 to -2,000 feet in one-quarter of a mile. Below the -2,000-foot level, the dip flattens and the base merges with the regional configuration of the base of fresh to slightly saline water. The large area enclosed by the -1,000-foot contour reveals the broad flat top of the dome. The presence of the area enclosed by the -2,200-foot contour, nearly the deepest occurrence of fresh to slightly saline water in the county, reflects the existence of a part of a rim syncline--a common adjunct to most piercement-type salt domes.

The approximate thickness of sand containing fresh to slightly saline water ranges from less than 200 feet to between 1,200 and 1,300 feet (Figure 25). The 200-foot isopachous line encloses only a very small area north of the structural high point on the dome. The 500-foot isopachous line enclosing about a 21-square-mile area also encloses two 400-foot isopachous lines on the crest of the dome, giving the impression that the dome has two structural high points separated by a "saddle" or structurally low area. This relationship can also be seen on the base of the fresh to slightly saline water where the -1,000-foot contour encloses two -800-foot contours. From the 500-foot isopachous line, the thickness increases progressively in all directions until near the western margin of the area, the 1,100 and 1,000-foot contours reveal a thinning effect created by the rising base of fresh to slightly saline water toward the Batson dome.

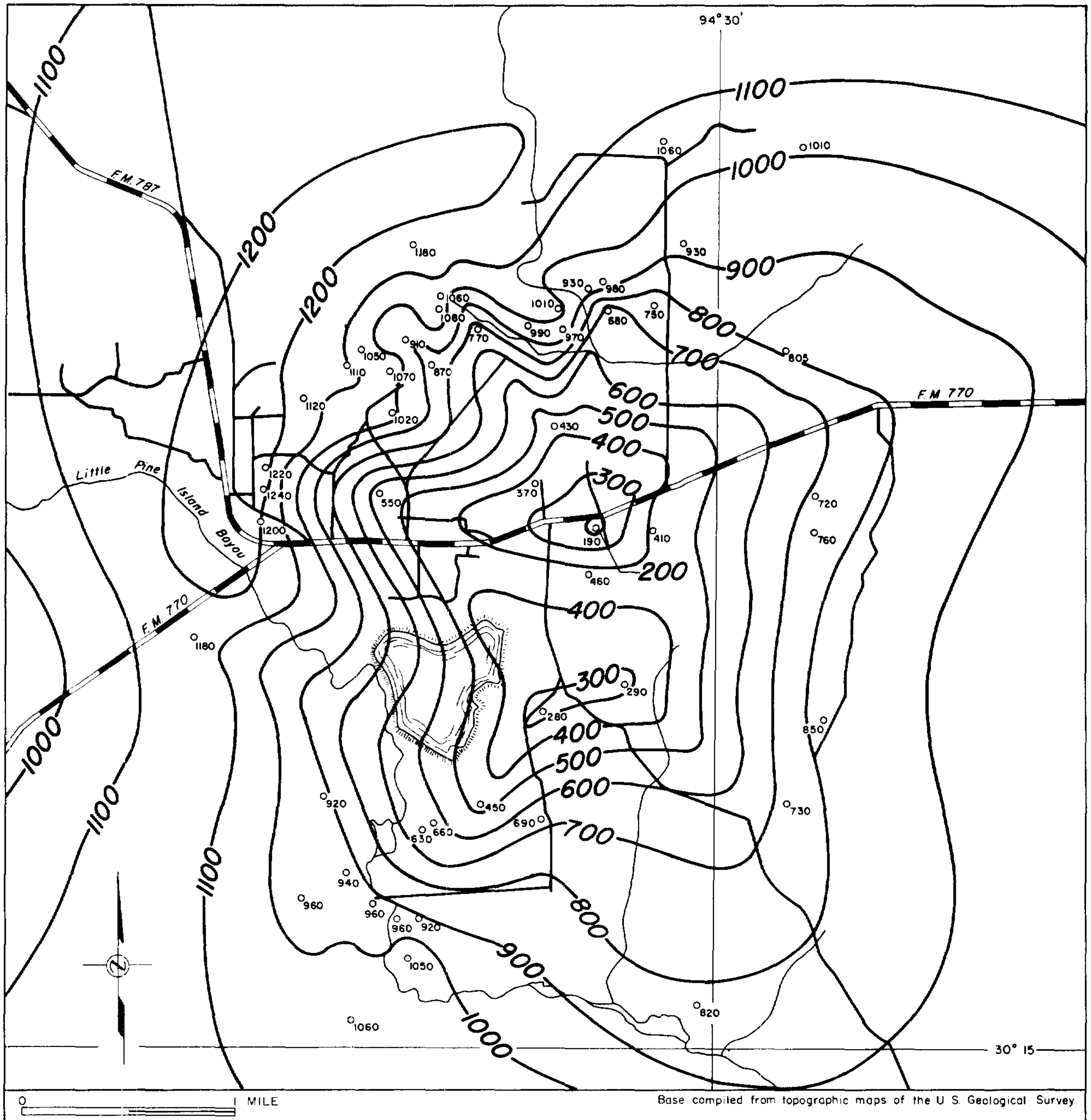
The isopachous map and the map showing the base of the fresh to slightly saline water correspond in configuration to each other and, in general, to the shape of the Saratoga dome. The ratio of sand to clay varies from 50 to 60 percent sand, the same as at Batson dome.

No data concerning the hydraulic characteristics of the aquifer were obtained in the Saratoga area because conditions were unfavorable for pumping tests.

Ground water has not been developed on a large scale in the Saratoga area. Three small-capacity public-supply wells serve only a part of the town; the remainder is served by private domestic wells of small diameter, averaging about 200 feet in depth. Well LH-61-44-918, 186 feet deep at the center of the town, showed an increase in chloride content from 108 ppm in April 30, 1942 to 135 ppm on May 10, 1962, and increase of about 1.3 ppm per year. No other comparisons of water quality are available.

One unique feature of the Saratoga area is the availability of shallow ground water under sufficient pressure to cause wells to flow. Many of the flowing wells in the area were oil tests, which, when abandoned, were left open at the surface. Because the pressure in the deeper oil sands had been depleted for the most part, the wells did not flow salt water. Years later, corrosion of the casings opposite shallower but higher pressure water sands gave the water access into the casings and the wells flowed.

The high pressure water sand in the Saratoga area occurs about 400 to 600 feet below land surface, depending on location. Field determinations of chloride content in water from 6 flowing wells, 450 to 569 feet deep, revealed a range of 545 to 848 ppm. Suman (1925, p. 279) reports that ground water in the Saratoga



EXPLANATION

1200

Line showing approximate thickness of sand containing fresh to slightly saline water, in feet

Contour interval 100 feet

○850

Well used for control. Number indicates thickness of saturated sand, in feet

Figure 25

Approximate Thickness of Sand Containing Fresh to Slightly Saline Water in the Saratoga Area, Hardin County

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oil field is fresh to a much greater depth than that in the other Hardin County fields and that the strong flow encountered at about 500 feet in the southwestern part of the field was always reported as fresh. Most of the flowing wells visited by the author were in the central part of the field; however, high pressure fresh-water sand beds are in the northern and northwestern part of the oil field also. Wells as shallow as 98.5 feet (well LH-61-44-603) and 107 feet (well LH-61-44-602) flow water of excellent quality, the chloride content ranging from about 50 to 60 ppm as determined in the field. Deeper wells (LH-61-44-609 and LH-61-44-610), 195 and 194 feet deep, respectively, do not flow and have water levels of about 6 feet below land surface. Thus, at least at two levels, the 100 and 400 to 600-foot sands, yield flows of fresh to slightly saline water.

The volume of fresh to slightly saline water in storage in the Gulf Coast aquifer in the Saratoga area is 4,400,000 acre-feet. However, only a small fraction of this water is recoverable. The amount of ground water per square mile averages 175,000 acre-feet compared to 195,000 acre-feet in Hardin County, excluding the salt-dome areas.

Suman (1925, p. 267) makes the following statement regarding the geology and development of water. "Underlying the Columbia sands which outcrop at Saratoga are the Lafayette sands and gravels. For the most part these are fresh-water sands, and boiler feed water is obtained from them to 500 feet. As the Beaumont Clays are not found at Saratoga, the ratio of sand to clays penetrated is much higher than in almost any other field on the Gulf Coast."

Planning a large development of fresh ground water from the Saratoga area should be carried on with caution as in the Batson area. However, at Saratoga, fresh to slightly saline water occurs deeper than in the Batson and Sour Lake areas, thus offering a better opportunity for the development of a large water supply. Nevertheless, in any future development of ground water in large amounts in the Saratoga area, the presence of a mound of salt water overlying the salt dome and the possibility of salt-water encroachment should be seriously considered. As in the Batson area, certain basic advice should be considered.

1. Exploratory holes should be drilled to determine optimum sand thickness and samples of water should be taken to indicate the quality at that location.

2. The wells should be as far from the salt dome as possible and preferably north of the dome where the accumulation of sand is thickest and where the natural southeast movement of fresh water may be intercepted before the water comes into contact with the salt dome.

3. The wells should be as shallow as possible, preferably no deeper than about 500 feet.

4. Pumping tests should be made upon completion of each production well to determine optimum pumping rates and pump settings and possible hydrologic boundaries that impede the flow of water. These data will aid also in determining the most efficient spacing of future wells.

Although saline water is nearby, a properly developed ground-water supply of moderate to large magnitude should be obtainable without danger of salt-water encroachment for many decades.

Sour Lake

Fresh to slightly saline water in the Sour Lake area is underlain by a mound of salt water and an anhydrite capped salt stock, the highest point of the caprock being between 600 and 700 feet below sea level. The dome is irregular in outline especially on the flanks, but has a tendency to be elliptical and elongated slightly in a north-south direction. At a depth below sea level of 1,500 feet, the dome is about 1 mile across its longest axis.

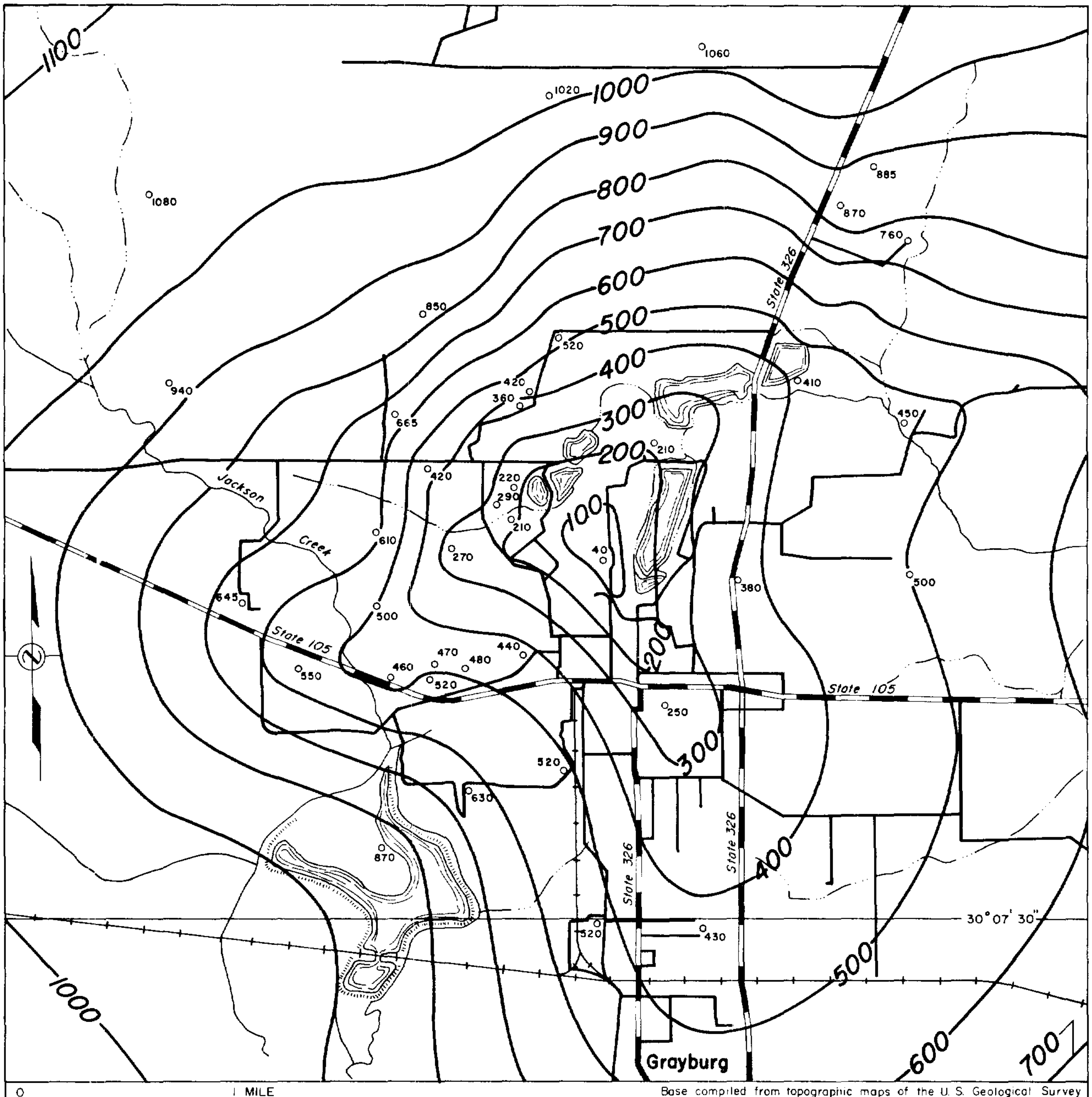
The base of the fresh to slightly saline water ranges from less than 100 feet below sea level, 1,000 feet southeast of the crest of the dome, to between 1,900 and 2,000 feet at the northwest corner of the area (Figure 17). The configuration of the base of the fresh to slightly saline water is shown in profile on cross section D-D' (Plate 8). The general shape of the top of the caprock (Sellards, 1930, Pl. 1) corresponds remarkably well with the general shape of the altitude of the base of the fresh to slightly saline water as shown in Figure 17. However, the interval between the top of the caprock and the base of the fresh to slightly saline water is not everywhere constant but ranges widely from about 500 to 1,400 feet near the crest of the dome to about 1,600 to 1,700 feet at the -2,400-foot contour on the top of the caprock. The dip of the base of the fresh to slightly saline water is steepest from the -200 to -1,400-foot contours beyound which the base flattens considerably and merges with the regional configuration of the base of the fresh to slightly saline water. No evidence of a trough of fresh to slightly saline water or rim syncline was noted at Sour Lake.

The approximate thickness of sand containing fresh to slightly saline water ranges from less than 100 feet to between 1,000 and 1,100 feet (Figure 26). The 100-foot isopachous line encloses only about 50 acres near the crest of the dome. Within this area at one location, only about 40 feet of sand containing fresh to slightly saline water was noted. From the 100-foot isopachous line, the thickness increases progressively in all directions in a concentric pattern. The greater degree of increase in saturated sand is to the north of the crest of the dome where a maximum thickness of between 1,000 and 1,100 feet is reached in the northwest corner of the area. Southward from the crest of the dome, the thickness of sand increases at a much smaller rate, and in the southeast corner of the area the thickness is between 700 and 800 feet. The area enclosed by the 900- and 1,000-foot isopachous lines is 4 square miles, the largest enclosure in the Sour Lake area.

The decrease in rate of thickening southward from the crest is in conformance with the altitude of the base of the fresh to slightly saline water. The elongation of the mound of salt water southward probably is the result of a reduction in circulation of ground water because of deformation such as faulting, lithologic factors, or contamination from old improperly cased oil tests, or a combination of these.

The ratio of sand to clay varies considerably in the Sour Lake area. The percentage of sand to clay ranges from 33 to 75 and averages about 50 percent.

A considerable amount of information concerning the hydraulic properties of the aquifer was obtained in the Sour Lake area. Drawdown and recovery tests were conducted on well LH-61-53-907, an irrigation well, and wells LH-61-53-928 and LH-61-53-929, both public supply wells of the city of Sour Lake. All three wells indicated similar permeabilities but widely different coefficients of transmissibility. The test on well LH-61-53-907, 952 feet deep, while pumping 1,975 gpm,



EXPLANATION

1200

Line showing approximate thickness of sand containing fresh to slightly saline water, in feet

Contour interval 100 feet

250

Well used for control. Number indicates thickness of saturated sand, in feet

Figure 26

Approximate Thickness of Sand Containing Fresh to Slightly Saline Water in the Sour Lake Area, Hardin County

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showed a coefficient of transmissibility of 45,000 gpd per foot, a permeability of 150 gpd per square foot, and a specific capacity of 21.5 gpm per foot of drawdown.

The city of Sour Lake wells LH-61-53-928 and LH-61-53-929 are 2.8 miles southwest of the irrigation well. The test at well LH-61-53-928, 812 feet deep and pumping 156 gpm, indicated a coefficient of transmissibility of 6,800 gpd per foot, a permeability of 174 gpd per square foot, and a specific capacity of 3.8 gpm per foot of drawdown. At well LH-61-53-929, 224 feet deep and pumping 180 ppm, a test indicated a coefficient of transmissibility of 9,000 gpd per foot, a permeability of 180 gpd per square foot, and a specific capacity of 6.8 gpm per foot of drawdown. The relatively low coefficients of transmissibility and specific capacity of the two city of Sour Lake wells are attributed to their short screened sections of 39 and 50 feet compared to 304 feet in the irrigation well.

The temperature gradients in all three wells reveal whether or not the Sour Lake salt dome exerts an appreciable effect on the producing sand and the water. Irrigation well LH-61-53-907 has a normal temperature gradient of 1°F per 90 feet of depth, while the two city of Sour Lake wells LH-61-53-928 and LH-61-53-929 have abnormal temperature gradients of 1°F per 65 feet of depth. All the wells are 2 miles from the crest of the dome; the only difference is in direction. The irrigation well is east-northeast and the public supply wells are due south. Apparently the main component of movement of water in the sand section tapped by the irrigation well is southeast from an undisturbed area; in the public supply wells, a large component of movement of water in the sand section tapped by the wells probably is southeast also but from the disturbed and structurally deformed area adjacent to the salt dome. The abnormal temperature gradients of the public supply wells at Sour Lake are believed to be the result of the conductance of heat by the salt stock and transfer to the adjacent water-bearing strata.

The volume of fresh to slightly saline water in storage in the Gulf Coast aquifer in the Sour Lake area is about 3,400,000 acre-feet; however, only a small fraction of the water is recoverable. The amount of ground water in storage per square mile is 136,000 acre-feet compared to 195,000 acre-feet per square mile for Hardin County, excluding the salt-dome areas.

Any development of a large supply of ground water in the Sour Lake area may be subject to salt-water encroachment. An example of salt-water encroachment is manifest in the public supply wells at Sour Lake. The original wells LH-61-53-913 and LH-61-53-914, 177 feet deep, are only three-fourths of a mile south of the crest of the salt dome. These wells, drilled in 1941, produced water having a chloride content of 209 ppm. Eight years later, the water contained 830 ppm chloride. These wells were later abandoned and new wells drilled 1-3/4 miles south of the crest of the dome. Water from well LH-61-53-928, 812 feet deep, increased in chloride content from 188 ppm shortly after being drilled to 645 ppm 10 years later. Water produced from well LH-61-53-929, 224 feet deep, increased in chloride content from 181 to 212 ppm in 10 years, a much more conservative increase (Figure 21).

Any future development of a large supply of ground water from the Gulf Coast aquifer in the Sour Lake area may be subject to salt-water encroachment unless a well planned development program is considered. In order to avoid salt-water encroachment, the following should be considered:

1. Exploratory holes should be drilled to determine optimum sand thickness and samples of water should be taken to indicate the quality at that location.

2. New wells should be as far removed from the crest of the salt dome as economically feasible, preferably on the north side of the dome where the accumulation of sand is thickest and in order to intercept the natural southeastward movement of fresh water before it reaches the salt dome.

3. The wells should be as shallow as possible in order to increase the distance of the screened portion of the well from the base of the fresh to slightly saline water.

4. Pumping tests should be made upon completion of each production well to determine optimum pumping rates, pump settings, and to indicate the possible presence of hydrologic boundaries such as faults, which may impede circulation of ground water. These data can be used also to determine the correct spacing of future wells.

CONCLUSIONS

The Gulf Coast aquifer in Hardin County is practically untapped. Although about 170,000,000 acre-feet of ground water is in storage in the county, only a part of this quantity is recoverable by known means and at present costs. A perennial supply of ground water from the Gulf Coast aquifer of 100 mgd probably can be developed with pumping levels not exceeding 400 feet, assuming a theoretical east-west line of discharge near Kountze; it would require 173 years of pumping 200 mgd to lower the water levels to 400 feet. A perennial supply of 80 mgd, 60 mgd, and 40 mgd can be similarly developed with pumping levels not exceeding 300, 200, and 100 feet, respectively.

As more and more ground water is used and new wells installed in Hardin County, the water levels will continue to decline to create the proper gradients toward the centers of discharge. This does not necessarily imply that the ground-water reserves are being depleted. Where there is sufficient recharge to meet withdrawals, declining water levels do not always indicate overpumping. Pumping is simply a means of diverting the water to the wells for use by man rather than permitting it to flow unused to its areas of natural discharge.

It is true that if recharge is insufficient to supply the withdrawals, the water levels will continue declining, and the ground-water reserves eventually will be depleted. However, because of the large amount of rainfall in the Hardin County area, the potential rate of recharge is large, and ground-water problems are chiefly ones of economics with respect to pumping lifts and correct spacing of wells for optimum efficiency rather than problems of inadequate amounts of water.

Ground water produced from depths as great as 1,000 feet or more in most places in Hardin County, except in the immediate vicinity of the salt domes, should have dissolved-solids content of less than 500 ppm, chloride less than 250 ppm, and iron less than 0.3 ppm. When fresh water (less than 1,000 ppm dissolved solids) is required, the wells should not be bottomed too near the slightly saline water (1,000 to 3,000 ppm dissolved solids) zone which underlies the fresh water in most places. The slightly saline water zone is relatively thin in Hardin County, generally less than 400 feet.

Although salt water is encroaching into southeastern Hardin County from northeastern Jefferson County, the rate of encroachment is very slow, perhaps only a few tens of feet per year. Consequently, large additional developments of ground water are possible in southeastern Hardin County with controlled pumping and proper depth and spacing of wells without danger of serious contamination for many decades.

Although vast quantities of fresh to slightly saline ground water are in storage in Hardin County and although the average transmissibility of the full thickness of the aquifer is between 100,000 and 200,000 gpd per foot, it may not be economically feasible to develop large, low-cost ground-water supplies in all parts of the county. In areas where the coefficient of transmissibility is very small, interference between wells may cause large declines of artesian pressure, and the resultant large pumping lifts may become uneconomical for some purposes. Large lifts may be caused also by too heavily concentrated withdrawals in areas of much higher transmissibilities.

The unit cost of pumping ground water depends on a great many variables. Differences in fuel-consumption rates, repairs, pumping lifts, well capacity, and volume of water pumped all have a bearing on the unit cost of water. It is sometimes presumed that cost per unit of water delivered is related to the capacity of the pump, although under field conditions, it has not been possible to relate water cost to pumping capacity. However, there is a definite relation between operating cost per unit and well capacity. The higher costs per unit of water delivered generally are associated with wells of low yield.

The cost per unit of water delivered may be higher in some of the deeper wells insofar as they might require a greater pumping lift and, therefore, more energy. On the other hand, the deeper wells may have a greater screened interval and, thus, a higher specific capacity. In many places in Hardin County, however, deep wells have natural flows, the volume of flow usually increasing with depth of the well. In these wells, there is no lifting cost provided the volume of flow is sufficient for the required purpose.

In field studies of irrigation supplies, it has been found that the cost-reducing effects of high-capacity wells usually more than offset the effects of higher lifts. In a recent study in the High Plains of Texas, high-capacity wells, having a pumping lift of 250 to 300 feet, produced the same unit of water at less than half the cost of low-capacity wells where the water was lifted about 100 feet. Only 9 hours of pumping per acre was required for the high-capacity, high-lift wells, whereas an average of 72 hours of pumping was required for the low-capacity, low-lift wells (United Nations, 1960, p. 23).

The purpose for which the water is to be used generally is a major factor in determining the economic feasibility of developing ground-water supplies. Municipalities and some industries as a rule can afford to pay more for water than can irrigation farmers. It may be uneconomical, however, to produce certain industrial products that require large quantities of water in processing if the cost of pumping water is appreciably increased by declines in pumping levels. On the other hand, a cheap source of power may permit a farmer to pump irrigation water from greater depths. Generally, few wells in Hardin County lift water from depths exceeding 300 feet. Also in some areas, the use of surface or ground water is open to choice; it may be feasible to develop one in preference to the other, or a joint development may have certain economic advantages. Many water users prefer ground water because of its uniformity of temperature and chemical quality and absence of turbidity and bacterial pollution. In addition, accessibility, abundance, and dependability are among the important aspects of ground water in Hardin County.

The construction of future large-capacity wells should take into consideration possible future declining water levels, especially in areas of large withdrawals. In recent years, declines have been anticipated by setting large-diameter casing at much greater depths to accommodate future lowering of large-capacity pumps. Also, the sands in the section 100 to 300 feet or more below the land surface are not generally screened becaused the pump pit (blank surface casing) must be deep enough to prevent water from cascading into the well above the pump bowls and thereby reducing the efficiency of the pump. Most of the large-capacity wells drilled for municipalities and industries are gravel packed from the top screen to the bottom of the well so that all sands in the screened section contribute some water whether there is a screen opposite them or not. Most of the large irrigation wells are completed with a gravel envelope which extends from the bottom of the well to the land surface, filling the annular space between the casing and the walls of the hole.

Regarding land subsidence, two conclusions can be drawn: (1) In areas where declines in artesian pressure are substantial in thick artesian aquifers of unconsolidated sediments, compaction of the aquifer and subsidence of the land surface can be expected. The magnitude of the compaction will depend on the thickness and physical character of the aquifer and on the amount of artesian pressure decline. (2) The quantity of water squeezed out of the aquifer by permanent compaction of clay beds or rearrangement of sand grains is water available only once, and where compaction is appreciable, studies evaluating water supply should consider the water yielded from compaction as a nonreplenishable resource.

To determine subsidence accurately, a network of bench marks should be established and releveled periodically, samples of many different clay beds should be analyzed so that vertical permeability may be determined, and compaction recorders should be installed in wells of different depths. In general, a ground-water monitoring program should be established to indicate potential problems so that timely corrective action can be taken before any problem gets out of hand.

Exploration by test drilling and test pumping, including chemical analyses of the water in various sand beds in the aquifer, is desirable before permanent locations are selected for any large-scale development of ground water. From such preliminary data can be determined the optimum pumping rate, pump setting, and the feasibility of developing additional wells. Test pumping also will provide data to help plan the correct spacing of wells in a large well field. Pumping tests should be made on additional wells as they are constructed.

The problem of developing and utilizing ground water for optimum efficiency in Hardin County requires much study. Proper development of the Gulf Coast aquifer depends upon information concerning the source of water, the amount of water in storage, the amount of recharge and fluctuations of water levels, the quality of the water, the transmission capacity of the aquifer, and, consequently, the most efficient methods of extracting the ground water. The foundation for determining such vital information is the collection of what is called "basic data," of which a substantial amount has been obtained and included in this report.

In many other areas, however, basic data are insufficient or lacking in relation to the needs for such information where large programs of development of ground water are being undertaken or are in the planning stages. Also, in many areas, basic data have not been obtained and are not available for use in ground-water development when the need has arisen for such information. Then, when the need is present, it is often too late to get all the desired basic data. For instance, if the effects on the water levels in an aquifer caused by pumping over a period of years are known, a detailed study and analysis of the past records will give a very good indication of what will happen to the water levels in the aquifer in the future if the pumping is increased or if pumping from another part of the aquifer is anticipated. Thus, in some areas where large ground-water developments have been made, they have sometimes had to be made haphazardly, using only data that could be obtained quickly and easily. The same will be true of developments planned for the future unless more attention is given now to the collection of such data as records of wells, electric and drillers' logs of wells, records of pumpage and water levels in wells, and chemical analyses of the water. Without these basic data, inaccurate computations could lead to improper well construction, the wrong spacing of wells, overpumping of aquifers, and excessive interference with existing developments.

The collection of basic data, though important, should not become an end unto itself, but should be an integral part of a comprehensive balanced program of continuing examination and interpretation of all factors related to the most effective development of ground water. Recommended programs of collection, compilation, interpretation, and publication of basic data, such as that which is contained in this study, should be given careful attention and supported wherever practicable in other areas where basic information is lacking. The cost of such programs is indeed small compared to the cost of alleviating ground-water problems that inevitably result from lack of sufficient hydrologic information.

The collection of basic data such as the inventory of pumpage, observation of water levels, and the collection of water samples for quality studies should be continued periodically in Hardin County. Collection of water samples should be continued to provide additional information on the status of salt-water encroachment. Sampling should be principally in the southeastern part of the county where the rate of salt-water encroachment is expected to increase and in the vicinity of salt domes where ground-water pumpage for irrigation and public supply is large and salt-water contamination is occurring. The interpretation of these data will aid ultimately in preventing accelerated salt-water encroachment when additional development is undertaken. A network of 25 uniformly distributed observation wells has already been established throughout Hardin County and water levels in these wells are measured and recorded annually by the Texas Water Commission.

Whenever accurate computations are made for the development of ground-water supplies, everyone concerned will have a better realization of the large magnitude of available ground-water supplies and, hence, more confidence in the utilization of ground water to its fullest extent. Thus, more wells can be drilled without fear of depleting the supply. In addition, satisfaction will be derived from seeing long lasting and efficient centers of ground-water development that are not in danger of eventual failure.

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Table 9.--Drillers' logs of wells in Hardin County

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)

Well LH-61-29-902

Owner: Humble Oil & Refining Co. Driller: B. & L. Water Well Service Co.

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Clay	50	50	Sand	40	332
Sand	25	75	Shale	232	564
Shale	217	292	Sand	47	611

Well LH-61-36-501

Owner: Gulf, Colorado & Santa Fe RR Co. Driller: Layne-Texas Co.

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Clay	243	243	Shale, sandy	194	639
Sand	31	274	Sand	33	672
Gumbo	84	358	Gumbo	139	811
Sand	87	445	Sand	57	868

Well LH-61-37-301

Owner: Humble Oil & Refining Co. Driller: B. & L. Water Well Service Co.

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Sand	58	58	Shale	30	446
Shale	96	154	Sand and rock	13	459
Sand	13	167	Shale	39	498
Shale	76	243	Sand	21	519
Sand	15	258	Shale	33	552
Shale	10	268	Sand	18	570
Sand	40	308	Shale	81	651
Shale	77	385	Sand	29	680
Sand and rock	31	416			

Table 9.--Drillers' logs of wells in Hardin County--Continued

Well LH-61-38-702

Owner: O. Sternenberg & Co. Driller: Jake Giles

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Sawdust	8	8	Gumbo, blue	43	156
Sand	28	36	Sand	26	182
Clay, yellow	28	64	Gumbo, blue	104	286
Sand	49	113	Sand, water	53	339

Well LH-61-38-802

Owner: Kountze Hardwood Co. Driller: Pitre Water Well Drilling & Supply Co.

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Sand, red	23	23	Shale, blue	142	290
Clay, red	17	40	Sand, white	13	303
Sand, white	15	55	Shale, blue	7	310
Clay, red	5	60	Sand, white	20	330
Sand, coarse, white	5	65	Shale, sandy, blue	20	350
Clay, red	20	85	Shale, sticky, blue	66	416
Sand, salt and pepper, blue	23	108	Sand, coarse, white	25	441
Shale, blue	20	128	Shale, blue	5	446
Sand, coarse, white	20	148			

Well LH-61-39-503

Owner: Sinclair Oil & Gas Co. Driller: Geo. Bellinger Water Well Service

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
No record	151	151	Sand	54	363
Sand	116	267	Shale	8	371
Shale, sandy	42	309	Sand	19	390

(Continued on next page)

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)

Well LH-61-39-503--Continued

Shale	4	394	Shale	26	442
Sand	22	416			

Well LH-61-44-101

Owner: O. D. Felps. Driller: Pitre Water Well Drilling & Supply Co.

Clay, red and yellow	15	15	Sand and gravel	13	830
Sand, brown and white	21	36	Shale	80	910
Sand, coarse, varigated	49	85	Shale, sandy	15	925
Sand and gravel, varigated	10	95	Shale	28	953
Clay, sandy, varigated	48	143	Sand, coarse	27	980
Sand, coarse, varigated	72	215	Shale	22	1,002
Clay, varigated	15	230	Shale, tough, blue	10	1,012
Sand and clay, varigated	20	250	Shale, sandy, blue	54	1,066
Sand, varigated	60	310	Sand, fine, tight	16	1,082
Sand and shale, varigated	6	316	Shale, sandy	66	1,148
Sand and gravel	220	536	Shale, hard	8	1,156
Sand and shale	70	606	Shale, sandy	9	1,165
Shale, sandy	25	631	Shale, hard	115	1,280
Shale, tough	21	652	Shale, sandy	10	1,290
Shale, sandy	83	735	Sand, fine packed	12	1,302
Shale	65	800	Conglomerate	11	1,313
Shale, sandy	17	817	Sand, rough	3	1,316
			Shale, hard	22	1,338

(Continued on next page)

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)

Well LH-61-44-101--Continued

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Shale, very hard	8	1,346	Shale, sandy	3	1,380
Sand	31	1,377			

Well LH-61-44-102

Owner: L. C. Truitt. Driller: Pitre Water Well Drilling & Supply Co.

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Clay	16	16	Shale	156	805
Sand	17	33	Sand, tight, hard	29	834
Clay	10	43	Shale	11	845
Sand and gravel	52	95	Sand and boulders, hard	26	871
Shale	40	135	Shale	5	876
Sand, red	35	170	Sand, fine	22	898
Shale	11	181	Shale, blue	5	903
Sand with shale streaks	33	214	Sand and gravel	72	975
Shale	17	231	Sand and shale	19	994
Sand	50	281	Shale, hard, brown	74	1,068
Shale with sand streaks	37	318	Shale, blue	12	1,080
Sand and gravel	72	390	Sand	21	1,101
Sand	118	508	Conglomerate	199	1,300
Shale	28	536	Shale, sandy	16	1,316
Sand and gravel	34	570	Sand, fine, tight	17	1,333
Shale	20	590	Conglomerate	27	1,360
Sand and gravel	59	649	Sand, water	40	1,400

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Well LH-61-44-502					
Owner: J. E. Payne. Driller: Pitre Water Well Drilling & Supply Co.					
Sand, surface, red	5	5	Shale, blue	43	155
Clay, red	15	20	Sand, fine, white	21	176
Sand, salt and pepper	10	30	Shale, blue	39	215
Shale, blue	60	90	Sand, white	26	241
Sand, salt and pepper	22	112	Shale, blue	9	250
Well LH-61-44-606					
Owner: Falcon Seaboard Oil Co. Driller: Pitre Water Well Drilling & Supply Co.					
Surface, brown	24	24	Sand, fine, gray	45	211
Clay	142	166	Clay, blue	1	212
Well LH-61-44-608					
Owner: Texaco, Inc. Driller: Pitre Water Well Drilling & Supply Co.					
Sand, white	15	15	Shale, blue	71	173
Clay, red	65	80	Sand, medium-coarse, salt and pepper	22	195
Sand, fine, white	22	102			
Well LH-61-44-610					
Owner: Harlan-Ray. Driller: Pitre Water Well Drilling & Supply Co.					
Sand, surface, white	15	15	Shale, blue	56	166
Clay, red	66	81	Sand, coarse, salt and pepper	29	195
Sand, fine	29	110	Shale, blue	6	201

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)

Well LH-61-44-612

Owner: Harlan-Ray. Driller: Pitre Water Well Drilling & Supply Co.

Clay, red	25	25	Sand, fine, blue	21	108
Sand, red	10	35	Shale, blue	61	169
Clay, yellow	52	87	Sand, coarse, white	24	193

Well LH-61-44-615

Owner: Texaco, Inc. Driller: Pitre Water Well Drilling & Supply Co.

Sand, brown	15	15	Clay, blue	40	157
Clay, white	25	40	Sand, fine, salt and pepper	31	188
Clay, brown	67	107	Clay	4	192
Clay, sandy, blue	10	117			

Well LH-61-44-704

Owner: Jim Donohoe. Driller: Pitre Water Well Drilling & Supply Co.

Clay, red	35	35	Sand and gravel	4	74
Sand, white	35	70			

Well LH-61-44-708

Owner: W. E. Arnold. Driller: Pitre Water Well Drilling & Supply Co.

Surface, black	4	4	Sand, fine, brown	9	63
Clay, yellow	26	30	Sand and gravel, salt and pepper	9	72
Clay, mealy, yellow	14	44			

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)

Well LH-61-44-901

Owner: West End Baptist Church. Driller: Pitre Water Well Drilling & Supply Co.

Sand, fine, red----------	15	15	Shale, sandy, blue-----	60	108
Clay, red---------------	3	18	Clay, red---------------	28	136
Sand, white-------------	6	24	Shale, sandy, blue-----	52	188
Clay, red---------------	6	30	Shale, sandy, white----	8	196
Sand, white-------------	18	48	Sand, coarse, varigated------------	67	263

Well LH-61-44-905

Owner: A. L. Ewing. Driller: Pitre Water Well Drilling & Supply Co.

Clay, red---------------	15	15	Sand, fine, blue-------	9	205
Sand, red---------------	45	60	Shale, sandy, blue-----	40	245
Clay, red---------------	35	95	Sand, broken, blue-----	3	248
Sand, white-------------	12	107	Sand, medium, salt and pepper---------------	37	285
Clay, sandy, blue-------	89	196	Sand, broken, blue-----	10	295

Well LH-61-44-907

Owner: Texaco, Inc. Driller: Pitre Water Well Drilling & Supply Co.

Clay, brown-------------	22	22	Shale, blue------------	117	247
Sand, brown-------------	27	49	Shale and sand, blue---	3	250
Clay, sandy, brown------	4	53	Shale, blue------------	8	258
Clay, yellow------------	53	106	Shale, sandy-----------	3	261
Shale, sandy, blue------	24	130	Sand, gray-------------	29	290

Table 9.--Drillers' logs of wells in Hardin County--Continued

Well LH-61-44-913

Owner: Harlan-Ray. Driller: Pitre Water Well Drilling & Supply Co.

	Thickness (feet)	Depth (feet)
Sand, fine, red	20	20
Clay, yellow	60	80
Sand, fine, white	8	88
Shale, sandy, blue	8	96
Clay, yellow	12	108
Shale, blue	8	116
Shale, sandy, blue	4	120
Sand, fine, white	10	130
Shale, blue	65	195
Shale, sandy, blue	15	210
Sand, salt and pepper	34	244

Well LH-61-44-917

Owner: Mrs. M. Kinkaid. Driller: Pitre Water Well Drilling & Supply Co.

	Thickness (feet)	Depth (feet)
Clay, red	5	5
Sand, red	5	10
No entry	50	60
Shale, blue	70	130
Sand, fine, blue	5	135
Shale, blue	53	188
Sand, coarse, salt and pepper, blue	28	216

Well LH-61-44-921

Owner: Herman Doucette. Driller: Pitre Water Well Drilling & Supply Co.

	Thickness (feet)	Depth (feet)
Clay, red	8	8
Clay, white	17	25
Clay, sandy, brown	3	28
Clay, white	7	35
Sand, fine, brown	5	40
Clay, mealy, blue	12	52
Clay, blue	13	65
Clay, mealy, blue	56	121
Clay, blue	26	147
Clay, sandy, brown	9	156
Sand, fine, white	4	160
Sand, coarse, salt and pepper	35	195

Table 9.--Drillers' logs of wells in Hardin County--Continued

Well LH-61-44-925

Owner: Allen Flowers. Driller: Pitre Water Well Drilling & Supply Co.

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Clay, sandy, brown------	15	15	Sand, fine, salt and pepper---------------	20	82
Clay, sandy, white------	8	23	Clay, gray-------------	18	100
Clay, sandy, brown------	11	34	Sand, coarse, salt and pepper---------------	30	130
Clay, sandy, blue-------	16	50			
Clay, sandy, brown------	12	62			

Well LH-61-44-935

Owner: Sun Pipe Line Co. Driller: Pitre Water Well Drilling & Supply Co.

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Clay-------------------	6	6	Rock and sand----------	2	266
Sand, surface, red------	20	26	Shale, blue------------	5	271
Shale, blue-------------	24	50	Rock-------------------	2	273
Sand, fine, blue--------	9	59	Sand, fine-------------	4	277
Shale, blue-------------	95	154	Shale, blue------------	43	320
Sand, fine, blue--------	7	161	Shale, sandy, blue-----	45	365
Rock--------------------	1	162	Sand, fine, blue-------	8	373
Sand, blue--------------	2	164	Shale, sandy, blue-----	16	389
Rock--------------------	1	165	Shale, sticky, blue----	79	468
Shale, blue-------------	2	167	Sand and shale streaks, blue----------------	17	485
Sand, blue--------------	11	178	Shale, blue------------	46	531
Rock--------------------	1	179	Rock-------------------	1	532
Sand, blue--------------	12	191	Shale, sandy, blue-----	4	536
Shale, blue-------------	63	254	Sand, coarse, salt and pepper---------------	33	569
Sand and shale, blue----	10	264			

Table 9.--Drillers' logs of wells in Hardin County--Continued

Well LH-61-45-601

Owner: Trunkline Gas Co. Well 1. Driller: Layne-Texas Co.

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Surface	2	2	Shale	46	325
Clay	28	30	Shale, sandy	35	360
Sand, red	18	48	Sand	15	375
Clay, sandy	42	90	Shale	45	420
Sand	24	114	Shale, sandy	14	434
Shale, blue	51	165	Shale	26	460
Sand and shale breaks	74	239	Sand, fine, white	18	478
Sand, gray	40	279	Sand, coarse	27	505

Well LH-61-45-602

Owner: Trunkline Gas Co. Well 2. Driller: Layne-Texas Co.

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Surface	2	2	Shale	46	325
Clay	28	30	Shale, sandy	35	360
Sand, red	18	48	Sand	15	375
Clay, sandy	42	90	Shale	45	420
Sand	24	114	Shale, sandy	14	434
Shale, blue	51	165	Shale	26	460
Sand and shale breaks	74	239	Sand, fine, white	18	478
Sand, gray	40	279	Sand, coarse	27	505

Well LH-61-46-301

Owner: Chas. D. Smith. Driller: Pitre Water Well Drilling & Supply Co.

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Sand, red	3	3	Sand, white	11	560
Clay, red	22	25	Sand and shale, gray	22	582
Sand, red	25	50	Sand, white	21	603
Shale, gray	9	59	Shale, gray	121	724
Clay, red	41	100	Sand, gas, gray	22	746
Sand, white	60	160	Sand, white	21	767
Shale, green	36	196	Shale, green	11	778
Sand and gravel, gray	40	236	Sand, white	12	790
Sand, white	6	242	Shale, green	10	800
Shale, green	37	279	Sand, white	15	815
Sand, fine, gray	41	320	Shale, sandy, green	35	850
Sand, white	24	344	Clay, red	60	910
Sand, gas, gray	22	366	Shale, green	15	925
Sand, white	21	387	Clay, red	26	951
Shale, green	7	394	Shale and sand, green	22	973
Sand, white	89	483	Sand and shale, gray	17	990
Shale, green	6	489	Sand, light gray	80	1,070
Shale, sandy, gray	48	537	Clay, red	5	1,075
Shale, green	12	549			

Well LH-61-46-305

Owner: A. F. Briggs. Driller: Pitre Water Well Drilling & Supply Co.

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Surface	3	3	Sand, medium, white	41	152
Clay	41	44	Clay, green	25	177
Sand, fine	21	65	Sand, white	38	215
Clay in iron ore gravel	46	111	Clay, blue	1	216

Well LH-61-46-601

Owner: Cecil Merril. Driller: Pitre Water Well Drilling & Supply Co.

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Clay, red	16	16	Sand and shale, blue	32	230
Sand, powder, white	6	22	Sand, salt and pepper	74	304
Clay, red	11	33	Shale, blue	30	334
Sand, powder, white	3	36	Sand, coarse, white	23	357
Clay, red	14	50	Shale, sandy, blue	8	365
Sand, powder, white	10	60	Shale, blue	5	370
Clay, red	6	66	Sand, coarse, salt and pepper	10	380
Sand, powder, blue	7	73	Sand and shale, blue	54	434
Clay, red	8	81	Sand, coarse, white	7	441
Sand, fine, white	74	155	Sand and shale, blue	21	462
Shale, blue	28	183	Sand, coarse, white	22	484
Sand, salt and pepper	15	198	Shale, blue	18	502

Table 9.--Drillers' logs of wells in Hardin County--Continued

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)

Well LH-61-47-201

Owner: Kirby Lumber Corp. Well 1. Driller: Layne-Texas Co.

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Topsoil and clay--------	25	25	Sand, coarse-----------	70	466
Sand--------------------	9	34	Shale, hard, blue	32	498
Shale, sandy, and shale------------------	66	100	Sand, coarse, and fine gravel---------------	35	533
Sand, coarse-----------	27	127	Shale-----------------	11	544
Shale, sandy, and streaks of sand and wood------	41	168	Sand------------------	5	549
			Shale and sand breaks--	16	565
Sand and streaks of rock------------------	20	188	Sand, fine-------------	40	605
Sand--------------------	88	276	Shale, sandy shale, and streaks of sand------	54	659
Sand and shale breaks---	42	318			
Shale-------------------	8	326	Shale, sandy, and streaks of sand------	31	690
Shale, sandy-----------	43	369	Shale-----------------	10	700
Shale-------------------	27	396			

Well LH-61-47-202

Owner: Kirby Lumber Corp. Well 2. Driller: Layne-Texas Co.

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Topsoil and clay--------	25	25	Sand, shale streaks, and rock layers------	89	277
Sand, fine-------------	10	35			
			Sand, fine-------------	28	305
Clay--------------------	65	100			
Sand, coarse-----------	25	125	Sand, fine gravel, and wood-------------	26	331
Shale-------------------	10	135	Shale-----------------	20	351
Sand and shale streaks--	53	188	Sand------------------	12	363

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	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)

Well LH-61-47-202--Continued

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Shale	10	373	Shale, sandy, and shale	28	567
Shale and sand streaks	11	384	Sand	39	606
Shale	21	405	Shale and sandy shale	19	625
Sand	63	468	Sand and sandy shale	25	650
Sand and shale streaks	12	480	Shale	41	691
Shale, hard	26	506	Sand	17	708
Sand, coarse	33	539	Shale	9	717

Well LH-61-47-204

Owner: Gulf, Colorado & Santa Fe RR Co. Well 2. Driller: W. J. Giles.

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Surface	12	12	Sand, coarse	14	476
Clay, yellow	34	46	Gumbo, blue	8	484
Sand, fine, gray	6	52	Shale, blue	31	515
Clay, red	21	73	Shale and limerock	22	537
Sand and gravel	285	358	Rock	24	561
Shale, hard, blue	20	378	Gumbo	19	580
Gumbo	16	394	Packsand	7	587
Shale, blue	20	414	Gumbo, blue	18	605
Gumbo	8	422	Limerock and gumbo	13	618
Packsand	8	430	Sand, fine, white	9	627
Sand	26	456	Gumbo	19	646
Gumbo, Blue	6	462	Sand and shale	15	661

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Well LH-61-47-204--Continued

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Gumbo	35	696	Sand, coarse	22	826
Shale, blue	14	710	Gumbo	14	840
Sand	37	747	Sand	41	881
Gumbo	24	771	Gumbo and shale	19	900
Sand and shale	33	804			

Well LH-61-47-206

Owner: City of Silsbee Well 2. Driller: Layne-Texas Co.

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Clay	15	15	Sand	125	310
Clay, sandy	85	100	Sand, coarse	90	400
Sand, fine, with hard layers	85	185	Clay	5	405

Well LH-61-47-207

Owner: City of Silsbee Well 1. Driller: Layne-Texas Co.

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Surface	16	16	Sand	14	65
Sand	15	31	Clay	17	82
Clay	20	51	Sand	275	357

Well LH-61-47-208

Owner: City of Silsbee Well 3. Driller: Layne-Texas Co.

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Surface	10	10	Shale and sandy shale	33	180
Clay and sand streaks	115	125	Sand	136	316
Sand	22	147	Sand and streaks of shale	54	370

(Continued on next page)

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)

Well LH-61-47-208--Continued

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Shale, sandy	38	408	Shale	13	640
Shale and logs	42	450	Sand	18	658
Shale and sand breaks	11	461	Shale	13	671
Sand	25	486	Shale and sand breaks	8	679
Sand and shale breaks	24	510	Sand, hard, coarse	18	697
Sand	36	546	Shale	5	702
Shale and few sand breaks	39	585	Sand and shale breaks	35	737
Sand	13	598	Shale and few sand breaks	54	791
Shale	20	618	Sand, hard, coarse	41	832
Sand	9	627	Shale	10	842

Well LH-61-52-110

Owner: William Jordan. Driller: Pitre Water Well Drilling & Supply Co.

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Sand	2	2	Sand, coarse	5	55
Clay	41	43	Sand and gravel	7	62
Sand, fine	7	50			

Well LH-61-52-112

Owner: R. E. Gilbert. Driller: Pitre Water Well Drilling & Supply Co.

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Surface	9	9	Clay, blue	5	45
Clay, yellow	19	28	Sand, coarse, blue	37	82
Clay, sandy, brown	4	32	Sand and gravel, variagated	3	85
Clay, mealy, brown	8	40			

Table 9.--Drillers' logs of wells in Hardin County--Continued

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)

Well LH-61-52-115

Owner: Homer Snyder. Driller: Pitre Water Well Drilling & Supply Co.

Clay, red	20	20	Clay, red	30	70
Sand, fine, white	25	45	Sand and gravel	14	84

Well LH-61-52-119

Owner: W. D. Johnson. Driller: Pitre Water Well Drilling & Supply Co.

Surface	2	2	Shale, sandy, blue	13	43
Clay, yellow	16	18	Shale, sticky, blue	2	45
Sand, brown	3	21	Sand, salt and pepper	50	95
Shale, blue	9	30			

Well LH-61-52-120

Owner: Mrs. -- McLane. Driller: Pitre Water Well Drilling & Supply Co.

Clay, red	30	30	Clay, red	15	70
Sand, powder, blue	25	55	Sand, coarse, white	20	90

Well LH-61-52-121

Owner: F. H. McPhail. Driller: Pitre Water Well Drilling & Supply Co.

Clay, white	21	21	Sand, salt and pepper	18	70
Sand, fine, white	4	25	Clay, sandy, brown	9	79
Clay, sandy, brown	12	37	Sand, coarse, salt and pepper	12	91
Clay, blue	15	52	Sand and gravel	17	108

Table 9.--Drillers' logs of wells in Hardin County--Continued

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)

Well LH-61-52-123

Owner: Mrs. T. A. Griffin. Driller: Pitre Water Well Drilling & Supply Co.

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Clay, red	25	25	Sand, salt and pepper	34	64
Sand, fine, white	5	30	Sand and gravel, varigated	21	85

Well LH-61-52-127

Owner: Otis & Everett Guedry. Driller: Layne-Texas Co.

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Surface	4	4	Sand and streaks of clay	12	126
Topsoil and clay	36	40	Sand	20	146
Sand	52	92	Clay	7	153
Clay	22	114	Sand	26	179

Well LH-61-52-132

Owner: Mrs. Woodrow Lee. Driller: Pitre Water Well Drilling & Supply Co.

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Surface	6	6	Clay	1	79
Clay, varigated	9	15	Sand and gravel, white, varigated	18	97
Sand, fine	63	78			

Well LH-61-52-133

Owner: Guedry Cemetary. Driller: Pitre Water Well Drilling & Supply Co.

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Clay, red	12	12	Clay, sandy	8	88
Sand, fine	23	35	Sand, coarse, and gravel	14	102
Clay, sandy	6	41	Clay	4	106
Sand, red	39	80			

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)

Well LH-61-52-601

Owner: Mrs. Floy Mauboules. Driller: Layne-Texas Co.

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Clay	60	60	Shale	43	500
Sand	100	70	Sand	10	510
Clay and sand layers	50	120	Shale	12	522
Clay	25	145	Sand	38	560
Clay and sand layers	30	175	Shale	15	575
Sand	18	193	Sand and shale breaks	75	650
Clay	12	205	Shale	10	660
Sand	63	268	Sand	12	672
Clay	85	353	Clay	30	702
Sand	14	367	Sand	58	760
Clay	61	428	Clay	4	764
Sand and shale breaks	29	457			

Well LH-61-52-901

Owner: Atlantic Pipe Line Co. Driller: Frank Balcar.

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Clay, red	20	20	Clay	7	53
Sand, red	1	21	Sand, fine	4	57
Clay, yellow	17	38	Clay, hard	11	68
Shale	8	46	Sand, coarse, white	28	96

Well LH-61-53-802

Owner: Texaco, Inc. Driller: Pitre Water Well Drilling & Supply Co.

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Surface	10	10	Sand, gray	34	44

(Continued on next page)

Table 9.--Drillers' logs of wells in Hardin County--Continued

Well LH-61-53-802--Continued

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Clay, yellow	10	54	Shale, sand, and gravel streaks	9	341
Sand, gray	32	86	Clay	29	370
Clay, blue	15	101	Boulders	10	380
Sand, gray	20	121	Shale, blue	57	437
Clay, blue	44	165	Sand and gravel, gray	53	490
Sand, gray	23	188	Shale, hard, blue	5	495
Clay	13	201			
Sand, fine, gray	131	332			

Well LH-61-53-803

Owner: Texaco, Inc. Driller: Pitre Water Well Drilling & Supply Co.

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Surface	4	4	Sand, fine, and sticky gray clay	21	127
Sand, gray	59	63	Clay, yellow	40	167
Clay, blue	22	85	Sand, gray	15	182
Sand, fine, gray	21	106			

Well LH-61-53-804

Owner: Texaco, Inc. Driller: Pitre Water Well Drilling & Supply Co.

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
No record	40	40	Clay, blue	18	261
Clay, blue	16	56	Sand, fine, and blue gravel	41	302
Sand, gray	19	75	Shale, blue	4	306
Clay, blue	97	172	Sand and shale streaks and boulders, blue	25	331
Sand, fine, blue	71	243			

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Table 9.--Drillers' logs of wells in Hardin County--Continued

Well LH-61-53-804--Continued

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Shale, blue	42	373	Sand and gravel, gray	39	480
Sand, gray	3	376	Shale, brown	7	487
Shale and boulders, brown	65	441			

Well LH-61-53-809

Owner: Texaco, Inc. Driller: Pitre Water Well Drilling & Supply Co.

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Clay, red	10	10	Sand, light blue	15	255
Sand, gray	53	63	Shale and sand, blue	22	277
Sand, salt and pepper, gray	21	84	Sand, green and blue	43	320
Sand, gray	25	109	Sand, blue	21	341
Clay, red	17	126	Boulders and sand, gray	22	363
Shale, blue	43	169	Shale, green	18	381
Sand, blue	71	240	Sand and shale, blue	70	451

Well LH-61-53-810

Owner: Texaco, Inc. Driller: Pitre Water Well Drilling & Supply Co.

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Clay, red	15	15	Sand, light	25	347
Sand, light	115	130	Clay, red	11	358
Shale, gray	95	225	Shale, green	72	430
Sand, light	51	276	Sand, light	20	450
Sand, boulder, red	22	298	Shale, blue	23	473
Sand, fine, light	24	322	Sand, gray	37	510

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	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)

Well LH-61-53-810--Continued

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Clay, tough, red	13	523	Rock, gray	8	539
Sand, gray	8	531			

Well LH-61-53-811

Owner: Texaco, Inc. Driller: Pitre Water Well Drilling & Supply Co.

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Clay, red	21	21	Sand, fine, blue	47	350
Sand, blue-gray	14	35	Shale, sandy, blue	22	372
Shale, sandy, blue	31	66	Sand, fine, blue	11	383
Sand, gray	54	120	Shale, blue	2	385
Shale, sandy, blue	78	198	Sand, blue	15	400
Sand, fine, gray	65	263	Shale, blue	2	402
Sand, fine-packed, gray	8	271	Sand, blue	13	415
Shale, blue	3	274	Shale, blue	65	480
Sand, fine, blue	8	282	Sand, gray	34	514
Shale, sandy, blue	21	303			

Well LH-61-53-815

Owner: Texaco, Inc. Driller: Pitre Water Well Drilling & Supply Co.

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Clay	32	32	Sand	42	132
Sand	11	43	Shale, blue	8	140
Clay	8	51	Sand	52	192
Sand	30	81	Sand and gravel	16	208
Clay	9	90			

Well LH-61-53-907

Owner: F. H. Carpenter Well 2. Driller: Layne-Texas Co.

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Clay, sandy	20	20	Sand and shale breaks	5	596
Sand	44	64	Sand and shale streaks	10	606
Clay, sandy	62	126	Sand and shale	19	625
Shale, sandy, and sand	29	155	Sand and boulders	18	643
Sand	33	188	Sand and shale streaks	41	684
Shale, sandy, and sand	11	199	Shale	10	694
Sand and sandy shale	21	220	Sand	20	714
Sand	9	229	Sand and fine gravel	52	766
Sand and sandy shale	19	248	Shale	5	771
Sand	106	354	Sand and fine gravel	32	803
Shale and sandy shale	112	466	Shale	5	808
Sand and shale streaks	8	474	Sand and shale	13	821
Shale, sandy	10	484	Sand	52	873
Shale and sandy shale	26	510	Shale	6	879
Sand	25	535	Sand	34	913
Shale	31	566	Shale	13	926
Sand	15	581	Sand	18	944
Shale, sandy	10	591	Shale and sandy shale	8	952

Well LH-61-53-913

Owner: City of Sour Lake. Driller: Homer Wright.

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Soil and sandy clay	30	30	Sand	12	88
Sand	8	38	Shale, blue	18	106
Clay and sand	16	54	Sand, dark-blue	16	122
Sand	8	62	Shale, blue	21	143
Clay, blue	14	76	Sand, water, coarse, white	34	177

Well LH-61-53-914

Owner: City of Sour Lake. Driller: Homer Wright.

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Soil and clay	30	30	Sand	12	88
Sand	8	38	Shale, blue	18	106
Clay and sand	16	54	Sand, dark-blue	16	122
Sand	8	62	Shale, blue	21	143
Clay, blue	14	76	Sand, coarse, water	34	177

Well LH-61-53-929

Owner: City of Sour Lake Well 2. Driller: Big State Water Wells, Inc.

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Surface	3	3	Sand	11	161
Clay	65	68	Clay	12	173
Sand and clay layers	38	116	Sand	51	224
Clay	34	150			

Well LH-61-54-701

Owner: F. H. Carpenter, Jr., Well 2. Driller: Layne-Texas Co.

	Thickness (feet)	Depth (feet)
Clay	28	28
Sand, white	22	50
Clay, sandy	46	96
Sand	11	107
Shale and sand	9	116
Sand and shale, broken	10	126
Shale	20	146
Sand and thin shale breaks	9	155
Sand	29	184
Sand and thin shale breaks	5	189
Sand	32	221
Sand and streaks of shale	7	228
Shale	10	238
Sand and streaks of shale	10	248
Sand	12	260
Shale, sandy	26	286
Sand	20	306
Shale	45	351
Sand	12	363
Shale	5	368
Sand	16	384
Shale	23	407
Sand	15	422
Shale breaks of sandy shale, hard	73	495
Shale	10	505
Shale and sandy shale	19	524
Sand	38	562
Shale	9	571
Sand	68	639
Shale, hard	23	662
Sand and shale	8	670
Shale, hard	8	678
Sand, shells, and shale	9	687
Sand	58	745
Sand and streaks of shale	11	756
Sand	46	802
Shale, hard	24	826
Sand	56	882
Shale, hard	5	887
Sand and shale streaks	4	891
Sand and thin shale streaks	5	896
Shale	3	899

Well LH-61-54-801

Owner: Pinewood Country Club. Driller: Layne-Texas Co.

	Thickness (feet(	Depth (feet)
Surface	2	2
Clay	23	25
Sand	36	61
Clay, blue	75	136
Sand	35	171
Clay	3	174
Sand	22	196
Clay	30	226
Clay, sandy	30	256
Sand	42	298
Clay	30	328
Sand	37	365
Clay	17	382
Sand	9	391
Clay	21	412
Sand	5	417
Clay	55	472
Clay and sand streaks	30	502
Sand, fine, white	18	520
Clay	13	533
Sand, fine, and shale breaks	73	606
Shale, sandy	63	669
Shale, blue	37	706
Shale and sand breaks	98	804
Sand	18	822
Shale	12	834
Sand and shale breaks	33	867
Shale	17	884
Sand	26	910

Well LH-61-55-203

Owner: City of Beaumont. Driller: Layne-Texas Co.

	Thickness (feet)	Depth (feet)
Clay	114	114
Sand, fine, gray	30	144
Clay, yellow	17	161
Sand, blue, and lime	54	215
Clay, blue and sandy clay	28	243
Sand, gray	37	280
Clay, gray	9	289

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Well LH-61-55-203--Continued

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Sand, gray, and shell streaks	42	331	Shell, sticky	15	556
Sand	2	333	Sand, gray	10	566
Shale, hard	53	386	Shale	10	576
Sand, coarse	67	453	Sand	22	598
Sand, gray	21	474	Shale	29	627
Shale and sandy shale	6	480	Sand	13	640
Sand, gray	14	494	Shale	27	667
Shale and sandy shale	15	509	Sand	106	773
Sand and sandy shale	32	541	Shell	22	795

Well LH-61-55-204

Owner: City of Beaumont. Driller: Layne-Texas Co.

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Surface	10	10	Sand	37	231
Sand	13	23	Shale	49	280
Clay and sandy clay	34	57	Sand	12	292
Sand	15	72	Shale	10	302
Clay and sand streaks	10	82	Sand	55	357
Sand	15	97	Shale	31	388
Shale, sandy	49	146	Sand and shale breaks	103	491
Shale and sandy shale	16	162	Shale	7	498
Sand and shale breaks	20	182	Sand, hard, and shale breaks	35	533
Shale	12	194			

(Continued on next page)

Table 9.--Drillers' logs of wells in Hardin County--Continued

	Thickness (feet)	Depth (feet)		Thickness ((feet)	Depth (feet)
Well LH-61-55-204--Continued					
Shale and sand breaks---	15	548	Sand and shale layers---------------	25	684
Sand, hard, and shale breaks----------	15	563	Shale-----------------	20	704
Shale and sand breaks---	10	573	Sand and shale breaks--------------	20	724
Shale------------------	24	597	Shale-----------------	17	741
Sand-------------------	16	613	Sand, coarse-----------	36	777
Sand and shale breaks---	36	649	shale-----------------	23	800
Shale------------------	10	659			

Well LH-61-55-205

Owner: City of Beaumont: Driller: Layne-Texas Co.

Surface, clay-----------	11	11	Shale-----------------	11	304
Sand-------------------	15	26	Sand, coarse, white----	55	359
Sand and brown clay-----	8	34	Shale and sandy shale--	36	395
Sand-------------------	19	53	Sand, coarse, white----	36	431
Clay, sandy------------	12	65	Shale-----------------	5	436
Sand, gray-------------	47	112	Sand, coarse, white----	62	498
Sand and shale breaks---	59	171	Shale-----------------	5	503
Sand-------------------	17	188	Sand a few shale breaks--------------	33	536
Shale, hard, sandy------	9	197	Shale-----------------	5	541
Sand-------------------	41	238	Shale and fine sand----	30	571
Shale------------------	46	284	Shale, sticky----------	29	600
Sand and shale breaks---	9	293			

(Continued on next page)

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Well LH-61-55-205--Continued					
Sand, fine	87	687	Sand	8	1,146
Shale	16	703	Sand and shale streaks	45	1,270
Sand, fine	23	726	Shale	27	1,297
Shale	21	747	Sand, coarse	11	1,308
Sand, coarse, loose	34	781	Shale	84	1,392
Shale	4	785	Sand	7	1,399
Shale, sandy, and shale	27	812	Shale	26	1,425
Shale, hard	44	856	Shale, sandy	8	1,433
Sand	13	869	Shale	8	1,441
Shale	31	900	Shale, sticky	59	1,500
Sand and shale, broken	6	906	Shale and sandy shale, red and blue	43	1,543
Sand	22	928	Sand	2	1,545
Shale	7	935	Shale	10	1,555
Sand	28	963	Sand	4	1,559
Shale	18	981	Shale, sandy	21	1,580
Sand and shale, broken	5	986	Sand	6	1,586
Sand	55	1,041	Shale and sandy shale	37	1,623
Shale	7	1,048	Sand and shale streaks	20	1,643
Sand	9	1,057	Shale	34	1,677
Shale	6	1,063	Shale, sandy	29	1,706
Sand	21	1,084	Rock	1	1,707
Shale	54	1,138			

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	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Well LH-61-55-205--Continued					
Shale	4	1,711	Shale, sandy	21	1,764
Shale and few sand breaks	32	1,743	Shale	40	1,804

Well LH-61-61-305

Owner: Hardin-Jefferson Independent School District. Driller: Layne-Texas Co.

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Clay, brown	15	15	Shale, sandy	28	150
Clay, blue	10	25	Sand	7	157
Sand and clay	20	45	Shale, sandy	25	182
Sand	18	63	Sand	116	298
Shale	53	116	Shale	3	301
Sand	6	122			

Table 10.-Water levels in wells in Hardin County
(in feet below land surface datum)

Date	Water level	Date	Water level	Date	Water level

Well LH-61-36-501

Owner: Gulf, Colorado, and Santa Fe RR Co.

Date	Water level	Date	Water level	Date	Water level
Apr. 13, 1942	24.75	Apr. 18, 1957	31.39	Oct. 11, 1960	32.44
Aug. 6, 1953	25.93	Apr. 18, 1958	30.70		
Apr. 10, 1956	29.09	Dec. 14, 1959	32.10		

Well LH-61-37-201

Owner: Mrs. G. J. Havel

Date	Water level	Date	Water level	Date	Water level
Apr. 29, 1942	3.38	Apr. 18, 1957	11.21	May 9, 1962	9.15
Aug. 6, 1953	6.71	Dec. 14, 1959	8.31		
Apr. 10, 1956	8.50	Oct. 11, 1961	8.41		

Well LH-61-38-701

Owner: O. Sternenberg

Date	Water level	Date	Water level	Date	Water level
Apr. 6, 1942	18.32	Apr. 10, 1956	20.43	Oct. 10, 1960	24.42
Apr. 29, 1942	18.11	Apr. 18, 1957	21.22		
Aug. 6, 1953	19.69	Dec. 14, 1959	19.08		

Well LH-61-39-202

Owner: Sinclair Oil and Gas Co.

Date	Water level	Date	Water level	Date	Water level
Aug. 9, 1953	47.26	Apr. 18, 1958	48.44	Aug. 22, 1962	47.94
Apr. 10, 1956	49.02	Nov. 11, 1960	50.26		
Apr. 19, 1957	49.90	May 9, 1962	50.34		

Table 10.-Water levels in wells in Hardin County--Continued

Date	Water level	Date	Water level	Date	Water level

Well LH-61-52-601

Owner: Mrs. Floy Mauboules

Feb. 23, 1948	21	Apr. 18, 1958	22.39	Oct. 11, 1960	27.02
Apr. 18, 1957	22.95	Dec. 15, 1959	23.04	May 9, 1962	24.25

Well LH-61-53-908

Owner: Gulf Refining Co.

Aug. 5, 1953	15.78	Apr. 18, 1959	8.78	Oct. 11, 1960	12.74
Apr. 10, 1956	6.70	Dec. 14, 1959	9.86	May 9, 1962	12.38

Well LH-61-53-913

Owner: City of Sour Lake

Apr. 9, 1942	6.02	Apr. 18, 1957	17.84	Oct. 11, 1960	20.15
Aug. 5, 1953	15.82	Apr. 18, 1958	15.34	June 14, 1962	18.13
Apr. 10, 1956	14.89	Dec. 14, 1959	15.93		

Well LH-61-53-914

Owner: City of Sour Lake

Apr. 9, 1942	6.03	Apr. 18, 1957	15.11	Oct. 11, 1960	16.60
Aug. 5, 1956	13.52	Apr. 18, 1959	11.90	May 9, 1962	12.31
Apr. 10, 1957	12.13	Dec. 14, 1959	12.98	June 13, 1962	13.31

Well LH-61-55-502

Owner: Kieth Estate

Apr. 8, 1942	Flows	Apr. 10, 1956	Flows	Aug. 23, 1962	2.49
Aug. 5, 1953	Flows	Dec. 21, 1959	Flows		

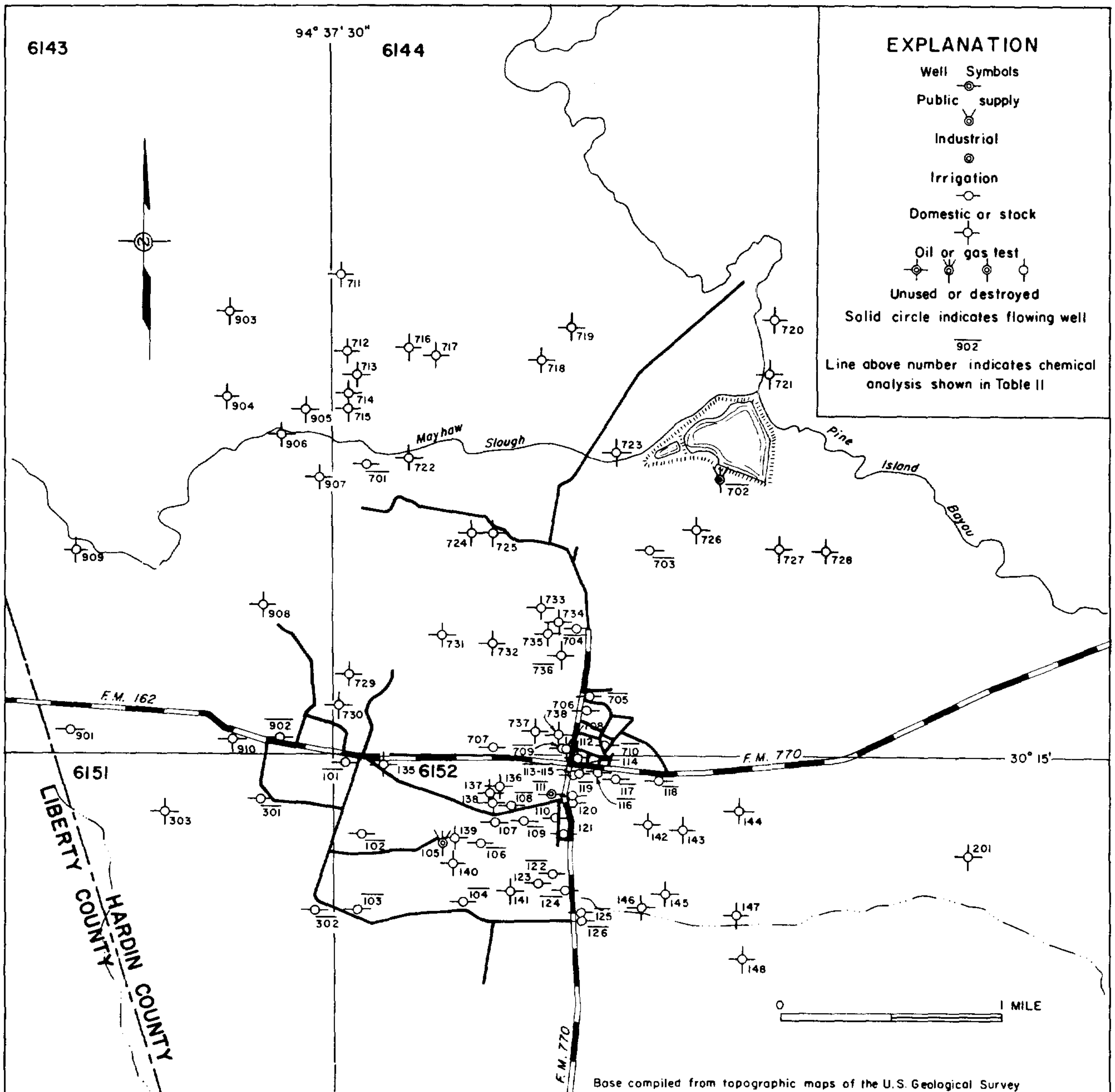

Plate 2

Map Showing Location of Wells in the Batson Area, Hardin County

U. S. Geological Survey in cooperation with the Texas Water Commission and the Lower Neches Valley Authority

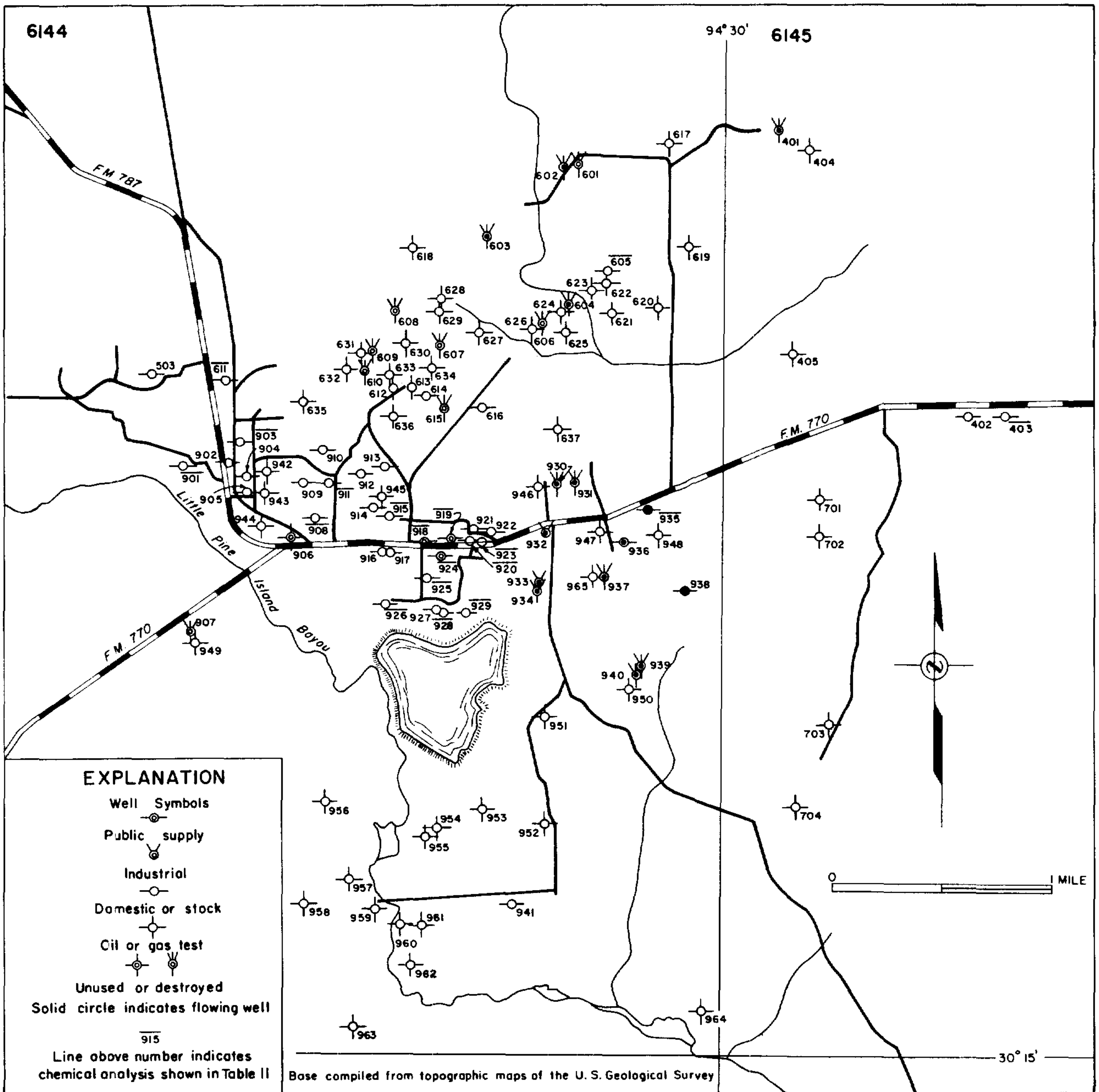

Plate 3

Map Showing Location of Wells in the Saratoga Area, Hardin County

U. S. Geological Survey in cooperation with the Texas Water Commission and the Lower Neches Valley Authority

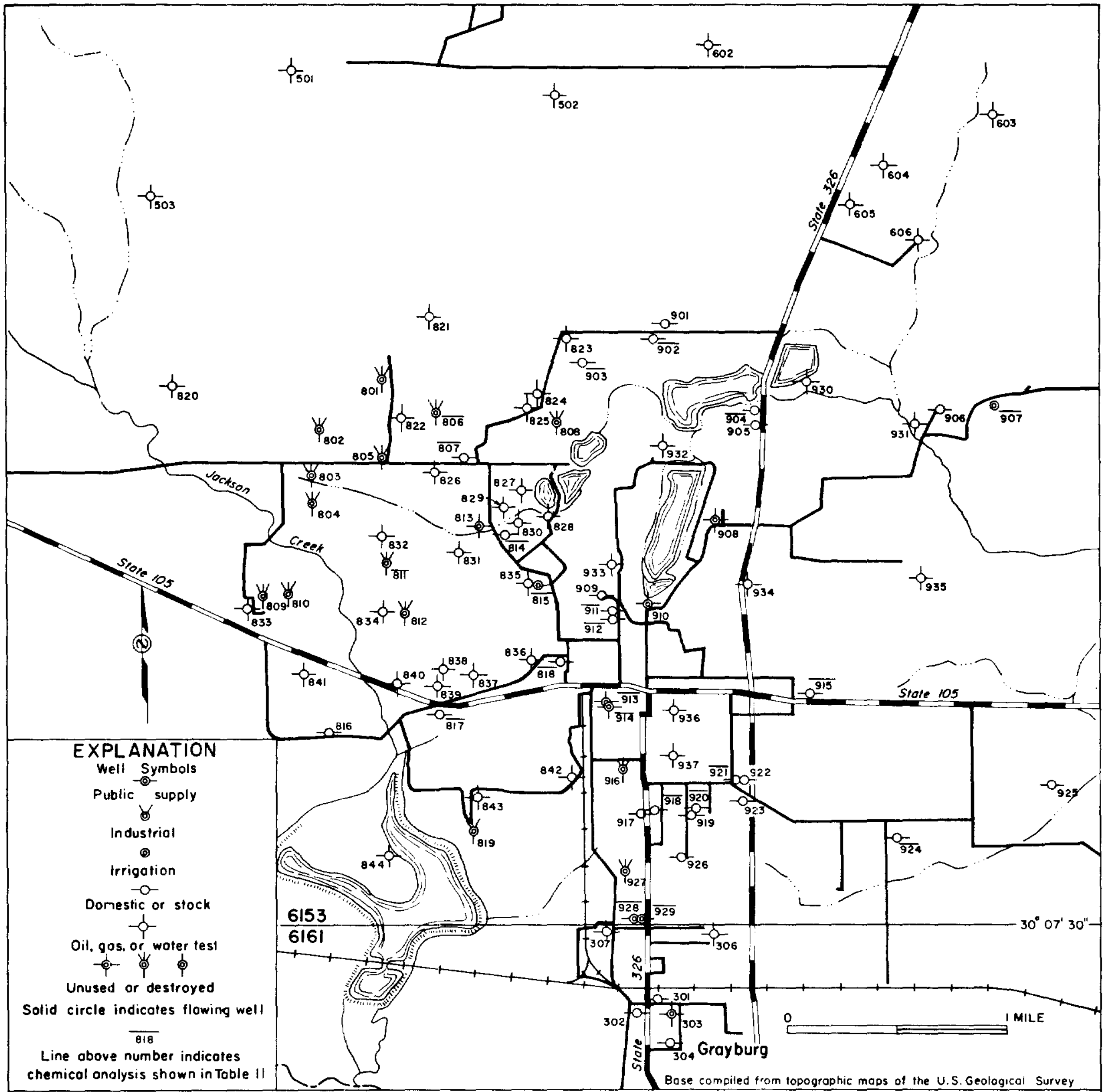

Plate 4

Map Showing Location of Wells in the Sour Lake Area, Hardin County

U. S. Geological Survey in cooperation with the Texas Water Commission and the Lower Neches Valley Authority