TEXAS WATER COMMISSION

BULLETIN 6305

RECONNAISSANCE INVESTIGATION OF THE GROUND-WATER RESOURCES OF THE GULF COAST REGION, TEXAS

By

Leonard A. Wood, R. K. Gabrysch, and Richard Marvin
United States Geological Survey

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

June 1963

Second Printing November 1971
by
Texas Water Development Board

FOREWORD

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

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

TEXAS WATER COMMISSION

Joe D. Carter

Joe D. Carter, Chairman

TABLE OF CONTENTS

TABLE OF CONTENTS (Cont'd.)

Page

TABLE OF CONTENTS (Cont'd.)

TABLES

TABLE OF CONTENTS (Cont'd.)

ILLUSTRATIONS

Figures

Plates

[All plates in pocket]

TABLE OF CONTENTS (Cont'd.)

RECONNAISSANCE INVESTIGATION OF THE GROUND-WATER RESOURCES OF THE GULF COAST REGION, TEXAS

ABSTRACT

The Gulf Coast region, as the term is used in this report, includes all or parts of 51 counties adjacent to the Gulf of Mexico between the Rio Grande on the Mexico border and the Sabine River on the Louisiana border, about 35,000 square miles. Its population is about 2,900,000.

The climate ranges from semiarid in the southwestern part to humid in the northern part. Irrigation is practiced throughout the region, rice being the principal irrigated crop in the northeastern half. Cotton, maize, and other row crops are irrigated during dry periods in all but the northeastern fourth, and citrus fruit and vegetables are irrigated in the Lower Rio Grande Valley.

Most of the Gulf Coast region is a smooth, featureless depositional plain rising from sea level to an altitude of 200 feet, although the interior boundary is as high as 900 feet. The sediments cropping out range in age from upper Eocene to Recent. In vertical section, the geologic formations underlying the region form a series of gently dipping truncated wedges which thicken toward the coast, causing each wedge to have a slightly steeper dip than the overlying wedge. Recent deposits form the wedge nearest the coast, and successively older deposits crop out toward the interior. The part of a wedge in and near the outcrop consists of beds, lenses, and stringers of gravel and coarse to fine sand interbedded with silt and clay beds and lenses; downdip the lithology changes gradually to dominantly silt and clay.

The principal aquifer includes the Goliad Sand, Willis Sand, and Lissie Formation. Of less importance is the aquifer that includes the Catahoula Sandstone, Oakville Sandstone, and the Lagarto Clay. The Beaumont Clay generally is an aquifer between the Nueces and Sabine Rivers, and the alluvium of Recent age is an aquifer in the Rio Grande Valley and the Brazos River Valley.

Ground water in the region is classified as fresh--less than 1,000 ppm (parts per million) of dissolved solids--or slightly saline--1,000 to 3,000 ppm of dissolved solids. The base of the fresh to slightly saline water zone and the thickness of water-bearing sand in the zone are shown on maps prepared from electric logs of oil and water wells. The base of the fresh to slightly saline water zone is as much as 3,600 feet below sea level, and sands in the zone are

as thick as 1,400 feet. The upper limits of dissolved solids used as a basis for the preparation of the map of the base of the fresh to slightly saline water varied according to the availability and use of the water in the region. Northeast of the Guadalupe River, most of the ground water classed as fresh to slightly saline contained less than 1,200 ppm of dissolved solids. In places southwest of the Guadalupe River, ground water that contains as much as 3,000 ppm of dissolved solids is being used, and, therefore, the boundaries of the fresh to slightly saline water were based on that quantity. In general, the fresh to slightly saline water zone is thickest, contains the most water-bearing sand, contains the best quality water, and is capable of yielding the largest quantities of water to wells in the part of the region northeast of the Guadalupe River.

In 1959, about 920,000 acre-feet of ground water, or about 820 million gallons per day, was pumped in the region. About 55 percent was for irrigation, about 23 percent was for industry, and about 20 percent was for public supply. About 3 percent was from domestic and livestock wells, from miscellaneous small wells, and from flowing wells.

A map showing the estimated transmissibility of all the sands in the fresh to saline water zone was prepared from the results of about 300 pumping tests and the map showing the thickness of the sand. To compare the potential quantity of ground water available in one area with that in another, the map was used with several assumptions to calculate the length of time necessary to lower the water level to a maximum depth of 400 feet along the line of discharge. The computations are summarized in a table for comparative purposes but many undetermined factors have a great bearing on the availability of ground water. Among these are the amount of recharge to the aquifers, the amount of natural discharge that could be salvaged, the effect of vertical leakage in areas of lowered artesian pressure, and the amount of water that will be released by compaction of the clays as the artesian pressures are lowered. The computations indicate that precipitation may be sufficient in all parts of the region to maintain adequate recharge to equal or surpass the transmission capacity of the aquifers (quantity of water transmitted through a given width of an aquifer at a given hydraulic gradient). The aquifers in the part of the region that have the lowest potential recharge have small transmission capacities.

RECONNAISSANCE INVESTIGATION OF THE GROUND-WATER RESOURCES OF THE GULF COAST REGION, TEXAS

INTRODUCTION

Purpose and Scope

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

To implement the directive of the Legislature, a cooperative project between the Texas Board of Water Engineers (Commission) and the U. S. Geological Survey was begun in September 1959. The project was titled, "Reconnaissance ground-water investigations in Texas."

The planning of the cooperative program was based on the needs and availability of water in major river basins. The U. S. Geological Survey is reporting on the Red, Sulphur, Cypress, Brazos, Upper and Lower Rio Grande, Guadalupe, Nueces, and San Antonio Basins, and the Gulf Coast region. The Texas Water Commission is reporting on the Canadian (Texas Board of Water Engineers, 1960), Sabine, Neches, Trinity, Colorado, and Middle Rio Grande Basins. All the reports were scheduled for completion in 1962 except that for the Canadian, which was completed in 1960, that for the Gulf Coast region, completed in 1961, and that for the Guadalupe, Nueces, and San Antonio Basins, which will be completed in 1963.

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

1. Inventory of large wells and springs.

2. Compilation of available logs of wells and preparation of generalized cross sections and maps showing subsurface geology.

3. Inventory of major pumpage.

4. Pumping tests of principal water-bearing formations.

5. Measurement of water levels in selected wells.

6. Determination of areas of recharge and discharge.

7. Compilation of chemical analyses of water and sampling of selected wells and springs for additional analyses.

8. Correlation and generalized analysis of all data to determine the magnitude of supplies available from each major formation and the general effects of future pumping.

9. Preparation of generalized reports on principal ground-water resources of each basin.

Fieldwork in the Gulf Coast region was done from September 1959 to August 1960. The inventory of wells consisted of locating all the major wells--that is, the public supply, industrial, and irrigation wells. Although all the wells were located, complete data on individual irrigation wells were obtained on only 10 to 15 percent of the wells in the areas of concentrated development. Several thousand electric logs of oil- and gas-test wells were used in mapping the base of the fresh to slightly saline water and in compiling the total thickness of the sand beds that contain the fresh to slightly saline water. Water samples from 92 wells were analyzed for the study. These and several hundred other analyses that had been made before the study began were used as guides in interpreting the electric logs. Pumping tests of about 300 wells were used to determine the water-bearing characteristics of the formations. By interpreting the water-bearing characteristics and total thickness of sands, the magnitude of ground-water supplies available in the several subregions was calculated. However, because of the complexity of the aquifers and the many assumptions necessary in the calculations, calculated amounts of available ground water should be considered as preliminary estimates expressing an order of magnitude that may require revision as development takes place and additional data become available.

Location and Extent of the Area

The Gulf Coast region (Figure 1), as the term is used in this report, includes the lower parts of the Rio Grande, Nueces, San Antonio, Guadalupe, Colorado, Brazos, Trinity, Neches, and Sabine drainage basins and all the San Jacinto, Lavaca, and small coastal basins. The region includes all or parts of 51 counties and has an area of about 35,000 square miles. The region ranges in width from 50 to 120 miles and averages about 90 miles; it is 467 miles long measured by highway from Orange to Brownsville, although by air, it is only about 400 miles, as the region is curved, and the shortest distance from one end to the other is across the Gulf of Mexico. Most of the region lies between latitude 26° and 31° north and longitude 94° and 99° west.

Figure 1

Map of Gulf Coast Region, Showing Locations of Subregions

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

95

Economic Development and Cultural Features

Although the Gulf Coast region constitutes less than 14 percent of the area of Texas, it has slightly more than 30 percent of the population, about 2,900,000. The largest center of population is Houston (938,219 in 1960). About 1,500,000 persons resided in Harris (Houston), Galveston, Brazoria, and Fort Bend Counties in 1960. The next largest concentration of population is in Cameron and Hidalgo Counties in the Lower Rio Grande Valley (about 331,000 in 1960). In the Beaumont-Port Arthur-Orange area of Jefferson and Orange Counties, the 1960 population was about 306,000. Another population center is the Corpus Christi area (Nueces and San Patricio Counties), about 210,000 in 1960.

The principal factor in the economic development of the region is water for agriculture, industry, municipal use, and transportation. Water for agriculture comes from three sources--rainfall, streams, and wells. In 1960 all but 520 acres of the 417,039 acres of rice grown in Texas was in the Gulf Coast region between the Guadalupe and Sabine Rivers, each acre requiring from 1-1/2 to 4 feet of water in addition to rainfall. About 40 percent was irrigated by ground water and the remainder by surface water. Another intensively irrigated area is in the Lower Rio Grande Valley in Cameron, Hidalgo, and Willacy Counties where citrus fruit, vegetables, and cotton are irrigated with water from the Rio Grande and from wells. Cotton and other row crops are irrigated in places throughout the region, but principally in the area between and including Fort Bend County and northern Brooks County, and in the Lower Rio Grande Valley.

The abundance of water for industrial use has been a principal factor in the location of most of Texas' oil refining and petrochemical plants in the Gulf Coast region. According to Resen (1955, p. 182-195), more than 85 percent of the 2,312,050 barrels per day handled by Texas' refineries was processed in the Gulf Coast region. The three important refinery centers are (1) Houston-Baytown-Texas City area in Harris and Galveston Counties, (2) Beaumont-Port Arthur area in Jefferson County, and (3) Corpus Christi area in Nueces and San Patricio Counties. Associated with the oil-refining industry on the Gulf Coast is a large and growing petrochemical industry. The Houston-Baytown-Texas City area has the largest concentration of petrochemical plants in the world (Resen, 1955, p. 189). The Beaumont-Port Arthur-Orange area has nearly a dozen plants and all together there are more than 40 petrochemical plants in the region. Other Texas industries that require large amounts of water are the paper mills in Harris and Jasper Counties, the metal refining industry (steel mill in Harris County, aluminum plants in Calhoun and San Patricio Counties, and a magnesium plant in Brazoria County), and the mining industry (recovering sulfur by the Frasch method or processing salt from one of the many salt domes in the Gulf Coast region).

Water transportation is a major factor in the economic growth of the Gulf Coast region. Houston is a deep-water port along the upper 22 miles of a 52-mile channel, and the port of Houston has been second in the Nation in total tonnage during several recent years. Other deep-water ports are at Orange, Beaumont, Port Arthur, Texas City, Galveston, Freeport, Port Aransas, Corpus Christi, Port Isabel, and Brownsville. In addition to the deep-water ports, many ports are suitable for barge shipments on the Gulf Intracoastal Waterway, which extends from the mouth of the Rio Grande on the southwest to and beyond the Mississippi River.

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

Previous Investigations

The first studies of the ground-water resources of the Gulf Coast region of Texas were by Singley (1893), Taylor (1907), and Deussen (1914). Further studies were not recorded until 1929 when a cooperative program was begun by the Texas Board of Water Engineers and the U. S. Geological Survey, and, in some areas, local units of government. Between 1929 and 1945, wells in nearly every county in the region were partly inventoried and reports were published containing records of wells, chemical analyses of water, water levels, and well logs. (See Selected Bibliography, p. 103).

Since 1945, detailed reports have been published on the Houston area (Lang and others, 1950), Galveston County (Petitt and Winslow, 1955), the Lower Rio Grande Valley (Baker and Dale, 1961), and Victoria and Calhoun Counties (Marvin and others, 1961). Special reports on salt water (Winslow and others, 1957) and land-surface subsidence (Winslow and Doyel, 1954; Winslow and Wood, 1959), in addition to several other progress reports and journal articles, have been published on the Houston area. Numerous other short reports on various areas in the region have been published also since 1945. Many reports describing areas smaller than counties have not been duplicated but are in the open files of the U. S. Geological Survey and Texas Water Commission.

In 1956, a report was prepared by the U. S. Geological Survey for the U. S. Bureau of Reclamation on the availability of ground water in the Gulf Coast region of Texas (Wood, 1956). Much of the basic data for that report, collected during 1955 and 1956, has been incorporated into this one.

Assignment of Work

Basic data for this report were collected and assembled between September 1, 1959, and August 31, 1960, by C. C. Mason, R. B. Anders, W. L. Naftel, R. K. Gabrysch, Richard Marvin, and O. C. Dale, all of the Geological Survey. The illustrations and the text were prepared by the authors between September 1, 1960, and August 1, 1961. The method of computing the magnitude of water available in the different subregions was determined with the aid of M. L. Klug of the Texas Water Commission.

Acknowledgments

The collection of the basic data upon which this report is based would have been impossible without the cooperation of innumerable well owners, well drillers, city and county officials, and consulting firms; the writers take this opportunity to thank them.

GEOGRAPHY

The Gulf Coast region is in the West Gulf Coastal Plain and is a nearly smooth, featureless depositional plain rising from sea level to 200 feet in 50 to 88 miles. The 200-foot contour is closest to the Gulf of Mexico in the area between the Nueces River and the Rio Grande. Between the 200-foot contour and the coast, the principal relief is caused by the youthful valleys of the small consequent streams that drain the region. The larger streams that cross the area have broad shallow valleys that for the most part are remnants of earlier erosional cycles. The land above the 200-foot contour is generally more rolling and has a greater relief.

The interior boundary of the region generally has an altitude between 200 and 400 feet, but attains an altitude of more than 500 feet in northeastern Jasper County and northern Newton County, and more than 900 feet in southeastern Webb County. The interior boundary descends to an altitude of 90 to 200 feet where it crosses the larger river valleys.

The largest streams crossing the region are the Sabine, Neches, Trinity, Brazos, and Colorado Rivers, and the Rio Grande. The Sabine and Neches Rivers rise in the Gulf Coastal Plain in northeastern Texas, whereas the others rise several hundred miles north and west of the Gulf Coastal Plain. Other major streams are the Guadalupe, San Antonio, and Nueces Rivers. The San Jacinto and Lavaca Rivers lie wholly within the region.

These and many other smaller streams are transporting sediments from the Gulf Coastal Plain and older inland areas to the shoreline where deposition is taking place much as it did at the time the formations comprising the Gulf Coastal Plain were laid down. In places the coastline has moved gulfward in historic time, notably at the mouths of the Colorado and Brazos Rivers and the Rio Grande.

The northeastern part of the region (east of U. S. Highway 75 and north of U. S. Highway 90 between Houston and the Sabine River) is mostly forested. The principal trees growing in the area are the longleaf, shortleaf, loblolly, and slash pines. Most of the remainder of the region northeast of the Guadalupe River is a treeless prairie, although many varieties of trees grow along the numerous watercourses. Much of the region southwest of the Guadalupe River is covered by brush, principally mesquite, small liveoak, postoak, prickly pear cactus, catclaw, black brush, white brush, huajillo, huisache, and other arid-land shrubs.

Barrier islands extend the full length of the region. In many places the bays behind the islands are only a few feet deep and in places, notably in Jefferson and Brazoria Counties, the bays have been nearly filled so that only marshes remain. The Rio Grande, Brazos and Colorado Rivers have constructed deltas across the bays and are enlarging their deltas as are the Trinity and Guadalupe Rivers, although the construction of dams upstream has probably slowed the delta-building activity of some of the rivers. The shoreline behind the barrier islands is characterized by numerous indentations and bays, some of which have areas of several hundred square miles. Galveston Bay is the largest; other large bays are Sabine Lake and Matagorda, San Antonio, Copano, Corpus Christi, and Baffin Bays.

Salt domes are unusual features of the region and are of great economic importance as many of the oil and gas fields and all the sulfur mines are associated with them. Although many of the domes have no surface expression, several form mounds rising more than 100 feet above the rather flat coastal plain. Conversely, other domes are marked at the surface by depressions which form small lakes, generally containing saline water.

Climate

According to Thornthwaite's classification (1952, p. 32), the Gulf Coast region is divided into an area of moisture deficiency west of a line through Calhoun, Jackson, and Lavaca Counties, and an area of moisture surplus east of this line. Thornthwaite's classification is based on a comparison of potential evapotranspiration and precipitation. If precipitation is exactly the same as potential evapotranspiration at all times and water is available just as needed, there is neither a deficiency nor a surplus of water, and the climate is neither moist nor dry. The area having surplus moisture is further broken down by Thornthwaite into a humid area (east of a north-south line through Galveston Bay) and a moist subhumid area (remainder of the moisture-surplus area). Similarly, the moisture-deficiency area is divided into a dry subhumid area (east of a north-south line through Corpus Christi Bay) and a semiarid area (remainder of the moisture-deficient area).

The validity of Thornthwaite's classification can be ascertained by the examination of Figures 2, 3, and 4, which show the variation in rainfall across the region and the average monthly precipitation, evaporation, and temperature at Beaumont, Angleton, Beeville, and Weslaco. The average precipitation ranges from about 20 inches a year in part of the Lower Rio Grande Valley to more than 56 inches a year in part of the Sabine River Basin. Figures 3 and 4 show that the potential evaporation increases generally from the area of higher precipitation to the area of lower precipitation. Evaporation data are less exact than precipitation data because of local conditions and the different types of equipment used. For example, the annual average evaporation at Weslaco is less than that at Beeville perhaps because the extensive irrigation in the vicinity of Weslaco causes a higher humidity.

Figure 4 shows the correlation between temperature and evaporation by months. Figure 3 shows the distribution of precipitation throughout the year. All four stations have their highest monthly precipitation during one of the warmer months between May and September, inclusive, when the precipitation is generally from thunderstorms. However, tropical storms may sweep in from the Gulf during these months and drop as much as 30 inches of rain in 24 hours.

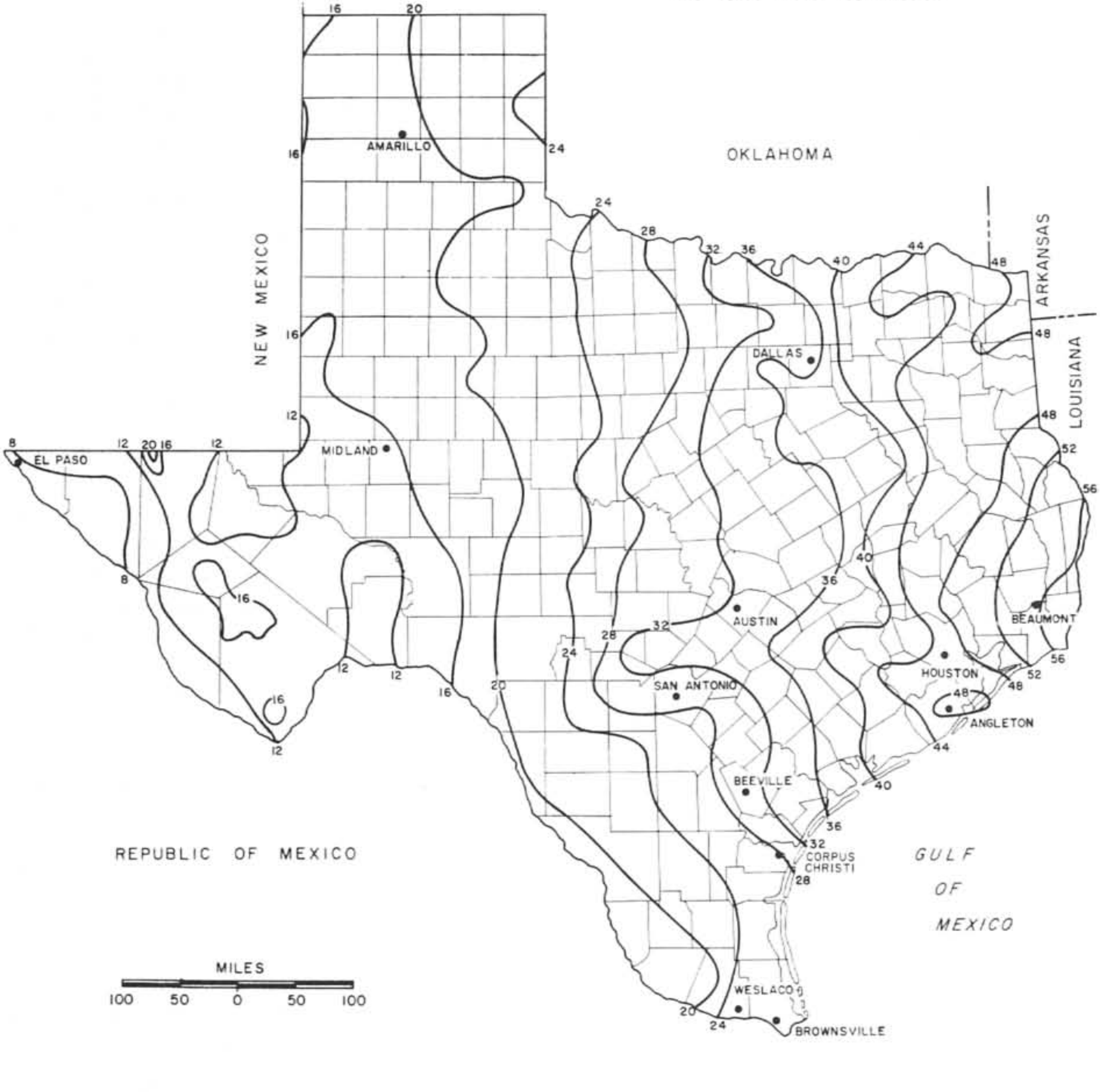
Although the average precipitation ranges from about 20 to 56 inches a year, the precipitation during the growing season in any particular year may not be adequate in any particular part of the region. In the semiarid part water is needed to supplement rainfall during all or at least some part of almost every growing season. In the dry subhumid part, irrigation is needed for most crops during part of most growing seasons and in some years during most of the growing season. Conversely, in the moist subhumid part, most crops can be grown without supplemental water, and in the humid part supplemental water is rarely needed, although during prolonged dry spells in the growing season it would be beneficial. Rice, which is the principal irrigated crop, is irrigated wherever

Figure 2

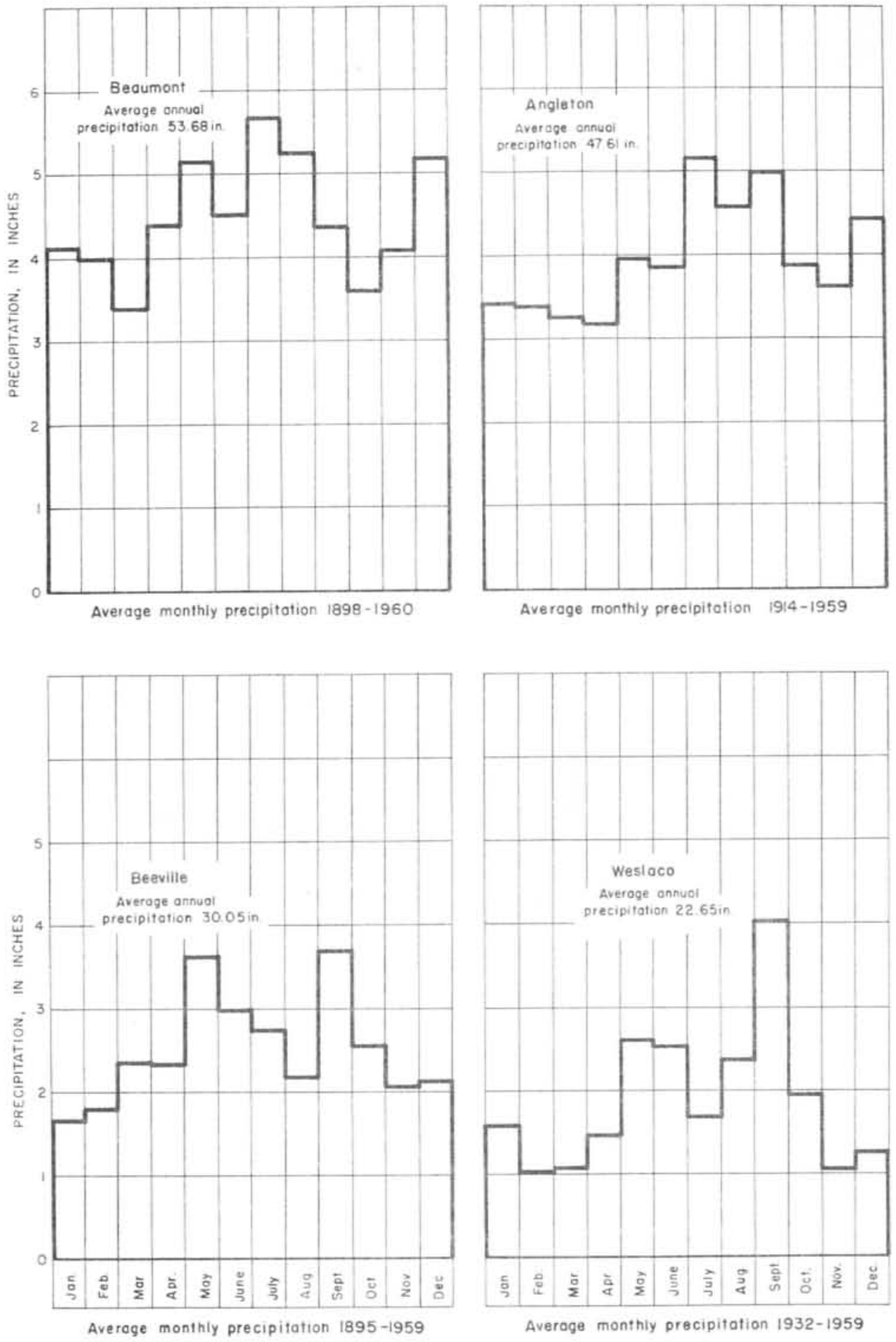
Map of Texas Showing Mean Annual Precipitation in Inches Based on the Period 1931-55

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

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



95



Average monthly precipitation 1898-1960

Average monthly precipitation 1914-1959

Average monthly precipitation 1895-1959

Average monthly precipitation 1932-1959

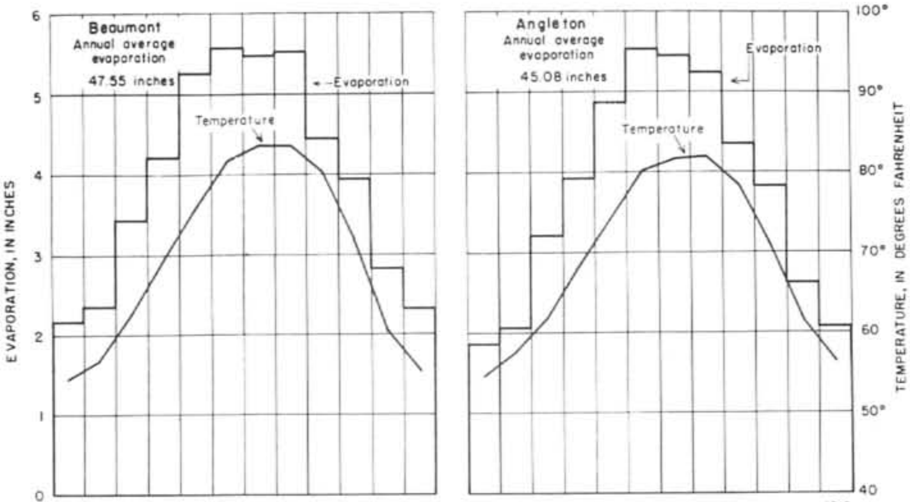
Figure 3

Average Monthly Precipitation at Beaumont, Angleton, Beeville, and Weslaco

(Data from Bloodgood, Patterson, and Smith, 1954, and from the Texas Water Commission)

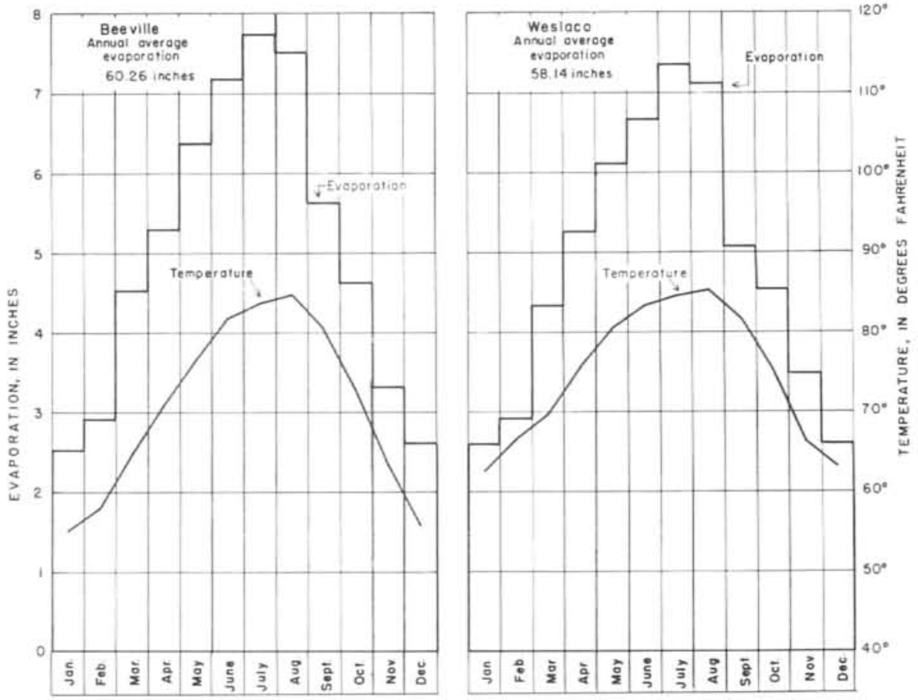
U. S. Geological Survey in cooperation with the Texas Water Commission

95



Average monthly evaporation and temperature, Jan. 1917–Aug. 1960. B.P.I. pan Jan. 1917–Aug 1950, Young screen pan Sept 1950–Aug. 1960

Average monthly evaporation and temperature, Jan. 1915–Aug. 1960. B.P.I. pan Jan 1915–Aug. 1952, Young screen pan Sept. 1952–Aug. 1960



Average monthly evaporation and temperature, Jan. 1915–Aug. 1960. B.P.I. pan Jan 1915–Feb 1955, Young screen pan Mar 1955–Aug. 1960.

Average monthly evaporation and temperature, Jan. 1932–Aug. 1960. B.P.I. pan Jan. 1932–May 1954, Young screen pan June 1954–Aug. 1960.

Figure 4

Average Monthly Evaporation and Temperature at Beaumont, Angleton, Beeville, and Weslaco

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

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

95

it is grown because during most of its growth it must be standing in several inches of water. Nearly all the rice produced in Texas is grown in the moist subhumid and humid parts of the Gulf Coast region.

Drainage Basins

For statewide water planning, the drainage basins and intervening coastal areas of the State have been delineated by the Planning Division of the Texas Water Commission. The river basins designated by them are the Canadian, Red, Sulphur, Cypress, Sabine, Neches, Trinity, San Jacinto, Brazos, Colorado, Lavaca, Guadalupe, San Antonio, Nueces, and Rio Grande. All but the Canadian, Red, Sulphur, and Cypress Rivers either cross or rise in the Gulf Coast region. The boundary of each river basin was delineated on the outer line of the catchment area tributary to the stream involved. Adjacent rivers share a mutual boundary except near their mouths where intervening areas are drained by small streams emptying directly into the Gulf of Mexico. The coastal parts of the Sabine, Neches, Trinity, Brazos, Colorado, Guadalupe, San Antonio, Nueces, and Rio Grande Basins and all the San Jacinto and Lavaca drainage basins and the coastal areas are included in the Gulf Coast region.

Each of the river basins is further divided into major subdivisions, which have areas of about 600 square miles or more. The major subdivisions are numbered beginning at the head of the basin and proceeding downstream to the mouth. The coastal areas are designated by the names of the bounding river basins and are also divided into from one to seven major subdivisions.

For convenience of discussion and to permit the use of adequate-scale maps, the region has been split into five subregions (Figure 1). Subregion I contains the coastal parts of the Trinity, Neches, and Sabine River Basins and the adjacent coastal areas. Subregion II contains the San Jacinto River Basin and the adjacent coastal areas. Subregion III contains the Lavaca River Basin, the coastal parts of the Brazos and Colorado River Basins, and the adjacent coastal areas. Subregion IV contains the coastal parts of the Guadalupe, San Antonio, and Nueces River Basins and the adjacent coastal areas. Subregion V contains the coastal part of the Rio Grande Basin and the adjacent coastal areas which have not been divided into major subdivisions.

GENERAL GEOLOGY

Regional Structure and Geologic History

The regional geology of the Gulf Coast region is simple. Sedimentary beds ranging in age from late Eocene to Recent lie as bands nearly parallel with the coast. The strike of the beds changes from north-south in the southern part of the region to northeast-southwest in the eastern part. Recent deposits form the coastline and successively older beds crop out toward the interior. Because of the age of the exposure of the rocks, the outcrop areas are successively more eroded and dissected toward the interior. Pleistocene and Recent formations still retain much of their depositional surface.

In vertical section, geologic formations underlying the region occur as a series of gently dipping truncated wedges that thicken toward the coast, causing each wedge to have a slightly steeper dip than the overlying wedge. At the coast the thickness of the upper Eocene to Recent sediments totals 4 to 5 miles. Near the outcrop area, the dip changes progressively from approximately 150 feet per mile for the upper Eocene sediments to 10-20 feet per mile for youngest Pleistocene sediments.

The lithology of the wedges reflects three depositional environments: continental (alluvial plain), transitional (delta, lagoon, and beach), and marine (continental shelf). The part of a wedge in and near the outcrop consists of beds, lenses, and stringers of gravel and coarse to fine sand interbedded with silt and clay beds and lenses; these sediments were deposited in a continental environment. Downdip the lithology changes gradually to dominantly silt and clay of marine depositional origin.

Faults are common in the region, but generally they have little or no surface expression. Most are normal strike faults, seemingly related to the gradual subsidence and tilting of the basement strata of the earth's crust and the subsequent adjustment of the overlying sediments. Some faults are related to the salt domes, which occur in many places throughout the region.

Salt domes are the result of upward movement of deep-seated salt. The movement is by means of plastic flow, initiated by the tremendous weight of the overlying sediments, the salt piercing or doming these same overlying sediments. Many salt domes have a surface expression but are in themselves minor structural features of the region.

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

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

During late Eocene time, about 40 million years ago, volcanos were active at times in areas near the Gulf Coast region. As a result, volcanic ash has been incorporated in some of the sediments of that time. Volcanic activity also occurred during the Oligocene(?) Epoch, but it was during Miocene time that nearby volcanos were most active. As a result, a great amount of pyroclastic material was deposited in the Miocene strata, some of it being reworked when a previous depositional plain was elevated and subjected to stream erosion.

During the Pliocene and Pleistocene Epochs, climatic conditions were propitious for the formation of caliche, generally in the form of calcium carbonate deposited at or near the land surface. Water moving through the sediments precipitated dissolved lime to form caliche nodules and continued formation of caliche produced thick, irregular layers.

The depositional processes that produced the thick sedimentary formations of late Eocene to Pleistocene age are continuing today as shown by the deltas of the Rio Grande, Colorado, Brazos, and Trinity Rivers. However, one feature that is different is the widespread blanket of sand and silt, covering about 2,800 square miles of southern Texas. Dominant west-blowing winds move sand from the beach dunes of Kenedy County toward the interior until decreasing winds, change in wind direction, and vegetation stop the movement. Such large-spread eolian deposits are not known in preceding cycles of deposition.

The 13 cross sections included in this report show the base of the fresh to slightly saline water and the thickness of water-bearing sand (Figures 5, 6, 7, and 8). The cross sections and subsurface maps were drawn from the interpretation of electric logs. Formational differences such as color, grain size, mineral composition, and others, cannot be determined by electric logs. Subsurface correlation is exceedingly difficult as the sands and gravels occur as beds, lenses, or stringers, which thicken and thin or grade into silts and clays within short lateral distances. Therefore, formation contacts are not shown on the sections.

Rock Formations and their Water-Bearing Properties

The coastal geologic formations underlying the Gulf Coast region change in lithology, dip, and thickness in the direction of the dip. The dip and thickness increase; the clastic materials change from sands, silts, and clays to dominantly clays. The following descriptions of formations (Table 1) are limited to the fresh to slightly saline water zone and outcrop area--that is, the updip part of the formation. Fresh water does not occur deeper than 3,600 feet below sea level and is generally much closer to the land surface. Figure 9 shows the areas where the major water-bearing formations yield fresh to slightly saline water within the region.

Tertiary System

Eocene Series

Jackson Group

The Jackson Group, late Eocene in age, is not divided into its formational units in this report. In the outcrop area, the dip ranges from 120 to 150 feet per mile. The group ranges in thickness from 800 to 1,300 feet, thickening downdip and toward the west. In the eastern part of the region, the Jackson consists of interbedd light-colored sandy or tuffaceous shale and fossiliferous sand and some limestone and lignite beds. In the central part of the region, the lower part of the Jackson Group is predominantly clay and silt; the upper part is composed of interbedded tuffaceous sand and bentonitic clay lenses. Some strata contain fossils, lignitized wood, and limestone concretions. The Jackson Group lithology in the southern part of the region is much the same as in the central part except abundant opalized or silicified wood is found instead of lignitized wood.

The Jackson Group is not an aquifer of major importance in the region except possibly in the eastern part where its potential was not determined. In general, wells that tap sand beds in the Jackson yield only small to moderate quantities of water. Sand beds of the Jackson Group yield water for municipal supply in Polk County and for municipal and industrial supply in Karnes County. A few wells in Karnes County yield water both from sands in the Jackson Group and the overlying Catahoula Tuff by means of multiple screen settings. The Jackson Group yields potable water only in and near the outcrop area, the water becoming saline at depths of a few hundred feet. In the southern part of the region even the shallow water is saline.

Oligocene(?) Series

Frio Clay

In the southern part of the region, the Frio Clay is predominantly a massive clay, containing noticeable amounts of gypsum and thin beds of sand and volcanic ash. The Frio ranges in thickness from 0 to 600 feet. In the central part, it becomes more sandy, conglomeratic, and appreciably thinner. The Frio Clay is recognized only in the subsurface in the eastern part. The formation is not an aquifer in the region.

Miocene(?) Series

Catahoula Sandstone (Catahoula Tuff)

The Catahoula Sandstone--called the Catahoula Tuff in the central and southern parts of the region--ranges in thickness from 0 to 1,500 feet and is characterized by its extensive and thick deposits of volcanic ash. In the eastern part, the base of the formation is a sand, in places conglomeratic, and partly cemented by silica. The rest of the formation consists of tuff, variegated clay, silts, tuffaceous silts, and sands, dipping toward the coast at an average of 50 to 60 feet per mile. Some deposits of volcanic ash have been weathered to fuller's earth.

In the central part, the Catahoula is more heterogeneous, consisting of conglomerate beds containing pyroclastic material, gravel, and sand, thick beds of tuff, tuffaceous and sandy clay, and even a few thin beds of lignite and limestone. At the outcrop the formation dips coastward at about 120 feet per mile.

In Duval County, the Catahoula is decidedly volcanic. Large amounts of volcanic debris form intergrading beds of conglomerate, arkosic sand, tuff, and tuffaceous clay. Extensive siliceous cementing of the clastic material has formed prominent hills in Duval County.

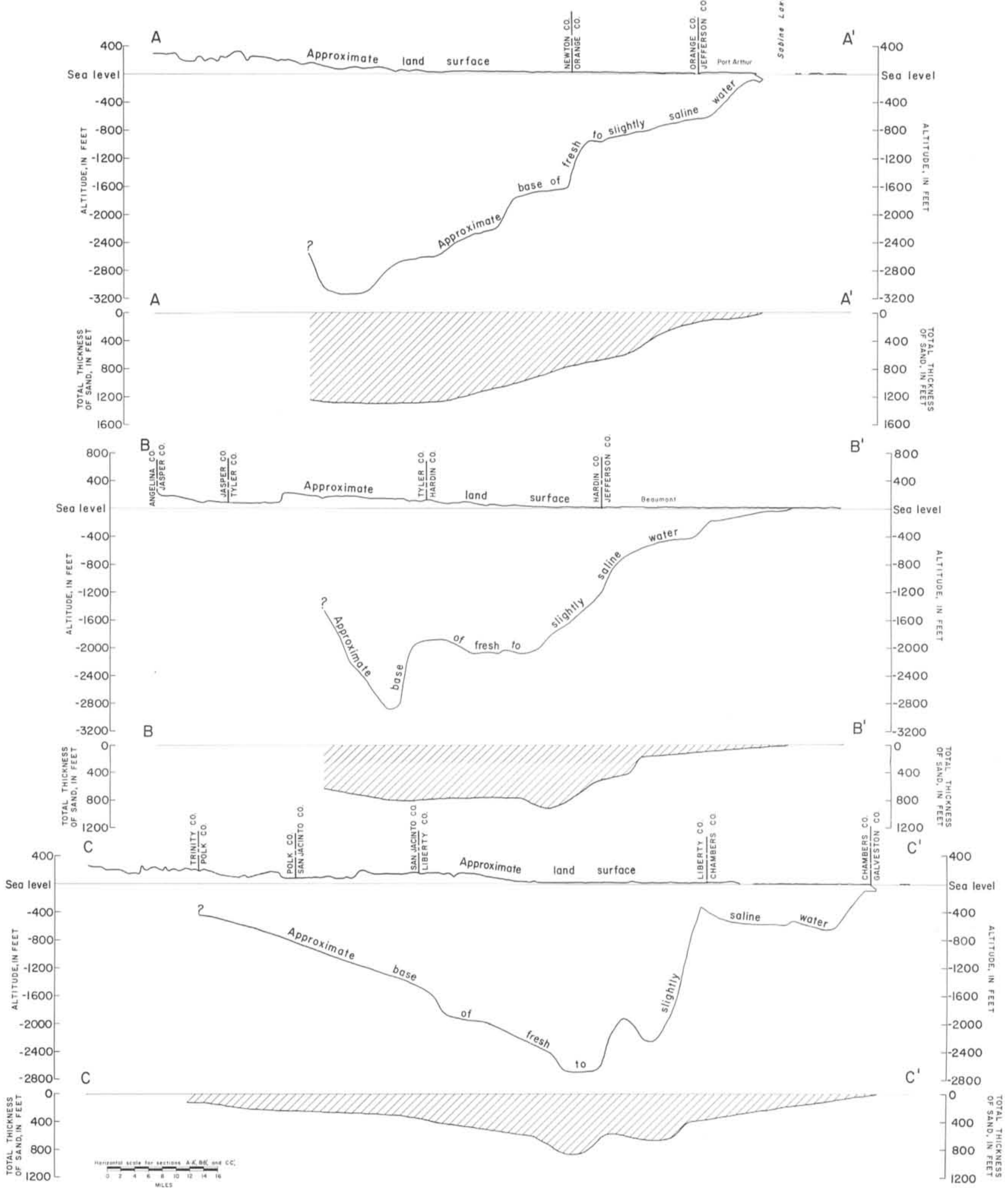


Figure 5

Cross Sections A-A', B-B', and C-C', Gulf Coast Region

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

Location of cross sections shown on Plates 2 and 3.

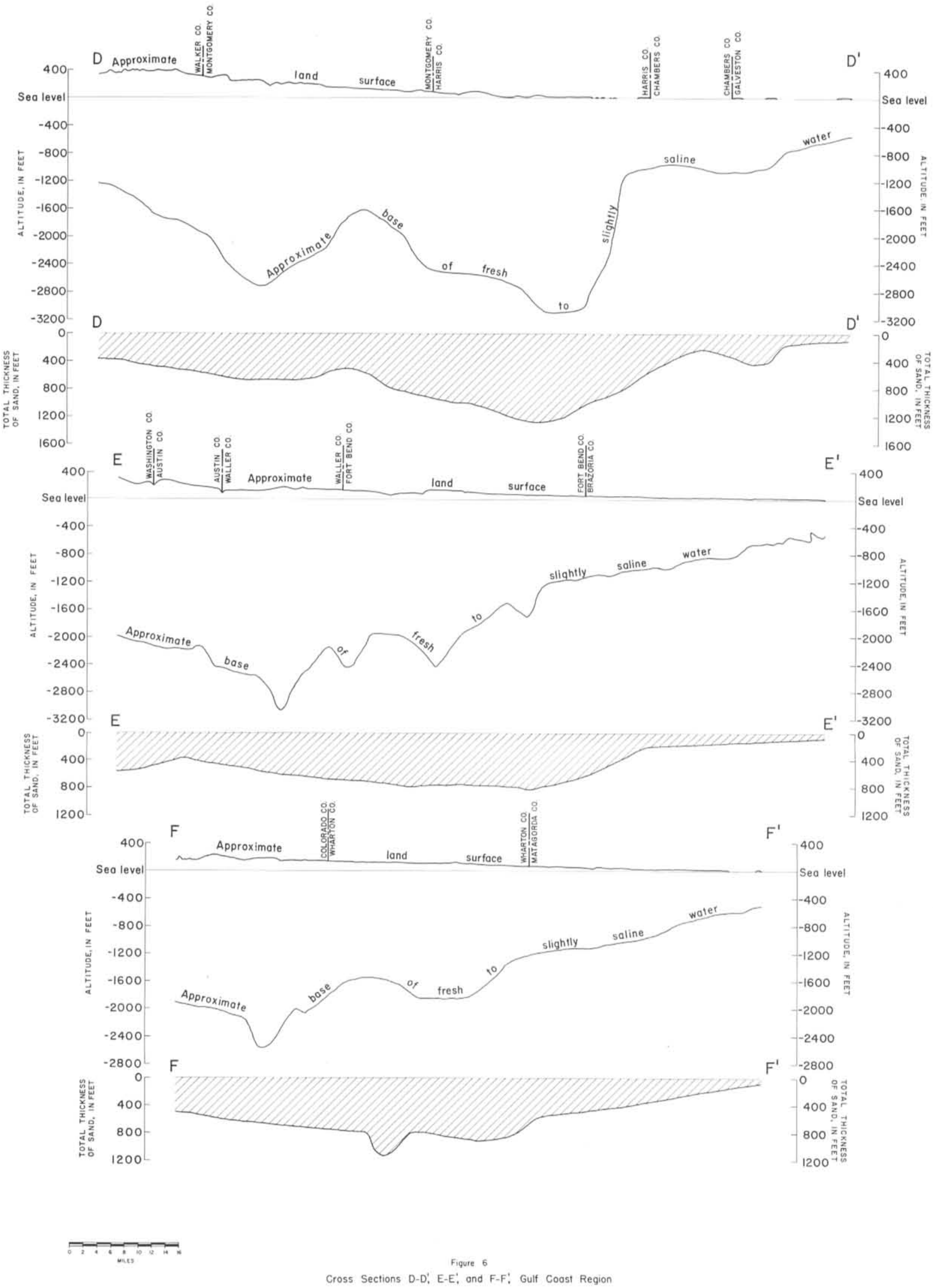


Figure 6

Cross Sections D-D', E-E', and F-F', Gulf Coast Region

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

Location of cross sections D-D' shown on Plates 5 and 6.
Location of cross sections E-E' and F-F' shown on Plates 8 and 9.

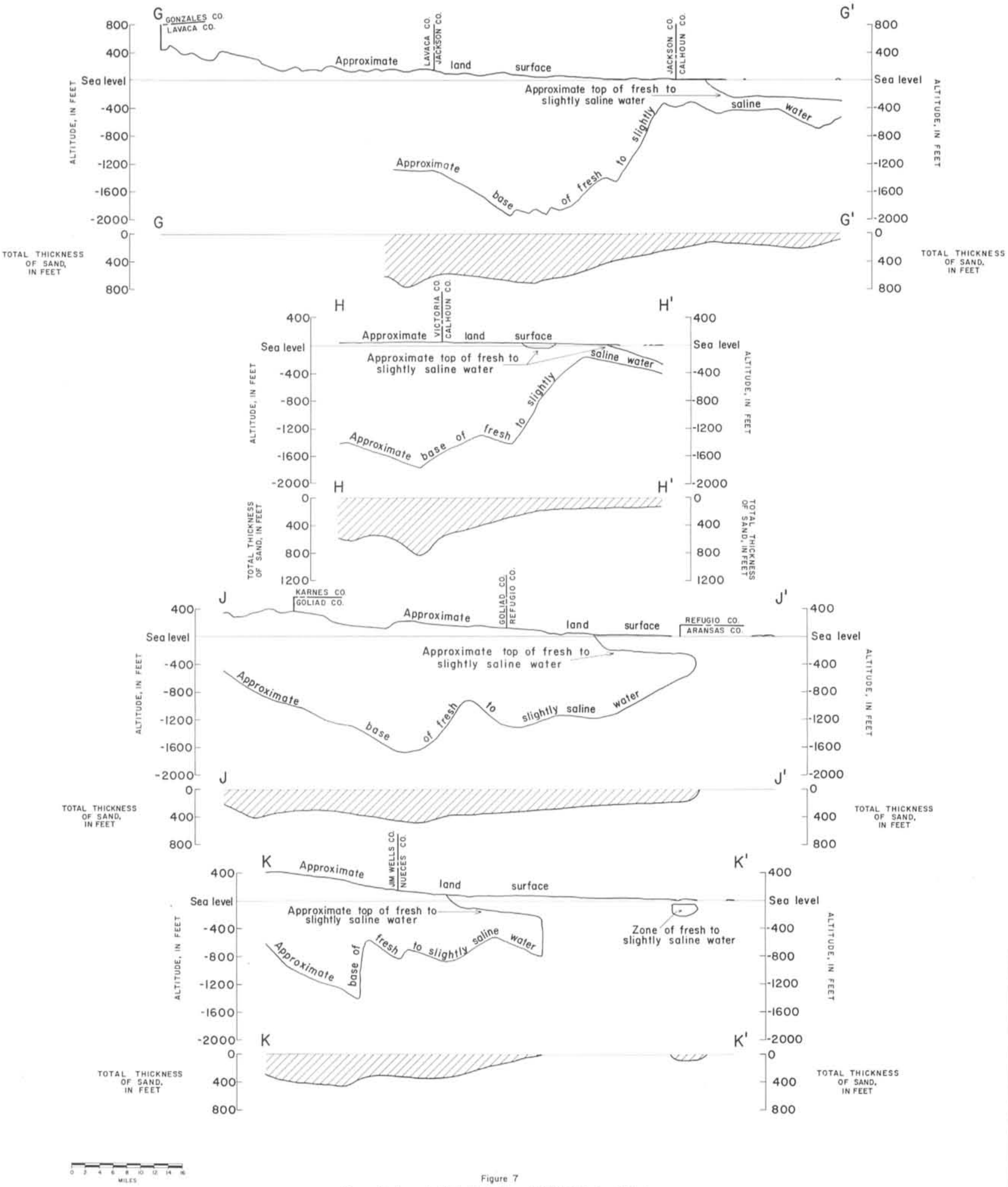


Figure 7

Cross Sections G-G', H-H', J-J', and K-K', Gulf Coast Region

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

Location of cross sections G-G' shown on Plates 8 and 9
Location of cross sections H-H' shown on Plates 8, 9, 11, and 12
Location of cross sections J-J' and K-K' shown on Plates 11 and 12

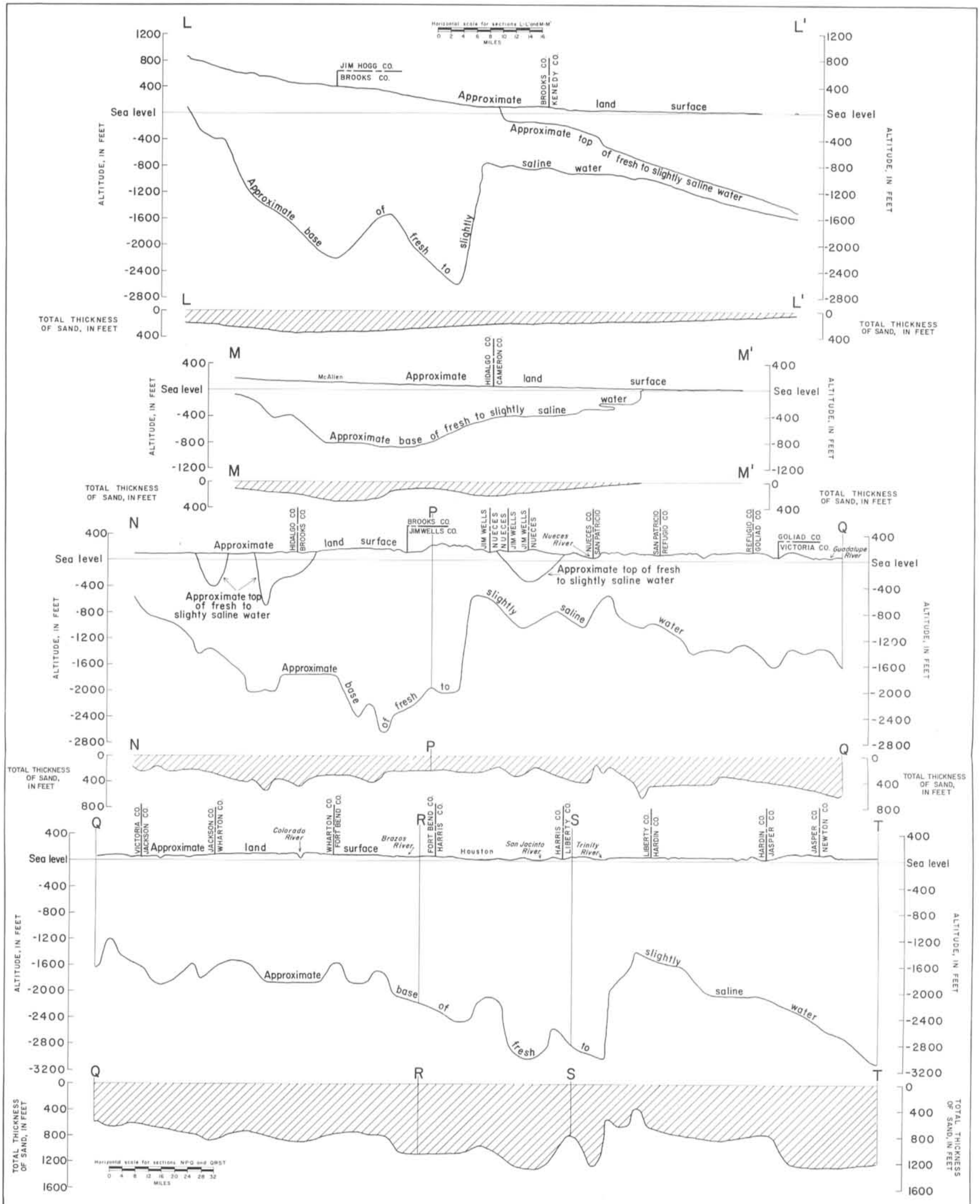


Figure 8

Cross Sections L-L', M-M', N-P, P-Q, Q-R, R-S, and S-T, Gulf Coast Region

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

Location of cross sections L-L', M-M', and N-P shown on Plates 14 and 15
Location of cross sections P-Q shown on Plates 11 and 12
Location of cross sections Q-R shown on Plates 8 and 9
Location of cross sections R-S shown on Plates 5 and 6
Location of cross sections S-T shown on Plates 2 and 3

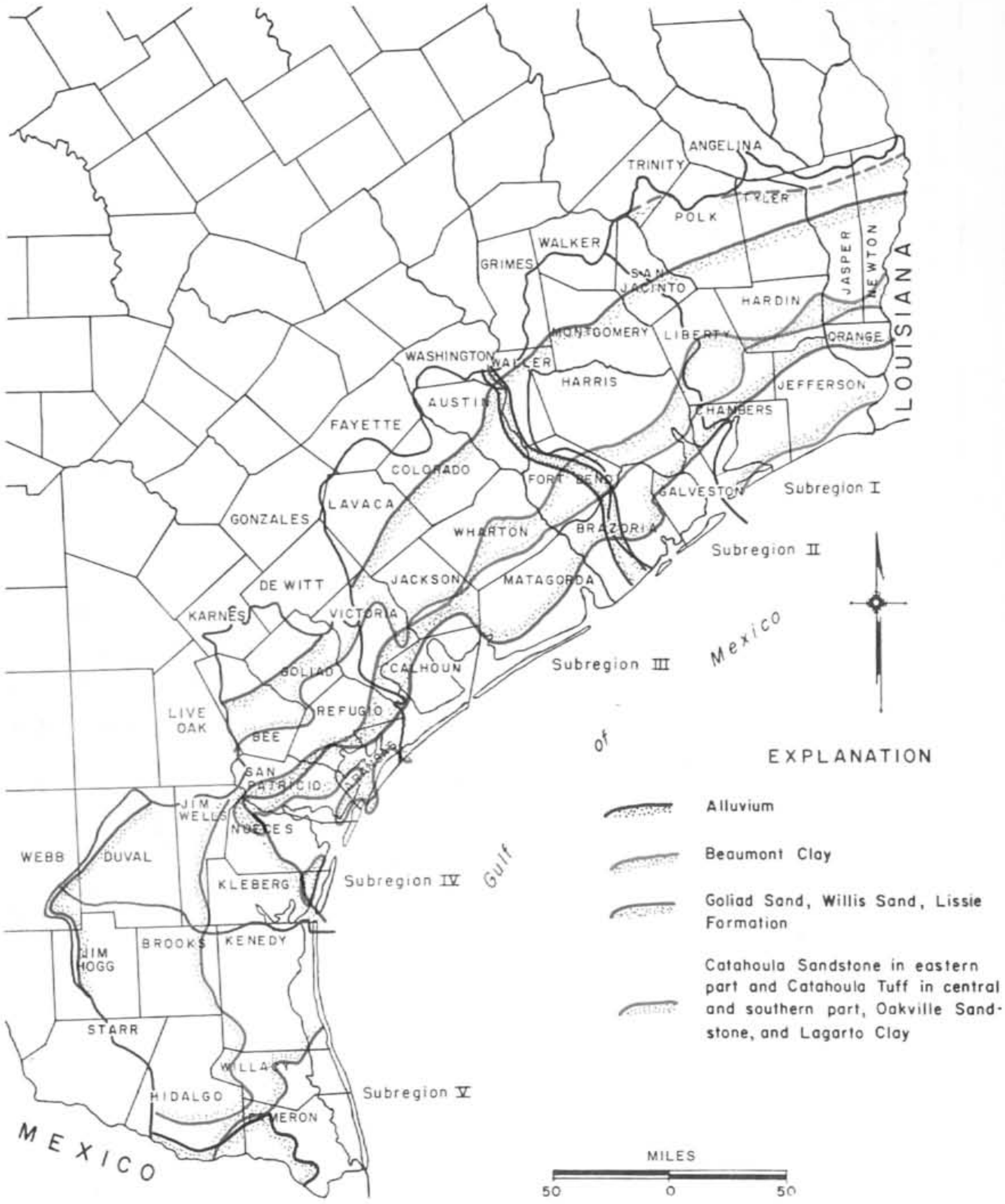


Figure 9

Areas Where Major Water-Bearing Formations of the Gulf Coast Region Yield Fresh to Slightly Saline Water

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

95

Table 1.--Geologic formations and their water-bearing characteristics in the Gulf Coast region

System	Series	Unit	Thickness (feet)	Lithologic description	Water-bearing characteristics
Quaternary	Recent	Alluvium	0- 300	Unconsolidated gravel, sand, silt, and clay.	Yields only small quantities of water except in the lower reaches of the Rio Grande and Brazos River Valleys where moderate to large quantities of water are obtained for public supply, industry, and irrigation.
		Eolian deposits	0- 50+	Unconsolidated sands.	Yields only small supplies of water locally.
	Pleistocene	Beaumont Clay	0-1,500	Unconsolidated, light-colored sands, silts, and clays in upper 200 feet. Predominantly varicolored clays and thin sand lenses in lower part except for a thick basal sand, the Alta Loma of Rose (1943), occurring in the eastern part of the region.	Yields small to moderate supplies of water for public supply, industry, and irrigation throughout most of the central and eastern parts of the region. Most extensively developed in Galveston and Orange Counties and southeastern Harris County where it yields large supplies of water from the Alta Loma Sand of Rose (1943). A poor source of fresh to slightly saline water south of the Nueces River.
		Lissie Formation	0-1,600	Alternating thin to thick beds of light-colored sand, gravel, sandy clay, and clay. Extensive caliche beds in the central and southern parts of the region.	Yields small to large supplies of water for public supply, industry, and irrigation throughout the length of the region. Extensively developed in the central and eastern parts of the region.
Tertiary(?)	Pliocene(?)	Willis Sand	0- 400	Sand and gravel interbedded with silt and clay.	Yields small to large supplies of water for municipal, industrial, and agricultural uses. Extensively developed in the eastern part of the region.

(Continued on next page)

Table 1.--Geologic formations and their water-bearing characteristics in the Gulf Coast region--Continued

System	Series	Unit	Thickness (feet)	Lithologic description	Water-bearing characteristics
Tertiary	Pliocene	Goliad Sand	0- 500	Sand, gravel, and lime-cemented sandstone interbedded with variegated clay and silt. Caliche beds present in the southern part of the region.	Yields small to moderate quantities of fresh to slightly saline water for public supply, industry, and irrigation. Extensively developed in some areas of the central and southern parts of the region.
	Miocene(?)	Lagarto Clay	0-1,000	Dominantly massive clay and sandy clay interbedded with sand and sandstone.	Yields moderate quantities of water for public supply, industry, and irrigation east of Bee County. In the southern part of the region, the formation yields only small supplies for domestic and livestock use.
	Miocene	Oakville Sandstone	0-1,650	Dominantly sand and sandstone interbedded with clay and silt.	Yields moderate quantities of fresh to slightly saline water for municipal, industrial, and agricultural purposes on outcrop and several miles downdip throughout the length of the region.
	Miocene(?)	Catahoula Sandstone (eastern part) Cathoula Tuff (central and southern part)	0-1,500	Volcanic ash, tuffaceous clay, clay, and sandstone.	Yields moderate quantities of water on outcrop and a few miles downdip for municipal, industrial, and agricultural uses.
	Oligocene(?)	Frio Clay	0- 600	Predominantly clay, thin beds of sand and silt.	Not an aquifer in the region.
	Eocene	Jackson Group	800-1,300	Sand, silt, tuffaceous sand and clay.	Yields moderate quantities of water for public and industrial supply in Karnes and Polk Counties. The group is of minor importance as an aquifer within the region except possibly in the eastern part where its potential was not determined.

The Catahoula Sandstone (Catahoula Tuff) is of importance as an aquifer near its outcrop area and for a few miles downdip throughout the region and it yields moderate quantities of water for public supply, industry, and irrigation. Fresh to slightly saline water extends downdip to depths greater than 2,500 feet below sea level in some areas. However, extensive cementation of the sands and conglomerates inhibit storage and movement of water and decrease the fresh water producing potential of the Catahoula.

Miocene Series

Oakville Sandstone

The Oakville Sandstone is not easily differentiated from the overlying Lagarto Clay, particularly in the eastern and central parts of the region, as the two formations are lithologically similar--interbedded and intergrading layers of sand, silt, and massive calcareous clay. Thin layers of lime-cemented sands are common. The Oakville Sandstone generally contains more sand than the Lagarto Clay. In the southern part, the Oakville Sandstone consists of massive, light-colored sand interbedded with gray or dirty yellow, calcareous clay, and silt. Locally, silica-cemented sands are found. Throughout its outcrop area, the Oakville is characterized by layers of reworked fossils of Cretaceous age and volcanic ash. The Oakville ranges in thickness from 0 to 1,650 feet, being thickest in the southern part. Generally, the formation dips from 50 to 60 feet per mile toward the coast, but the dip may be as much as 80 feet per mile in some areas.

The sands of the Oakville Sandstone are important aquifers throughout the region. Wells tapping the Oakville yield moderate supplies of fresh to slightly saline water for public supply, industry, and irrigation. In some areas, fresh to slightly saline water extends downdip to depths greater than 3,000 feet below the land surface.

Miocene(?) Series

Lagarto Clay

The Lagarto Clay is not easily differentiated from the underlying Oakville Sandstone in the eastern and central parts of the region. Together they constitute a thick series of light-colored, massive, calcareous clay and silt beds interbedded with sand beds which are locally more or less cemented with lime. The sand beds diminish in thickness and extent downdip. South of the Nueces River, the Lagarto Clay maintains much the same lithologic character except that the over-all percentage of sand decreases. Like the Oakville Sandstone, it contains reworked fossils of Cretaceous age and volcanic ash. The Lagarto ranges in thickness from 0 to about 1,000 feet, being thinnest in the southern part. The Lagarto generally dips coastward at a rate of 50 to 60 feet per mile.

The sand beds of the Lagarto Clay are important aquifers for public supply, industry, and irrigation east of Bee County. Wells tapping the sand beds in the Lagarto generally yield moderately large quantities of water. However, in the southern part of the region, the Lagarto Clay yields only sufficient water for domestic and livestock needs; fresh-water sands are thin.

Pliocene Series

Goliad Sand

The Goliad Sand crops out in the southern and central parts of the region and dips toward the coast at the rate of 20 to 45 feet per mile. Although the formation is not recognized in the outcrop in the eastern part of the region, it is present in the subsurface as a bentonitic clay interbedded with reddish-colored sand and gravel which are cemented with lime. In the southern and central parts, the Goliad is predominantly sand interbedded with gravel and variegated clay and silt. The sand and gravel beds are extensively cemented with lime. "Salt and pepper" sands (black chert and colorless quartz) commonly occur in the Goliad. Caliche is prevalent, beds of caliche as much as 100 feet thick being reported in the formation in the southern part. The Goliad ranges in thickness from 0 to 500 feet, being thickest in the southern and central parts.

A description of the water-bearing characteristics of the Goliad Sand follows the lithologic description of the Lissie Formation.

Pliocene(?) Series

Willis Sand

Although Sellards, Adkins, and Plummer (1932, p. 750), Darton, Stephenson, and Gardner (1937), and early American Association of Petroleum Geologists publications list the Willis Sand as Pliocene or Pliocene(?) in age, Weeks (1945) and Doering (1956) believe it is Pleistocene in age. Paleontological evidence of late Pliocene or early Pleistocene age is still lacking, but it is considered Pliocene(?) in age in this report.

The Willis Sand of Pliocene(?) age is present only in the eastern part of the region, according to Plummer (<u>in</u> Sellards, Adkins, and Plummer, 1932, p. 750). Doering, however, (1956, p. 1823) after extensive study of the Gulf Coastal Plain, believes that the Willis Sand has been mapped with the overlying Lissie Formation in the central and southern parts except in the Rio Grande Valley, where the Willis does not seem to be present.

In the eastern part of the region, the Willis Sand is dominantly a fine to coarse sand, reddish in color in many places, containing gravel, silt, and clay intimately mixed with the sand or as lenses interbedded with the sand. The Willis ranges in thickness from 0 to 400 feet and dips coastward about 25 feet per mile.

A description of the water-bearing characteristics of the Willis Sand follows the lithologic description of the Lissie Formation.

Quaternary System

Pleistocene Series

Lissie Formation

The Lissie Formation, dipping coastward at 10 to 20 feet per mile, is widely exposed throughout the region. It ranges in thickness from 0 to 1,600 feet and is composed mainly of beds and lenses of coarse to fine light-colored sand, grading into and interbedded with sandy clay, clay, and gravel. Most of the sand beds are in the lower part of the formation; some of the sand beds are massive, more than 80 feet thick. Sandstone layers (sand cemented with lime) are present in places. Caliche deposits several feet thick are common in the outcrop area in the central and southern parts.

The sands of the Goliad Sand, Willis Sand, and Lissie Formation constitute the greatest source of ground water for municipal, industrial, and agricultural uses throughout the region. Not only are the three formations difficult or impossible to differentiate in the subsurface with the usual electric or drillers' logs, the sand beds of these three formations are hydraulically connected; thus, they are grouped together as a single aquifer forming the thickest section of sand in the fresh to slightly saline water zone. The water moves downdip through the sand beds of the Goliad, Willis, and Lissie for great distances from their outcrops and constitutes the only usable ground water of sufficient quantity for municipal or industrial use in much of the region. However, in the southern part, the fresh to slightly saline water sands tend to be laterally discontinuous or to thin and thicken so that productive and unproductive wells may be drilled within short distances of each other.

Beaumont Clay

The Beaumont Clay, dipping coastward at an average of 20 feet per mile, is, except for a basal sand east of the Brazos River, principally a poorly bedded, calcareous clay of various colors, containing thin stringers and beds of silt and fine sand. In the central and southern parts of the region, the sand beds are less abundant than in the eastern part. Calcareous nodules are commonly present. The total thickness of the Beaumont ranges from 0 to 1,500 feet.

East of the Brazos River and paralleling the present coastline, a thick (80 to 370 feet), well-sorted, fine to medium sand--possibly an old beach deposit--occurs at the base of the Beaumont Clay. It is narrow and does not crop out. This sand is known locally as the Alta Loma sand (Rose, 1943, p. 3).

Sand beds in the lower part of the Beaumont Clay yield small to moderate amounts of water to public-supply and industrial wells in the central and eastern parts of the region. Wells drilled into the Alta Loma sand obtain large quantities of water, the Alta Loma being one of the most prolific aquifers of the region. The water in the sands of the lower part of the Beaumont becomes increasingly mineralized toward the west and is saline south of the Nueces River. In the southern part, the formation is not an aquifer except in the Rio Grande Valley where small amounts of usable water are obtained for industrial, municipal, and agricultural use.

The upper part of the Beaumont Clay fronts many of the lagoons and bays along the coast and extends inland adjacent to the major river valleys as alluvial plains. The formation here is composed of interbedded, unconsolidated, light-colored sands and clays and minor lenses of gypsum, coquina, and caliche. It ranges in thickness from 0 to 200(?) feet.

Sands in the alluvial plains are a minor source of water for domestic and livestock needs except in the Rio Grande Valley where they may yield small to large amounts for irrigation, industry, and public supply. Sand beds in the upper part of the Beaumont Clay near the coast yield only small to moderate amounts of water used chiefly for public supply and industry. However, as these sand beds contain only small quantities of fresh water, they generally cannot sustain heavy pumping without resultant salt-water invasion.

Recent Series

Eolian Deposits

Widespread eolian deposits cover almost 2,800 square miles in the southern part of the region, being thickest in Kenedy County where dunes are 30 to 50 feet high. Farther west, the dunes are smaller and more stable. Dominantly west-blowing winds, semiarid climate, and the concentration of sand on the beaches of Kenedy County by longshore currents are the factors that create a more or less constant movement of sand dunes toward the interior. The sand is very fine, light-colored, well sorted, and unconsolidated. The sands readily absorb rains and in some places they yield small quantities of water to wells but should not be considered a dependable source for large supplies.

Alluvium

The upper delta deposits of the Rio Grande are an important source of ground water and they yield moderate to large quantities of fresh water for irrigation, public supply, and industry. The unconsolidated deltaic sands, silts, and clays are 100 to 300 feet thick near the river.

Along the lower reaches of the Brazos River, unconsolidated sands and gravels of the Brazos River alluvium yield moderate to large quantities of water for irrigation, public supply, and industrial purposes.

Except along the Brazos River and the Rio Grande, most of the Recent alluvial deposits along the rivers crossing the region are less than 30 feet thick and are not principal sources of water.

Wave and storm action along the coast have built off-shore islands and sand dunes. These dune and island deposits, which consist of well-sorted, unconsolidated, fine sand, 50 or more feet thick, produce sufficient water for livestock and domestic needs in many places. Larger supplies of moderately saline water have been developed for sanitary and fire-fighting purposes on Matagorda and Mustang Islands, but are no longer used. The unconsolidated clay and silt that gradually is filling the bays and lagoons are not sources of fresh water.

Aquifers

Because of the difficulty in differentiating the rocks of Miocene, Pliocene, and Pleistocene age in the subsurface, the rocks are grouped into four major aquifers. Figure 9 shows the areal extent of the aquifers.

The principal aquifer in the region includes the Goliad Sand, Willis Sand, and Lissie Formation. The aquifer yields large quantities of fresh to slightly saline water in a wide belt extending from the Rio Grande to the Sabine River (Figure 9). Most of the water in the Goliad, Willis, and Lissie in subregions I, II, and III is fresh--less than 1,000 ppm (parts per million) dissolved solids--and the sands have a large coefficient of transmissibility. Much of the water in subregions IV and V is slightly saline and the thinner sands have a much smaller coefficient of transmissibility.

The aquifer that includes the Catahoula Sandstone, Oakville Sandstone, and the Lagarto Clay yields small to large quantities of fresh to slightly saline water in a wide belt extending from near the Rio Grande to the Sabine River (Figure 9). The aquifer in the Catahoula, Oakville, and Lagarto has less sand thickness than that in the Goliad, Willis, and Lissie and a smaller coefficient of transmissibility. Also, the chemical quality of the water is much less consistent. In many parts of the region, water from the Catahoula, Oakville, and Lagarto is slightly saline, although fresh water is yielded from many wells, especially in subregions I, II, and III.

The Beaumont Clay is an aquifer in a large part of the region between the Nueces and Sabine Rivers; wells tapping sand beds in the Beaumont Clay yield small to moderate amounts of water throughout much of the area outlined on Figure 9. Where the wells tap the basal sand (Alta Loma of Rose (1943)) in southeastern Harris County, Galveston County, and Orange County, they yield large quantities of fresh to slightly saline water. The quality of water from the Beaumont Clay generally is better east of the Colorado River than west.

Alluvium of Recent age is a principal aquifer in the Rio Grande Valley in Hidalgo and Cameron Counties (Figure 9). The chemical quality of water from the alluvium in the Lower Rio Grande Valley varies considerably from place to place, but generally is better nearer the river (Baker and Dale, 1961, p. 49).

Alluvium also is an aquifer in other major river valleys crossing the region, although it is used extensively only in the Brazos River Valley. Major wells tapping the alluvium in the Freeport area yield water for public supplies and industries. Irrigation wells tap the alluvium in Waller, Fort Bend, and Brazoria Counties.

Figure 9 shows that in many parts of the region a single well might tap two or more of the major aquifers; in fact, many wells do, especially the large-capacity wells in the Houston area.

GENERAL GROUND-WATER HYDROLOGY

Source and Occurrence

The understanding of basic principles involved in a study of the source and occurrence of ground water entails a knowledge of the hydrologic cycle. A diagrammatic representation of the cycle is given in Figure 10, but only the part that is concerned with ground water will be discussed in this report.

Precipitation is the source of all fresh ground water. Most precipitation on the land surface runs off or is consumed by evaporation and transpiration, or is stored in the soil, later to be evaporated or transpired. A part of the water infiltrates through the pores of the soil and subsoil or through the fractures and solution channels of the rocks to the zone of saturation by the forces of gravity and molecular attraction. The zone of saturation is the zone below the water table where the interstices are filled with fluid. The upper part of the zone of saturation is filled with fresh water in most of the region.

Formations that will yield water freely to wells are called water-bearing formations. An aquifer is a water-bearing unit which may consist of a formation, a group of formations, or a part of a formation. It may be a water-table or artesian aquifer, depending on whether water in it is unconfined (under atmospheric pressure only) or confined, respectively. Water in the outcrop of a water-bearing formation generally is under water-table conditions; water in the upper part of the zone of saturation in the region is under water-table conditions.

Where the aquifer is overlain by a layer of less permeable material downdip from the outcrop, the water in the aquifer is confined under pressure, and artesian conditions exist. Water in a well penetrating an artesian aquifer will stand at a higher elevation than the bottom of the confining layer. The pressure head that causes the water to rise in the well is maintained by the water in the updip part of the formation. Part of the head is lost due to friction caused by movement of the water through the formation. The weight of the water updip in the formation is dependent on the height of the column of water above the well site, which is the difference in the elevation of the top of the aquifer at the well and the elevation of the water table in the outcrop. Most of the ground water in the region is under artesian pressure in beds of sand and gravel.

Ground water is present also in clay that is interbedded with sand and gravel. Withdrawal of water from an artesian aquifer lowers the pressure head in the sand and gravel and water moves into the sand and gravel from the clay. Under natural conditions before withdrawals are begun, the entire pressure system is in balance, the weight of the overburden being supported partly by the pressure head and partly by the resistance of the aquifer to deformation. When withdrawals are begun, the balance is changed, the pressure head decreases, and the system yields to compression and the land surface subsides. Meinzer (Meinzer and others, 1942, p. 458) states that most of the compression takes place in the finer-grained material. Although part of land-surface subsidence is from elastic deformation of the aquifer, most is directly related to release of water from and the compaction of the adjacent clay beds. The volume of land-surface subsidence is a measure of the quantity of water released from the sand beds and associated clays. The amount of head decline, the total thickness and permeability of the clay, and the type of material making up the clay are important

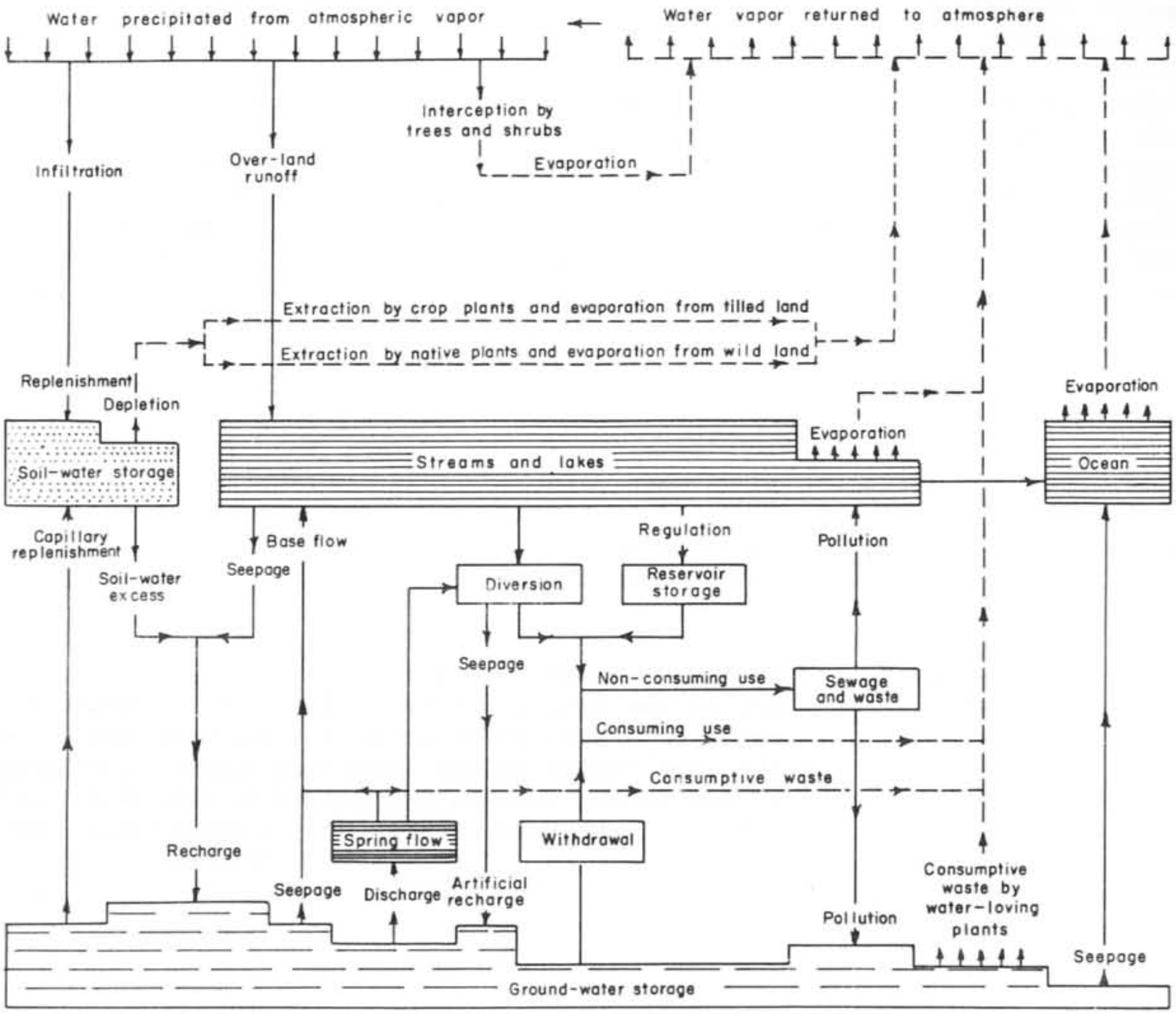


Figure 10

The Hydrologic Cycle in the Gulf Coast Region

(Modified from Piper, 1953, p. 9)

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

95

factors that determine the total amount of water released from the clay by compaction. Winslow and Wood (1959, p. 1034) calculated the amount of water derived from compaction in the Houston area to be about 254 billion gallons or 22 percent of the total pumpage between 1943 and 1954.

Plates 2, 3, 5, 6, 8, 9, 11, 12, 14, and 15 show the approximate base of the fresh to slightly saline water zone and the aggregate sand thickness in the region. Information used to compile these maps was obtained from a few thousand electric logs of oil-test wells, drillers' logs of water wells, and chemical analyses of water samples. The electric logs show the electrical resistivity and voltage potential of individual beds penetrated in a hole drilled in the earth's crust. In the Gulf Coast region, a large deflection of the resistivity curve in a positive direction or increase in resistivity (curve moves to right) usually indicates a fresh water-bearing sand. Clays and sands containing salt water are less resistant to current flow and will cause smaller or no deflections. An increase in the deflection of the voltage-potential or self-potential curve in a negative direction (curve moves to left) generally indicates increased salinity. The logs are extremely useful in ground-water studies because, among other reasons, few water wells are drilled to the base of the fresh-water zone and chemical analyses of water at great depths generally are not available. The maps indicate the areas that have the greatest amount of fresh to slightly saline water available and are useful in computing the magnitude of fresh ground water in transient storage. Estimates based on the maps, however, must be on a regional basis because data around local geologic structures, such as salt domes, have not been included.

The upper limits of dissolved solids used as a basis in preparation of the map of the base of fresh to slightly saline water varied with conditions of availability and use of the water in the region. Northeast of the Guadalupe River, most of the water included as fresh to slightly saline contained less than about 1,200 ppm dissolved solids. In some parts of the area southwest of the Guadalupe River, water that contained as much as 3,000 ppm dissolved solids is being used and, therefore, the boundaries of the fresh to slightly saline waters were based on that quantity.

Movement

Fresh ground water in the saturated zone is not static. It is continuously acted upon by gravitational forces and moves from the intake area through the interconnected interstices of the aquifer skeleton toward areas of lesser hydraulic head or discharge area. The movement under water-table conditions generally is not restricted in an upward direction by beds of low permeability and water moves chiefly laterally to discharge areas which, under natural conditions, are topographically lower than the recharge area.

A somewhat more complex system of movement exists in an artesian aquifer. The artesian pressure head at a point in an artesian aquifer downdip from the outcrop is dependent on the difference in the altitude of the top of the aquifer at that point and the altitude of the water in the outcrop. Normally, the pressure head in deep formations is greater than that in shallow or younger formations because generally the deep formations crop out at higher altitudes. In response to this difference in pressure head or vertical hydraulic gradient, water tends to move vertically upward through the confining layers at a very slow rate.

The velocity of movement through a confining layer depends on the vertical permeability and thickness of the confining layer and the difference in head across the confining layer. If the pressure head in the deeper formations is lower than that of the overlying formations, water will move downward. Vertical movement, either upward or downward, occurs throughout the region.

The rate of lateral movement through the aquifer varies widely with changes in hydraulic gradient, temperature, and different properties of the aquifer, but in the Gulf Coast region the rate is probably a few hundred feet a year.

Recharge and Discharge

Water that reaches the zone of saturation is recharge. This may be from precipitation directly on the outcrop or downward percolation of water from streams and ponded areas. The amount and intensity of the precipitation, the permeability of the aquifer, quantity of water in the aquifer, depth to water, soil type, and the evapotranspiration rate are factors affecting recharge. Even though rainfall may supply large amounts of water, potential recharge will be rejected to stream as storm-water runoff or through the soil as baseflow if the rate of rainfall exceeds the rate of intake by the aquifer or if the water level in the outcrop is at a greater elevation than the stream beds that cross the outcrop.

Potential recharge is greater northeast of the Guadalupe River because precipitation is greater and the evaporation rate is less than it is southwest of the river. However, more water is transpired to the atmosphere in the subhumid to humid northeastern part because vegetation is more dense than it is in the southwestern part. Recharge is being rejected northeast of the river because of large amounts of rainfall and the relatively "full" condition of the aquifer in the outcrop. Probably no recharge is being rejected in the semiarid southwestern part of the region because most of the water from precipitation that does not run off is transpired or evaporated. Recharge to the aquifer in the southwestern part is furnished by streams crossing the outcrop and by downward percolation of precipitation during periods of wet weather. Downdip from the outcrop, individual sand beds also are recharged by leakage from adjacent sediments.

Water in the aquifer may be discharged naturally in several ways. It may be transpired from the capillary fringe (belt overlying the zone of saturation) or from the water table by vegetation, or it may be evaporated from the capillary fringe or from the water table where they are near the surface. It may seep into streams and run off, or it may move upward through confining clays and seep directly into the Gulf.

The natural recharge-discharge relationship is altered by pumpage or artificial discharge. Whenever pumping occurs, at least part of the water is taken from storage. A reversal of gradient between beds of a leaky artesian aquifer will induce recharge in the area influenced by pumpage. If the area of influence or cone of depression extends to the outcrop of the artesian aquifer, rejected recharge and evapotranspiration from the water table, if either is present, will be salvaged. If the area of influence extends to an area of natural discharge, the gradient will be reversed and the area of natural discharge will become an area of natural recharge. Probably none of the cones of depression in any of the heavily pumped areas of the region has reached the outcrop. Vertical movement of water through the clays in the cone of depression itself partially recharges the sands in those areas.

Aquifer Coefficients

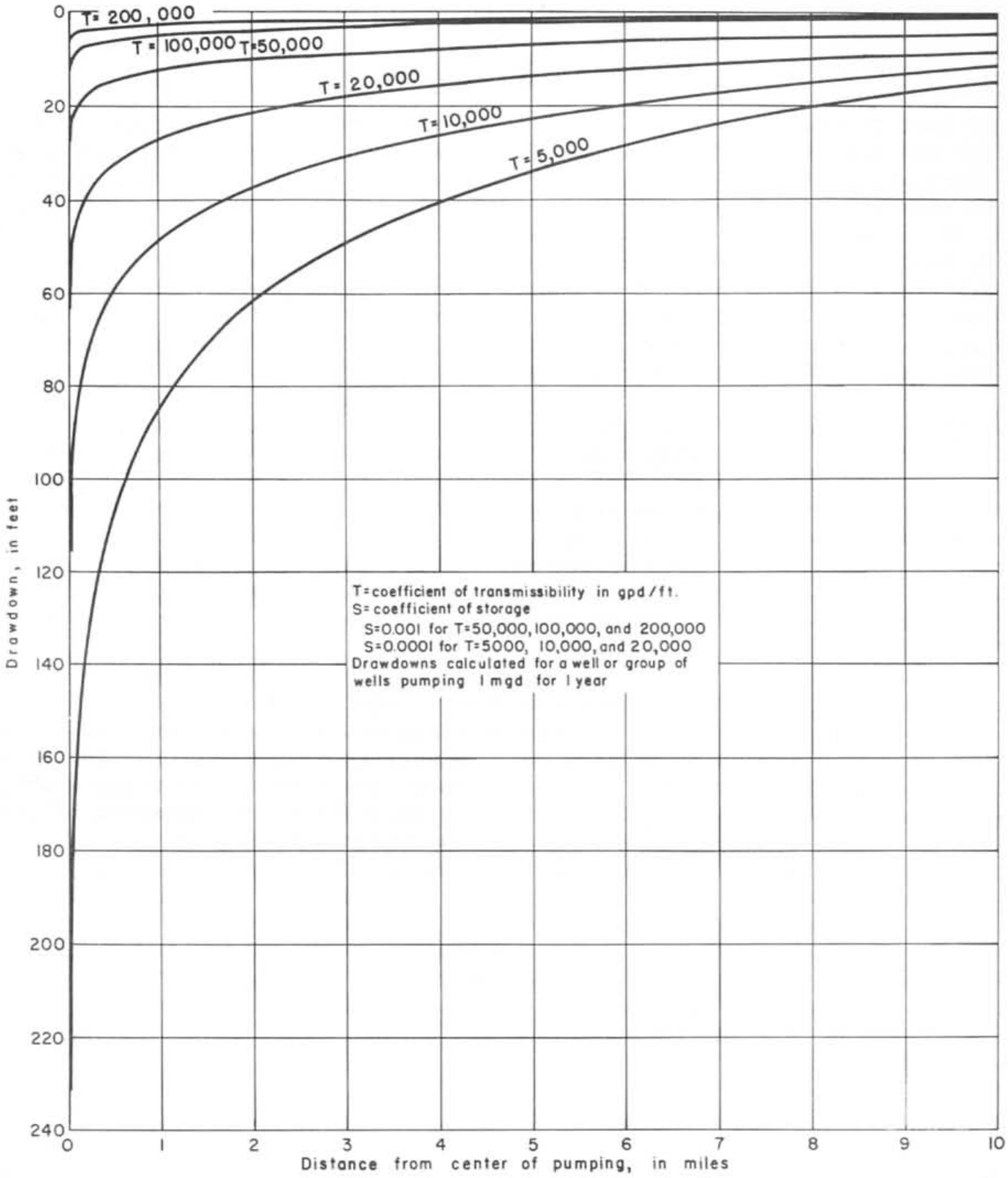
A part of the water in an aquifer passes through the interstices of the aquifer and the other part remains fixed to the aquifer skeleton by molecular or capillary attraction. The volume retained and the volume moving are dependent on the size and arrangement of the voids within the aquifer. The field coefficient of permeability is the rate of flow of water through a cross section of 1 square foot under a unit hydraulic gradient (1 foot per foot) at the prevailing temperature in the aquifer and is expressed in gallons per day per square foot. The coefficient of transmissibility is the product of the field coefficient of permeability and the saturated thickness of the aquifer. Both coefficients are measures of the ability of the aquifer to transmit water.

The specific yield of a saturated formation is the amount of water the formation will yield by draining under the force of gravity. If the saturated formation is under artesian pressure, a withdrawal of water will cause a compression of the formation which is proportional to the change in water level (change in pressure head). The volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in the component of head normal to that surface is called the coefficient of storage. In the water-table aquifer, the coefficient of storage is nearly equal to the specific yield.

The coefficient of storage is important in any calculation of the total amount of water that could be obtained from an aquifer, but the availability of the water depends primarily on the transmitting ability of the aquifer. Drawdown in and around wells is related to permeability and, therefore, to the coefficient of transmissibility. Figure 11 shows the theoretical relationship between drawdown and distance for different coefficients of transmissibility. The calculations of drawdown were based on a withdrawal of 1 mgd (million gallons per day) for 1 year from an extensive aquifer having coefficients of storage and transmissibility as shown. After 1 year, pumping of 1 mgd from the theoretical aquifer would cause about 5 feet of decline at a distance of 1 mile if the coefficients of storage and transmissibility were 0.001 and 100,000 gallons per day per foot (gpd per ft.), respectively. If the coefficient of storage were 0.0001 and the coefficient of transmissibility were 5,000 gpd per ft., the same pumping rate for the same time would cause about 85 feet of decline at the same distance.

Figure 12 shows the drawdown effect of pumping with time in an aquifer of infinite areal extent. The rate of water-level decline decreases with time, but is not affected by distance. The "equilibrium curve" shows the maximum drawdowns that would result from pumpage from a well that is 20 miles from a line source of recharge.

Figure 13 is a map (adapted from Wood, 1956b, p. 37) showing the estimated transmissibility of all fresh to slightly saline water sands in the region. The map may be used with the maps of the base of fresh to slightly saline water and thickness of fresh to slightly saline water sands to estimate the quantity of water available.



T=coefficient of transmissibility in gpd/ft.
S= coefficient of storage
S=0.001 for T=50,000, 100,000, and 200,000
S=0.0001 for T=5000, 10,000, and 20,000
Drawdowns calculated for a well or group of wells pumping 1 mgd for 1 year

Figure 11

Graph Showing Relationship of Drawdown to Transmissibility

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

95

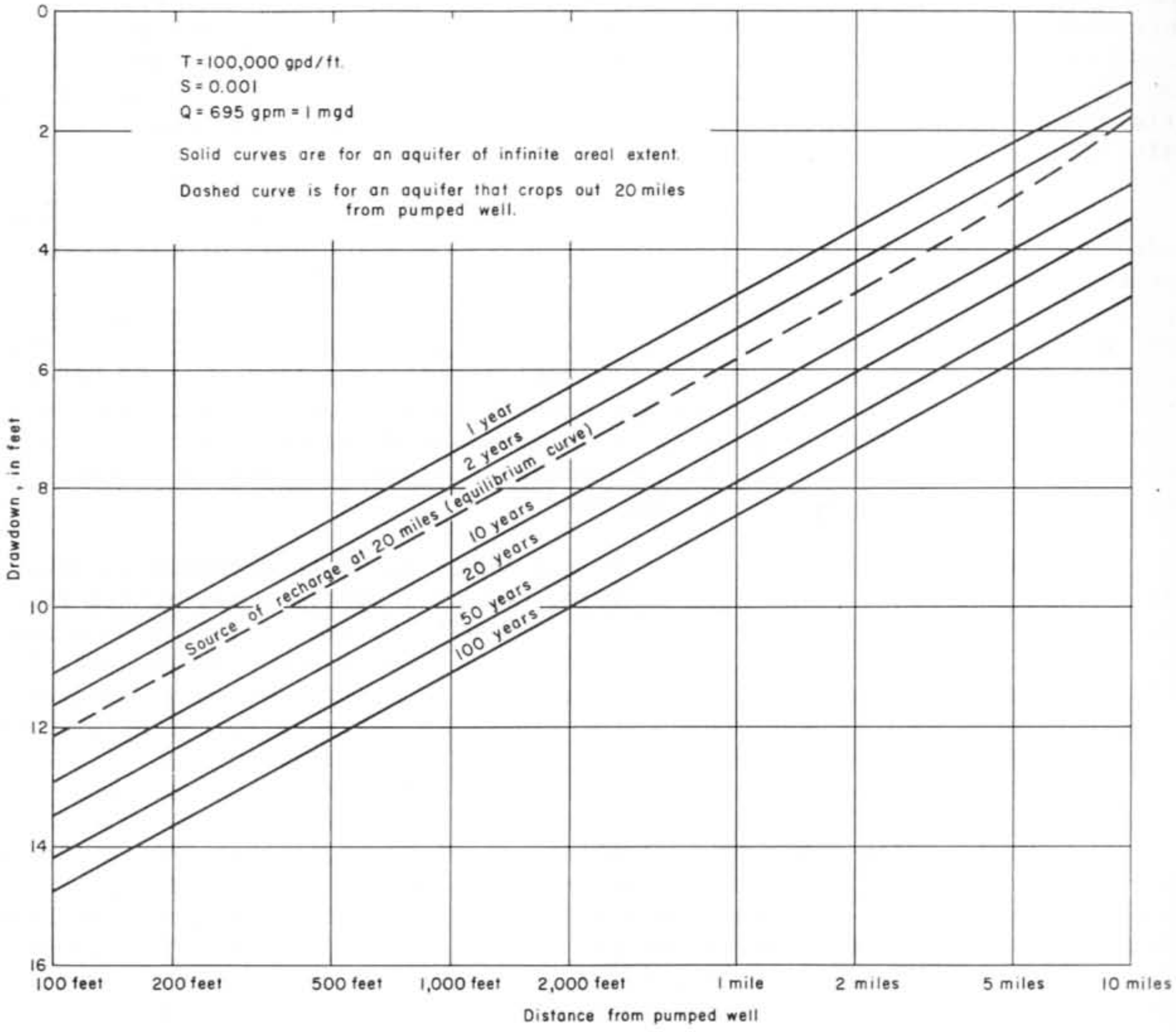


Figure 12

Graph Showing Relationship of Drawdown to Time

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

95

Data from about 300 pumping tests were used to determine transmissibility of the sands in the pumped zone at various locations. Average permeabilities of the sands in the pumped zone were computed and the average transmissibility of all fresh to slightly saline water sands was estimated from the isopachous maps (Plates 3, 6, 9, 12, and 15). Few wells in the region are drilled through the entire fresh to slightly saline water zone. Therefore, estimated values of permeability (and transmissibility) of all sands are based on the permeability of part of the fresh to slightly saline water zone, generally the middle or upper part of the zone. The calculated values of permeability of the tested section may be in error because wells are rarely, if ever, screened opposite all sands penetrated. However, many wells are constructed in a manner whereby a sand may contribute some water to the well even though it is opposite blank casing. Gravel packing, filling the annular space between the casing and the drilled hole from top to bottom with selected gravel, is common in construction of irrigation wells and gravel packing of the screened interval is common in construction of public-supply and industrial wells.

Northeast of the Guadalupe River, the indicated transmissibility of the sands is much higher than it is southwest of the river. Most of the northeastern part is underlain by sands that have a transmissibility in excess of 50,000 gpd per ft., and the sands in this area can produce large quantities of water without excessive drawdown. Practically all the area southwest of the Guadalupe River contains sands whose transmissibility is less than 50,000 gpd per ft. Large quantities of water are present in the sands, but drawdowns may be excessive for economical pumping if large-scale development occurs. Of course, pumping lifts that are not economical for one user may be economical for another, depending on power costs and use.

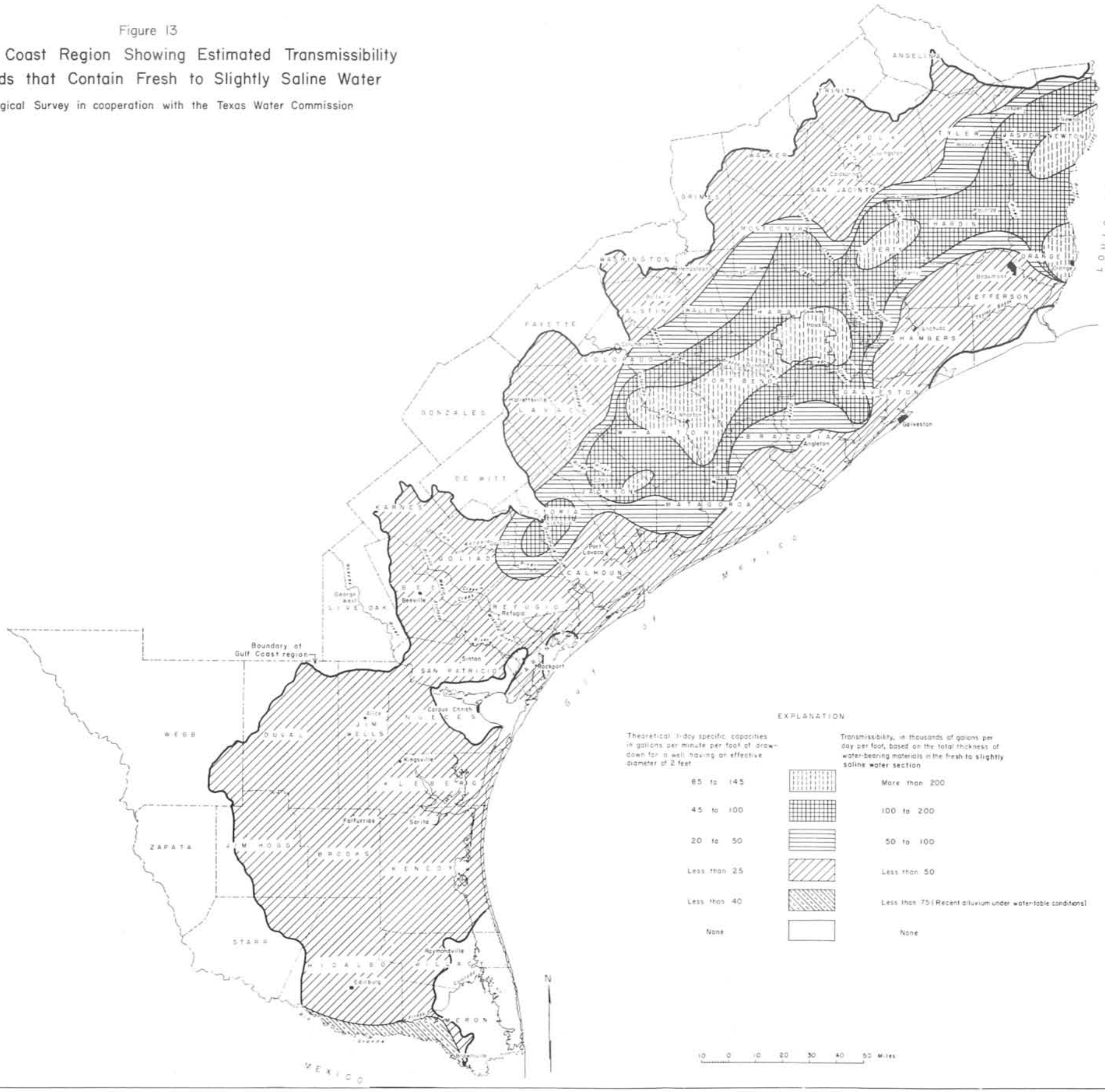
The specific capacity of a well or the yield per unit drawdown is directly related to transmissibility. The measured specific capacity may differ from the computed theoretical specific capacity for a well because of one or more reasons. Poor well construction and development, screen losses, unfavorable local geologic conditions, or partial penetration of the aquifer decrease measured specific capacities. On the other hand, if the effective diameter of the well is increased by proper development or gravel packing, measured specific capacities larger than the theoretical may result. Properly sized gravel packing generally increases and maintains the permeability around screens in wells drilled in fine material. The range in theoretical specific capacities that might be expected in the region is shown on the transmissibility map (Figure 13). Specific capacities greater or less than those indicated by the average transmissibility have been measured throughout the Gulf Coast region, but although the coefficient of transmissibility calculated from measurements of the recovery of water level in a pumped well after pumping ceases may be the product of the permeabilities and thicknesses of all the sands in the gravel-packed zone, the measured specific capacities of most wells in the region are smaller than the theoretical, indicating that many of the sands in the gravel-packed zone are poorly connected to the interior of the screen so that "screen losses" are considerable during pumping.

In this report, small yields are less than 100 gpm, moderate yields are from 100 to 1,000 gpm, and large yields are more than 1,000 gpm.

Figure 13

Map of Gulf Coast Region Showing Estimated Transmissibility of all Sands that Contain Fresh to Slightly Saline Water

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



Chemical Quality

The chemical quality of water depends upon the dissolved minerals present and commonly determines its suitability for use. A general classification of water according to dissolved solids is as follows (Winslow and Kister, 1956, p. 5).

Description	Dissolved solids (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

Most ground water used for municipal supplies in the region is classified as fresh, but some is slightly saline.

The U. S. Public Health Service (1946, p. 383) specifies the following limits of concentration for some of the constituents in water used by common carriers in interstate commerce.

Magnesium (Mg) should not exceed 125 ppm.

Chloride (Cl) should not exceed 250 ppm.

Sulfate (SO_4) should not exceed 250 ppm.

Fluoride (F) must not exceed 1.5 ppm.

Dissolved solids should not exceed 500 ppm. However, if water of such quality is not available, a dissolved-solids content of 1,000 ppm may be permitted.

Some effects of high concentrations of dissolved solids on individuals are as follows: A sulfate content in excess of 200 to 500 ppm has a laxative effect on some people, and a chloride content of more than 300 ppm will cause the water to taste salty to most people. A concentration of about 1.0 ppm of fluoride is beneficial in controlling tooth decay, but concentrations in excess of about 1.5 ppm causes the teeth of children to become mottled (Dean and others, 1935, p. 424-442). Individuals can, however, become accustomed to more highly mineralized water than that recommended by the Public Health Service. In the southern part of the region, water furnished by many municipalities exceeds the limits shown; northeast of the Guadalupe River, water furnished by most municipalities is within the limits.

The suitability of water for industrial use is dependent upon the process in which the water is used. Some processes are more tolerant of high mineral concentration than are others, but in some places the water must be treated to reduce the concentration. For example, it may be necessary to soften water and reduce high concentrations of silica to lessen formation of scale in boilers.

Hardness is the term used to describe a property of water created mainly by compounds of calcium and magnesium. It is recognized by the amount of soap necessary to produce a lather and the precipitate that forms with the addition of soap to the water. A classification commonly used with reference to hardness is as follows: 60 ppm or less, soft; 61 to 120 ppm, moderately hard; 121 to 200 ppm, hard; and more than 200 ppm, very hard. If water used in steam boilers has more than 75 ppm hardness (American Society for Testing Materials, 1959, p. 24) as calcium carbonate, it should be treated to prevent the formation of scale, and in high pressure boilers the tolerance is much less than 75 ppm. It also may be desirable to treat very hard water that is used for household purposes. Water for domestic and livestock use in the region is generally from wells less than 600 feet deep, and most of the water is hard to very hard. Water from most wells that are more than 600 feet deep is soft or moderately hard.

Oxides of iron and manganese cause staining if the concentration of iron and manganese together is greater than 0.3 ppm. The staining properties are especially objectionable if the water is used in some manufacturing processes such as those of paper and textile mills.

The chemical quality of water used for irrigation affects plants irrigated and the soil in which the plants grow. Several criteria are used in judging the quality of water used for irrigation. According to the U. S. Salinity Laboratory Staff (1954, p. 69), "...the characteristics of an irrigation water that appear to be most important in determining its quality are: (1)total concentration of soluble salts; (2)relative proportion of sodium to other cations; (3)concentration of boron or other elements that may be toxic; and (4)under some conditions, the bicarbonate concentration as related to the concentration of calcium plus magnesium."

A direct relationship exists between the total concentration of soluble salts or salinity and the electrical conductivity of the water. The Salinity Laboratory uses electrical conductivity to judge the salinity hazard of irrigation waters.

The absolute and relative concentrations of sodium, calcium, and magnesium are important in determining the alkali hazard of irrigation waters. The sodium-adsorption ratio (SAR) describes the relative activity of the sodium ion and is defined by the following equation:

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

where the concentrations of the ions are expressed in milliequivalents per liter. The Salinity Laboratory uses the SAR to classify irrigation waters with respect to the alkali hazard. The diagram showing the classification of irrigation water with respect to the salinity hazard and the alkali hazard is shown on Figure 14.

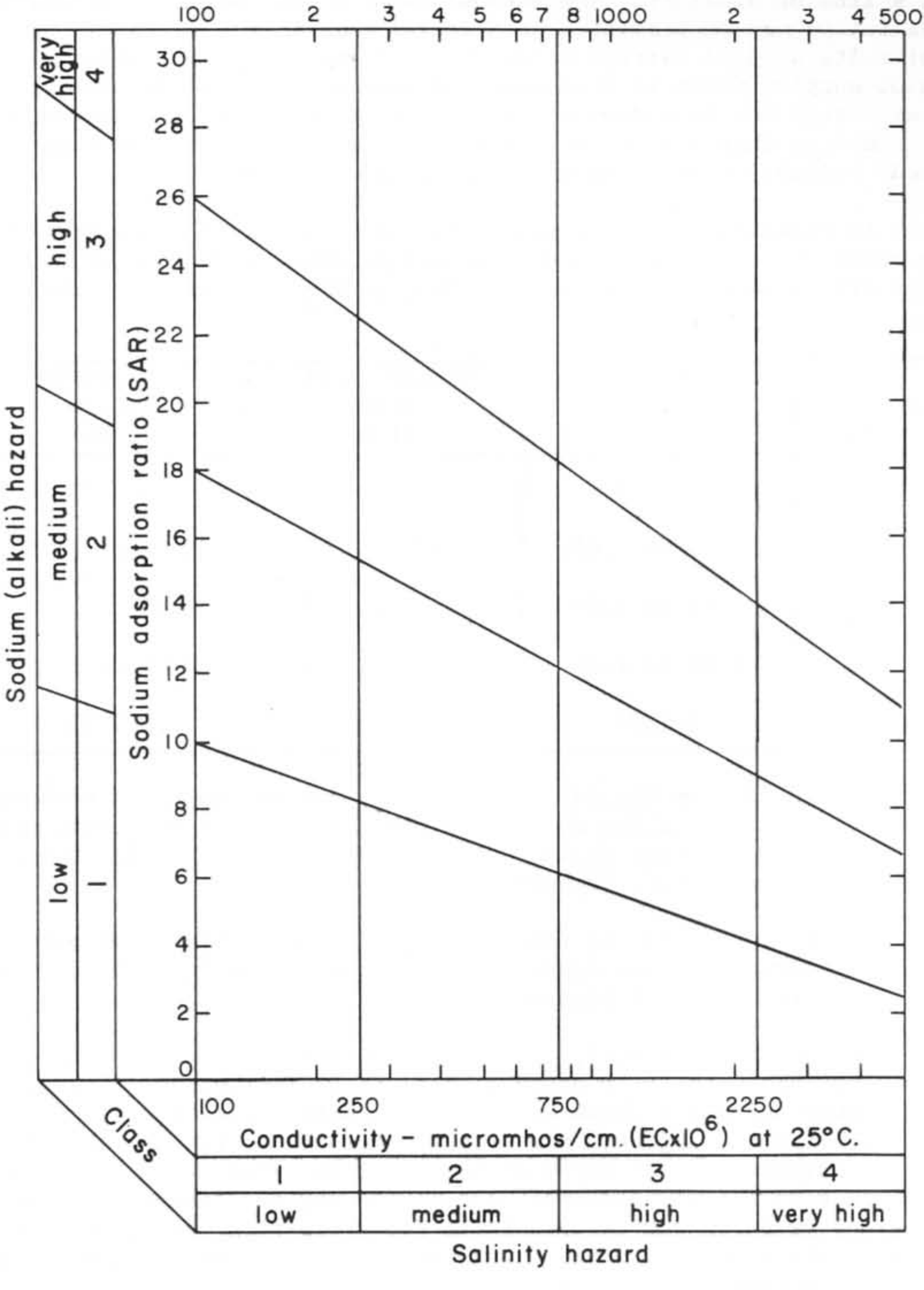


Figure 14

Diagram for the Classification of Irrigation Waters

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

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

95

Plant growth and crop production are inhibited or prevented if soils become too saline or alkaline. The accumulation of too large a concentration of salts (salinity) may be prevented to a certain extent by leaching. The accumulation of salts will be carried below the root zone by either rainfall or by the addition of surplus water if drainage is adequate. To control alkalinity, calcium or magnesium may be added to the soil or water to replace the exchangeable sodium. Leaching then may be used to remove the sodium. If the hazards cannot be reduced, possibly more tolerant plants might be grown.

Boron is essential to plant growth but is toxic if in concentrations only slightly above optimum. Suggested permissible limits of boron for several classes of irrigation water (Scofield, 1936, p. 286) are given in the following table:

Boron class	Sensitive crops (ppm)	Semitolerant crops (ppm)	Tolerant crops (ppm)
1	< 0.33	< 0.67	< 1.00
2	0.33 to .67	0.67 to 1.33	1.00 to 2.00
3	.67 to 1.00	1.33 to 2.00	2.00 to 3.00
4	1.00 to 1.25	2.00 to 2.50	3.00 to 3.75
5	> 1.25	> 2.50	> 3.75

Boron can be removed from the soil by leaching, but enough boron to cause toxic effects may be retained in the soil after other salts have been sufficiently reduced. If the boron content in the soil is toxic to a particular crop, it may be necessary to plant a more tolerant crop.

Other elements that may be toxic are calcium, magnesium, and potassium. Because these elements rarely appear in large enough concentrations to cause toxicity, they will not be discussed.

Type and condition of soil, drainage, and amount of rainfall are important in determining the suitability of water for use in irrigation. The classifications and limits described above were based on data collected in arid and semiarid regions. Limits suggested are used for comparison but probably do not apply to the eastern part of the Gulf Coast region, where rainfall is heavy. Some deep water in the southwestern part of the region contains extremely high concentrations of boron and is unsuitable for irrigation, but generally waters that contain harmful constituents in excess of the permissible limits are being used with no apparent ill effects.

Relation of Fresh Ground Water to Salty Ground Water

Many of the formations comprising the fresh-water aquifers in the region consist of sediments that were deposited beneath the Gulf and contained salt water at the time of deposition, or were deposited in fresh water but were later filled with salt water at a time of higher sea level. At some time after deposition, the sea receded and the process of recharge and discharge began. Fresh water furnished to the recharge area began to force the saline water downdip to discharge areas until the pressure exerted by the saline water equaled the pressure of the fresh water. Flushing of the salt water from the sands may have been accomplished in several ways. Winslow and others (1957, p. 387-388) concluded that the discharge took place through the overlying clays. Before large withdrawals by wells was begun, the system was probably in dynamic equilibrium--that is, the fresh water-salt water interface was nearly stationary because the pressure head of the fresh water that was moving downdip from the outcrop and discharging upward through the clays was balanced by static head of the salt water. Figure 15 is a diagrammatic sketch of the theoretical relationship of the fresh water to the salt water in the region. There is a zone of a mixture of fresh water and salt water at the fresh water-salt water interface.

In some areas, notably the Texas City and Houston areas, large ground-water withdrawals have upset the equilibrium, and updip movement of salty water has begun in response to a reversal of the hydraulic gradient. Updip movement of salt water can be expected at any place in the region where large concentrated withdrawals lower the artesian pressure head and upset the equilibrium at the fresh water-salt water interface. The rate of movement updip, of course, depends on the hydraulic gradient and permeability of the sands and is slow. In the Houston and Texas City areas, the rate is a few hundred feet a year.

GROUND WATER IN THE COASTAL PARTS OF THE TRINITY, NECHES, AND SABINE RIVER BASINS AND ADJACENT COASTAL AREAS (SUBREGION I)

General

Subregion I includes all or parts of 13 counties--approximately 7,900 square miles (Plate 1). The population was about 435,000 in 1959, of which 305,000 or 70 percent was urban. Beaumont, population 119,000, is the largest city.

The climate is humid throughout the subregion. Precipitation ranges from 47 inches in the northwestern part to more than 56 inches in the eastern part; the average annual temperature ranges from about 49°F in the northern part to about 52°F in the southern part.

Occurrence

Prolific fresh-water sands attain a maximum thickness of about 1,400 feet and extend to a depth greater than 3,000 feet below sea level in subregion I (Plates 2 and 3). The zone containing fresh to slightly saline water thickens rapidly northward and northeastward from Chambers and Jefferson Counties and eastward from Polk and Tyler Counties to an area of maximum thickness in Newton and Jasper Counties.

Thickening of the sands northward from near the coast is shown by the sections through the Neches, Sabine, and Trinity basins (sections A-A', B-B', and C-C', Figure 5). Information was not available in the northern part of

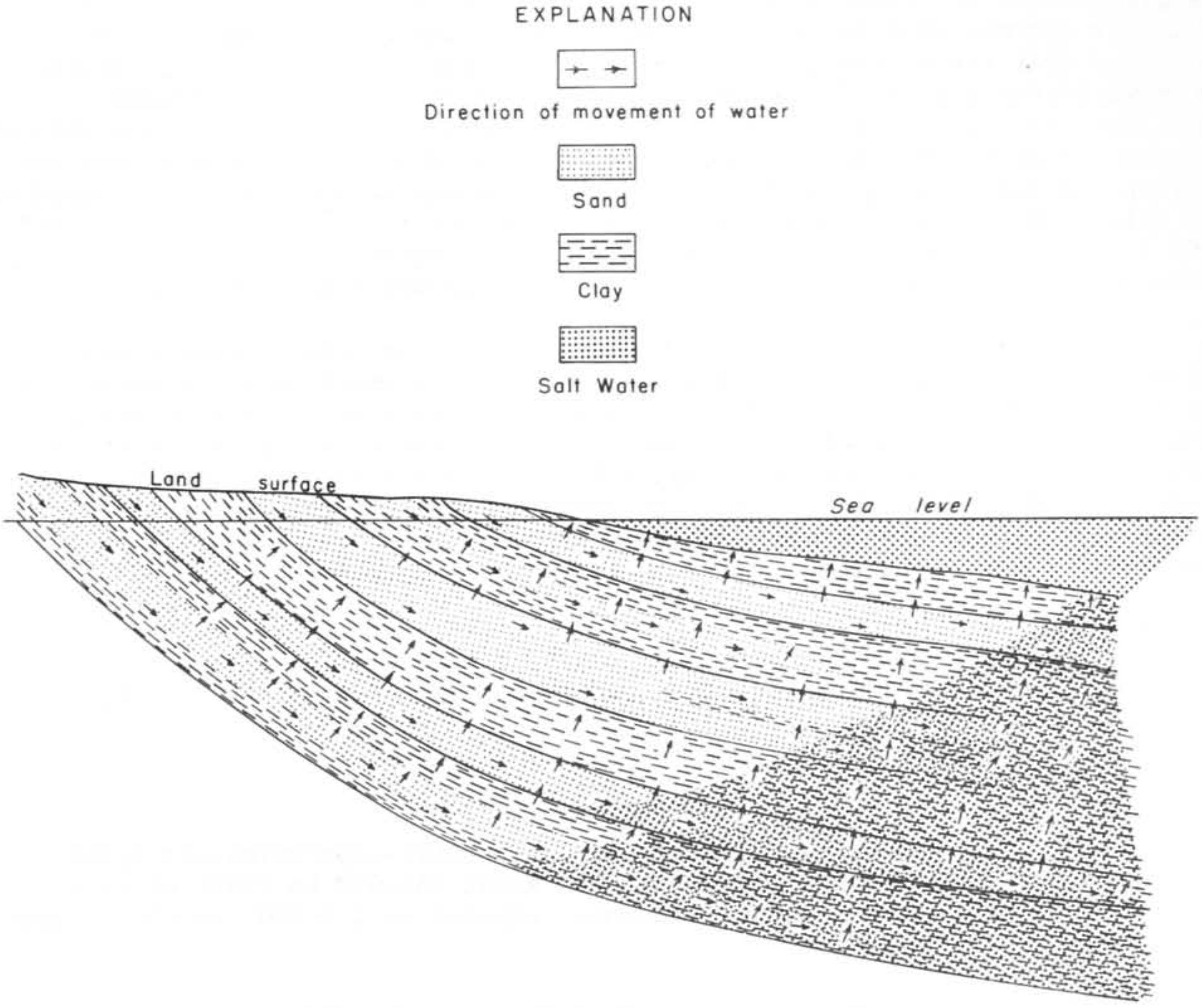


Figure 15

Diagrammatic Sketch of the Theoretical Relationship of the Fresh Water to Salt Water in the Gulf Coast Region

(After Winslow and others, 1957, p. 386)

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

95

subregion I to estimate the base of fresh water or sand thickness. However, the Jackson Group and Catahoula Sandstone that crop out along the extreme northern part generally contain much less fresh to slightly saline water sand than the younger formations.

The altitude of the water levels in wells in subregion I generally increases with depth of well. Exceptions to this may exist where large amounts of water are drawn from a particular zone, thereby lowering the pressure head or water level. Levels in water-table wells range from a few feet to about 75 feet below the land surface and average about 35 feet. Flowing wells are common in the artesian part of the aquifer in many parts of subregion I north of Chambers and Jefferson Counties.

Hundreds of millions of acre-feet of fresh to slightly saline water are in transient storage in the saturated zone in the subregion. Only a part of this water can be withdrawn for use; the optimum rate of withdrawal will depend primarily on the properties of the aquifer, yields and spacing of wells, and pumping levels. Yields and specific capacities are extremely variable from place to place, depending on thickness and permeability of the sands tapped by the wells. Specific capacities as measured by pumping tests ranged from 1.5 gpm per ft. (gallons per minute per foot of drawdown) in a well in Polk County to 55 gpm per foot in a well in Orange County. Yields as great as 2,500 gpm with pumping levels less than 200 feet are obtained where sand thickness and permeabilities are large. Much lesser yields and deeper pumping levels are to be expected where transmissibility is small. For example, wells tapping the Catahoula Sandstone or the Jackson Group in the northern part of the subregion will yield less than 500 gpm, and the pumping level will be greater than 300 feet. Wells tapping the Oakville and Lagarto sequence will yield between 500 and 1,000 gpm with pumping levels greater than 200 feet, and wells tapping the Goliad, Willis, and Lissie will yield as much as 2,500 gpm with pumping levels less than 200 feet.

Transmissibility as high as 490,000 gpd per ft. in the thick, well-sorted, coarse sands and gravels in Orange County and as low as 1,900 gpd per foot in the thin beds of finer material in Polk County have been calculated from pumping-test data. Parts of Liberty, Newton, Jasper, and Orange Counties are underlain by sands whose transmissibilities are greater than 200,000 gpd per foot (Figure 13). The average transmissibility throughout the central part of the subregion is probably about 100,000 gpd per ft. Although large supplies of fresh water can be obtained readily throughout most of the subregion, availability is more favorable through the central part where sand thickness and transmissibility are greatest.

Chemical Quality

Almost all the water in the fresh to slightly saline zone (Plate 2) is fresh, but perhaps as much as 300 feet of material along the basal part of the zone may contain slightly saline water.

Ground water of good to excellent quality suitable for most uses may be obtained in most of the subregion. However, ground water from a large part of Jefferson and Chambers Counties is slightly saline to saline and is unsuitable for most purposes, although some slightly saline ground water is used for livestock and industrial purposes. Water from the Jackson Group in the extreme northern part of the subregion is of good quality in most of the outcrop area but becomes highly mineralized a short distance downdip where it passes beneath the Catahoula Sandstone.

Table 2 shows chemical analyses of water from selected wells in subregion I. The locations of the wells sampled are not shown on the well map but the analyses are considered representative of the general depth and location indicated in the table. The analyses shown are only a few of the hundreds on record but are representative of the water being used in the subregion. The analyses indicate that the softer waters are more likely to occur at greater depths.

Analyses of water from 36 public-supply systems in subregion I show that all systems furnished water with less than 900 ppm dissolved solids; only 9 systems furnished water that contained more than 500 ppm; 16 systems furnished water that contained less than 300 ppm dissolved solids. The range in chloride content was from 5 ppm to 375 ppm. Four municipalities furnished water that contained more than 250 ppm chloride. Twenty-one of the supplies furnished soft water. The iron content of the untreated water of many of the systems was greater than 0.3 ppm; some of the water is treated either to reduce the concentration or inhibit the precipitation of the iron. Generally, the water is of good quality for public supply.

Analyses of water in the subregion indicate that the water is suitable for most industrial uses but may require treatment for particular uses. Reduction of the iron concentration for some uses may be necessary. In the northern part of the subregion, some waters may have to be treated to prevent corrosion where the pH is less than 7.0. Industries that need water for boilers may have to soften near-surface waters or drill deeper wells to obtain softer waters. In cooling operations, most equipment can be designed to use highly mineralized water with a minimum of expense or operational trouble.

The analyses of water from sands below about 500 feet indicate that the alkali and salinity hazards are medium to high for irrigation according to standards for arid regions (Figure 14). Sands above about 500 feet yield water in the low to medium alkali and salinity hazard classification.

The dissolved-solids content increases generally from the northern parts of Chambers and Jefferson Counties toward the coast. The increase in dissolved-solids content is reflected by increases of chloride and sulfate. Some water in the northern parts of the two counties is being used to supplement surface water for irrigation even though the alkali and salinity hazards are extremely high. The dissolved-solids content of water from one well used for supplementary irrigation was 2,240 ppm; the chloride content was 770 ppm. Inland from Chambers, Jefferson, and southern Orange Counties, irrigation waters generally contain less than 500 ppm dissolved-solids content and less than 100 ppm of chloride. Notable exceptions were a dissolved-solids content of 1,120 ppm and a chloride concentration of 558 ppm in water from an irrigation well drilled to 1,180 feet in southeastern Liberty County and a dissolved-solids content of 1,210 ppm and chloride concentration of 425 ppm in water from an irrigation well drilled to 460 feet in western Polk County.

Water of different quality may be expected from different sands at any given location; however, the composite water or combination of the waters from

Table 2.--Analyses of water from wells in subregion I

(Results are in parts per million except specific conductance, pH, and SAR.)
Water-bearing unit: B, Beaumont Clay; C, Catahoula Sandstone; G, Goliad Sand; J, Jackson Group; L, Lissie Formation; La, Lagarto Clay; O, Oakville Sandstone; W, Willis Sand.

Analysis No.	Location of Well	Screened interval (ft.)	Water-bearing unit	Silica (SiO_2)	Iron (Fe) (Total)	Manganese (Mn)	Calcium (Ca)	Magnesium (Mg)	Sodium and potassium (Na + K)		Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Phosphate (PO_4)	Boron (B)	Dissolved solids	Hardness as $CaCO_3$	Sodium adsorption ratio (SAR)	Specific conductance (micromhos at 25°C)	pH
1	12 mi. N Anahuac, Chambers County	* 330-387	G,W,L	19	--	--	100	24	686	--	388	443	770	--	2.5	--	0.74	2,240	348	16	3,750	7.5
2	Anahuac, Chambers County	73-113	B	21	1.0	0.20	70	15	212	2.3	526	18	172	0.5	.0	0.23	.20	770	236	6.0	1,330	6.9
3	18 mi. E Anahuac, Chambers County	116-146	B	18	.34	.02	28	7.7	260	3.5	546	.0	158	.5	.0	.54	.27	749	102	11	1,330	7.2
4	13 mi. SE Beaumont, Jefferson County	520-540	B	27	.15	.02	3.6	1.4	234	1.2	277	.0	213	1.1	.2	.77	.25	623	15	26	1,100	7.4
5	Beaumont, Jefferson County	* 494-612	B	21	.46	--	64	30	1,660		286	2	2,590	.2	--	--	--	4,510	283	43	--	--
6	18 mi. SW Beaumont, Jefferson County	234-254	L,B	--	--	--	38	9.7	272		445	2	255	--	--	--	--	796	136	10	--	--
7	14 mi. W Orange, Orange County	* 350-410	L,B	23	.06	.02	8.0	2.0	194	1.2	240	.0	185	.8	.0	.32	.00	548	28	16	961	7.2
8	Orange, Orange County	626-706	B	50	.07	.02	16	5.4	167	2.9	189	.0	196	.3	.0	.26	--	531	62	9.2	927	7.0
9	8 mi. SW Orange, Orange County	600-672	B	34	.08	.02	2.0	.5	135	1.0	225	.0	83	.4	.0	.84	--	372	7	22	610	7.4
10	20 mi. NE Newton, Newton County	?-225	La(?)	50	--	--	34	.7	38		184	8.8	6.5	.1	.0	--	--	228	88	1.8	313	7.6
11	Newton, Newton County	?-720	La	48	.27	--	6.5	1.7	7.7	4.8	31	9.2	8.2	.1	.0	--	.08	111	23	.7	102	5.5
12	16 mi. SW Newton, Newton County	489-529	G,W,L	--	--	--	17	1.0	8.5		61	4	7.0	.1	0	--	--	68	46	.5	--	--
13	35 mi. S Newton, Newton County	* 181-432	G,W,L	56	--	--	10	4.6	37	3.4	58	5.2	54	--	.0	--	.00	210	44	2.4	279	6.3
14	In Jasper County, 8 mi. E Silsbee	* 716-1,328	G,W,L	18	.09	--	13	2.6	64	1.7	203	5.4	7.5	.3	.0	--	.20	213	43	4.2	342	7.8
15	20 mi. SE Jasper, Jasper County	*1,186-1,326	G,W,L	--	--	--	19	1.0	38		146	7	3.5	.1	0	--	--	141	51	2.3	--	--
16	Jasper, Jasper County	* 382-703	O,La(?)	59	1.2	.08	5.3	.6	8.1	4.3	25	12	3.5	.2	.3	1.1	.03	111	16	.9	90	6.2
17	10 mi. S Silsbee, Hardin County	?-804	G,W,L	14	.02	.02	2.6	.4	133	.5	319	.8	25	.8	.0	.22	.13	336	8	20	562	7.9

See footnotes at end of table.

Table 2.--Analyses of water from wells in subregion I--Continued

Analysis No.	Location of Well	Screened interval (ft.)	Water-bearing unit	Silica (SiO_2)	Iron (Fe) (Total)	Manganese (Mn)	Calcium (Ca)	Magnesium (Mg)	Sodium and potassium (Na + K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Phosphate (PO_4)	Boron (B)	Dissolved solids	Hardness as $CaCO_3$	Sodium adsorption ratio (SAR)	Specific conductance (micromhos at 25°C)	pH
18	20 mi. SW Silsbee, Hardin County	171-221	G,W,L	22	.37	--	--	--	196	238	4.0	190	0.5	0.2	--	--	529	42	13	985	7.8
19	do	770-809	G,W,L	16	.57	--	--	--	396	511	5	330	3.6	.2	--	--	1,180	37	28	1,790	7.8
20	22 mi. SW Silsbee, Hardin County	166-186	G,W,L	--	--	--	11	1.9	144	232	4	108	.6	0	--	--	384	36	10	--	--
21	Silsbee, Hardin County	303-384	G,W,L	54	1.2	.12	19	2.2	18 2.6	79	5.6	21	.0	.0	0.07	--	162	56	1.0	202	6.5
22	15 mi. W Silsbee, Hardin County	1,747-1,953	O,La(?)	19	--	--	--	--	188	371	1	76	1.4	.2	--	--	458	8	29	810	8.6
23	22 mi. NW Silsbee, Hardin County	* 227-866	G,W,L	--	--	--	39	1.0	40	201	3	14	.1	0	--	--	196	101	1.7	--	--
24	5 mi. W Woodville, Tyler County	?-629	La	48	17	--	30	1.7	21	114	2	23	.1	.2	--	--	182	82	1.0	260	6.8
25	Woodville, Tyler County	346-392	La	48	[1] .09	--	38	3.5	21	134	7.4	26	.0	.2	--	--	216	109	.9	292	7.9
26	10 mi. S Woodville, Tyler County	?-478	G,W,L	38	[1] .01	--	59	4.5	15 4.6	219	4.0	16	.0	.0	--	--	249	166	.5	384	7.4
27	17 mi. NE Livingston, Polk County	305-325	O,C	48	--	--	13	2.4	29	79	12	19	.3	.0	--	--	171	42	1.9	--	--
28	12 mi. NW Livingston, Polk County	300-320	J(?)	--	[1] .50	--	141	13	656	560	2	970	--	1.5	--	--	2,060	406	14	3,680	--
29	Livingston, Polk County	?-610	La,O(?)	32	.04	.01	16	1.0	155 4.6	362	3.8	62	.3	.0	.03	--	453	44	10	738	7.2
30	16 mi. SE Livingston, Polk County	?-1,200	G,W,L (?)	--	[1] .39	--	24	5.8	65	222	6	26	--	.2	--	--	236	84	3.1	391	--
31	San Jacinto County, 16 mi. SW Livingston	350-400	La	20	.11	.00	21	4.3	111 3.0	296	15	36	.5	.0	.09	0.12	357	69	5.8	579	8.0
32	San Jacinto County, 16 mi. SE Livingston	?-300	La(?)	--	[1] .23	--	10	2.3	92	240	11	18	--	.0	--	--	253	34	6.9	--	--
33	San Jacinto County, 13 mi. NW Livingston	396-411	J	--	[1] .11	--	31	1.9	317	585	1	208	--	.0	--	--	918	86	15	--	--
34	26 mi. N Liberty, Liberty County	?-659	G,W,L, La	--	[1] .08	--	41	7.1	31	210	4	16	--	.0	--	--	268	132	1.2	--	--

See footnotes at end of table.

Table 2.--Analyses of water from wells in subregion I--Continued

Analysis No.	Location of Well	Screened interval (ft.)	Water-bearing unit	Silica (SiO_2)	Iron (Fe) (Total)	Manganese (Mn)	Calcium (Ca)	Magnesium (Mg)	Sodium and potassium (Na + K)		Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Phosphate (PO_4)	Boron (B)	Dissolved solids	Hardness as $CaCO_3$	Sodium adsorption ratio (SAR)	Specific conductance (micromhos at 25°C)	pH
35	15 mi. NE Liberty, Liberty County	?- 639	G,W,L	32	--	--	66	3.3	14	2.7	200	6.2	30	--	0.0	--	0.05	252	178	0.5	419	7.4
36	7 mi. NE Liberty, Liberty County	?- 678	G,W,L	23	--	--	144	10	84	2.6	257	22	250	--	.0	--	.02	669	400	1.8	1,240	6.9
37	4 mi. E Liberty, Liberty County	?- 1,180	G,W,L	21	--	--	75	8.5	331	2.9	210	2.7	558	--	2.0	--	.32	1,100	222	9.7	2,100	8.3
38	Liberty, Liberty County	?- 960	G,W,L	18	0.80	0.20	64	14	171	3.0	169	.0	318	0.2	1.8	0.05	--	731	217	5.0	1,290	7.6

* Not screened throughout interval.

[1] Iron in solution at time of analysis.

the different sands generally is of good quality for irrigation in most of the subregion.

Utilization

Plate 1 shows the location of major water wells, and Table 3 shows the amount of water pumped by the major wells for various uses. Pumpage from small domestic and livestock wells was estimated to be about 10 percent of the total for all uses. Only those domestic and livestock wells that discharged more than 50 gpm are shown on the well-location maps.

All public-supply systems in the subregion withdraw water from wells with the exception of the following four cities in Jefferson County: Beaumont, Port Arthur, Port Neches (which is 5 miles northwest of Port Arthur), and Nederland (adjoining Port Neches). They obtain water from the Neches River. In 1958, however, Beaumont completed a well in southeastern Hardin County which will be used to supplement its surface-water supply. Approximately 19 wells in the Sabine Basin, 27 in the Neches Basin, 18 in the Trinity Basin, and 5 wells in the adjacent coastal areas pumped a total of about 5 mgd for public supply. The use for public supply represents about 7 percent of the approximately 71 mgd pumped for all purposes.

Industry was the principal user of ground water in the subregion in 1959. Of the 38 mgd pumped for industrial use, more than 27 mgd was pumped in the Neches Basin, about 7 mgd in the Sabine Basin, about 1 mgd in the Trinity Basin, and about 2.5 mgd was pumped in the Neches-Trinity coastal area. Most of the 2.5 mgd of water pumped in the Neches-Trinity coastal area was slightly saline, and almost 0.5 mgd was moderately saline water that was used in Jefferson County in the production of saturated sodium chloride brine from a salt dome.

In the northern part of the subregion, some flowing wells are allowed to flow continuously, the water apparently being wasted. Only three of the flowing wells discharged 50 gpm or more; they had a combined flow of more than 0.6 mgd. Not enough information is available to determine accurately the total amount of water discharged from other flowing wells, but it is estimated to be less than 2 mgd.

The inventory of wells used for irrigation and other data obtained indicate that normally rainfall is sufficient for row crops and pasture growth in subregion I. Only rice is irrigated extensively; about 20 mgd of ground water was pumped in 1959 for rice irrigation. The water was pumped from 63 wells, 35 of which were in Liberty County. Of the 20 mgd pumped for irrigation, 14 mgd or 70 percent was pumped from 38 wells in the Trinity River Basin. In the Neches-Trinity coastal area, where surface water is used extensively for irrigation, only 1 irrigation well was used in 1959. Rice irrigation accounted for 28 percent of the total pumpage for all uses in the subregion.

Changes in Water Levels

Where pumpage has caused a decline in water levels in subregion I, the decline in most wells represents a decline in artesian head rather than a dewatering of the sands. Some wells that flowed when drilled have ceased to flow

Table 3.--Ground-water pumpage in major subdivisions of subregion I, 1959

Major subdivisions	Public supply		Industrial		Irrigation		Total*	
	mgd	acre-ft./yr.	mgd	acre-ft./yr.	mgd	acre-ft./yr.	mgd	acre-ft./yr.
Sabine River Basin:								
S-14	0.01	11	--	--	--	--	0.01	11
S-15	.28	314	0.06	67	--	--	.34	380
S-17	.75	840	6.92	7,751	1.8	2,000	9.5	11,000
Neches River Basin:								
NE- 8	--	--	.10	112	--	--	.10	110
NE-16	.76	851	--	--	--	--	.76	850
NE-17	--	--	--	--	--	--	--	--
NE-18	.18	202	--	--	--	--	.18	210
NE-19	1.09	1,221	1.34	1,501	--	--	2.4	2,700
NE-20	.16	179	1.02	1,143	3.5	3,900	4.7	5,300
NE-21	.17	190	25.39	28,440	1.2	1,300	27	30,000
Trinity River Basin:								
TR-37	--	--	--	--	--	--	--	--
TR-38	.39	437	.15	168	--	--	.54	600
TR-39	.70	784	.85	952	14	16,000	16	18,000
Neches-Trinity Coastal Area:								
NE-TR-1	.11	123	[1] 2.52	2,823	--	--	2.6	2,900
NE-TR-2	.21	235	--	--	--	--	.21	240
NE-TR-3	.12	134	--	--	--	--	.12	130
Subtotal, major wells	4.9	5,500	38	43,000	20	23,000	64	72,000
Domestic, livestock, and miscellaneous small wells							7	7,800
Total							71	80,000

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

[1] Includes 0.35 mgd slightly saline to saline water.

because the pressure head has been lowered below the land surface at the well by pumping. There is no evidence of large-scale water-level declines throughout the subregion and, in many areas, wells still flow.

In many areas where water levels declined during the drought years 1948-57, water levels have risen after above-normal precipitation in 1957 and following years. However, the rise in water level was due to decreased pumpage in the wet years after the subnormal rainfall period.

One area of water-level decline is in southern Jasper County where withdrawal of about 20 mgd has caused a decline in levels locally from above ground level in 1954 to more than 50 feet below ground level in 1959. Most of the decline occurred during the first year of withdrawal, but as the cone of influence spread, the rate of decline decreased rapidly with time (Figure 12). During 1958-60 the decline probably was about 2 feet per year.

Water levels in some parts of the subregion will continue to decline, but, unless future development greatly exceeds the 1959 development, the decline in most areas probably will remain less than 0.5 foot per year. A hydrograph of a well near Orange (Figure 16) shows that the decline has been only about half a foot per year, even though pumpage is moderately heavy.

Problems

One of the most serious problems in subregion I is the threat of salt-water encroachment, especially in Chambers, Jefferson, and southern Orange Counties. In this area salt water may move toward wells through the sands either vertically or laterally. Some wells tap sands that contain fresh water in the upper part and saline water in the lower part. Such wells probably will become contaminated sooner from vertical movement of salt water than from lateral movement. Some wells in the east-central part of Jefferson County have been abandoned because of contamination by saline water that could have entered the wells either by vertical or lateral movement.

Farther inland, salt-water contamination is more likely around improperly cased, leaky, or improperly plugged wells drilled to the salt-water zone. Other sources of contamination include leaky salt-water disposal wells and pits, oil-field blowouts, and leakage into the fresh-water zone due to repressurizing of oil fields by injection, causing salt water to rise in old abandoned casings.

Another possible problem near areas of large ground-water withdrawal is subsidence of the land surface that might damage structures such as power plants, which have critical tolerances of attitude or alignment. Adequate design of large structures to eliminate or to minimize damage will be necessary in areas where large ground-water withdrawal is expected.

Much additional information is needed in the subregion to determine the amount of ground water available to wells, to develop the resource further, and to shed more light on the problems of possible land-surface subsidence and contamination by salt water. Electric logs are scarce in the northern part of the subregion, and few records of water levels are available through most of the subregion. More detailed information also is needed concerning the fresh-water interface near the coast and movement of the interface due to pumping.

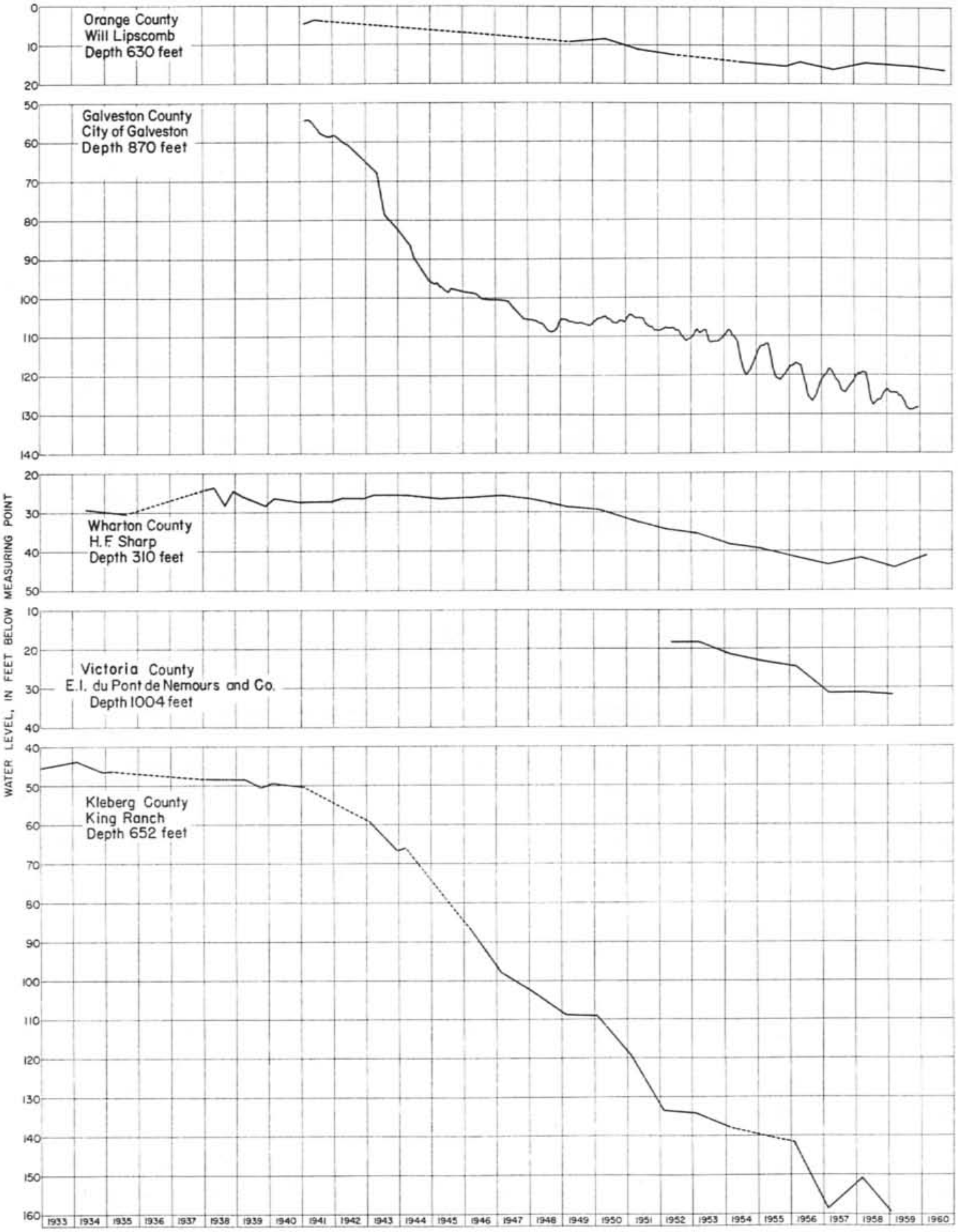


Figure 16

Hydrographs of Wells in Orange, Galveston, Wharton, Victoria, and Kleberg Counties, Gulf Coast Region

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

95

GROUND WATER IN THE SAN JACINTO RIVER BASIN AND ADJACENT COASTAL AREAS (SUBREGION II)

General

Subregion II is the smallest subregion, having an area of about 5,500 square miles, but it has about 50 percent of the population (about 1,500,000). Houston, the largest city, had a population of more than 938,000 in 1960. Galveston, the second largest, had a population of about 67,000.

The climate is moist subhumid; the average annual precipitation at Houston is about 45 inches.

For discussion, subregion II is divided into thirds, roughly of the same size, designated the northern, central, and southern. The northern third lies north of a line extending through the intersection of U. S. Highway 290 and the Harris-Waller County line and the intersection of U. S. Highway 59 and the Liberty-Montgomery County line. The southern third lies south of a line that passes through the common corner of Fort Bend, Harris, and Brazoria Counties and the point where the San Jacinto River enters Galveston Bay just south of Baytown (Plate 4).

Occurrence

Fresh to slightly saline water is present in nearly every part of subregion II. The most prolific water-bearing sands are in the central third in Harris County and adjoining parts of Waller, Fort Bend, and Liberty Counties. The base of the fresh to slightly saline water in part of this area is more than 3,000 feet below sea level, although in most of the area it is between 2,000 and 3,000 feet below sea level and is at or above sea level near a salt dome in western Harris County (Plate 5). Nearly all of the areas where the base of fresh to slightly saline water is at a shallow depth are associated with salt domes or oil fields.

The total thickness of the fresh to slightly saline water-bearing sands in the central third of the subregion is generally between 800 and 1,200 feet (Plate 6). Most of the sand in this area is in the upper 1,500 feet of sediments (principally the aquifer in the Goliad, Willis, and Lissie) where the ratio of sand to clay is from 1:1 to 2:1. The deeper sediments contain a smaller ratio of sand to clay and are principally in the aquifer in the Lagarto, Oakville, and Catahoula.

In the southern third, the base of the fresh to slightly saline water rises rather sharply from about 2,400 feet below sea level in Harris County to 1,000-1,400 feet below sea level in Brazoria and Galveston Counties, thence it rises gently to 600-800 feet at the coastline.

The principal aquifer in the southern third is the Beaumont Clay. In western Chambers County, southeastern Harris County, and Galveston County, a massive sand 100 to 250 feet thick at the base of the Beaumont Clay, the Alta Loma sand, yields large quantities of water to wells. However, the Alta Loma contains salty water in southern Galveston County in the Texas City and Galveston areas.

The Alta Loma is present in extreme eastern and southern Brazoria County near the coast, but is not recognizable in the central and northern parts of the County. The sand beds in the upper part of the Beaumont Clay throughout most of Galveston and Brazoria Counties in subregion II furnish moderate to large quantities of water to major wells, although near the coast the water is generally slightly saline. In northern Brazoria County and the southeast corner of Fort Bend County, the upper part of the Goliad, Willis, and Lissie yields water to wells, but the lower part contains moderately saline to saline water. The total thickness of fresh to slightly saline water sand in the southern third ranges from less than 100 to more than 800 feet, averaging about 400 feet (Plate 6).

In the northern third, the base of the fresh to slightly saline water zone is generally from 1,400 feet to 2,000 feet below sea level. However, an area in central Montgomery County possibly has fresh to slightly saline water at a depth as great as 3,600 feet below sea level. The presence of fresh to slightly saline water to this depth is indicated by electric logs but has not been confirmed by sampling. Sand beds containing moderately saline to saline water lie above the deep fresh to slightly saline water and below the general level of the base of the fresh to slightly saline water (Plate 5). Some of the northern third was not contoured because of the lack of electric logs and other data.

The principal aquifer in the northern third is in the Catahoula, Oakville, and Lagarto. The Goliad, Willis, and Lissie yield moderate to large quantities of water to wells in northeastern Waller, southern Montgomery, and northwestern Liberty Counties but thins rapidly northward so that only shallow wells tap the section in the latitude of Conroe. The Catahoula, Oakville, and Lagarto yields moderate to large quantities of water to wells throughout the northern third.

Section D-D' (Figure 6) through subregion II shows that the thickest part of the fresh to slightly saline water zone and the greatest total thickness of sands are in the central third. Although much of the northern third has a thick fresh to slightly saline water zone, the thickness of sand is proportionately less because most of the zone is made up of the aquifer in the Catahoula, Oakville, and Lagarto, which has a much lower ratio of sand to clay than does the aquifer in the Goliad, Willis, and Lissie.

Major wells in the central third discharge from 1,000 to more than 3,000 gpm and average about 2,000 gpm. The specific capacities of wells in this part of the subregion range from 20 to 55 gpm per ft. The major wells tap from 1 to 20 or more different sand beds, and most withdraw water from more than one formation, although those wells that tap the Alta Loma sand in eastern Harris County generally do not tap underlying sand beds. Most major wells in the central third tap sands in the aquifer in the Goliad, Willis, and Lissie, although many also tap sand beds in the Catahoula, Oakville, and Lagarto. Wells are as deep as 2,500 feet. The coefficient of transmissibility of the Alta Loma sand ranges from 90,000 to 150,000 gpd per ft. The coefficient of transmissibility measured in the other aquifers in the central third ranged from 50,000 to more than 200,000 gpd per ft., depending on the thickness of sands tapped by the well.

Major wells that tap the Alta Loma sand in the southern third yield from 750 to 1,500 gpm; the wells have specific capacities ranging from 20 to 40 gpm per ft. Major wells tapping the sand in the upper part of the Beaumont Clay yield from 100 to 500 gpm and have specific capacities of from less than 5 gpm per ft. to as much as 20 gpm per ft. The coefficient of transmissibility of the sands in the upper part of the Beaumont ranges from less than 5,000 to as much as 40,000 gpd per ft. In subdivision SJ-BR-3, several major wells are less than 150 feet deep, tapping alluvium of Recent age. Most of them are used for the irrigation of row crops during periods of below-normal precipitation.

Major wells tapping the aquifer in the Goliad, Willis, and Lissie in the northern third yield from 300 to 2,500 gpm. The specific capacities of wells tested ranged from 8 to 40 gpm per ft. and the coefficient of transmissibility ranged from 6,000 to 85,000 gpd per ft. Major wells tapping sand beds in the Catahoula Sandstone and the Lagarto Clay yield from 100 to 1,000 gpm. The specific capacity in those wells tested was about 8 gpm per ft. or less and the coefficient of transmissibility ranged from 14,000 to 45,000 gpd per ft.

Chemical Quality

The chemical quality of ground water in subregion II is generally very good, especially in the central third. Except for the water in the slightly to moderately saline zones, the hardest water is yielded by wells generally less than 500 feet deep. Most of the water from deeper wells is softer than that from shallow wells except where the dissolved-solids content is more than 1,000 ppm. Most of the water in subregion II in the fresh to slightly saline zone has a dissolved-solids content of less than 500 ppm.

Table 4 contains chemical analyses of water from representative wells in subregion II--31 fresh, 4 slightly saline, and 2 moderately saline. All three types of water can be obtained anywhere in the subregion except that fresh water is unavailable in an area near the coast in Brazoria and Galveston Counties. In the rest of subregion II slightly saline and moderately saline water lie successively beneath the fresh water. In sands that are continuous over several miles, all three types of water can be obtained in the same sand because progressively more saline water is present downdip beyond the body of fresh water.

Because of the many different sand beds tapped by most major wells, the quality of the water produced from adjacent wells may be significantly different. The permeability and thickness of the sand beds change from place to place. Thus, if two similarly screened wells are 1,000 feet apart, one may obtain a greater proportion of water from a different depth. The temperature of the water discharged from wells also is different in many places for the same reason. The temperature of ground water in subregion II normally is equal to the average annual air temperature plus about 1°F for each 75 to 100 feet of depth. Wells less than 1,000 feet deep generally yield water between 70° and 80°, wells between 1,000 and 1,800 feet deep yield water between 80° and 90°, and wells deeper than 1,800 feet yield water of 90°, or more.

Water suitable for public supply is obtained in the northern third from wells tapping the aquifer in the Catahoula, Oakville, and Lagarto and in the southern part from the aquifer in the Goliad, Willis, and Lissie (wells 1-9, Table 4). In the northern third the lower part of the Catahoula, Oakville, and Lagarto contains slightly saline water.

In the central third, water suitable for public supply is obtained from wells tapping the Goliad, Willis, and Lissie and the upper part of the Catahoula, Oakville, and Lagarto. In southeastern Harris County the sands in the

Table 4.--Analyses of water from wells in subregion II

(Results are in parts per million except specific conductance, pH, and SAR.)
Water-bearing unit: B, Beaumont Clay; C, Catahoula Sandstone; G, Goliad Sand; L, Lissie Formation; La, Lagarto Clay; O, Oakville Sandstone; W, Willis Sand.

Analysis No.	Location of Well	Screened interval (ft.)	Water-bearing unit	Silica (SiO_2)	Iron (Fe) (Total)	Manganese (Mn)	Calcium (Ca)	Magnesium (Mg)	Sodium and potassium (Na + K)		Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Phosphate (PO_4)	Boron (B)	Dissolved solids	Hardness as $CaCO_3$	Sodium adsorption ratio (SAR)	Specific conductance (micromhos at 25°C)	pH
1	Huntsville, Walker County	360-659	C	--	--	--	86	3.2	71		314	20	73	--	0.0	--	--	480	228	2.0	748	--
2	7 mi. SSW Huntsville, Walker County	?-115	O,La	35	--	--	228	8.1	62		364	28	290	--	2.0	--	--	835	602	1.1	1,490	--
3	13 mi. SSE Huntsville, Walker County	160-180	O,La	45	1/ 0.04	--	98	2.5	40		249	11	90	0.1	.0	--	--	434	255	1.1	684	6.7
4	San Jacinto County, 22 mi. NE Conroe	574-586	C,O, La	--	1/ .03	--	79	7.4	52		270	10	77	--	.0	--	--	386	228	1.5	--	--
5	San Jacinto County, 6 mi. NW Cleveland	560-582	C,O, La	--	1/ 4.3	--	52	12	60		320	15	22	--	.0	--	--	319	180	1.9	539	--
6	8 mi. N Conroe, Montgomery County	* 805-880	C,O, La	32	.61	0.02	52	7.6	40	5.9	272	12	17	.2	.0	0.08	0.07	301	161	1.4	472	7.7
7	In Conroe, Montgomery County	*1,090-1,320	C,O, La	26	.18	.01	34	6.6	90	7.5	281	26	45	.2	.0	.08	.06	373	112	3.7	613	7.6
8	15 mi. WNW Conroe, Montgomery County	?-230	C,O, La	25	1/ .05	--	126	7.6	20	6.4	403	4.9	42	.6	.2	--	--	433	346	.5	717	7.0
9	Montgomery County, 14 mi. SW Cleveland	?-39	G,W,L	24	--	--	15	.9	14		64	4.3	9.0	--	2.5	--	--	101	41	1.0	144	6.7
10	28 mi. NW Houston, Harris County	?-400	G,W,L	26	--	--	25	3.4	41		124	4.4	42	--	--	--	--	203	76	--	--	2.0
11	19 mi. N Houston, Harris County	1,037-1,052	G,W,L	17	.80	--	10	3.4	140	2.2	294	11	68	.8	.2	--	.30	398	39	9.7	678	8.2
12	In Houston, Harris County	?-745	G,W,L	24	4.8	--	42	11	35	4.0	203	14	40	.0	.5	--	.32	271	150	1.2	457	8.1
13	do	*1,001-2,510	C,L	22	1/ .1	--	4.3	1.1	202	4.0	400	3.7	87	1.8	.0	--	.46	520	15	23	882	8.0
14	do	* 785-1,755	G,W,L	17	.07	.00	4.8	1.0	173	.9	370	9.3	53	1.1	.0	.3	.34	443	16	19	737	8.2
15	do	* 692-1,490	G,W,L	23	1/ .02	--	33	7.6	66	5.8	243	12	38	.2	.2	--	--	349	114	2.7	507	8.2

See footnotes at end of table.

Table 4.--Analyses of water from wells in subregion II--Continued

Analysis No.	Location of Well	Screened interval (ft.)	Water-bearing unit	Silica (SiO_2)	Iron (Fe) (Total)	Manganese (Mn)	Calcium (Ca)	Magnesium (Mg)	Sodium and potassium (Na + K)		Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Phosphate (PO_4)	Boron (B)	Dissolved solids	Hardness as $CaCO_3$	Sodium adsorption ratio (SAR)	Specific conductance (micromhos at 25°C)	pH
16	do	* 530-1,000	G,W,L	28	0.07	0.00	42	8.0	56	2.0	243	14	36	0.3	0.2	0.1	0.08	310	138	2.1	516	7.8
17	do	*1,050-1,715	G,W,L	15	.11	.00	10	3.1	120	1.7	284	11	37	.6	.0	.5	.26	344	38	8.5	574	8.0
18	16 mi. W Houston, Harris County	449-464	G,W,L	22	[1] .28	--	72	7.4	34	2.3	266	4.6	46	.0	.2	--	--	310	210	1.0	544	7.0
19	In Houston, Harris County	?-1,224	G,W,L	17	[1] .00	--	4.0	1.1	225		474	.4	82	--	.0	--	--	585	14	26	967	7.7
20	do	?-1,710	G,W,L	17	.00	--	5.5	1.5	139		296	13	47	--	.0	--	--	379	20	14	625	7.8
21	22 mi. E Houston, Harris County	?-606	B	--	--	--	8.2	2.5	170		364	5	68	--	.2	--	--	448	31	13	728	--
22	25 mi. W Houston, Harris County	2,830-2,930	C,O, La	29	1.1	--	62	7.9	2,000	18	806	2.6	2,710	.7	--	--	7.9	5,230	187	64	8,990	7.5
23	Fort Bend County, 30 mi. W Houston	?-172	G,W,L	--	--	--	100	10	28		290	4	78	--	.5	--	--	407	290	.7	--	--
24	Fort Bend County, 20 mi. SW Houston	* 555-802	G,W,L	--	--	--	68	12	35		238	10	63	--	--	--	--	305	219	1.0	--	--
25	do	1,545-1,606	G,W,L	14	[1] .03	--	14	3.6	119	6.6	259	16	61	1.0	.2	--	--	363	50	7.3	661	7.6
26	Chambers County, 9 mi. NE Baytown	?-886	B	19	--	--	100	24	686	--	388	443	770	--	2.5	--	.74	2,240	348	16	3,750	7.5
27	Brazoria County, 14 mi. S Houston	?-87	B	--	--	--	80	28	96		427	--	110	--	--	--	--	544	318	2.3	--	--
28	Brazoria County, 25 mi. S Houston	590-715	L(?),B	18	.04	--	16	5.0	259		342	1	240	1.0	.0	--	--	709	60	15	--	8.1
29	3 mi. SE Angleton, Brazoria County	?-235	B	17	[1] .05	--	14	5.2	284		428	2	224	1.3	.8	--	--	759	56	17	--	--
30	23 mi. SE Houston, Harris County	480±-610±	B	30	--	--	9.3	2.9	142		308	.2	65	--	.0	--	--	400	35	10	670	8.0
31	11 mi. NW Texas City, Galveston County	* 498-576	B	14	[1] .02	--	5.4	1.3	182	3.6	370	2	79	1.0	.2	--	--	471	19	18	838	8.1
32	4 mi. W Texas City, Galveston County	* 578-700	B	15	.50	--	7.7	2.2	265	3.4	430	2	178	1.0	1.2	--	--	698	28	22	1,270	7.9
33	In Texas City, Galveston County	897-1,004	B	--	--	--	39	15	797		350	2	1,100	--	1.2	--	--	2,130	159	27	4,560	--

See footnotes at end of table.

Table 4.--Analyses of water from wells in subregion II--Continued

Analysis No.	Location of Well	Screened interval (ft.)	Water-bearing unit	Silica (SiO_2)	Iron (Fe) (Total)	Manganese (Mn)	Calcium (Ca)	Magnesium (Mg)	Sodium and potassium (Na + K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Phosphate (PO_4)	Boron (B)	Dissolved solids	Hardness as $CaCO_3$	Sodium adsorption ratio (SAR)	Specific conductance (micromhos at 25°C)	pH
34	10 mi. W Texas City, Galveston County	* 703-884	B	28	--	--	50	19	561	332	0.8	815	--	0.2	--	--	1,640	203	17	3,070	8.1
35	12 mi. NW Texas City, Galveston County	* 647-767	B	26	--	--	19	5.6	236	347	2.0	210	0.6	.0	--	--	680	70	12	1,200	8.4
36	In Galveston, Galveston County	?-397	B	17	--	--	18	14	562	745	1.8	490	--	7.8	--	--	1,480	102	24	2,670	8.5
37	do	*1,185-1,310	B	35	--	--	87	53	2,130	330	.0	3,400	--	--	--	--	5,870	435	44	10,500	7.5

* Not screened throughout interval.

[1] Iron in solution at time of analysis.

Beaumont Clay also furnish water of good quality; however, here the Catahoula, Oakville, and Lagarto contains slightly to moderately saline water and the base of the fresh to slightly saline zone rises rapidly. At the Harris-Galveston County line the Goliad, Willis, and Lissie contains slightly saline water.

In the southern third, the only water suitable for public supply is obtained from sands in the Beaumont Clay except for the uppermost sands of the Goliad, Willis, and Lissie in Brazoria County. No major wells obtain fresh water south of a line intersecting the boundary of the subregion 10 miles south of Angleton and running through Texas City.

Industrial water is obtained from wells throughout the subregion although the wells in southern Brazoria and Galveston Counties yield slightly to moderately saline water, which generally is used for cooling. Water from the rest of the subregion commonly can be selected for the purpose for which it is to be used by testing the different sands as the wells are drilled and screening only those yielding the most favorable water. For example, many laundries in Houston drilled wells tapping sands 1,000 to 1,500 feet deep to obtain soft water. Iron generally is not a problem in water from major wells in the subregion.

Water for irrigation is obtained generally from wells that are shallower than the public-supply and industrial wells. The shallower water generally has a higher calcium and magnesium content and, therefore, a lower SAR. However, with the ample rainfall and the rotation practices of rice irrigators, even a high SAR water may be used successfully.

Utilization

The total pumpage from all major wells (Plate 4) in subregion II in 1959 was about 380,000 acre-feet, an average rate of about 340 mgd. Of course, the daily rate was much higher during the warmer months than during the winter because nearly all the irrigation water was pumped during the spring and summer; much of the industrial water is used for cooling and more is used in summer than in winter; also more water is used for public supply in summer than in winter. The largest withdrawal from major wells in 1959 was for public supply, about 140,000 acre-feet, although withdrawals for industrial uses and for irrigation were nearly as large, about 130,000 and 120,000 acre-feet, respectively (Table 5). In several of the dry years during the 1950's, the largest use of ground water was for irrigation.

Most of the pumpage in subregion II is from major subdivisions SJ-8, SJ-9, and SJ-10, SJ-BR-1, and TR-SJ-1 (Plate 4), these subdivisions also having the greatest concentration of major wells. The principal use of ground water in SJ-8 is for irrigation, in SJ-9 for public supply, and in SJ-10 for industry.

The city of Houston and its suburbs depend upon wells for 80 percent of the water in the public-supply systems, and pumped 97 mgd of the approximately 120 mgd pumped for public supply in subregion II in 1959. In addition to the ground water used, about 25 mgd of treated surface water was sold by the Houston Water Department in 1959 for public supply. Also, about 75 mgd of untreated surface water was sold to industries along the Houston Ship Channel. All cities in the subregion (II) except Houston depend exclusively on wells for their public supplies, although industries in the Baytown and Texas City areas use both ground water and surface water.

Table 5.--Ground-water pumpage in major subdivisions of subregion II, 1959

Major subdivisions	Public supply		Industrial		Irrigation		Total*	
	mgd	acre-ft./yr.	mgd	acre-ft./yr.	mgd	acre-ft./yr.	mgd	acre-ft./yr.
San Jacinto River Basin:								
SJ- 1	0.49	549	--	--	--	--	0.49	550
SJ- 2	.13	146	0.18	201	--	--	.31	350
SJ- 3	.24	269	--	--	0.49	550	.73	820
SJ- 4	--	--	.12	134	--	--	.12	130
SJ- 5	.35	392	.34	381	.66	740	1.4	1,500
SJ- 6	.50	560	--	--	19	21,000	20	22,000
SJ- 7	1.37	1,535	.96	1,075	2.9	3,200	5.2	5,800
SJ- 8	7.39	8,278	3.39	3,797	50	56,000	61	68,000
SJ- 9	66.41	74,388	20.26	22,694	4.5	5,100	91	100,000
SJ-10	22.61	25,326	61.53	68,922	2.0	2,300	86	97,000
Trinity-San Jacinto: Coastal Area TR-SJ-1	3.31	3,708	13.88	15,548	11	12,000	28	31,000
San Jacinto-Brazos Coastal Area:								
SJ-BR-1	17.84	19,983	11.50	12,881	3.6	4,000	33	37,000
SJ-BR-2	1.03	1,153	.50	560	5.7	6,400	7.2	8,100
SJ-BR-3	.70	784	.55	616	4.9	5,500	6.1	6,900
Subtotal, major wells	120	140,000	110	130,000	100	120,000	340	380,000
Domestic, livestock, and miscellaneous small wells							10	11,000
Total							350	390,000

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

The oil refining industry and the related petrochemical industry were the principal industrial users of ground water in subregion II. Although most of the water used by the refining and chemical plants is used for cooling, it is recirculated several times so the dissolved solids are concentrated by evaporation until they are doubled or tripled before the water is discharged. Other large users of ground water are electric power plants, steel mills, and a paper mill.

Nearly all the ground water used for irrigation is for rice, only a small amount being used for truck vegetables and row crops during periods of below-normal rainfall. Approximately 60,000 acres of rice was irrigated with about 2 feet of ground water in 1959. Both the acreage and duty of water were less in 1959 than in the peak year of 1954, when about 200,000 acre-feet of ground water was pumped in subregion II for irrigation. Acreage limitations under the U. S. Department of Agriculture price-support program and increased rainfall since 1956 have been factors in reducing ground-water withdrawals for irrigation.

The quantity of ground water pumped by small wells for purposes such as domestic, livestock, and drilling oil wells is unknown but probably was 10 mgd, or more.

Changes in Water Levels

The first major wells drilled in subregion II, after drilling techniques as we know them today were developed in the last half of the 19th century, generally flowed. Before large-scale withdrawals of ground water were made, a rule of thumb was the deeper the well, the higher the artesian pressure head, and this is still true in areas remote from the areas of heavy withdrawals. The rice industry was begun in the area before 1900 using flowing wells, although most of the wells required low-lift centrifugal pumps before the first World War to increase their discharge. The first public supply of ground water for Houston used flowing wells on the banks of Buffalo Bayou. Galveston's first potable supply was obtained from flowing wells in the 1890's. As pumpage increased, water levels declined and most wells in Houston ceased flowing by 1925 and those in Galveston County by about 1930.

Levels in the Houston area declined slowly until 1937 when industry along the Ship Channel greatly increased withdrawal (Figure 17). Levels declined rapidly until surface water from Lake Houston began to augment the supply in 1954. The reduction in pumpage in the Houston area at that time was accompanied by a leveling off of water levels, although outside of the area of reduced pumpage levels continued to decline.

Levels in the Texas City area declined so that the water level at the center of pumpage was more than 100 feet below sea level in 1948. Because of land-surface subsidence and the incursion of salt water into the water-bearing sand in the area, water from the Brazos River was brought in for Texas City industries, and in 1957 the cone of depression was gone and water levels were between 50 and 60 feet below sea level (Wood, 1958b, p. 11).

The rate of water-level decline in the irrigation areas has been small, about 2 feet or less a year, except near centers of large withdrawals for public supply or industry (Figure 18). In shallow wells in the northern third of

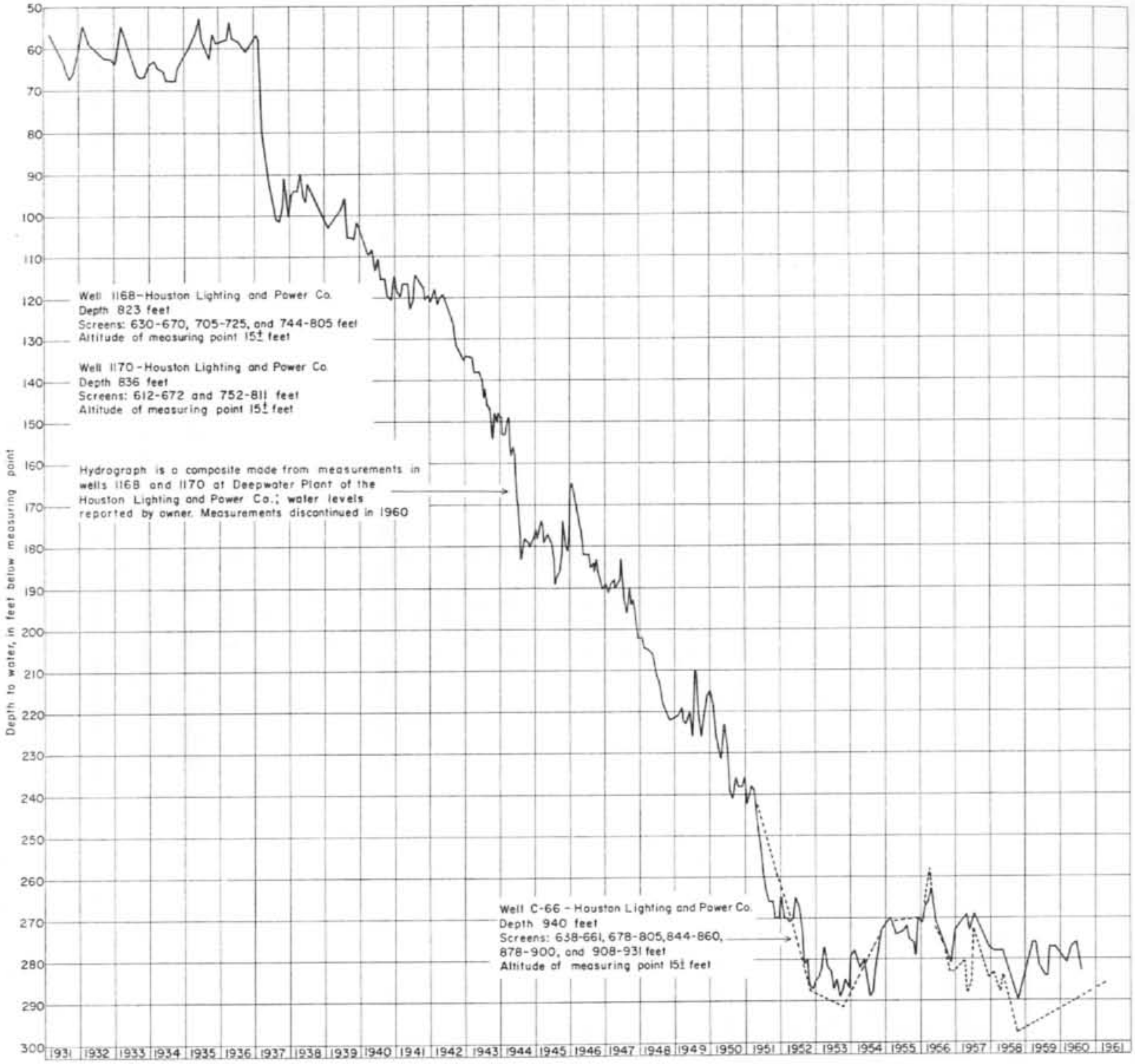


Figure 17

Changes in Water Levels in Harris County Wells 1168, 1170, and C-66

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

95

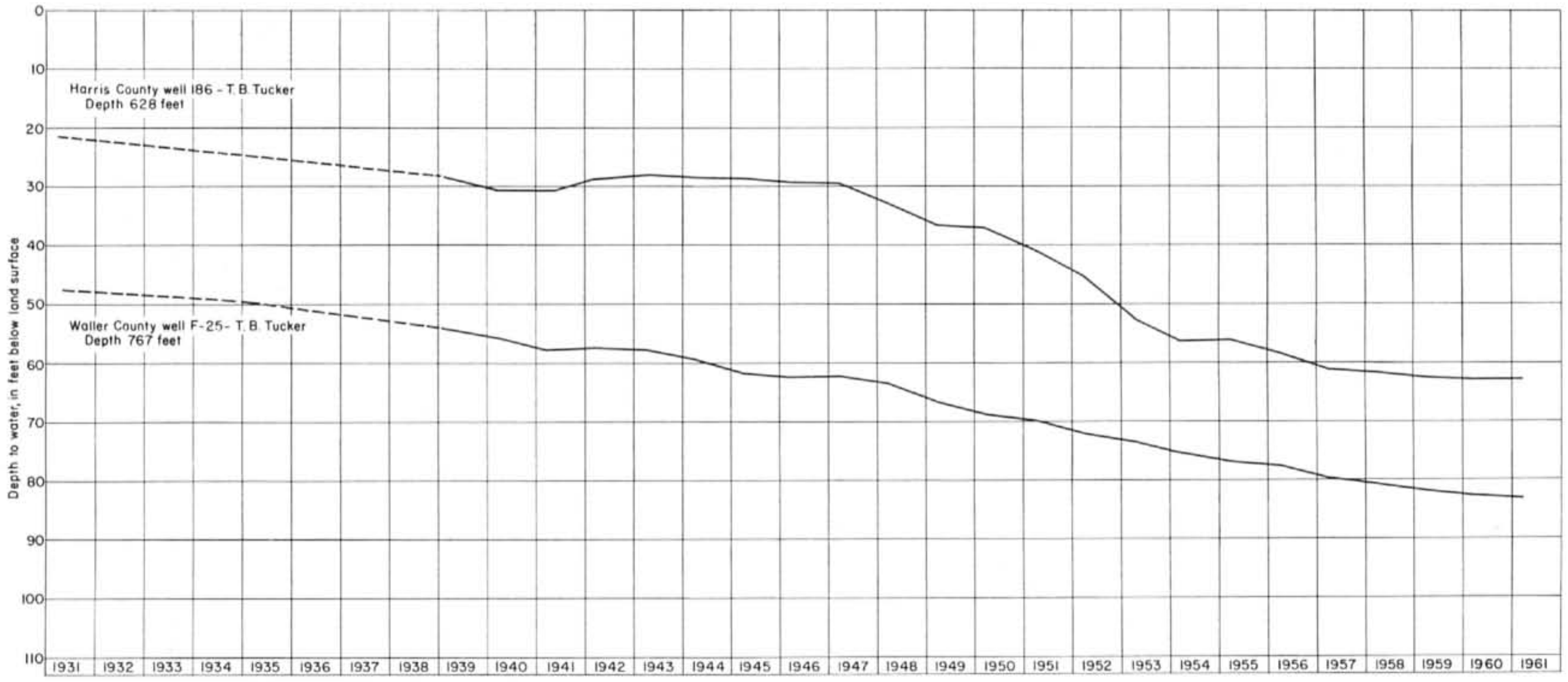


Figure 18

Changes in Water Levels in Wells in the Katy Area

U. S. Geological Survey in cooperation with the Texas Water Commission subregion II, changes in water level seem to be related to changes in annual precipitation--that is, during periods of below-normal precipitation, levels decline and during periods of above-normal precipitation, levels rise. In the irrigation areas, seasonal declines may lower the level 50 to 100 feet below that of the late winter or early spring.

Because withdrawals in the Houston area have been largely from wells tapping sands 500 to 1,800 feet below the land surface, levels in that zone are lower than in the zones above 500 feet and below 1,800 feet. Because of this, water moves toward the heavily pumped zone not only laterally but vertically from above and below.

Changes in water level will occur in subregion II as long as the levels in the different zones are not in equilibrium--that is, the zone having the highest outcrop (and highest water level in the outcrop area) should have the highest water level. As each successively deeper formation in the heavily pumped areas of subregion II has a higher outcrop, changes in water level will occur even though pumpage is stabilized.

Problems

Decline of water level (artesian pressure head) has resulted in several diverse effects, some easily recognized and others not so apparent. The immediate effect of declining level is increased lift, which increases the cost of the water. Continued decline has made it necessary to install more powerful equipment in places to obtain the same quantity of water, again increasing the cost. Many wells have had to be abandoned before their useful life should have been finished because their construction did not allow a pump setting deep enough to reach the declining levels. In most places new wells were drilled. In recent years, declines have been anticipated by setting large-diameter casing at much greater depths to accommodate large-capacity pumps.

Another result of water-level decline has been the incursion of salt water into centers of heavy withdrawal. As all the fresh-water sands in subregion II contain saline water at some distance downdip, the reversal of the natural gradients has caused the salt water to move updip toward the zone of lowered pressure head. In heavily pumped areas that originally were close to the fresh water-salt water interface or to parts of the sands that were in contact with underlying salt-water sands, the salt water has moved toward the wells, resulting in the deterioration of the chemical quality of the water. This has happened in two places in subregion II, both in Galveston County. The chloride content of water from the Alta Loma Sand of Rose (1943) in the Texas City area increased from 1936 or before until use of most of the wells was stopped in 1948. In the city of Galveston well field, about 20 miles northwest of Galveston, the chloride content of the water increased to a point that new wells were drilled from 2 to 3 miles farther north (Petitt and Winslow, 1955, p. 81). Evidence of updip movement of poor quality water has also been noted in the Houston area (Winslow and others, 1957, p. 397) but the saline water is about 5 miles from the heavily pumped area and may be many years away. However, very few wells are strategically located for observing the movement of the salty water, and much work needs to be done to define the problem in that area.

Another effect of water-level decline that has been unnoticed in many areas, especially at first, is land-surface subsidence. As levels declined in the sand beds, the load of the overlying sediments caused elastic deformation in the sand beds because part of the load was borne by the artesian pressure head, although most of it was borne by the skeleton of the aquifer. The land surface subsided because the overlying beds are not competent to carry the load. The subsidence from elastic deformation generally is small, only a few tenths of a foot for each several hundred feet of decline of pressure head. However, the intervening clay beds also contain water under artesian pressure that, before pumping, was nearly in equilibrium with the pressures of the water in the sand beds. As the water level declined in the sand beds, some of the water in the clay beds was 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 making up the clay bed, plastic deformation takes place. In the Houston area, total land-surface subsidence from both elastic and plastic deformation has been from less than 1 to more than 3 feet between 1935 and 1959. The differential subsidence in a distance of 1,000 feet has been small generally so that few effects are directly observable. In the Texas City area the subsidence was as much as 5 feet in the same period, and difficulties such as poor drainage, broken pipelines, and others, occurred near the center of the area. In one respect the subsidence may be viewed as beneficial because 22 percent of the water pumped in the Houston area between 1943 and 1959 was derived from compaction of clay beds.

Before any of the problems of subregion II can be completely solved, they must be understood better. To define the quality of water in the heavily pumped Houston area, many test wells will have to be constructed and observed. To define the subsidence problem, samples of many different clay beds will have to be analyzed, and compaction recorders will have to be installed in wells of different depths. Also, determination of the vertical permeabilities of clay beds will be necessary for both subsidence and recharge studies.

Among the important problems in subregion II are those concerning the rate at which ground water can be pumped, the magnitude of the resultant decline of water levels and the length of life of the ground water. The rate of recharge, rate of salt-water movement, and future subsidence are all factors in the problems. A proposed analog model study by the U. S. Geological Survey in cooperation with the city of Houston and the Texas Water Commission will probably provide some of the answers, at least regarding the magnitude of water available per year and the expected water-level declines.

GROUND WATER IN THE LAVACA RIVER BASIN, IN COASTAL PARTS OF THE BRAZOS AND COLORADO RIVER BASINS, AND IN ADJACENT COASTAL AREAS (SUBREGION III)

General

Subregion III, lying within the drainage basins of the Brazos, Colorado, and Lavaca Rivers and the adjacent coastal areas (Plate 7), includes all or parts of 15 counties and about 8,300 square miles. The total population is about 240,000, of which about 25 percent is urban. Freeport in Brazoria County had the largest population in 1959, about 11,600; the twin cities of Richmond and Rosenberg in Fort Bend County together had a population of about 13,400. Victoria had a population of about 33,000 in 1959; however, only part of the city is in subregion III.

The climate is wet subhumid east of a north-south line through Calhoun, Jackson, and Lavaca Counties, and dry subhumid west of the line. The average annual precipitation at the western edge is about 35 inches and at the eastern edge about 45 inches.

Occurrence

The base of fresh to slightly saline water in subregion III ranges from slightly above sea level in small areas in Calhoun County and southern Jackson County to more than 3,000 feet below sea level in Fort Bend County. In most of the subregion the base is between 600 and 2,000 feet below sea level (Plate 8).

The water-bearing sands attain their maximum thickness in Wharton and Fort Bend Counties, where as much as 1,000 feet is present in the fresh to slightly saline water zone (Plate 9). The total thickness of the sands is greatest through the central part of the subregion, thinning in all directions except northeastward, as shown by cross sections E-E', F-F', G-G', and Q-R (Figures 6, 7, and 8).

The range in transmissibility of the sands as determined by field tests is from 10,000 gpd per ft. in the northwestern part to as much as 250,000 gpd per ft. in the central part. Most of the subregion is underlain by sands whose composite transmissibility is greater than 100,000 gpd per ft. and parts of Colorado, Wharton, and Fort Bend Counties are underlain by sands whose composite transmissibility is more than 200,000 gpd per ft. (Figure 13). An average through the central part is probably about 125,000 gpd per ft. Northwest of southern Lavaca County and central Colorado and Austin Counties, less thickness of fresh to slightly saline water sand is present, yields of wells are less, and drawdowns are greater than in Victoria, Jackson, Wharton, southern Colorado, southern Austin, Fort Bend, and northern Matagorda Counties.

Wells in the northwestern part obtain water from the aquifer in the Lagarto, Oakville, and Catahoula, and the Jackson Group and range in depth from 300 to 900 feet and in yield from 100 to 500 gpm. The average specific capacity in this area is about 5 gpm per ft., and yields of less than 500 gpm causing drawdowns greater than 100 feet are common.

In the central part, yields as great as 3,000 gpm are obtained from wells less than 1,000 feet deep in sands of the Goliad, Willis, and Lissie and the Beaumont Clay. Some wells in the central part that are less than 300 feet deep yield more than 1,000 gpm; however, most of the large wells are deeper than 300 feet and the average yield of the deeper wells is about 2,000 gpm. Yields of 2,000 gpm with drawdowns of about 50 feet are not unusual in the deeper wells and pumping levels less than 150 feet are common. Specific capacities as high as 140 gpm per ft. were measured in central Wharton County, but the average specific capacity is generally less than 50 gpm per ft. in wells less than 1,000 feet deep.

Chemical Quality

Fresh to slightly saline ground water can be obtained throughout the subregion, except in small parts of southern Jackson and Central Calhoun Counties;

however, some of the fresh-water sands in Calhoun County, the southern part of Jackson County, and southwestern part of Matagorda County are overlain by sands containing salty water (Plate 8). Ground water in that part of Brazoria County included in subregion III (Plate 7), in Calhoun County, and in parts of Jackson, Matagorda and Victoria Counties is of poorer quality than elsewhere in the subregion. The concentration of dissolved solids in water from wells deeper than about 300 feet exceeds 1,000 ppm in most of the western half of Brazoria County.

Table 6 shows selected chemical analyses of water from wells in subregion III. In general, water from sands deeper than 500 feet is softer than water from sands less than 500 feet deep, but the water from the deeper sands contains greater concentrations of bicarbonate than that from the shallow sands. Most of the water, especially from sands less than 500 feet deep, is hard to extremely hard. The hardness is of the carbonate type and softening can be accomplished economically by using lime as a precipitant.

Chemical analyses of ground water from 40 public-supply systems show that 6 furnish water containing dissolved-solids content greater than 1,000 ppm; 13 systems furnish water containing more than 500 ppm but less than 1,000 ppm; 16 furnish water containing more than 300 ppm but less than 500 ppm; and 5 furnish water containing less than 300 ppm. All systems that furnish water having more than 1,000 ppm of dissolved solids are in Brazoria and Calhoun Counties. Wells at the Matagorda Island Air Force Base in Calhoun County yield water that contain as much as 2,370 ppm of dissolved solids. The water is used for sanitary facilities and is demineralized for human consumption. Seven public-supply systems furnish water that contains in excess of 250 ppm of chloride and only 4 supplies furnished soft water. The range in iron content was from about 0.05 to about 5.2 ppm. Thirteen municipal systems in Austin, Brazoria, Colorado, Jackson, Wharton, and Matagorda Counties have wells that yield water containing iron concentrations in excess of 0.3 ppm. Some of the municipalities are treating the water to reduce both the iron concentration and hardness. The concentration of all other constituents was less than the limits of the Public Health Service standards.

The ground water in subregion III is suitable for most industrial uses but may require treatment for special purposes. Much of the water used by industry is heated to high temperatures in boilers for use in mining sulphur by the Frasch process. The water is hard and requires treatment to prevent the formation of scale in boilers and lines. Water in many parts of the subregion contains a high concentration of iron which is undesirable in certain types of industry because of staining properties.

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

Utilization

Plate 7 shows the location of the major wells and Table 7 shows the 1959 pumpage for subregion III. In 1959 about 230 mgd of fresh to slightly saline

Table 6.--Analyses of water from wells in subregion III

(Results are in parts per million except specific conductance, pH and SAR.)

Water-bearing unit: A, Alluvium; B, Beaumont Clay; G, Goliad Sand; L, Lissie Formation; La, Lagarto Clay; O, Oakville Sandstone; W, Willis Sand.

Analysis No.	Location of Well	Screened interval (ft.)	Water-bearing unit	Silica (SiO_2)	Iron (Fe) (Total)	Manganese (Mn)	Calcium (Ca)	Magnesium (Mg)	Sodium and potassium (Na + K)		Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Phosphate (PO_4)	Boron (B)	Dissolved solids	Hardness as $CaCO_3$	Sodium adsorption ratio (SAR)	Specific conductance (micromhos at 25°C)	pH
1	Hempstead, Waller County	* 476-724	O,La	21	0.37	0.02	29	6.6	119	3.4	356	3.2	48	0.6	0.0	0.09	0.18	406	100	5.2	674	7.5
2	17 mi. S Hempstead, Waller County	?-1,602	O,La, G,W,L	22	--	--	37	14	145		269	118	86	--	.2	--	--	557	150	5.1	955	8.2
3	Bellville, Austin County	* 487-740	O,La	29	1/ .08	--	68	12	92	9.1	367	46	58	.2	.2	--	--	495	219	2.7	801	7.3
4	6 mi. W Sealy, Austin County	* 80-752	G,W,L	32	--	--	41	3.2	26	1.6	148	7.6	34	--	1.0	--	.09	246	115	1.1	358	7.5
5	Columbus, Colorado County	40-48	A(?)	13	1/ .02	--	115	10	13	4.8	352	18	19	.2	34	--	--	407	328	.3	668	8.4
6	Eagle Lake, Colorado County	* 360-525	G,W,L	29	.01	.00	44	3.2	16	1.4	144	4.2	28	.2	.5	.02	.03	198	123	.6	326	7.6
7	7 mi. W Eagle Lake, Colorado County	* 100-601	La,G, W,L	28	--	--	37	5.3	85	--	255	8.9	52	--	.5	--	.10	342	114	3.5	563	8.0
8	22 mi. SW Eagle Lake, Colorado County	703-804	La,G, W,L	26	--	--	66	5.9	28	1.8	238	6.8	44	--	.0	--	--	300	189	.9	495	7.6
9	Hallettsville, Lavaca County	?-480	O,La	17	.23	--	16	5.4	285	9.4	367	129	183	.1	.0	--	--	835	62	16	1,580	8.5
10	16 mi. W Hallettsville, Lavaca County	* 110-250	O	28	--	--	88	6.1	58	6.1	300	33	64	--	5.2	--	--	446	244	1.6	734	7.0
11	14 mi. SE Hallettsville, Lavaca County	450-751	La,G	24	--	--	50	10	119	2.8	358	41	65	--	.2	--	--	488	166	4.0	806	7.1
12	Victoria, Victoria County	509-538	G,W,L	21	1/ 4.7	--	34	11	146	7.9	402	14	80	.4	.0	--	--	517	130	5.6	868	7.0
13	15 mi. NE Victoria, Victoria County	140-146	G,W,L	30	--	--	83	14	77	2.9	324	18	106	--	.0	--	.16	496	265	2.1	847	7.7
14	19 mi. SE Victoria, Victoria County	* 158-290	G,W,L	18	--	--	31	12	222	2.3	382	.0	218	--	.0	--	.44	694	127	8.6	1,230	8.1
15	Edna, Jackson County	* 970-1,195	La,G, W,L	15	.08	.01	6.5	2.7	251	1.7	375	.4	185	.8	.0	.04	.40	653	27	21	1,120	7.3
16	10 mi. N Edna, Jackson County	* 182(?) 934	La,G, W,L	22	--	--	40	12	114		337	19	71	.4	.0	--	.09	444	150	4.0	740	7.1

See footnotes at end of table.

Table 6.--Analyses of water from wells in subregion III--Continued

Analysis No.	Location of Well	Screened interval (ft.)	Water-bearing unit	Silica (SiO_2)	Iron (Fe) (Total)	Manganese (Mn)	Calcium (Ca)	Magnesium (Mg)	Sodium and potassium (Na + K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Phosphate (PO_4)	Boron (B)	Dissolved solids	Hardness as $CaCO_3$	Sodium adsorption ratio (SAR)	Specific conductance (micromhos at 25°C)	pH
17	27 mi. SE Edna, Jackson County	* 300-690	G,W,L	15	--	--	14	6.0	205	399	19	112	--	0.0	--	0.19	574	60	12	964	7.5
18	3 mi. W Port Lavaca, Calhoun County	173-233	B	22	0.23	0.10	44	17	267 3.5	446	18	265	0.9	.0	0.05	.66	857	180	8.7	1,520	8.0
19	16 mi. SW Port Lavaca, Calhoun County	?-70	B,A	24	.37	--	40	16	162 5.5	325	38	149	1.0	.5	--	.64	597	166	5.5	1,040	7.3
20	11 mi. SW El Campo, Wharton County	* 134-599	G,W,L	18	--	--	105	20	61 2.2	291	24	158	--	1.0	--	.06	532	344	1.4	1,040	7.5
21	13 mi. NW El Campo, Wharton County	* 110-388	G,W,L	39	--	--	105	7.2	54 1.0	274	16	121	--	.5	--	.12	479	292	1.4	838	7.4
22	11 mi. W Wharton, Wharton County	* 77-186	G,W,L, B	24	--	--	60	6.7	23 1.7	220	6.0	28	.2	3.2	--	.18	264	177	.8	440	7.5
23	Wharton, Wharton County	* 212-393	G,W,L	--	1/ .15	--	67	14	32	256	16	47	--	.8	--	--	303	225	.9	--	--
24	13 mi. SE Wharton, Wharton County	* 246-791	G.W,L	24	--	--	63	17	42 2.5	292	16	49	--	.0	--	--	359	227	1.2	614	7.3
25	8 mi. NE Wharton, Wharton County	140-532	G,W,L	28	--	--	74	15	39 2.6	255	14	79	.4	.5	--	.09	411	246	1.1	668	7.2
26	15 mi. N Wharton, Wharton County	40-405	G,W,L	33	--	--	96	7.6	59 1.2	279	16	115	--	1.0	--	.34	499	270	1.6	830	7.5
27	12 mi. W Rosenberg, Fort Bend County	?-245	G,W,L	20	--	--	67	20	99	475	14	41	.8	.0	--	--	496	249	2.7	826	7.0
28	Rosenberg, Fort Bend County	* 970-1,590	G,W,L	15	.13	.00	22	6.1	87 2.1	253	.2	43	.4	.0	.04	--	300	80	4.2	516	7.5
29	14 mi. S Rosenberg, Fort Bend County	234-1,090	G,W,L	19	--	--	74	18	185 2.6	278	14	305	--	2.5	--	.21	792	258	5.0	1,430	7.5
30	In Brazoria County, 22 mi. SE Rosenberg, Fort Bend County	192-837	G,W,L, B	18	--	--	36	8.1	128	324	2.8	93	.5	.0	--	--	445	124	5.0	769	7.0
31	In Brazoria County, 19 mi NE Bay City, Matagorda County	?-875	G,W,L, B	15	--	--	26	9.5	428	382	2.4	508	1.1	.0	--	--	1,180	104	18	2,150	7.3
32	12 mi. NW Freeport, Brazoria County	439-468	G,W,L, B	14	.96	.2	22	12	357 2.9	382	.4	408	.8	.0	.07	.24	1,010	104	15	1,810	7.2

See footnotes at end of table.

Table 6.-- Analyses of water from wells in subregion III--Continued

Analysis No.	Location of Well	Screened interval (ft.)	Water-bearing unit	Silica (SiO_2)	Iron (Fe) (Total)	Manganese (Mn)	Calcium (Ca)	Magnesium (Mg)	Sodium and potassium (Na + K)		Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Phosphate (PO_4)	Boron (B)	Dissolved solids	Hardness as $CaCO_3$	Sodium adsorption ratio (SAR)	Specific conductance (micromhos at 25°C)	pH
2/ 33	Freeport, Brazoria County	206-247	G,W,L,B	16	0.4	--	23	15	302	--	572	2	203	--	--	--	--	1,145	--	--	--	7.7
34	4 mi. NE Bay City, Matagorda County	?-530	G,W,L,B	24	--	--	83	27	119	2.3	456	16	134	--	0.0	--	0.23	630	318	2.9	1,120	7.5
35	16 mi. SE Bay City, Matagorda County	* 193-728	G,W,L,B	22	--	--	126	35	151		460	44	256	0.3	1.8	--	--	935	458	3.1	1,570	6.8
36	14 mi. S Bay City, Matagorda County	150-720	G,W,L,B	21	--	--	37	8.8	143	--	366	11	90	--	.2	--	.28	498	128	5.5	849	8.0
37	13 mi. W Bay City, Matagorda County	520-761	G,W,L,B	28	--	--	61	19	52	2.7	291	17	68	--	.0	--	.00	391	230	1.5	660	7.1
38	19 mi. SW Bay City, Matagorda County	* 85-466	G,W,L,B	28	--	--	62	30	143	1.9	422	46	140	.6	.0	--	.33	671	278	3.7	1,160	7.0
39	5 mi. NW Palacios, Matagorda County	?-696	G,W,L,B	21	--	--	26	16	93	2.3	286	18	60	.5	.0	--	.26	378	131	3.5	647	7.8
40	4 mi. E Palacios, Matagorda County	?-770	G,W,L,B	17	--	--	9.9	4.3	177		344	11	94	--	.0	--	--	488	42	12	846	8.3

* Not screened throughout interval.
1/ Iron in solution at time of analysis.
2/ Analysis by Southwestern Laboratories, Houston.

Table 7.--Ground-water pumpage in major subdivisions of subregion III, 1959

Major subdivisions	Public supply		Industrial		Irrigation		Total*	
	mgd	acre-ft./yr.	mgd	acre-ft./yr.	mgd	acre-ft./yr.	mgd	acre-ft./yr.
Brazos River Basin:								
BR-91	0.23	258	--	--	--	--	0.23	260
BR-92	.85	952	--	--	2.1	2,400	2.9	3,300
BR-93	.90	1,008	4.34	4,861	7.9	8,900	13	15,000
BR-94	2.32	2,599	[1] 6.56	7,348	6.2	6,900	15	17,000
Brazos-Colorado Coastal Area:								
BR-CO-1	.39	437	.38	426	9.7	11,000	10	12,000
BR-CO-2	.07	78	2.97	3,326	2.5	2,800	5.5	6,200
BR-CO-3	.84	941	6.59	7,381	1.8	2,000	9.2	10,000
BR-CO-4	1.11	1,243	--	--	1.0	1,100	2.1	2,300
Colorado River Basin:								
CO-76	.39	437	.05	56	8.6	9,600	9.0	10,000
CO-77	--	--	.22	246	6.2	6,900	6.4	7,100
Colorado-Lavaca Coastal Area:								
CO-LA-1	1.34	1,501	--	--	20	22,000	21	24,000
CO-LA-2	.12	134	.78	874	27	30,000	28	31,000
Lavaca River Basin:								
LA-1	.64	717	.02	22	1.2	1,300	1.9	2,000
LA-2	.69	773	--	--	3.7	4,100	4.4	4,900
LA-3	.26	291	--	--	6.4	7,200	6.7	7,500
LA-4	--	--	.45	504	35	39,000	35	40,000
LA-5	.74	829	.03	34	39	44,000	40	45,000
Lavaca-Guadalupe Coastal Area:								
LA-GU-1	.01	11	.17	190	14	16,000	14	16,000
LA-GU-2	.98	1,097	.01	11	1.4	1,600	2.4	2,700

See footnotes at end of table.

Table 7.--Ground-water pumpage in major subdivisions of subregion III, 1959--Continued

Major subdivisions	Public supply		Industrial		Irrigation		Total*	
	mgd	acre-ft./yr.	mgd	acre-ft./yr.	mgd	acre-ft./yr.	mgd	acre-ft./yr.
Lavaca-Guadalupe Coastal Area:								
LA-GU-3	.11	123	--	--	--	--	.11	120
LA-GU-4	.09	100	.01	11	.20	220	.30	320
Subtotal, major wells	12	14,000	23	25,000	190	220,000	230	260,000
Domestic, livestock, and miscellaneous small wells							8	9,000
Total							240	270,000

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

1/ Includes 2.65 mgd of slightly saline to saline water.

water was pumped for the major uses and about 8 mgd was pumped for domestic and livestock uses.

Water for all public supplies is obtained from wells. In 1959, 121 public-supply wells pumped 12 mgd or about 5 percent of the pumpage for all major uses. The greatest pumpage for public supply was in the Brazos River Basin where 4.3 mgd was pumped in 1959.

Of the 23 mgd used for industry more than 20 mgd or about 90 percent was pumped from 30 wells in the Brazos Basin and 37 wells in the Brazos-Colorado coastal subdivisions 2 and 3. Of the 20 mgd, 2.65 mgd was water classified as slightly saline to saline. Most of the industrial water was used for sulfur mining, refining of oil products, and in manufacturing chemicals.

More water was pumped for irrigation than for any other use. Approximately 190 mgd was pumped in 1959 for irrigation of which 185 mgd was pumped from about 690 wells to irrigate rice. About 85 mgd or 40 percent of the rice irrigation water was pumped from 310 wells in the Lavaca Basin.

Prior to 1955, very few wells were used primarily for row-crop irrigation. The period of subnormal rainfall from 1947 to 1957 pointed out the need for supplementary irrigation of some crops, and by 1959 more than 250 wells had been drilled for the irrigation of crops other than rice, such as cotton and corn. The development is principally in Wharton and Fort Bend Counties, but there are some row crop wells in each of the other counties. There is little need for most of the row-crop wells during years of normal or above-normal rainfall, and many of the wells were not used in 1959, the pumpage in that year being only about 5 mgd for row-crop irrigation in the subregion.

Changes in Water Levels

The most significant changes in water levels have occurred in the Freeport area of Brazoria County and in the eastern part of Fort Bend County. Heavy pumpage in the Freeport area caused local declines of as much as 95 feet during the period 1941 to 1956. In 1956, the use of a well field in the southwestern part of the Freeport area that formerly yielded about 1 mgd was discontinued, and between 1956 and 1961 water levels in the vicinity of the well field rose as much as 60 feet. Since 1958, pumpage in the Freeport area has decreased by about 1-1/2 mgd, resulting in a significant recovery of water levels, although not enough information is available to determine the areal extent or amount of the recovery.

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

Elsewhere levels have declined at lesser rates. Before 1947, the decline was about 0.5 foot per year in most of the subregion. Between 1947 and 1957, the rate was about 2 feet per year, and from 1957 to 1960 the decline again was less than 0.5 feet per year. In many areas levels have risen during the latter period because of increased recharge and decreased pumpage caused primarily by increased rainfall (Figure 16).

The rates of decline and total decline discussed above were based on water-level measurements made during the early months of each year, when pumpage was at a minimum. In the rice-irrigation areas, seasonal declines of 50 feet or more may be expected. The largest seasonal declines probably occur in northern Jackson, eastern Lavaca, southern Colorado, and western Wharton Counties.

Water levels in artesian sands throughout the subregion are less than 100 feet below the land surface. The levels are declining and will continue to decline, but the rates will be small except in the vicinity of areas where the pumpage is increased substantially.

Problems

Fresh water sands are overlain by sands containing saline water in southern Jackson County, the southwest part of Matagorda County and most of Calhoun County. If water of the best quality available is to be obtained in those areas, the sands containing the saline water must be effectively sealed to prevent downward leakage around the well casings. If pumpage in the area becomes large enough, salt water may percolate downward through the intervening clay into the fresh water sands. As of 1961 evidence was lacking of downward percolation of salt water through the clays, but reportedly, water from some wells that screen both fresh and saline water sands has become too salty for use.

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

Land-surface subsidence in areas of large ground-water withdrawal is probable. Land-surface subsidence has not been observed in the subregion but if water levels decline so that a large amount of fine material is dewatered, subsidence will occur.

Much additional information is needed in subregion III to determine: (1)the relation between fresh water and salt water and the rate of movement of salt water, (2)properties of the aquifers, (3)details of present development and the availability of water to wells, (4)possible areas of land-surface subsidence, and (5)possible areas of contamination. Electric-log coverage of much of the northwestern part and along the coast is sparse and detailed subsurface maps have not been prepared because of the lack of data. More information on water levels also is needed throughout the subregion.

GROUND WATER IN THE COASTAL PARTS OF THE GUADALUPE, SAN ANTONIO, AND NUECES RIVER BASINS AND ADJACENT COASTAL AREAS (SUBREGION IV)

General

Subregion IV includes about 7,700 square miles--all or parts of 17 counties (Plate 10). About 400,000 persons live in the subregion, more than three-fourths of the population being urban. Corpus Christi is the largest city, having a 1960 population of 167,690. The climate ranges from dry subhumid to semiarid, the annual rainfall decreasing from 36 inches along the lower reaches of the Guadalupe River to 20 inches in Webb County.

Occurrence

As shown by Plate 11, fresh to slightly saline water is found at various depths throughout most of subregion IV, reaching a maximum depth of more than 2,000 feet below sea level in Jim Wells and Duval Counties. However, there are areas in Aransas, San Patricio, and Nueces Counties where no appreciable amounts of fresh to slightly saline ground water are found. Within these areas, the demand for water is satisfied by rain-filled cisterns and stock tanks or water from Lake Corpus Christi (on the Nueces River in Jim Wells, San Patricio, and Live Oak Counties) or the Nueces River. On the Gulf-shore islands, sufficient water for domestic and livestock needs may be found in shallow sand deposits.

The vertical extent of the fresh to slightly saline zone and corresponding sand thickness is shown by the four sections, H-H', J-J', K-K', and P-Q (Figures 7 and 8). The first three sections are drawn nearly parallel to the dip of the sands; section P-Q is constructed nearly parallel to the strike. As seen by these sections, the fresh to slightly saline zone is continuous from the surface throughout most of the subregion except near the coast, where sands containing moderately saline to saline water overlie the fresh to slightly saline zone. The areal extent of these overlying moderately saline to saline water sands is shown on Plate 11.

Although the fresh to slightly saline water zone may extend from the surface down to about 2,500 feet below the surface, only a few hundred feet may constitute the actual thickness of the water-bearing sands in the zone. Thus, a more quantitative evaluation of the amount of fresh to slightly saline water present is obtained from the sand-thickness map (Plate 12) which shows that the sand thickness averages about 400 feet in the northeastern half of the subregion and about 200 feet in the southwestern half.

The major wells tap the aquifers at various depths, but most are more than 100 feet and less than 1,000 feet deep. The shallowest major wells, 70 to 80 feet deep, are in Aransas County, and the deepest wells, 2,400 to 2,500 feet deep, are in southern Jim Wells County.

The depth to water ranges from 0 to 20 feet along the coast and from 0 to 150 feet in the interior, depending on depth of the well and artesian pressure head. As most of the ground water is under artesian conditions, in general, the deeper the well, the higher the water level. Flowing wells can be obtained in most of the subregion and many have been drilled, the largest number, estimated to be 75 to 100, being in Refugio County.

Each of the major aquifers in the Gulf Coast region yields fresh water to wells in some parts of subregion IV. One major well in Karnes County obtains water from sands in the Jackson Group; however, the well is screened also opposite sands in the Catahoula Tuff. Sands in the Catahoula, Oakville, and Lagarto serve as an aquifer for most of the major wells in Goliad and Karnes Counties, in the northwestern half of Bee County including most of the city of Beeville wells, in western Duval County, and in the parts of Jim Wells County and eastern Duval County where the wells are more than 1,000 feet deep.

The chief aquifer is in the Goliad, Willis, and Lissie which yields water to the major wells in Victoria, Live Oak, Kleberg, and Nueces Counties, the southeastern half of Bee County, San Patricio County, most of Refugio County, and in Jim Wells County and eastern Duval County where the wells are less than 1,000 feet deep. The maximum total thickness of the Goliad, Willis, and Lissie sands in the fresh to slightly saline zone is 400 to 600 feet, the thickness decreasing towards the coast. In southeastern Nueces County, the quality of water from the sands of the aquifer in the Goliad, Willis, and Lissie changes abruptly and irregularly from well to well. Presumably the difference in quality of water within short lateral distances is the result of the lenticularity of the sands which hinders the flushing action of water moving downdip.

Sands in the Beaumont Clay serve as an aquifer for major wells in Aransas County and the southeastern part of San Patricio County, and many of the wells in eastern Refugio County.

The coefficient of transmissibility of the aquifer sands in the Catahoula, Oakville, and Lagarto in subregion IV ranges from about 6,000 to about 35,000 gpd per foot. The coefficient generally is higher in Karnes, DeWitt, and Bee Counties than in Webb, Duval, and Jim Wells Counties. The average discharge of wells tapping the Catahoula, Oakville, and Lagarto in Karnes, DeWitt, and Bee Counties is about 250 gpm, although yields of 1,000 gpm have been measured in wells in Beeville. The specific capacities of wells in Karnes, DeWitt, and Bee Counties ranges from less than 3 to more than 9 gpm per foot of drawdown. The average discharge of wells tapping the Catahoula, Oakville, and Lagarto in Duval and Jim Wells Counties is 200 gpm or less; however, yields as large as 800 gpm have been recorded. The specific capacities of the wells in Duval and Jim Wells Counties range from less than 2 to 5 gpm per foot of drawdown.

Coefficients of transmissibility of the aquifer sands in the Goliad, Willis, and Lissie determined in the part of subregion IV north of the Nueces River range from 11,000 to 67,000 gpd per foot. The average discharge of wells is between 500 and 900 gpm; some wells yield as much as 2,000 gpm in the vicinity of Victoria. The specific capacities of wells tapping the Goliad, Willis, and Lissie north of the Nueces River range from 5 to 65 gpm per foot of drawdown.

South of the Nueces River, coefficients of transmissibility ranging from 4,000 to 25,000 gallons per day per foot have been determined in the aquifer in the Goliad, Willis, and Lissie. The average discharge of wells is about 300 gpm, although discharge rates of as much as 1,000 gpm are reported. Specific capacities range from less than 4 to nearly 17 gallons per minute per foot of drawdown.

Sands in the Beaumont Clay in Refugio, San Patricio, and Aransas Counties generally have a maximum coefficient of transmissibility of 2,000 to 3,000 gallons per day per foot. Although discharge rates of as much as 300 gpm have been measured, generally the discharge from wells tapping the Beaumont Clay is much smaller.

Chemical Quality

Ground water changes in chemical quality from fresh to saline both laterally and vertically; however, this discussion will be limited to the general quality trends of the water in the fresh to slightly saline zone. The water in that zone is predominantly slightly alkaline, being hard to very hard near the surface but becoming softer with increasing depth. Most of the water of better quality occurs in the northeastern part, the quality tending to deteriorate toward the southwest as the chloride and sulfate content increases. Analyses of water from representative wells in subregion IV are shown in Table 8.

In some areas there is no fresh water, all the water in the fresh to slightly saline zone being slightly saline. However, the water is the best available and it is used for human consumption although it may contain enough chloride and/or sulfate--and more rarely fluoride--to give the water a disagreeable taste or produce irritating but not necessarily debilitating reactions in metobolic processes (U. S. Public Health Service, 1946, p. 383). Water of this quality is acceptable for industrial washing and cooling but is generally too mineralized for use in manufacturing processes where the water is an ingredient or for use in boilers.

Very little of the ground water in subregion IV would be acceptable for irrigation, according to the standards suggested by the Department of Agriculture for use in arid and semiarid areas. Most of the water has either a high salinity or alkalinity hazard, or both. Some of the water of the fresh to slightly saline zone is being used for irrigation and more could be used but it should be used with restraint. Soil conditioning probably will be necessary at some future time to combat the harmful cumulative effects from using this water for irrigation. In addition to the high salinity and alkalinity hazards, excessive content of boron is found in water from the Oakville Sandstone in Jim Wells County. (See analyses 21 and 22, Table 8.)

Table 9, which contains analyses made by the Campbell Laboratory of Corpus Christi, shows the chemical composition of the water in the major sand zones penetrated while drilling an irrigation well in San Patricio County. The analyses show an abrupt change in calcium-magnesium content and SAR below 443 feet. By careful placement of well screens in such a well, water for irrigation possibly can be obtained that will have only a small potential to cause possible soil or plant damage, but the quantity of water obtained probably will be too small for irrigation needs. Therefore, well screening or slotting usually is indiscriminant. Analysis 23, Table 8, shows the resultant composition of the water from an irrigation well in which the casing was slotted opposite most of the sands between 281 feet and 751 feet. The well is in the same area as the one from which analyses of water for Table 9 were obtained.

The composition of the water from the sands between 398 and 443 feet below the surface is anomalous to its depth (Table 9), the composition being more representative of a shallow water. This is a common anomaly and probably results from the lenticularity of the sands.

Much of the water pumped from aquifers older than the Beaumont Clay carries dissolved natural gases. The smell of hydrogen sulfide is noticeable around many major wells while they are pumping. Aeration dispels the gas.

Table 8.--Analyses of water from wells in subregion IV

(Results are in parts per million except specific conductance, pH, and SAR.)
Water-bearing unit: B, Beaumont Clay; C, Catahoula Tuff; G, Goliad Sand; L, Lissie Formation; La, Lagarto Clay; O, Oakville Sandstone; W, Willis Sand.

Analysis No.	Location of Well		Screened interval (ft.)	Water-bearing unit	Silica (SiO_2)	Iron (Fe) (Total)	Manganese (Mn)	Calcium (Ca)	Magnesium (Mg)	Sodium and potassium (Na + K)		Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Boron (B)	Dissolved solids	Hardness as $CaCO_3$	Sodium adsorption ratio (SAR)	Specific conductance (micromhos at 25°C)	pH
1	5 mi. W Victoria, Victoria County	*	525-572	G,W,L	19	[1] 0.21	--	27	15	174	3.4	420	11	113	0.6	0.0	0.56	572	129	6.7	971	8.2
2	Refugio, Refugio County	*	578-864	G,W,L	16	[1] .04	--	5.9	2.7	365	7.2	418	53	302	1.4	.8	--	963	26	31	1,720	8.5
3	2 mi. NW Sinton, San Patricio County	*	440-750	G,W,L	18	[1] .01	0.00	4.6	.6	385	1.3	405	26	355	1.0	.2	1.5	992	14	45	1,770	8.2
4	20 mi. W Corpus Christi, Nueces County		580-610	G,W,L	16	.11	.01	21	5.8	599	5.2	268	324	600	.9	.0	2.0	1,710	76	30	2,850	7.7
5	24 mi. SW Corpus Christi, Nueces County	*	630-850	G,W,L	16	.23	.02	28	9.6	521	7.3	240	510	372	.7	5.5	2.0	1,590	110	22	2,510	7.7
6	Kingsville, Kleberg County		?-730	G,W,L	17	[1] .03	--	21	7.5	308	12	315	162	235	.5	9.2	--	951	84	15	1,560	7.9
7	Karnes City, Karnes County		810-850	C	77	.03	.00	6.4	.0	476	18	322	101	492	1.6	.1	2.7	1,330	16	52	2,230	8.0
8	Kenedy, Karnes County		360-410	O	59	.11	.00	128	14	660	35	366	277	900	.6	13	1.9	2,270	378	15	3,690	7.7
9	8 mi. SE Kenedy, Karnes County	*	80-336	La	56	.25	--	146	24	118	5.4	327	39	265	.7	41	.34	856	464	2.4	1,450	7.2
10	Goliad, Goliad County	*	379-540	La	34	.04	.00	100	28	113	3.6	338	37	212	.8	2.2	.25	697	364	2.6	1,230	7.7
11	14 mi. S Refugio, Refugio County		1,033-1,050	G,W,L	--	--	--	6.8	3.9	735		472	40	852	--	.5	--	1,870	33	56	--	--
12	Rockport, Aransas County		53-78	B	15	[1] .15	--	96	13	116	13	315	5.7	211	.2	.8	--	670	293	2.9	1,190	7.6
13	15 mi. SW San Diego, Duval County	*	209-518	G,W,L	29	[1] .02	--	41	17	364	12	297	231	338	.8	20	--	1,200	172	12	2,060	7.8
14	San Diego, Duval County	*	390-492	G,W,L	22	.05	--	28	12	248	8.2	370	109	169	.7	15	--	794	120	9.8	1,380	7.8

See footnotes at end of table.

Table 8.--Analyses of water from wells in subregion IV--Continued

Analysis No.	Location of Well	Screened interval (ft.)	Water-bearing unit	Silica (SiO_2)	Iron (Fe) (Total)	Manganese (Mn)	Calcium (Ca)	Magnesium (Mg)	Sodium and potassium (Na + K)		Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Boron (B)	Dissolved solids	Hardness as $CaCO_3$	Sodium adsorption ratio (SAR)	Specific conductance (micromhos at 25°C)	pH
15	Alice, Jim Wells County	* 395-850	G,W,L	18	0.03	--	28	15	402	9.4	350	176	380	0.8	15	1.9	1,220	132	15	2,090	7.6
16	10 mi. S Corpus Christi, Nueces County	?-1,173	G,W,L	--	1.8	--	30	7.5	962		266	722	870	--	.8	--	2,720	106	41	--	--
17	37 mi. SW San Diego, Duval County	438	C	--	--	--	8	--	319	--	420	114	179	--	11	--	799	30	25	--	--
18	9 mi. NE Kenedy, Karnes County	156-190	O	32	.01	0.00	121	30	128	7.9	286	35	312	.5	5.1	.28	813	426	2.7	1,450	7.6
19	17 mi. N Beeville, Bee County	* 727-907	O	19	.79	.01	15	4.0	543	9.1	475	219	450	1.0	.2	3.1	1,500	53	32	2,530	7.9
20	Beeville, Bee County	1,484-1,533	O	19	1/ .15	--	7.1	1.3	514	27	601	.9	480	1.8	.8	--	1,350	23	47	2,310	7.5
21	3 mi. SW Alice, Jim Wells County	1,850-1,900	O	22	--	--	17	1.6	704	3.8	260	690	452	3.5	.0	9.2	2,030	49	44	3,190	8.0
22	3 mi. N Premont, Jim Wells County	2,330-2,425	O	27	.08	.02	6.6	.2	646	2.9	390	414	462	5.0	.2	13	1,770	18	67	2,880	8.3
23	15 mi. NW Sinton, San Patricio County	* 280-751	G,W,L	24	--	--	53	14	480	4.5	404	15	625	--	.6	2.1	1,420	190	15	2,520	7.9
24	Premont, Jim Wells County	* 427-568	G,W,L	38	1/ .00	.00	51	17	196	10	284	82	212	0.6	21	.67	768	198	6.1	1,270	8.0
25	27 mi. E Refugio, Refugio County	?-500	B	21	1.2	--	36	18	257	3.9	385	92	228	.8	.2	1.0	847	164	8.7	1,430	7.6
26	5 mi. SW Refugio, Refugio County	* 180-270	B	18	1/ .00	.00	14	4.6	298	2.2	358	69	235	.6	.1	.94	818	53	18	1,410	8.1
27	7 mi. SE Sinton, San Patricio County	* 158-216	B	16	1/ .02	--	17	7.6	490	8.8	437	66	508	1.8	2.2	--	1,330	85	23	2,310	7.8

* Not screened throughout interval.

1/ Iron in solution at time of analysis.

Table 9.--Analyses of water from individual sands in a well 8 miles northwest of Sinton, San Patricio County.

(Analyses by Campbell Laboratory, Corpus Christi. Results are in parts per million except SAR.)

Depth (feet)	Silica (SiO_2)	Calcium (Ca)	Magnesium (Mg)	Sodium and potassium (Na + K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Boron (B)	Dissolved solids	Hardness as $CaCO_3$	SAR
175-205	41	137	47	330	218	75	708	--	1,484	536	6.4
260-302	41	75	20	201	318	65	268	0.5	860	270	5.3
316-344	20	69	21	186	322	116	196	.6	732	259	5.0
398-443	21	183	44	246	272	284	464	.6	1,470	638	4.2
596-644	16	12	5	329	286	55	316	1.8	918	51	20
750 ±	17	8	3	316	377	85	208	--	876	32	24
900 ±	23	9	3	326	395	80	217	--	838	35	24

Chemical analyses 1 through 6 (Table 8) show the change in composition of the water in the aquifer in the Goliad, Willis, and Lissie from Victoria County to Kleberg County along the strike of the formations, analyses 5 and 6 showing a decided change in nitrate content.

Chemical analyses 2 and 7 through 12 show the changing composition of water in the downdip direction in Karnes, Goliad, Refugio, and Aransas Counties. The quality of the water from the Lagarto Clay seems to improve downdip (analyses 9 and 10, Table 8); conversely, water in the Goliad, Willis, and Lissie (analyses 2 and 11) deteriorates in quality downdip. The latter is more typical of the water in the aquifers of the subregion.

Analyses 5 and 13 through 16 exemplify the variation of quality of waters used for public supply in the southern part of the subregion.

Analyses 8 and 18 through 22 are of water from the Oakville Sandstone. They clearly show the change in hardness with depth. The high fluoride and boron content shown by analyses 21 and 22 is of water from the lower part of the fresh to slightly saline zone.

Analysis 24 is representative of the composition of water used for irrigation in southern Jim Wells County and northeastern Brooks County.

Analyses 25 through 27 are typical of the water from sands of the Beaumont Clay. Analysis 25 probably is representative of water used for irrigation in the eastern part of Refugio County.

Utilization

About 36 million gallons of ground water was used in subregion IV each day in 1959 for domestic, municipal, industrial, and agricultural uses (Table 10), the largest part being used for public supply.

During 1959, about 13 mgd was pumped from 133 public supply wells. All the cities, towns, and villages depend on wells for public supply except Corpus Christi, its suburbs, and seven other nearby towns. The exceptions obtain their water from Lake Corpus Christi (on the Nueces River in Jim Wells, San Patricio, and Live Oak Counties) or the Nueces River. Almost half the 400,000 (estimated) population, both urban and rural, obtain their water from wells.

Wells supplied about 7.3 mgd in 1959 for industrial use from approximately 96 wells; however, surface-water sources--the Guadalupe River, Lake Corpus Christi, and the Nueces River--supply most of the demand for water for industry.

About 9.3 mgd of ground water was pumped from approximately 115 wells in 1959 for irrigation in two principal areas--southern Bee and western San Patricio Counties and southern Jim Wells and northeastern Brooks Counties. During 1959, propitious rains lessened the need for irrigation and less water was pumped than during normal years. In some years, the amount of water pumped for irrigation probably exceeds the amount of water pumped for other uses. At the end of 1960, a total of 147 irrigation wells was in use.

Table 10.--Ground-water pumpage in major subdivisions of subregion IV, 1959

Major subdivisions	Flowing wells		Public supply		Industrial		Irrigation		Total*	
	mgd	acre-ft./yr.	mgd	acre-ft./yr.	mgd	acre-ft./yr.	mgd	acre-ft./yr.	mgd	acre-ft./yr.
Guadalupe River Basin:										
GU-13	0.14	157	0.56	627	0.88	986	0.14	160	1.7	1,900
San Antonio River Basin:										
SA-8	--	--	1.06	1,187	.20	224	.1	110	1.4	1,500
SA-9	--	--	--	--	--	--	.14	160	.14	160
San Antonio-Nueces Coastal Area:										
GU-NU-1	.29	325	.05	56	.18	202	.04	45	.56	630
GU-NU-2	--	--	--	--	.42	470	--	--	.42	470
GU-NU-3	--	--	.03	34	.22	246	.02	22	.27	300
GU-NU-4	--	--	.73	818	.11	123	--	--	.84	940
GU-NU-5	--	--	2.78	3,114	.15	168	4.5	5,000	7.4	8,300
GU-NU-6	--	--	.39	437	.23	258	--	--	.62	690
Nueces River Basin:										
NU-33	--	--	.27	302	--	--	1.0	1,100	1.3	1,400
Nueces-Rio Grande Coastal Area:										
NU-RG-1	--	--	.01	11	--	--	--	--	.01	11
NU-RG-2	--	--	.22	246	.85	952	.01	11	1.1	1,200
NU-RG-3	--	--	--	--	.16	179	--	--	.16	180
NU-RG-4	--	--	6.57	7,359	1.34	1,500	.1	110	8.0	9,000
NU-RG-5	--	--	.25	280	.98	1,097	.29	320	1.5	1,700
NU-RG-6	--	--	.05	56	.65	729	.58	650	1.3	1,400
NU-RG-7	--	--	.48	538	.96	1,075	2.4	2,700	3.8	4,300
Subtotal, major wells	0.43	480	13	15,000	7.3	8,200	9.3	10,000	30	34,000
Domestic, livestock, and miscellaneous small wells									5	6,000
Total									35	41,000

* Figures are approximate because some of the pumpage rates are estimated. Irrigation figures are shown to not more than two significant figures. Public supply and industrial and other pumpage figures are shown to nearest 0.01 mgd and to nearest acre-foot. Totals are rounded to two significant figures.

Two wells in subregion IV are classified as major wells because they flow more than 50 gpm. A well in Victoria County flows about 100 gpm and a well in Refugio County flows about 200 gpm. The water from the wells is not used except by livestock. There are many other flowing wells but the individual flows are small. The total discharge of all the flowing wells is estimated to be about 0.9 mgd.

Livestock is dependent chiefly on ground water pumped by windmills or provided by controlled flowing wells, and the entire rural population also is dependent on ground-water sources. About 5 mgd was pumped from the fresh to slightly saline zone in 1959 for domestic and livestock use. Some of the livestock wells yield moderately saline water.

Changes in Water Levels

The ground-water resources of subregion IV have not been as extensively developed as those in the other subregions, most of the 396 major wells shown on Plate 10 having been drilled since 1940. Consequently, declines in water level have been small. Comparisons of recent water-level measurements in livestock and domestic wells with measurements made in the 1930's showed practically no change in water levels for a great part of the subregion.

Water levels have declined in small areas near major wells throughout the subregion, but only in the southeastern part have they declined generally. In south-central San Patricio County, water levels have declined 10 to 20 feet since 1939, although apparently very little ground water has been pumped. No appreciable decline has been noted in the irrigation area of northwestern San Patricio County from the few measurements that have been made in the last few years. However, a seasonal decline of several feet in the water levels in domestic wells in the irrigation area during the pumping season has been reported by well owners.

The greatest declines have occurred in three areas: (1)central Jim Wells County, (2)southwestern Nueces and northwestern Kleberg Counties, and (3)southern Jim Wells and northeastern Brooks Counties. In the vicinity of Alice in central Jim Wells County, water levels have declined approximately 70 to 80 feet between 1932 and 1960. The decline near the Kleberg-Nueces County line, north of Kingsville, has been more than 100 feet since 1932 (Figure 16). Similarly, the greatest decline in southern Jim Wells County and northeastern Brooks County has been about 70 feet since 1932, and the depth to water in most wells in these areas is now more than 100 feet. Most of the decline in the three areas occurred during the 1940's; the decline has leveled off since the early 1950's although some adjustment still continues. The declines in areas adjoining the centers of greatest decline have continued at slower rates and the areas have nearly merged so that now much of southwestern Nueces County, Jim Wells County, western Kleberg County, northeastern Brooks County, and a small part of southeastern Duval County show a decline of water levels.

The declines in water levels are related to the intensive pumping of water from the major wells in the area, to climatic differences, and to the distribution of sand thickness. Some areas in Jackson and Wharton Counties in subregion III have been as intensively pumped as the heavily pumped areas in subregion IV, but the water levels have not declined as much because of the much greater sand thickness (more than 600 feet), and the higher rate of recharge and greater rainfall. In the heavily pumped areas in Nueces, Kleberg, and eastern Jim Wells Counties, the sand thickness averages only about 200 feet, and the rate of recharge is lower due to less rainfall, higher evaporation, and possibly to the retardation of percolation by caliche which underlies much of the area. Most of the wells in Nueces and Kleberg Counties are pumping water from the same "tongue" of sand. Section L-L' (Figure 8) shows this "tongue" of sand in the aquifer in the Goliad, Willis, and Lissie extending almost to the coast. Where declines in water levels have occurred, they have been greatest where the sand thickness is least.

Problems

The fresh to slightly saline water zone of subregion IV must be protected from the introduction of contaminating fluids. Contamination could occur during exploration for oil and gas and subsequent activities or during the disposal of salt water either on the surface or through injection wells. The maintenance of high artesian pressure head helps protect the fresh to slightly saline zone. A diminishing of artesian pressures enhances the possibility of updip salt-water invasion, and may permit entry of overlying saline waters into the fresh to slightly saline zone through corroded casings or through improperly constructed wells.

Water adequate in both quantity and quality is of primary importance to the life and growth of a population center or industry. In much of the southern half of subregion IV, the quantity of water available from ground-water sources is small. The best water obtainable in some areas is slightly saline, and, therefore, the uses that can be made of it unless it is treated are limited. In these areas of small supply, it is especially important that the wells be adequately spaced so as to minimize interference effects and the resultant decrease of artesian pressure.

Irrigators should be conscious of the potential harm that can be done by using water having a high sodium, boron, and dissolved-solids content. Damage to soil structure commonly can be corrected, but it can be more easily prevented.

GROUND WATER IN THE COASTAL PART OF THE RIO GRANDE BASIN AND ADJACENT COASTAL AREAS (SUBREGION V)

General

Subregion V includes about 6,300 square miles -- all or part of 10 counties (Plate 13): Webb, Duval, Jim Hogg, Jim Wells, Brooks, Kenedy, Willacy, Cameron, Hidalgo, and Starr. The population, about 350,000, is concentrated chiefly along the Rio Grande; approximately two-thirds of the population is urban. The climate is semiarid; the rainfall ranges from approximately 30 inches per year along the coast to 20 inches along the western boundary.

Occurrence

Fresh to slightly saline ground water occurs in most of this subregion; the lateral extent of the water is shown on Plate 14. Only in eastern Cameron and Willacy Counties and a few small areas in Kenedy and Hidalgo Counties is water of this quality lacking. Even in these areas shallow reservoirs of small extent but containing water of usable quality may be present; such reservoirs are common under the dune areas of the off-shore islands.

Plate 14 shows the depth to the base of the fresh to slightly saline water. In some areas of Brooks and Jim Hogg Counties, the base extends to more than 2,500 feet below sea level; however, the total thickness of the sands in these areas is not large. In most of the subregion, the thickness of the sands totals 200 to 400 feet (Plate 15), the greatest sand thickness, more than 600 feet, being in north-central Hidalgo County. In the same area, the deepest water wells in the subregion, more than 1,500 feet deep, withdraw water from near the base of the fresh to slightly saline zone. Most of the wells in the subregion are less than 1,000 feet deep.

The base of the fresh to slightly saline water zone, as shown on Plate 14, is generalized because of incomplete data and because the base changes so abruptly that the details of the changes could not be shown on a map of the scale used. The aquifers thicken and thin and are laterally discontinous; productive and nonproductive wells can be drilled within short distances of each other. In the western part natural gas commonly occurs in the sands. On the electric logs, such gas-containing sands may seem to contain fresh water when they do not.

In southeastern Hidalgo County, the map of the base of the fresh to slightly saline water shows a small area which contains no water of that quality. This represents a gap between two sand zones, one below 800 feet extending to the north, the other above 650 feet extending to the south.

In more than half of the subregion, sands containing salt water overlie the fresh to slightly saline zone. Plate 14 shows the approximate western limits of these sands.

Section L-L' (Figure 8), extending across the northern part, shows the fresh to slightly saline zone, the corresponding sand thickness, and the inland extent of the overlying salt-water zone. Fresh to slightly saline water travels long distances downdip in the sands of the Catahoula Tuff and Oakville Sandstone and even greater distances in the aquifer sands of the Goliad, Willis, and Lissie. The latter aquifer underlies Kenedy County and parts of Brooks, Willacy, Cameron, and Hidalgo Counties, constituting the only source of fresh to slightly saline water in most of Kenedy and Willacy Counties.

Section M-M' (Figure 8), in the southern part, shows the fresh to slightly saline zone and corresponding sand thickness in the sediments underlying the Rio Grande Valley. Formational contacts could not be discerned, but the sediments are probably Goliad (Pliocene) to Recent in age.

Section N-P (Figure 8), lying in a north-south direction through the center of the subregion, shows the fresh to slightly saline zone and corresponding sand thickness, but no formational contacts.

In western Jim Hogg and southeastern Webb Counties, water is obtained from the sands of the Catahoula Tuff. The major wells in northeastern Starr and southeastern Jim Hogg Counties and the wells more than 1,000 feet deep in southeastern Duval County tap the sands of the Oakville Sandstone. Sands of the Goliad, Willis, and Lissie yield water to most of the wells in Brooks, Kenedy, Willacy, and northern Hidalgo Counties. Sands in the Beaumont Clay and Recent sediments are the principal aquifers along the Rio Grande in Hidalgo and Cameron Counties.

The average coefficient of transmissibility of the fresh to slightly saline water sands in the Catahoula, Oakville, and Lagarto in subregion V is about 5,000 gpd per ft., although it may be as much as 2 or 3 times greater locally. The average specific capacity of wells tapping that aquifer probably is less than 2 gpm per foot of drawdown and the average yield generally is less than 300 gpm.

The coefficient of transmissibility of the fresh to slightly saline water sands in the Goliad, Willis, and Lissie ranges from less than 5,000 to as much as 40,000 gpd per ft., the larger coefficients being measured in Hidalgo and Cameron Counties. The specific capacities of major wells tapping the Goliad, Willis, and Lissie in the subregion range from less than 5 to 20 gpm per foot of drawdown. The average discharge is about 300 gpm although some major wells yield 1,000 gpm, or more.

The alluvium in the Rio Grande Valley in Cameron and Hidalgo Counties has a coefficient of transmissibility ranging from 5,000 to 70,000 gpd per ft. The range is great because of the extreme heterogeneity of the deposits constituting the alluvium. The specific capacities of wells tapping the alluvium range from less than 5 to 35 gpm per foot of drawdown. The average discharge of major wells probably is less than 500 gpm; however, discharges have been measured in excess of 2,500 gpm.

Chemical Quality

The chemical quality of the ground water of subregion V varies from fresh to saline; however, this discussion will be limited to the general trends and characteristics of the water in the fresh to slightly saline zone. Most of the water within this zone is slightly saline; it is predominately slightly alkaline, having high sulfate, chloride, and sodium contents. Ground waters in the southern half of the subregion generally have a higher sulfate content than the waters in the northern half. Nitrate content ranges from 0 to more than 50 ppm. The hardness is variable, in most places decreasing with depth in the fresh to slightly saline zone. The dissolved-solids content increases with depth except in areas where saline water overlies fresh water. In these areas the dissolved-solids content decreases with depth before increasing again as the base of the fresh to slightly saline water is approached.

Industry can readily use water of the quality which is predominant for cooling and washing. However, the slight salinity of most of the water precludes its use in boilers and in some refined products without first being treated. The U. S. Public Health Service (1946, p. 383) does not advise the use of slightly saline water for human consumption, but it is the best quality water available in many areas and the water is consumed by residents with no apparent ill effects. Some ground waters have a nitrate content higher than 44 ppm. Such waters may be harmful to infants (Maxcy, 1950, p. 271).

Most of the water in the fresh to slightly saline zone is slightly saline and is, therefore, either marginal or unsuited for irrigation. The constant use of slightly saline water may cause high salinity in the soil which would cause damage to crops and possibly harm the soil. However, under proper irrigation management and on favorable soil, some slightly saline water can be used for irrigation.

Of more significance to the irrigator is the sodium-adsorption-ratio (SAR) of his irrigation water. Water having a high SAR may cause serious soil damage because most of the dissolved sodium of the water has the potential for entering the soil structure by base exchange; the soil then becomes less permeable and less tillable. Adding calcium to the soil (for example, by spreading gypsum) may alleviate the damage done to a soil irrigated with water having a high SAR.

The sodium-adsorption-ratios range from 1.3 to more than 50. Water from the lower part of the fresh to slightly saline zone generally has a high SAR (see analyses 7 to 9, Table 11), making it undesirable for irrigation. The same waters may also have a high boron content.

In summary, much of the ground water of subregion V is unsuitable for irrigation because of high salinity hazard, high SAR, and high boron content. Most of the water used for irrigation in 1959 in northeastern Brooks County, north-central and southern Hidalgo County, southwestern Willacy County, and western Cameron County is marginal. The ground water of best quality in the subregion occurs along the Rio Grande in southeastern Hidalgo County (analysis 14, Table 11). Periodic treatment of the soil with gypsum and correct irrigation practices will prevent soil or crop damage by these marginal waters. Where more mineralized waters are used for irrigation, the soil or crop probably will be damaged to some extent.

The chemical analyses given in Table 11 were chosen from hundreds of analyses to be representative of water of subregion V. Analysis 1 is representative of the composition of water from the lower part of the fresh to slightly saline zone in Jim Hogg County, the water coming from sands in the Catahoula Tuff. Analysis 4 shows the composition of water from the Oakville Sandstone in northeastern Starr County. The water is slightly alkaline, slightly saline, and moderately hard. During the past 10 to 20 years, it has been used by industry in the area as a coolant in industrial processes. It is used also for irrigation and domestic purposes, but the amount pumped for such purposes is small.

Analyses 2, 3, and 5 through 10 are representative of the variable composition of water from the aquifer sands of the Goliad, Willis, and Lissie in the subregion. Analyses 2 and 3 are representative of the quality of ground water in Jim Hogg County in the upper part of the fresh to slightly saline zone. The ground water commonly found in the northern half of the subregion has a high nitrate content as shown by analyses 2, 3, and 6. Although analysis 5 is of water from a public-supply well, it is also typical of the water used for irrigation in northeastern Brooks County. Waters represented by analyses 7 and 8 are used for irrigation in north-central Hidalgo County. Analysis 9 is of water from a public-supply well in Willacy County; the sulfate and chloride content and the amount of dissolved solids greatly exceed the limits recommended by

Table 11.--Analyses of water from wells in subregion V

(Results are in parts per million except specific conductance, pH, and SAR.)
Water-bearing unit: A, Alluvium; B, Beaumont Clay; C, Catahoula Tuff; G, Goliad Sand; L, Lissie Formation; O, Oakville Sandstone; W, Willis Sand.

Analysis No.	Location of Well	Screened interval (ft.)	Water-bearing unit	Silica (SiO_2)	Iron (Fe) (Total)	Manganese (Mn)	Calcium (Ca)	Magnesium (Mg)	Sodium and potassium (Na + K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Boron (B)	Dissolved solids	Hardness as $CaCO_3$	Sodium adsorption ratio (SAR)	Specific conductance (micromhos at 25°C)	pH
1	Hebbronville, Jim Hogg County	?-980	C	38	1/ 0.17	--	18	3.7	342 12	198	131	361	0.4	12	--	1,020	60	19	1,740	7.7
2	6 mi. S Hebbronville, Jim Hogg County	104-125	G(?)	36	--	--	163	48	274	183	82	648	--	62	--	1,400	604	4.8	2,460	7.0
3	31 mi. S Hebbronville, Jim Hogg County	260-275	G(?)	28	--	--	104	27	347	263	118	538	1.8	28	0.95	1,320	370	7.8	2,240	7.2
4	Starr County, 31 mi. NW Edinburg, Hidalgo County	?-911	O	18	--	--	30	8.8	458	250	214	480	--	1.5	--	1,330	111	19	2,310	7.8
5	Falfurrias, Brooks County	675-705	G	30	1/ .02	0.00	35	15	169 8.6	285	43	172	.6	.0	.58	614	148	6.0	1,060	8.1
6	19 mi. S Falfurrias, Brooks County	385-400	G	31	--	--	58	20	249	283	97	288	.3	35	.55	918	226	7.2	1,550	7.1
7	23 mi. N Edinburg, Hidalgo County	1,400-2,050	G,W,L	40	--	--	4.0	1.7	494	518	220	310	--	1.5	6.6	1,330	17	52	2,160	--
8	15 mi. N Edinburg, Hidalgo County	915-935	G,W,L	28	--	--	7.8	2.4	437	290	217	365	--	1.0	4.1	1,210	30	35	2,030	--
9	21 mi. N Harlingen, Cameron County	* 850-1,054	G,W,L	16	1/ .01	--	26	8.4	771 4.3	166	830	570	2.4	.0	5.8	2,320	100	33	3,650	7.9
10	8 mi. W McAllen, Hidalgo County	290-412	G(?)	20	1/ .00	--	66	36	545 15	322	275	685	.9	5.9	2.8	1,810	312	14	3,130	7.7
11	20 mi. E McAllen, Hidalgo County	* 230-338	B(?), L(?)	30	.06	--	49	24	364 4.9	376	347	242	1.8	1.0	1.5	1,250	221	11	2,030	7.8
12	4 mi. SW Harlingen, Cameron County	150-166	A	45	1/ .00	--	80	28	238 5.5	425	261	155	.8	2.5	.65	1,030	314	5.8	1,600	7.6
13	Brownsville, Cameron County	182-197	A	36	1/ .05	--	34	25	546 5.1	588	471	295	1.8	.0	1.5	1,700	188	17	2,700	7.8
14	18 mi. SE McAllen, Hidalgo County	?-180	A	--	--	--	104	36	152	449	188	124	--	.0	--	872	408	3.3	--	--
15	14 mi. N Edinburg, Hidalgo County	?-80	B(?), L(?)	88	--	--	23	25	198	251	58	222	--	15	1.1	779	160	6.8	1,260	--

* Not screened throughout interval.
1/ Iron in solution at time of analysis.

the U. S. Public Health Service; however, this is the best available ground water in this area. Most of the water obtained from aquifer sands in the Goliad, Willis, and Lissie underlying Kenedy, Willacy, and Cameron Counties and the eastern part of Hidalgo County is of similar quality to that shown in analysis 9.

Analyses 10 through 15 illustrate the range of composition of water in Hidalgo and Cameron Counties. Analyses 10 through 13 are of water from public-supply wells, although nearby wells pump water from the same aquifers for irrigation. Analyses 14 and 15 are of water from irrigation wells. Most of the ground water used in this area is slightly saline and even some moderately saline waters are used for irrigation.

The waters of the nearby Rio Grande are generally of better quality than the ground water underlying Hidalgo and Cameron Counties; thus, when possible, waters of the Rio Grande are used for public supply. Most of the public-supply wells in this area are "stand-by" wells, an emergency source of water. Much water from the Rio Grande is used also for irrigation but the demand for irrigation water cannot be entirely satisfied with surface water. Therefore, the irrigation wells are used in two ways: (1)they pump ground water for use on the immediately adjacent land, and (2)they pump ground water into one of the extensive canal systems which carry water from the Rio Grande to increase the amount of water available for irrigation to canal users.

Utilization

Ground water has long been important in the coastal part of the Rio Grande Basin and adjacent coastal areas as the only dependable source of supply, the only perennial river being the Rio Grande. Before and during the recent drought which ended in 1957, the waters of the Rio Grande were insufficient to fulfill the many demands; therefore, many wells were drilled to obtain supplementary water. Most of the wells are still being used to extend the surface-water supplies, although the supply of water from the Rio Grande has been much larger and more dependable since the completion in 1954 of Falcon Reservoir, 60 miles west-northwest of McAllen. Most of the water used for irrigation and public supply is obtained from surface-water sources.

No large springs are known, but there are many flowing wells, most of which are controlled by valves or other means of restricting the flow. Kenedy County has the largest number of flowing wells; the largest reported flow is 75 gpm from a controlled well in Kenedy County.

Most of the livestock and much of the rural population are dependent on windmill or flowing wells for water in subregion V and about 4 mgd was pumped in 1959 for livestock and rural domestic use. Part of the water so used is probably moderately saline.

About 120 mgd of ground water was pumped in 1959, 1.5 mgd being for industrial uses, 5.7 mgd for public supply, and 110 mgd for irrigation. The estimated pumpage for 1959 is given in Table 12. There were 58 public-supply wells, 39 industrial wells, and approximately 1,500 irrigation wells in 1959, although not all were pumped in 1959.

Table 12.--Ground-water pumpage in major subdivisions of subregion V, 1959

Major subdivisions	Public supply		Industrial		Irrigation		Total*	
	mgd	acre-ft./yr.	mgd	acre-ft./yr.	mgd	acre-ft./yr.	mgd	acre-ft./yr.
Nueces-Rio Grande undivided coastal area NU-RG-U-1	1.2	1,344	0.74	829	29.0	32,000	31	34,000
Nueces-Rio Grande undivided coastal area NU-RG-U-2 and Rio Grande Basin RG-63	4.5	5,041	.78	874	85.0	95,000	90	100,000
Subtotal, major wells	5.7	6,400	1.5	1,700	110	130,000	120	140,000
Domestic, livestock, and miscellaneous wells							4	4,400
Total							120	140,000

* Figures are approximate because some of the pumpage rates are estimated. Irrigation figures are shown to not more than two significant figures. Public supply and industrial and other pumpage figures are shown to nearest 0.01 mgd and to nearest acre-foot. Totals are rounded to two significant figures.

The main areas of irrigation are in the northeast part of Brooks County, the north-central and southern half of Hidalgo County, the southwestern part of Willacy County, and western Cameron County. As mentioned above, more ground water is pumped for irrigation than for all other uses combined. The pumpage for irrigation is very difficult to determine as the need for irrigation with ground water varies according to the rainfall, type of crop, and availability of surface water. The estimated pumpage figures shown in Table 12 were determined from an evaluation of the number of acres irrigated (Keese, 1959), estimated water requirements of irrigated crops, and estimated rainfall.

Changes in Water Levels

Water levels have changed little where the ground water has been only slightly developed, but appreciably in a few areas. According to water-level measurements made during the last 10 to 25 years, declines have been substantial in the following areas: (1)northeastern Brooks, southwestern Jim Wells, and southeastern Duval Counties, and (2)in north-central Hidalgo County. Although comparative water-level measurements are not available, declines may have been sizeable also in northeastern Starr County. Comparative water-level measurements in wells in the southwestern part of Cameron County show that water levels declined during the drought years 1945-57 and have since returned to or are above their former levels, and drainage problems have been created in some areas. Ground-water conditions and development in southern Hidalgo County are similar to those in southwestern Cameron County and water-level changes there probably have been similar.

In the northeastern Brooks-southwestern Jim Wells-southeastern Duval County area, water levels generally have declined many feet. Comparisons of water-level measurements made in 1932-33 with 1960 measurements show a maximum decline of 65 feet in the vicinity of Falfurrias, Brooks County. The decline diminishes to the south, southwest, and west. The rate of decline seems to have slowed since 1953 although the water levels are still declining somewhat.

In the area of intensive irrigation about 15 miles north of Edinburg, Hidalgo County, water levels have declined 10 to 20 feet in wells less than 260 feet deep during the approximate period 1950-60. Water levels in the few deeper wells in the same area apparently have not declined appreciably.

Problems

Subregion V has not been as well endowed with ground water as the other subregions. Fresh to slightly saline water may be found at great depths, but the total thickness of sands in the aquifers is small in comparison with that in the other subregions. Water of desirable quality, such as water containing less than 1,000 ppm dissolved-solids content for public supply, is difficult or impossible to obtain from ground-water sources in many areas. Even so, ground water must be conserved and protected. Man's conversion of saline water to fresh water is still too costly to compete with naturally converted water. The fresh to slightly saline zone must be protected from contaminating fluids, the introduction of which may occur during oil and gas exploration and subsequent activities or during the disposal of wastes either on the surface or through injection wells. Conservation of artesian pressure should be encouraged by publicizing the most efficient methods of using water. A lessening of artesian pressure causes a decline of water levels and a corresponding increase in pumping costs, enhances the possibility of updip salt-water invasion, and may permit the entry of overlying saline waters into the fresh to slightly saline zone through the corroded casings of old wells or improperly constructed wells.

In part of the irrigation area of southern Hidalgo County and western Cameron County, the water table is so close to the land surface that the land cannot be worked; some lands will be "drowned" if corrective measures are not applied. This water-logging has resulted from clearing the land of phreatophytes and applying surface waters for irrigation.

Soil and crop damage is a constant threat when ground water of the quality found in most of the fresh to slightly saline zone is used for irrigation. In some places, adding gypsum to the irrigation water or applying it directly to the soil should prevent destruction of favorable soil structure by the sodium content of the water. Proper water management will lessen the chance of crop damage from waters having a high salinity hazard or containing injurious concentrations of harmful elements such as boron.

Additional detailed ground-water studies are needed in subregion V particularly to define the extent and quality of the ground-water body in the Lower Rio Grande Valley and to determine the interrelation between ground water and water in the Rio Grande.

AVAILABILITY OF GROUND WATER

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

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

The maps depicting the transmissibility of the aquifer and the thickness of the water-bearing sands (Figure 13 and Plates 3, 6, 9, 12, and 15) were used with the following assumptions to estimate the relative ground-water availability:

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

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

3. For computation of water available from storage:

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

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

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

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

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

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

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

   d. All the sands between the line source of recharge and the line of discharge transmit water from the outcrop area to the line of discharge. The assumed average coefficient of transmissibility of these sands in each subregion is shown in Table 13.

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

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

Table 13.--Comparative estimates of the availability of ground water in the Gulf Coast region

Subregion	Estimated fresh to slightly saline water in storage (million acre-ft.)		Assumed coefficient of trans-missibility (gpd/ft.)	Trans-mission capacity at average gradient (acre-ft./yr.)	Trans-mission capacity at maximum gradient (acre-ft./yr.)	Rates of withdrawal		Time, in years, to lower water levels along line of dis-charge to 400 feet below land surface			Recharge [1] (inches)	
	Per linear mile of aquifer	Total				mgd	acre-ft./yr.	With no recharge at average gradient	With recharge equal to trans-mission capacity at average gradient	With recharge equal to trans-mission capacity at maximum gradient	At average gradient	At maximum gradient
I	0.37	30.2	100,000	137,000	235,000	71 [2] 500	80,000 [2] 560,000	380 50	[3] 70	[3] 90	1.1	1.9
II	.42	26.7	150,000	129,000	217,000	350 [2] 500	390,000 [2] 560,000	70 50	100 60	150 80	1.3	2.1
III	.40	36.1	125,000	190,000	330,000	240 [2] 500	270,000 [2] 560,000	130 60	450 100	[3] 150	1.6	2.7
IV A [4]	.24	15.3 [5]	25,000	43,000	73,000	16 [2] 50	18,000 [2] 56,000	850 270	[3] 1,170	[3] [3]	.5	1.0
IV B [6]	.13	7.6 [5]	7,000	7,400	9,900	20 [2] 50	22,000 [2] 56,000	340 130	520 150	620 160	.04	.05
V [7]	.12	10.1 [5]	7,000	8,000	13,000	54 [2] 75	60,000 [2] 84,000	170 120	190 130	210 140	.04	.07

[1] Recharge equal to transmission capacity.

[2] Estimated 1959 rate of withdrawal.

[3] Average transmission capacity is greater than withdrawal.

[4] Subregion IV northeast of Nueces Basin.

[5] Allowance made for overlying salty ground water.

[6] Subregion IV southwest of northeast boundary of Nueces Basin.

[7] Exclusive of alluvium in Lower Rio Grande Valley.

For purposes of computation, different rates of withdrawal include (1)the present rate of withdrawal (Table 14) and (2)rates arbitrarily chosen based on reasonable estimates of potential development. These rates of withdrawal, the amount of water in transient storage, and the average transmission capacity were used to determine the time required to meet the above assumptions. Only the amount of water in transient storage was used in computing the time required to meet the condition of no recharge. Results of the calculations are presented in Table 13 with the warning that the figures can be changed by a factor of several times by a small change in any one of several of the above assumptions. Limited basic data analyzed on a regional basis under assumed development conditions provide a preliminary estimate of potential water available. Thus, these preliminary estimates, which are especially suited for comparative purposes, will need to be revised and kept current as development takes place and more data become available.

Subregions I, II, and III, the parts of the region northeast of the Guadalupe River, contain more fresh to slightly saline water per mile of outcrop in transient storage than do subregions IV and V, the parts southwest of the Guadalupe River. Also, northeast of the Guadalupe River, the aquifer is capable of transmitting more water, as shown by the higher transmission capacities. In the northeast where precipitation is greater and evaporation is less than in the southwest, precipitation is probably sufficient to overcome losses of evapotranspiration and still maintain adequate recharge under the conditions imposed. Recharge may be adequate to maintain water levels in the outcrop even southwest of the Guadalupe because the amount of recharge necessary to equal the transmission capacity is so small.

In a large part of subregions IV and V, salt-water sands overlie fresh to slightly saline water sands (Plates 11 and 14). The estimate of total water in storage above the base of the fresh to slightly saline water zone was decreased by 65 percent in subregion IV and 75 percent in subregion V and presented as an estimate of the amount of fresh to slightly saline water in transient storage.

The most favorable area for availability of ground water is northeast of the Guadalupe River, and the areas of most concentrated withdrawal lie within the area of greatest availability. Although water levels have declined significantly in the Houston area, the Gulf Coast region as a whole could support additional ground-water withdrawals of the same magnitude. The problems that would be encountered with more intensive development in the next 50 years are those of salt-water invasion and land-surface subsidence rather than excessive depth of pumping levels.

The amounts of water listed as available in Table 13 are conservative because the assumptions ignore water contributed by compaction of the fine-grained materials and by recharge and vertical movement of water throughout the cone of depression--that is, water is derived not only from the line source in the center of the outcrop. In the Houston area (subregion II), for example, the principal sources of water pumped to date appear to be from storage, from compaction, and from local recharge rather than being transmitted from the outcrop of the Lissie Formation and the Willis Sand.

Another factor that would increase the water available is the distribution of withdrawals throughout the subregion instead of along a line of discharge as

Table 14.--Summary of ground-water pumpage in the Gulf Coast region, 1959

Sub-region	Public supply		Industrial		Irrigation		Miscellaneous		Total*	
	mgd	acre-ft./yr.	mgd	acre-ft./yr.	mgd	acre-ft./yr.	mgd	acre-ft./yr.	mgd	acre-ft./yr.
I	4.9	5,500	38	43,000	20	23,000	7	7,800	71	80,000
II	120	140,000	110	130,000	100	120,000	10	11,000	350	390,000
III	12	14,000	23	25,000	190	220,000	8	9,000	240	270,000
IV	13	15,000	7.3	8,200	9.3	10,000	5.4	6,000	36	40,000
V	5.7	6,400	1.5	1,700	110	130,000	4	4,400	120	140,000
Total*	160	180,000	180	210,000	430	500,000	34	38,000	820	920,000

* Totals are approximate because most figures in the table have been rounded to two significant figures and totals are further rounded to two significant figures.

assumed. By moving wells closer to the outcrop, steeper gradients could be established that would increase the flow of water through the aquifer.

A factor which might be overlooked in a cursory examination of Table 13 is the extremely large quantity of water in storage. For example, the table shows that about 36 million acre-feet of fresh to slightly saline water is in storage in subregion III. It also shows that it would take 60 years of pumping 500 mgd in subregion III (about twice the 1959 rate of pumping) to lower the water levels along the line of discharge to 400 feet. This is based on the assumption of no recharge--that is, all of the water is being taken from storage.

Continuing study as development continues plus the utilization of new techniques, such as the analog model of the aquifer in the Houston district under construction in 1962, will aid in the calculation of more reliable estimates than those presented in Table 13.

SELECTED BIBLIOGRAPHY

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

Alexander, W. H., Jr., 1947, Ground-water resources of San Jacinto County, Texas: Texas Board Water Engineers duplicated rept., 29 p., 3 figs.

Alexander, W. H., Jr., and Breeding, S. D., 1950, Ground-water resources of Liberty County, Texas: U. S. Geol. Survey Water-Supply Paper 1079-A, 61 p., 4 figs., 1 pl.

American Society for Testing Materials, 1959, Manual on industrial water and industrial waste water: Am. Soc. for Testing Materials Spec. Tech. Pub. 148-D, 2nd Ed., with new and revised methods--1959 [1960], 653 p.

Anders, R. B., 1960, Ground-water geology of Karnes County, Texas: Texas Board Water Engineers Bull. 6007, 92 p., 16 figs., 4 pls.

_______1961, Ground-water geology of Live Oak County, Texas: Texas Board Water Engineers Bull. 6105, 119 p., 7 figs., 5 pls.

Austin, A. M., 1959, Occurrence of ground water in the Palangana brine field, Duval County, Texas: Texas Board Water Engineers duplicated rept., 8 p., 2 pls.

Baker, R. C., and Dale, O. C., 1961, Ground-water resources of the Lower Rio Grande Valley area, Texas: Texas Board Water Engineers Bull. 6014, v. I, 81 p., v. II, 336 p., 10 figs., 14 pls.

Barnes, B. A., 1940a, Memorandum on the public water supply of Alice, Jim Wells County, Texas: U. S. Geol. Survey open-file rept., 5 p., 3 figs.

_______1940b, Memorandum on the public water supply of Premont, Jim Wells County, Texas: U. S. Geol. Survey open-file rept., 2 p., 1 fig., 1 pl.

_______1940c, Memorandum on the public water supply of Falfurrias, Brooks County, Texas: U. S. Geol. Survey open-file rept., 3 p., 1 fig., 1 pl.

_______1941a, Records of wells and springs, drillers' logs, water analyses, and map showing location of wells and springs in Galveston County, Texas: Texas Board Water Engineers duplicated rept., 155 p., 2 figs.

_______1941b, Water supply in the vicinity of Texas City, Texas: U. S. Geol. Survey open-file rept., 4 p.

_______1941c, Ground-water investigation in the vicinity of Galveston, Texas, with special reference to salt-water intrusion: U. S. Geol. Survey open-file rept., 11 p.

_______1943, Results of test drilling by city of Galveston and conclusions: U. S. Geol. Survey open-file rept., 33 p., 3 figs., 1 pl.

Barnes, B. A., 1948, Ground-water resources of Wharton County, Texas: Texas Board Water Engineers duplicated rept., 80 p., 1 fig., 3 pls.

Bloodgood, D. W., Patterson, R. E., and Smith, R. L., Jr., 1954, Water evaporation studies in Texas: Texas Agr. Expt. Sta. Bull. 787, 83 p.

Broadhurst, W. L., 1941, A few notes regarding ground water in Brownsville-San Benito-La Feria district, Texas: U. S. Geol. Survey open-file rept., 6 p., 1 pl.

_______1951, Ground water in Texas for irrigation: U. S. Geol. Survey open-file rept., 5 p.

_______1953, Coastal Plain near Houston, Texas, in The physical and economic foundation of natural resources, v. IV, subsurface facilities of water management and patterns of supply-type area studies: U. S. Cong., House of Representatives, Committee on Interior and Insular Affairs, p. 51-78.

Broadhurst, W. L., Sundstrom, R. W., and Rowley, J. H., 1950, Public water supplies in southern Texas: U. S. Geol. Survey Water-Supply Paper 1070, 113 p., 1 pl.

Cromack, G. H., 1940, Records of wells and springs, drillers' logs, water analyses, and map showing location of wells and springs in Wharton County, Texas: Texas Board Water Engineers duplicated rept., 52 p., 1 fig.

_______1942a, Records of wells and springs, drillers' logs, water analyses, and map showing location of wells and springs in Hardin County, Texas: Texas Board Water Engineers duplicated rept., 35 p., 1 fig.

_______1942b, Records of wells and springs, drillers' logs, water analyses, and map showing location of wells and springs in Jasper and Newton Counties, Texas: Texas Board Water Engineers duplicated rept., 50 p., 1 fig.

_______1945, Water wells in the Linn district, Hidalgo County, Texas: U. S. Geol. Survey open-file rept., 7 p., 1 fig.

Cumley, J. C., 1940a, Ground water in Jim Hogg County, Texas (northern part): Texas Board Water Engineers duplicated rept., 15 p., 1 fig.

_______1940b, Ground water in Victoria County, Texas: Texas Board Water Engineers duplicated rept., 33 p., 1 fig.

Dale, O. C., 1952, Ground-water resources of Starr County, Texas: Texas Board Water Engineers Bull. 5209, 47 p., 1 fig.

Dale, O. C., and George, W. O., 1954, Ground-water resources of Cameron County, Texas: Texas Board Water Engineers Bull. 5403, 63 p., 1 fig.

Dale, O. C., Moulder, E. A., and Arnow, Ted, 1957, Ground-water resources of Goliad County, Texas: Texas Board Water Engineers Bull. 5711, 85 p., 8 figs., 3 pls.

Darton, N. H., Stephenson, L. W., and Gardner, Julia [compilers], 1937, Geologic Map of Texas: Dept. Interior, U. S. Geol. Survey.

Davis, L. G., 1942, Records of wells and springs, drillers' logs, water analyses, and map showing location of wells and springs in Chambers County, Texas: Texas Board Water Engineers duplicated rept., 94 p., 2 figs.

Dean, H. T., Dixon, R. M., and Cohen, Chester, 1935, Mottled enamel in Texas: U. S. Public Health Service Public Health Repts., v. 50, p. 424-442.

Deussen, Alexander, 1914, Geology and underground waters of the southeastern part of the Texas Coastal Plain: U. S. Geol. Survey Water-Supply Paper 335, 66 p., 22 pls.

Doering, John, 1935, Post-Fleming surface formations of coastal southeast Texas and south Louisiana: Am. Assoc. Petroleum Geologists Bull., v. 19, no. 5, p. 651-688.

______1956, Quaternary surface, Gulf Coast: Am. Assoc. Petroleum Geologists Bull., v. 40, no. 8, p. 1816-1862.

Doyel, W. W., 1956, Basic data and summary of ground-water resources of Chambers County, Texas: Texas Board Water Engineers Bull. 5605, 78 p., 9 figs., 1 pl.

Doyel, W. W., Winslow, A. G., and Naftel, W. L., 1954, Pumpage of ground water and decline of artesian pressure in the Houston district, Texas: Texas Board Water Engineers Bull. 5401, 7 p., 21 figs.

Elledge, G. A., 1937, Records of wells and springs, drillers' logs, water analyses, and map showing location of wells and springs in Fort Bend County, Texas (west of the Brazos River): Texas Board Water Engineers duplicated rept., 47 p., 5 pls.

Fenneman, N. M., 1938, Physiography of the eastern United States: New York, McGraw-Hill Book Co., 714 p., 197 figs., 7 pls.

Fluellen, T. R., and Goines, W. H., 1952, Water resources of Waller County, Texas: Texas Board Water Engineers Bull. 5208, 49 p., 8 figs.

Follett, C. R., 1943, Records of wells and springs, drillers' logs, water analyses, and map showing location of wells and springs in Washington County, Texas: Texas Board Water Engineers duplicated rept., 45 p., 1 fig.

______1947, Ground-water resources of Brazoria County, Texas: Texas Board Water Engineers duplicated rept., 101 p., 1 fig.

Follett, C. R., and Cumley, J. C., 1942, Records of wells and springs, drillers' logs, water analyses, and map showing location of wells and springs in Jackson County, Texas: Texas Board Water Engineers duplicated rept., 49 p., 1 fig.

Follett, C. R., White, W. N., and Irelan, Burdge, 1949, Occurrence and development of ground water in the Linn-Faysville area, Hidalgo County, Texas: Texas Board Water Engineers duplicated rept., 50 p., 1 fig.

Foster, M. D., 1939, Ground waters of the Houston-Galveston area; chemical character and industrial utility: Indus. and Eng. Chem., v. 31, p. 1028, August.

George, W. O., 1936, Records of wells, drillers' logs, water analyses, and map showing location of wells in Lavaca County, Texas: Texas Board Water Engineers duplicated rept., 61 p., 1 fig.

______1939, Records of wells and springs, drillers' logs, water analyses, and map showing location of wells and springs in San Patricio County, Texas: Texas Board Water Engineers duplicated rept., 62 p., 2 figs.

______1947, Ground water in the Linn district, north-central Hidalgo County, Texas: U. S. Geol. Survey open-file rept., 6 p., 1 pl.

George, W. O., and Turner, S. F., 1938, Memorandum on the ground-water resources of Seadrift, Texas: U. S. Geol. Survey open-file rept., 5 p.

Goines, W. H., Winslow, A. G., and Barnes, J. R., 1951, Water supply of the Houston Gulf Coast region: Texas Board Water Engineers Bull. 5101, 16 p., 23 figs.

Guyton, W. F., 1941, Application of coefficients of transmissibility and storage to regional problems in the Houston district, Texas: Am. Geophys. Union Trans., p. 756-770.

Guyton, W. F., and Rose, N. A., 1945, Quantitative studies of some artesian aquifers in Texas: Econ. Geology, v. 40, no. 3, p. 193-226, May.

Hayes, C. W., and Kennedy, William, 1903, Oil fields of the Texas-Louisiana Gulf Coastal Plain: U. S. Geol. Survey Bull. 212, 174 p., 11 pls.

Heuser, J. F., 1937, Records of wells and springs, drillers' logs, water analyses, and map showing location of wells and springs west of the Brazos River, Brazoria County, Texas: Texas Board Water Engineers duplicated rept., 41 p., 4 figs.

Jacob, C. E., 1940, Summary of results of recovery and interference tests: U. S. Geol. Survey open-file rept., 13 p., 1 fig.

______1941, Coefficients of storage and transmissibility obtained from pumping tests in the Houston district, Texas: Am. Geophys. Union Trans., p. 744-756.

Johnson, C. E., 1940, Records of wells and springs, drillers' logs, water analyses, and map showing location of wells and springs in Aransas County, Texas: Texas Board Water Engineers duplicated rept., 45 p., 2 figs.

Keese, C. W., 1959, Extension Service County Agent Work, Irrigation Survey, Cooperative Extension Work in Agriculture and Home Economics: Agricultural and Mechanical College of Texas and the U. S. Dept. of Agri. cooperating, duplicated rept., 16 p.

King, P. B., 1951, The tectonics of middle North America: Princeton Univ. Press, Princeton, New Jersey, p. 169-182.

King, P. B., 1959, The evolution of North America: Princeton Univ. Press, Princeton, New Jersey, p. 76-82.

Lang, J. W., 1949a, Geology and ground-water resources of the Houston-Galveston area, Texas: U. S. Geol. Survey open-file rept., 6 p., 6 figs.

_______1949b, Ground-water conditions in the vicinity of the South Houston oil field and need for protecting fresh-water sands from contamination: U. S. Geol. Survey open-file rept., 6 p., 1 pl.

Lang, J. W., and Sundstrom, R. W., 1946, Results of pumping tests at new Southwest plant, Houston, Texas: U. S. Geol. Survey open-file rept., 14 p., 1 fig.

Lang, J. W., Winslow, A. G., and White, W. N., 1950, Geology and ground-water resources of the Houston district, Texas: Texas Board Water Engineers Bull. 5001, 37 p., 15 figs., 3 pls.

Livingston, Penn, 1939, Records of wells and springs, drillers' logs, water analyses, and map showing location of wells and springs in Montgomery County, Texas: Texas Board Water Engineers duplicated rept., 13 p., 1 fig.

_______1941, Ground water in the vicinity of Sabine Pass, Texas: U. S. Geol. Survey open-file rept., 4 p.

Livingston, Penn, and Bridges, T. W., 1936, Ground-water resources of Kleberg County, Texas: U. S. Geol. Survey Water-Supply Paper 773-D, 35 p., 5 pls.

Livingston, Penn, and Broadhurst, W. L., 1942, Exploration of salty wells on the King Ranch, Kleberg County, Texas: U. S. Geol. Survey open-file rept., 10 p.

Livingston, Penn, and Cromack, G. H., 1942a, Records of wells and springs, drillers' logs, water analyses, and map showing location of wells and springs in Jefferson County, Texas: Texas Board Water Engineers duplicated rept., 64 p., 2 figs.

_______1942b, Records of wells and springs, drillers' logs, water analyses, and map showing location of wells and springs in Orange County, Texas: Texas Board Water Engineers duplicated rept., 42 p., 1 fig.

Livingston, Penn, and Turner, S. F., 1939a, Records of wells and springs, drillers' logs, water analyses, and map showing location of wells and springs in Fort Bend County, Texas (east of the Brazos River): Texas Board Water Engineers duplicated rept., 11 p., 1 fig.

_______1939b, Records of wells and springs, drillers' logs, water analyses, and map showing location of wells and springs in Galveston County, Texas: Texas Board Water Engineers duplicated rept., 27 p., 1 fig.

_______1939c, Records of wells and springs, drillers' logs, water analyses, and map showing location of wells and springs in Harris County, Texas: Texas Board Water Engineers duplicated rept., 97 p., 2 figs.

Lohr, E. W., and others, 1952, The industrial utility of public-water supplies in the United States, Pt. 2, States west of the Mississippi River: U. S. Geol. Survey Water-Supply Paper 1300, 462 p., 3 figs., 5 pls.

Lonsdale, J. T., and Day, J. R., 1933, Ground-water resources of Webb County, Texas: U. S. Geol. Survey Water-Supply Paper 778, 104 p., 12 pls.

Lonsdale, J. T., and Johnson, C. E., 1941, Records of wells and springs, drillers' logs, water analyses, and map showing location of wells and springs in Calhoun County, Texas: Texas Board Water Engineers duplicated rept., 67 p., 1 fig.

Lonsdale, J. T., and Nye, S. S., 1941, Records of wells and springs, drillers' logs, water analyses, and map showing location of wells and springs in Hidalgo County, Texas: Texas Board Water Engineers duplicated rept., 102 p., 1 fig.

Lynch, W. A., 1934, Records of wells and springs, drillers' logs, water analyses, and map showing location of wells and springs in Nueces County, Texas: Texas Board Water Engineers duplicated rept., 12 p., 1 fig.

Lynch, W. A., and Frazier, J. M., Jr., 1941, Records of wells and springs, drillers' logs, water analyses, and map showing location of wells and springs in Bee County, Texas: Texas Board Water Engineers duplicated rept., 30 p., 1 fig.

Mapp, H. M., 1938, Records of wells, drillers' logs, water analyses, and map showing location of wells in DeWitt County, Texas: Texas Board Water Engineers duplicated rept., 43 p., 1 fig.

Marvin, R. F., Shafer, G. H., and Dale, O. C., 1960, Ground-water resources of Victoria and Calhoun Counties, Texas: U. S. Geol. Survey open-file rept., 195 p., 18 figs.

Maxcy, D. F., 1950, Report on the relation of nitrate concentration in well waters to the occurrence of methemoglobinemia in infants: Natl. Research Council Bull. Sanitary Engineering and Environment, p. 265-271, App. D.

May, R. E., 1938a, Records of wells and springs, drillers' logs, water analyses, and map showing location of wells and springs in Austin County, Texas: Texas Board Water Engineers duplicated rept., 36 p., 1 fig.

_______1938b, Records of wells and springs, drillers' logs, water analyses, and map showing location of wells and springs in Colorado County, Texas: Texas Board Water Engineers duplicated rept., 24 p., 1 fig.

Meinzer, O. E., 1923a, The occurrence of ground water in the United States, with a discussion of principles: U. S. Geol. Survey Water-Supply Paper 489, 321 p., 31 pls.

_______1923b, Outline of ground-water hydrology, with definitions: U. S. Geol. Survey Water-Supply Paper 494, 71 p.

Meinzer, O. E., and others, 1942, Physics of the earth, v. 9, Hydrology: New York, McGraw-Hill Book Co., p. 385-478.

Muenster, R. A., and Michal, E. J., 1938, Records of wells and springs, drillers' logs, water analyses, and map showing location of wells and springs in Refugio County and part of Goliad County, Texas: Texas Board Water Engineers duplicated rept., 88 p., 4 figs.

Petitt, B. M., Jr., and Winslow, A. G., 1955, Geology and ground-water resources of Galveston County, Texas: Texas Board Water Engineers Bull. 5502, 184 p., 33 figs., 13 pls.

Piper, A. M., 1953, The Nation-wide water situation, in The Physical and Economic Foundation of Natural Resources, v. IV, subsurface facilities of water management and patterns of supply-type area studies: U. S. Cong., House of Representatives, Committee on Interior and Insular Affairs, p. 1-20.

Price, W. A., 1935, Corpus Christi structural basin postulated from salinity data: Am. Assoc. Petroleum Geologists Bull., v. 19, no. 3, p. 317-355, March.

Rayner, F. A., 1958, Records of water-level measurements in Jackson, Matagorda, and Wharton Counties, Texas: Texas Board Water Engineers Bull. 5804, 28 p., 6 figs.

_______1959a, Records of water-level measurements in Chambers, Liberty, and Montgomery Counties, Texas: Texas Board Water Engineers Bull. 5901, 27 p., 6 figs.

_______1959b, Records of water-level measurements in Brazoria, Fort Bend, and Waller Counties, Texas: Texas Board Water Engineers Bull. 5904, 58 p., 9 figs.

Resen, L. R., 1955a, Texas refining story: Modernization: Oil and Gas Jour., v. 54, no. 6, p. 185.

_______1955b, Petrochemical center, U.S.A.--That's Texas: Oil and Gas Jour., v. 54, no. 6, p. 188-189.

Rorabaugh, M. I., 1949, Memorandum on multiple-step drawdown test, Southwest well field, Houston, Texas: Texas Board Water Engineers duplicated rept., 8 p., 4 figs.

Rose, N. A., 1943a, Ground water and relation of geology to its occurrence in the Houston district, Texas: Am. Assoc. Petroleum Geologists Bull., v. 27, no. 8, August.

_______1943b, Progress report on the ground-water resources of the Texas City area, Texas: U. S. Geol. Survey open-file rept., 45 p., 3 figs.

_______1943c, Records of wells, drillers' logs, water analyses, and map showing locations of wells in Montgomery County, Texas: Texas Board Water Engineers duplicated rept., 28 p., 3 figs.

_______1944, Notes on a field study of the ground-water resources in the Agua Dulce gas field, September 5-7, 1944: Texas Board Water Engineers typewritten rept.

Rose, N. A., 1945, Ground water in the Beaumont area, Texas, with special reference to southeastern Hardin County and southwestern Jasper County, Texas: U. S. Geol. Survey open-file rept., 5 p., 1 fig.

______1954, Investigation of ground-water conditions in Hidalgo, Cameron, and Willacy Counties in the Lower Rio Grande Valley of Texas: Lower Rio Grande Valley Chamber of Commerce, 100 p., 8 figs.

Rose, N. A., Alexander, W. H., Jr., 1944, Progress report on ground-water resources of the Houston district, Texas: Texas Board Water Engineers duplicated rept., 25 p., 12 figs.

______1945, Relation of phenomenal rise of water levels to a defective gas well, Harris County, Texas: Am. Assoc. Petroleum Geologists Bull., v. 29, no. 3, March.

Rose, N. A., and Stuart, W. T., 1943a, Results of pumping tests at the Abercrombie-Harrison gasoline plant, Sweeney, Texas: U. S. Geol. Survey open-file rept., 7 p., 1 fig.

______1943b, Pump settings and pumping levels in Houston district, Texas: Texas Board Water Engineers duplicated rept., 24 p.

Rose, N. A., White, W. N., and Livingston, Penn, 1940, Test drilling in the San Jacinto River flood plain, Texas: U. S. Geol. Survey open-file rept., 100 p., 8 figs.

______1944, Exploratory water-well drilling in the Houston district, Texas: U. S. Geol. Survey Water-Supply Paper 889-D, 24 p., 5 pls.

Sayre, A. N., 1937, Geology and ground-water resources of Duval County, Texas: U. S. Geol. Survey Water-Supply Paper 776, 116 p., 8 pls.

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

Sellards, E. H., Adkins, W. S., and Plummer, F. B., 1932, The geology of Texas, v. 1, Stratigraphy: Univ. Texas Bull. 3232, 1007 p., 54 figs., 11 pls. [1933].

Singley, J. A., 1893, Preliminary report on the artesian wells of the Gulf Coastal slope: Texas Geol. Survey 4th Ann. Rept.

Stearman, Jack, 1960, Water levels in observation wells in Cameron, Hidalgo, and Starr Counties, Texas: Texas Board Water Engineers Bull. 6008, 4 p., 3 figs.

Storm, L. W., 1945, Resume of facts and opinions on sedimentation in Gulf Coast region of Texas and Louisiana: Am. Assoc. Petroleum Geologists Bull., v. 29, no. 9, p. 1304-1335.

Sundstrom, R. W., 1941a, Beaumont water supply: U. S. Geol. Survey open-file rept., 2 p.

Sundstrom, R. W., 1941b, Ground-water resources in the vicinity of Jasper, Jasper County, Texas: U. S. Geol. Survey open-file rept., 9 p., 1 fig.

_______1941c, Water supply at La Marque, Galveston County, Texas: U. S. Geol. Survey open-file rept., 6 p.

_______1941d, Freeport water supply: U. S. Geol. Survey open-file rept., 7 p.

_______1944a, Results of pumping tests of wells to the 700-foot sands at the celanese plant near Bishop, Texas: U. S. Geol. Survey open-file rept., 4 p.

_______1944b, Results of pumping tests of wells to the 900-foot sands at the celanese plant near Bishop, Texas: U. S. Geol. Survey open-file rept., 8 p.

Sundstrom, R. W., Cromack, G. H., and West, N. N., 1949, Ground-water resources of Matagorda County, Texas: Texas Board Water Engineers duplicated rept., 38 p., 2 figs.

Sundstrom, R. W., Hastings, W. W., and Broadhurst, W. L., 1948, Public water supplies in Eastern Texas: U. S. Geol. Survey Water-Supply Paper 1047, 285 p.

Swartz, B. W., 1957, Records of water levels in Aransas and San Patricio Counties, Texas: Texas Board Water Engineers Bull. 5703, 20 p., 4 figs.

Taylor, T. U., 1902, Irrigation systems of Texas: U. S. Geol. Survey Water-Supply Paper 71, 137 p., 9 pls.

_______1904, Water powers of Texas: U. S. Geol. Survey Water-Supply Paper 105, 116 p., 17 pls.

_______1907, Underground waters of the Coastal Plain of Texas: U. S. Geol. Survey Water-Supply Paper 190, 73 p., 3 pls.

Texas Board Water Engineers, 1936, Water-table survey in the Lower Rio Grande Valley, Pt. 1, Willacy County, Texas: Texas Board Water Engineers duplicated rept., 198 p., 1 fig.

_______1958, Texas water resources planning--a progress report to the 56th Legislature: Texas Board Water Engineers duplicated rept., 136 p., 4 figs., 19 pls.

_______1960, Reconnaissance investigation of the ground-water resources of the Canadian River Basin, Texas: Texas Board Water Engineers Bull. 6016, 26 p., 1 fig., 4 pls.

_______1961, A plan for meeting the 1980 water requirements of Texas: Texas Board Water Engineers duplicated rept., 198 p., 7 figs., 25 pls.

Thornthwaite, C. W., 1952, Evapotranspiration in the hydrologic cycle, <u>in</u> The physical and economic foundation of natural resources, v. II, The physical basis of water supply and its principle uses: U. S. Cong., House of Representatives, Committee on Interior and Insular Affairs, p. 25-35.

Tolman, C. F., 1937, Ground water: New York, McGraw-Hill Book Co., 567 p.

Trowbridge, A. C., 1932, Tertiary and Quaternary geology of the Lower Rio Grande region, Texas: U. S. Geol. Survey Bull. 837, 260 p., 45 pls.

Turner, S. F., and Cumley, J. C., 1940a, Records of wells, drillers' logs, water analyses, and map showing location of wells, Brooks County, Texas: Texas Board Water Engineers duplicated rept., 63 p., 1 fig.

_______1940b, Records of wells, drillers' logs, water analyses, and map showing location of wells in Kenedy County, Texas: Texas Board Water Engineers duplicated rept., 56 p., 1 fig.

Turner, S. F., and Foster, M. D., 1934, A study of salt-water encroachment in the Galveston area, Texas: Am. Geophys. Union Trans., June, p. 432-435.

Turner, S. F., and Livingston, Penn, 1933, Records of wells of Harris County, Texas: U. S. Geol. Survey open-file rept., 59 p., 1 pl.

_______1935, Ground-water studies in the humid and semiarid parts of the Texas Coastal Plain: Am. Geophys. Union Trans., August, p. 503-507.

_______1939a, Records of wells and springs, drillers' logs, water analyses, and map showing location of wells and springs in Waller County, Texas: Texas Board Water Engineers duplicated rept., 20 p., 1 fig.

_______1939b, Records of wells and springs, drillers' logs, water analyses, and map showing location of wells and springs east of the Brazos River, Brazoria County, Texas: Texas Board Water Engineers duplicated rept., 11 p., 2 figs.

_______1939c, Records of wells, Harris, Galveston, Waller, Fort Bend, Brazoria, and Grimes Counties, Texas: Texas Board Water Engineers duplicated rept., 280 p., 21 figs.

Turner, S. F., Lynch, W. A., and Cumley, J. C., 1940, Records of wells and springs, drillers' logs, water analyses, and map showing location of wells and springs in Jim Wells County, Texas: Texas Board Water Engineers duplicated rept., 55 p., 1 fig.

U. S. Public Health Service, 1946, Public Health Service drinking-water standards: Public Health Repts., v. 61, no. 11, p. 371-384.

U. S. Salinity Laboratory Staff, 1954, Diagnosis and improvement of saline and alkali soils: U. S. Dept. Agriculture Agr. Handbook 60, 160 p., 32 figs.

Weeks, A. W., 1945, Quaternary deposits of Texas Coastal Plain between Brazos River and Rio Grande: Am. Assoc. Petroleum Geologists Bull., v. 29, no. 12, p. 1693-1720, December.

Wenzel, L. K., 1942, Methods for determining permeability of water-bearing materials, with special reference to discharging well methods: U. S. Geol. Survey Water-Supply Paper 887, 192 p., 6 pls.

White, W. N., 1933, Ground water in Nueces County, Texas: U. S. Geol. Survey open-file rept., 14 p.

White, W. N., 1938, Progress report on the ground-water resources of the Houston district, Texas: Texas Board Water Engineers duplicated rept., 6 p., 1 fig.

_______1939, Progress report on the ground-water resources of the Houston district, Texas: Texas Board Water Engineers duplicated rept., 12 p., 5 figs.

_______1940, Ground water in the Corpus Christi area, Texas: U. S. Geol. Survey open-file rept., 7 p., 1 fig.

_______1941a, Water supply of Baytown: U. S. Geol. Survey open-file rept., 3 p.

_______1941b, Water supply of Mission, Texas, national defense area: U. S. Geol. Survey open-file rept., 2 p.

_______1941c, Ground water in the vicinity of Port O'Connor, Calhoun County, Texas: U. S. Geol. Survey open-file rept., 4 p.

_______1942, Emergency water supply for naval reserve air base near Corpus Christi, Texas: U. S. Geol. Survey open-file rept., 4 p.

_______1944, Ground-water problems in the Texas City-Alta Loma-Baytown district, Texas: U. S. Geol. Survey open-file rept., 3 p.

_______1945, Ground water in Beaumont, Nederland, Port Neches, and Port Arthur areas, Texas: U. S. Geol. Survey open-file rept., 8 p.

White, W. N., Livingston, Penn, and Turner, S. F., 1932, Ground-water resources of the Houston-Galveston area, Texas: Dept. Interior memo. for the Press, 14 p., 5 figs.

White, W. N., Rose, N. A., and Guyton, W. F., 1940, Progress report on the ground-water resources of the Houston district, Texas: Texas Board Water Engineers duplicated rept., 34 p., 10 figs.

_______1942, Progress report on the ground-water resources of the Houston district, Texas: Texas Board Water Engineers duplicated rept., 22 p., 8 figs.

_______1944, Ground-water resources of the Houston district, Texas: U. S. Geol. Survey Water-Supply Paper 889-C, 148 p., 4 pls.

White, W. N., and Sundstrom, R. W., 1941, Water resources in the vicinity of Freeport, Texas: U. S. Geol. Survey open-file rept., 20 p., 2 figs.

White, W. N., Turner, S. F., and Livingston, Penn, 1937, Progress report on the ground-water resources of the Houston district, Texas: Texas Board Water Engineers duplicated rept., 59 p., 5 figs.

Wilcox, L. V., 1955, Classification and use of irrigation waters: U. S. Dept. Agriculture Circ. 969, 19 p., 4 figs.

Winslow, A. G., 1950, Geology and ground-water resources of Walker County, Texas: Texas Board Water Engineers Bull. 5003, 43 p., 4 figs., 2 pls.

Winslow, A. G., and Doyel, W. W., 1954, Land-surface subsidence and its relation to the withdrawal of ground water in the Houston-Galveston region, Texas: Econ. Geology, v. 49, no. 4, June-July.

Winslow, A. G., Doyel, W. W., and Wood, L. A., 1957, Salt water and its relation to fresh ground water in Harris County, Texas: U. S. Geol. Survey Water-Supply Paper 1360-F, 32 p., 10 figs., 4 pls.

Winslow, A. G., and Fluellen, T. R., Jr., 1952, The Houston district, Texas, pumpage and decline of artesian pressure during 1950-51: Texas Board Water Engineers Bull. 5201, 8 p., 17 figs.

Winslow, A. G., and Kister, L. R., Jr., 1956, The saline water resources of Texas: U. S. Geol. Survey Water-Supply Paper 1365, 105 p., 12 figs., 9 pls.

Winslow, A. G., and Wood, L. A., 1959, Relation of land subsidence to ground-water withdrawals in the upper Gulf Coast region, Texas: Mining Eng., p. 1030-1034.

Wood, L. A., 1956a, Pumpage of ground water and changes in artesian pressure in the Houston district and Baytown-La Porte area, Texas, 1953-55: Texas Board Water Engineers Bull. 5602, 15 p., 23 figs.

______1956b, Availability of ground water in the Gulf Coast region of Texas: U. S. Geol. Survey open-file rept., 29 p., 26 pls.

______1958a, Pumpage of ground water and fluctuations of water levels in the Houston district and the Baytown-La Porte area, Texas, 1955-57: Texas Board Water Engineers Bull. 5805, 13 p., 27 figs.

______1958b, Pumpage of ground water and changes in water levels in Galveston County, Texas, 1952-57: Texas Board Water Engineers Bull. 5808, 10 p., 13 figs., 1 pl.

Records of water levels in the Gulf Coast region are published in the following U. S. Geol. Survey Water-Supply Papers:

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