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GEOLOGY AND GROUND-WATER RESOURCES OF THE HOUSTON DISTRICT, TEXAS

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In collaboration with W N White
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ABSTRACT

The water for all public supplies, nearly all the industrial supplies, and a large part of the irrigation supplies of the Houston district, which embraces an area of about 1,800 square miles, is drawn from wells. Most of the wells range from 450 to 2,000 feet in depth. In 1930, the estimated average pumpage for the district was 68 million gallons a day, but by 1949 it had increased to about 250 million gallons a day. Most of the pumpage is from three areas: (1) the City of Houston and the closely adjoining metropolitan localities; (2) the Pasadena area, which includes the vast industrial section along the Houston Ship Channel from the Turning Basin to the vicinity of Deer Park; and (3) the Katy rice-irrigation area roughly centering around the town of Katy.

This report covers the current phase of an investigation of the supply of ground water available for the Houston district, and in addition summarizes the results of several previous reports. The field operations have included routine inventories of pumpage, measurements of water levels in observation wells, and the collection of other hydrologic data. Pumping tests were made on 14 city-owned wells to determine coefficients of permeability and storage. Special attention was given to the valuable program of deep-well exploratory drilling and development and associated research conducted by the Houston Water Department in 1948-49. A deep test hole was drilled at the site for each of the 18 production wells which were put down in the expansion and decentralization of the municipal well fields.

Geologic studies and the recent exploratory drilling and research by the Houston Water Department, have shown that some parts of the Houston district are underlain by potable water at greater depths than previously had been supposed possible. This source of supply was practically untouched until the past year and probably represents an important reserve.

The water-bearing beds, consisting of sands interbedded with clays that range in age from upper Miocene to Pleistocene, dip generally southeastward at a rate somewhat greater than the slope of the land surface, thus creating favorable artesian conditions. Potable water is found in sands having an aggregate thickness of more than 600 feet and extending from the surface to depths ranging from 1,200 to 1,800 feet in the Webster and Pearland areas on the southeast, 1,700 feet at Clodine on the southwest, and about 2,600 feet in the southeast Houston and Pasadena areas. Owing to their origin and mode of deposition, the beds throughout the section are lithologically similar and are difficult to correlate from place to place. However, the sediments have been divided into seven zones, chiefly on the basis of electrical logs. (See pls. 1 and 2.) Most of the large water supplies are drawn from zones 3, 5, and 7. Although the clay zones appear to extend across the district, a study of the electrical logs leads to the conclusion that none of the beds of clay between the Beaumont clay and the Lagarto clay persists throughout the district. In studying a large area, therefore, the section between the Beaumont clay and the Lagarto clay might be considered one reservoir. This is further suggested by a similarity in the fluctuations of artesian pressures in wells that are screened in sands above zone 4 and below the Beaumont.

The withdrawals of ground water in the Houston and Pasadena areas, which remained fairly constant from 1930 to 1936, averaged about 50 million gallons a day and a state of approximate equilibrium was reached in the artesian pressure. But as a result of an increase in the rate of pumping in the Pasadena area in 1937, amounting to about 20 million gallons a day, the pressure declined throughout the Houston and Pasadena areas in 1937-38. Small additional increases in pumpage in 1939-41 caused the decline to continue, although at a somewhat slower rate.

The pumpage increased from 77 million gallons a day in 1941 to 146 million gallons a day in 1948, and the artesian pressures declined an average of about 90 feet around Pasadena and 70 to 80 feet in eastern Houston. Smaller but substantial declines were recorded throughout most of the Houston district. However, in 1949 the pumpage increased only slightly over 1948 which was the first time in 8 years that the pumpage approached the same net average rate for a 2-year period. As a result the average net decline of artesian pressure was small.

The movement of ground water in the Houston district, before heavy withdrawals were made through wells, was down the dip southeastward from the outcrops, where recharge occurs, toward places of natural discharge, probably along the continental shelf beneath the Gulf and by upward movement through the overlying strata. This movement was accompanied by some frictional loss in head, even though the rate of movement was perhaps only a few hundred feet a year; but the pressure remained sufficiently high to raise the water 60 feet or more above the land surface at Houston in the first wells, which ranged in depth from about 250 to 1,000 feet. When wells were put down and allowed to flow or were pumped, the rate of movement toward the wells increased, frictional losses became greater around the wells, and cones of depression developed. Figures 10, 11, and 12 illustrate the large depression cones thus created in the Houston and Pasadena areas. These depressions are the result of pressure declines in wells which represent a substantial drop in static and pumping levels over a wide area, but the water-bearing sands are not being unwatered and will not be unwatered unless the pumping levels are lowered below the top of the sands.

Computations were made of the loss of water from storage in the artesian aquifer in the Houston and Pasadena areas during the period 1941-49. Using the map of declines for the period (fig.12), the area enclosed by the 30-foot contour was calculated to be 740 square miles and the average decline in pressure 57 feet. The average coefficient of storage was selected as 0.0015, and was based upon the results of many pumping tests and consideration of the aggregate thickness of the water-bearing sands. The results indicate that approximately 13 billion gallons of water was removed from storage, which would represent about 4 percent of the total volume pumped in the areas during the 8-year period. Additional water came from storage in the area outside the 30-foot contour, of course.

Data at hand show that the water table in the outcrops of the sands that supply the artesian reservoirs has reflected closely the effects of precipitation since 1938. (See fig. 10.) In the areas not affected by pumpage for rice irrigation, and comprising by far the greater part of the outcrop, the records do not indicate any substantial lowering of the water table, and, therefore, no substantial loss of water from storage in the outcrop. The low flow of Spring Creek, which drains the outcrops of the Lissie and Willis formations in northern Harris County and southern Montgomery County, is rejected recharge. There was rejected recharge before pumping began at Houston and there is still rejected recharge on the outcrops. Continuous records are not available of the flow of Spring Creek previous to 1939, and it is not known whether there has been a net decrease in the amount of rejected recharge since pumping was started at Houston. The data indicate that, during the period 1938-50, the quantity of recharge on the outcrop was equal to the quantity of water that moved down dip from the outcrop toward the heavily pumped areas. In turn, water has moved into the cones of depression (fig. 11) from the immediately adjacent localities. The only loss from storage, therefore, was limited to the artesian part of the reservoir.

Analyses of water samples collected periodically since 1931 from a large number of pumped wells widely spaced throughout the district show no significant change of chloride content in any of the wells regardless of their depth. Recent geologic studies based mostly on electrical logs of water wells and oil tests show that the water-bearing beds contain potable water farther down the dip to the south and southeast of Houston than was formerly supposed. Therefore, it is less probable than formerly considered that, as a result of the heavy pumping in the Houston and Pasadena areas, the fresh-water beds may be contaminated in the near future by the invasion of salt water. However, because a hydraulic gradient now exists from the Gulf toward the pumped area, additional test wells should be put down to determine the location of the fresh water-salt water interface and to observe the progress of any salt-water encroachment that may be occurring.

The available evidence leads to the conclusion that the ground-water reservoir in the Houston district has not been overdrawn, and that additional withdrawals can be sustained north and northeast of Houston, outside the present areas of heavy draft, provided that the future developments are properly planned and executed. Measurements of water levels and artesian pressures should be continued at periodic intervals in the present observation wells. Additional wells for observation should be selected, particularly in the outcrop areas. Annual pumpage inventories should be continued. In view of the tremendous importance of the quality of the ground water, it is advisable that periodic sampling from the present observation wells should be continued indefinitely, and additional outpost observation wells should be installed to test the deeper sands in the southeastern part of the district in order to determine the accuracy of the conclusions regarding the possibility of salt-water invasion. These data, together with other hydrologic studies that are being made, will give advance warning, should future conditions require a decrease of the pumpage rate or the development of new wells, many years before the actual need for such changes arise.

INTRODUCTION

LOCATION AND IMPORTANCE OF THE DISTRICT

The Houston district, as the term is here used, comprises an area of about 1,800 square miles and includes Harris County west of the San Jacinto River and adjoining parts of Montgomery, Waller, and Fort Bend Counties (fig. 1).

Houston, near the center of the district, is the largest city in Texas. The estimated population for late 1949 was 633,000. It is the leading seaport, oil refining, and railroad center on the Gulf Coast and ranks high in miscellaneous manufacturing, especially the manufacture of chemicals, steel, oil-field equipment, and paper. Large quantities of water are needed to meet the requirements of the rapidly growing population and expanding industries, and for irrigation in the rice-growing area to the west and northwest of the City. The water supplies of the Houston district are obtained mostly from wells and the continuously increasing demand for water has been met by greater and greater withdrawals of ground water. Large quantities of water are pumped from three areas as follows: (1) The Houston area, which includes the city of Houston and the closely adjoining territory, except that on the east; (2) the Pasadena area, which includes the industrial section that extends from east Houston eastward along the Houston Ship Channel to the vicinity of Deer Park; and (3) the Katy area, an irregularly shaped area of several hundred square miles in western Harris County, the northern part of Fort Bend County, and the southeastern part of Waller County, where well water is used for the irrigation of rice.

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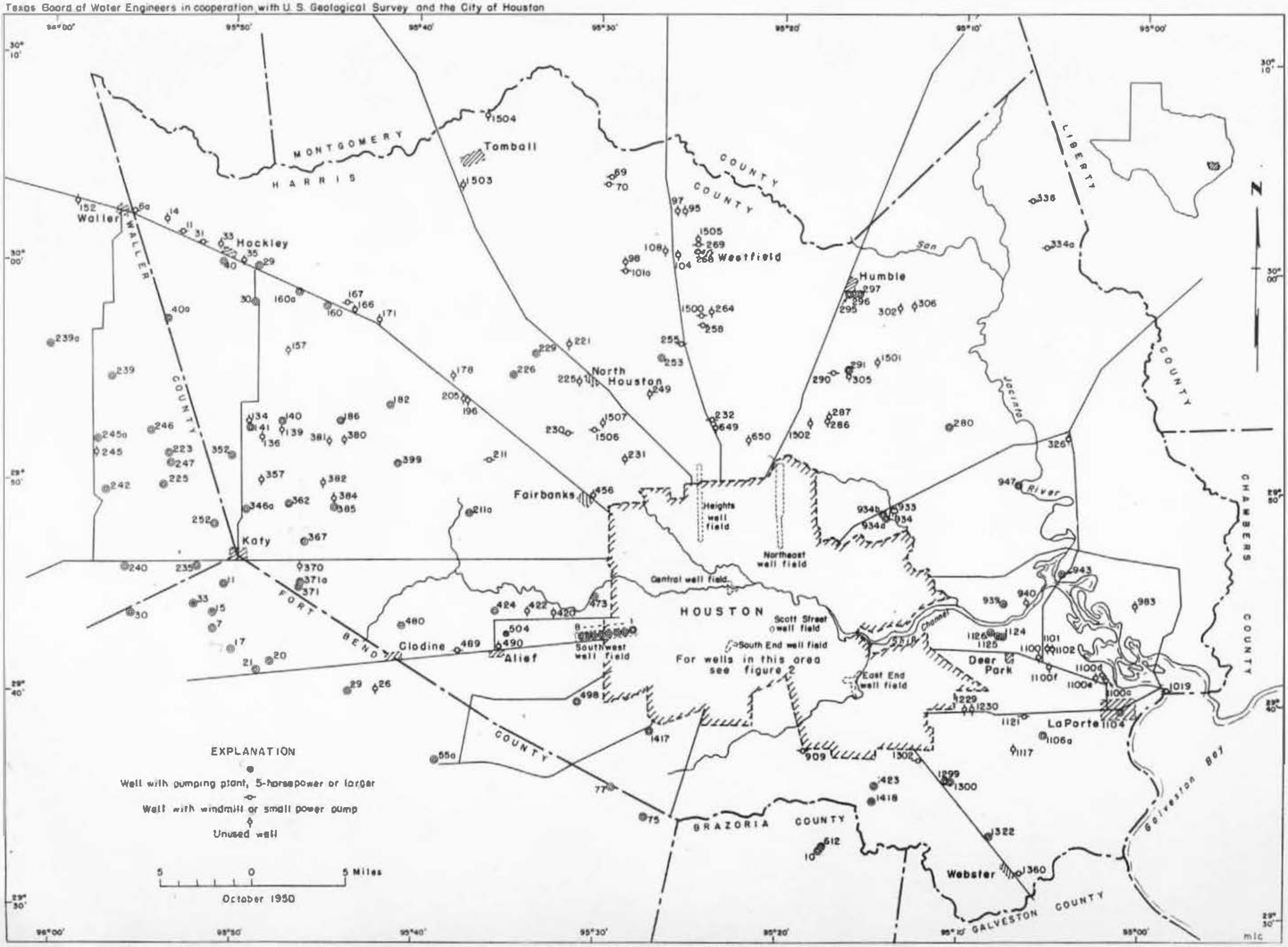

FIGURE 1.-Map of Houston district, Texas, showing observation wells.

PURPOSE AND SCOPE OF THE INVESTIGATION

Because of the widespread development of industry and irrigation, and the large population increase, the importance of the quantity and quality of the available ground water in the district has become apparent. In fact, the rapid development of the ground-water resources has become a matter of growing public concern to the Gulf Coast region, the State of Texas, and the Nation as a whole lest the reservoirs be seriously overdrawn or become contaminated by the encroachment of salt water. Therefore, in response to public interest and requests, the U. S. Geological Survey, in cooperation with the Texas State Board of Water Engineers, started in December 1930 a systematic survey of the water supply available for the Houston district. Each year since 1938 the City of Houston has appropriated $5,000.00 in funds and has cooperated in many other ways in carrying on the studies.

The information obtained includes the following: (1) data concerning the areal extent and thickness of the water-bearing beds and the depths at which they occur throughout the district; (2) the average daily withdrawals of ground water for municipal, industrial, and irrigation purposes by years in different parts of the district; (3) the relationship between the rate of ground-water withdrawals and the rate of decline of the artesian pressures as shown by the depths to water in wells; (4) the rate at which water is being replenished at the outcrops of the water-bearing beds; (5) the rate at which the sands transmit water from the outcrop to the localities of withdrawal; (6) the chemical character of the ground water; (7) the possibilities of salt-water invasion into the fresh-water sands; and (8) data on localities in the adjoining areas where potential ground-water supplies may exist.

The over-all purpose of the studies is to obtain facts from which the limits of pumping can be computed or approximated for different parts of the district and which can be used as a guide for the most practicable long-term development of the ground-water reservoirs. The results of the investigations have been summarized in two Survey Water-Supply Papers, seven mimeographed reports, twelve special reports and technical papers, and reports on five counties that are adjacent and hydrologically related to the Houston district.

Since 1940 the Houston Water Department has carried out a well-organized plan of ground-water development. A consistent effort has been made to distribute the pumpage over the area and among the different sands, and thereby reduce the mutual interference between the individual wells and the different well fields. On occasions when the ideal plan has not been strictly carried out it generally has been on account of lack of pipe line facilities or to the difficulty of obtaining well sites for distributing the increased draft among the different pumping plants. In general, no such systematic plan of development has been followed by the large users of ground water for industrial supply.

In 1948, as a result of geologic studies and exploratory test drilling, additional supplies of fresh water were discovered in deeper sands not previously utilized. In addition special attention and considerable time was given to the program of deep well exploratory drilling and development and associated research conducted by the City Water Department in 1948-49.

Important items of office work include the following: compilation of field data for current use by the city and for publication; compilation of geologic cross sections for city use and for publication; tabulation of well records and preparation of manuscripts for five county reports; and preparation of the text and illustrations in this report.

ACKNOWLEDGMENTS

Acknowledgment is due to many persons who have contributed information and assistance in the field and in the preparation of this report. In this connection special mention is made of the valuable assistance rendered in the furthering of the ground-water studies in the Houston area by Frank N. Baldwin, Director, Department of Utilities, and Clyde R. Harvill, Sanitary Engineer, and L. H. Earnest, Production Engineer, Water Division of the Utilities Department. Well-drilling contractors of the district, especially The Layne-Texas Company, Ltd. and Texas Water Wells, Inc., have given freely of logs and other pertinent data. Industrial representatives have supplied useful information including quantity of water used; and farmers and ranchers have given information, all of which has been invaluable in conducting this study. Geologists of the Humble Oil and Refining Company, The Gulf Oil Corporation, and the Atlantic Refining Company have supplied valuable information about the geology of the district.

The field work was done and this report prepared under the administrative direction of A. N. Sayre, Geologist in charge of the Ground Water Branch of the U. S. Geological Survey and under the direct supervision of W. L. Broadhurst, District Geologist in charge of ground-water investigations in Texas.

HISTORY OF GROUND-WATER DEVELOPMENT

DEVELOPMENT PRIOR TO 1946

Public supply.- The first public water supply for Houston was obtained from Buffalo Bayou by the Houston Water Works Company, an independent agency that was organized in 1878. The first well was drilled in 1886 to a depth of 140 feet, cased with 15-inch pipe, and is reported to have had an initial flow of more than 1,000 gallons a minute. From June 1888 to May 1905 the company drilled 65 wells that ranged in depth from 115 to 1,330 feet on a 14-acre tract along Buffalo Bayou near the present Central pumping plant.

In October 1906 the City of Houston purchased the water system which then included 45 flowing wells, most of which were equipped with airlift pumps. The total capacity of the pumps and flowing wells was 19,000,000 gallons a day, but only about 11,000,000 gallons a day was used. The wells of the original system were gradually replaced by new wells and by 1935 all the old wells had been abandoned and sealed. In 1935 the pumpage by the City averaged 24,500,000 gallons a day. This slowly increased to 27,200,000 gallons a day in 1941. Since 1941 a substantial increase has been recorded each year and the pumpage for 1949 was more than double that for 1941. Likewise during the same period the pumpage by independent water-supply and improvement districts increased about 100 percent. In the fall of 1948 and in 1949 the City carried out the major part of the most extensive program of exploratory drilling and well development that it has ever undertaken. These operations and associated studies are described in the section entitled "Deep well exploratory investigations by the Houston Water Department". In the autumn of 1949 the Houston water supply was obtained from 39 wells in seven widely-spaced well fields (see fig.2). The wells ranged in depth from 777 to 2,580 feet and had a combined capacity of about 90,000,000 gallons a day. Records of the pumpage by the City and by independent agencies for public-water supply by years are given in tables 1 and 3, pages 12 and 14.

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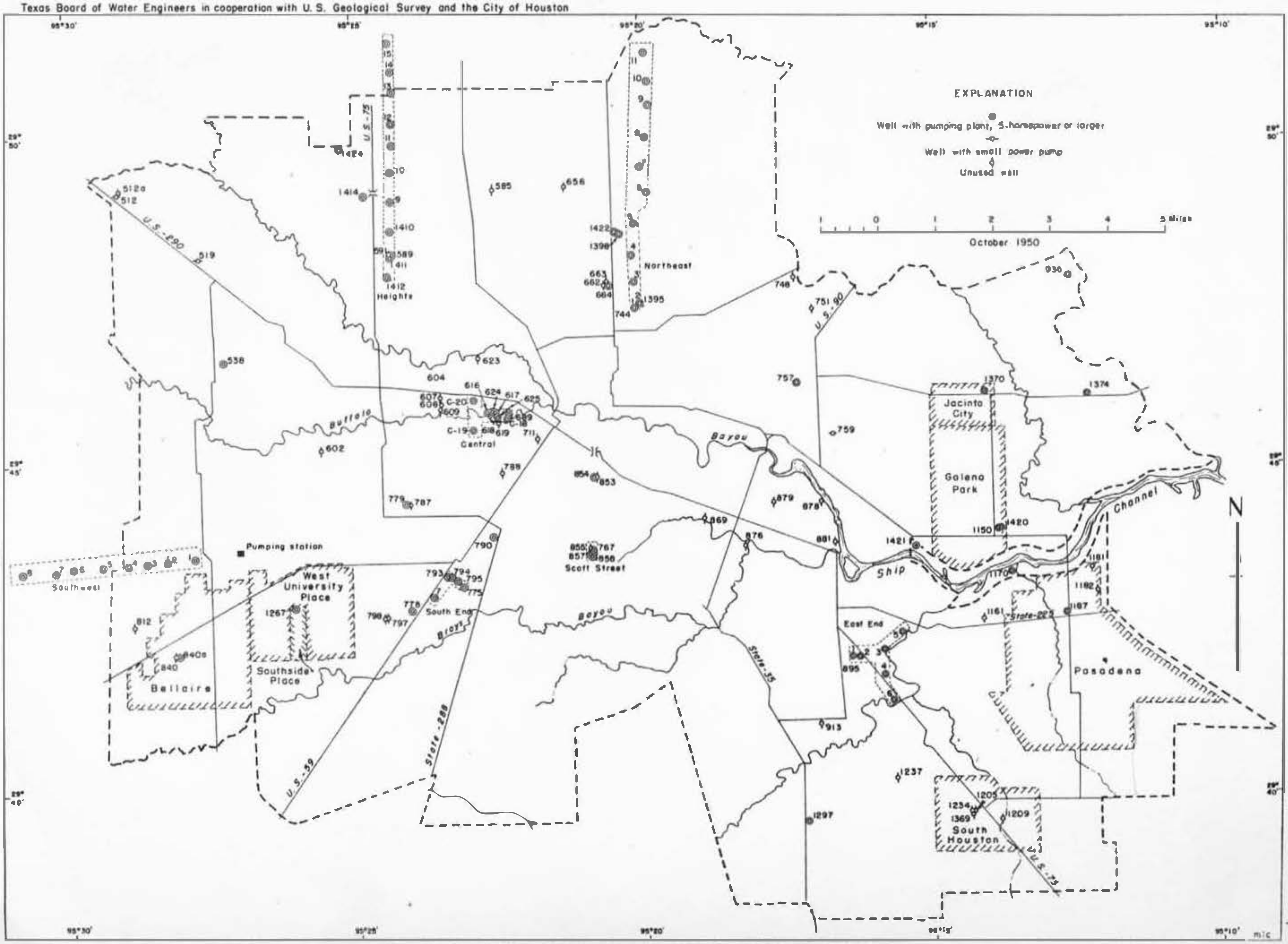

FIGURE 2.-Observation wells and municipal well fields, Houston, Texas.

Industrial supply.- After the opening of the Houston Ship Channel to ocean-going vessels in August 1915, the development of large-scale industrial plants began. The first large consumer of ground water in the Pasadena-Ship Channel area was the Galena Signal Refinery, now The Texas Company, which began operating in 1916. The Sinclair Refinery followed in 1919, the Crown Central Refinery in 1920, Deep Water plant of the Houston Lighting and Power Company in 1923, Shell Refinery in 1926, the American Petroleum Company in 1931, and the Champion Paper and Fibre Company in 1937. Between 1937 and 1943 several large industrial plants were constructed in the Houston and Pasadena-Ship Channel areas, all of which used ground water, and the pumpage was greatly accelerated. After World War II, industrial development increased at a still greater rate and the demands for ground water increased accordingly. The industrial wells range in depth from about 330 to 1,925 feet, and average about 1,000 feet.

In 1949 the pumpage from wells for industrial use in the Pasadena-Ship Channel area was about twice that in 1946 and six times that in 1930. Details are given in tables 1 and 3, pages 12 and 14.

Rice irrigation.- During the early part of the century, rice irrigation was practiced on a moderately large scale in southeastern Harris County near Webster and in southern Harris County near Almeda, but only a few planters still operate in those localities. In the Katy area west and northwest of Houston, rice irrigation from wells was begun in 1902 with the planting of about 75 acres. Prior to 1915 all the water was pumped from wells less than 300 feet deep; but in that year a well was sunk to a depth of about 500 feet, and in 1922 another was sunk to about 800 feet. The average depth of the irrigation wells drilled since 1922 has been more than 500 feet. In 1930 about 9,400 acres was planted to rice, and by 1941 there were 95 wells irrigating 27,350 acres. In 1948 there were 150 wells irrigating 47,600 acres in an area of about 300 square miles. The 1949 acreage was about the same as that for 1948. The total pumpage from rice-irrigation wells in the area is given by years in table 7, page 25.

DEVELOPMENT DURING 1946-50

From July 1946 through 1949 records show that 95 wells of large capacity were drilled in the Houston district. Of this number, 29 were drilled for industrial use, 32 for the public supply of municipalities and water districts, and 34 for rice irrigation. Of the industrial wells, 23 were drilled to supply old plants and six to supply new plants. Of the 32 wells developed for public supply, 16 were for the Houston Water Department and the remainder were for water districts and municipalities in the suburban areas around the city. The Houston wells were developed in the following well fields: two at Southwest, two at Central, four at East End, four at Heights, and four at Northeast. Most of the new irrigation wells were put down in the Katy district, however, a few were installed in widely separated areas southwest, southeast, and northwest of Houston.

During the fall of 1948 and in 1949 and 1950 the Houston Water Department completed 18 production wells. One of these wells (C-20) was drilled in the Central field, two (nos. 5 and 6) at East End, seven (nos. 9 to 15) at the Heights field, and eight (nos. 4 to 11) at the Northeast field. The map, figure 2, shows by the conventional symbol the locations of wells that were completed or in operation in October 1950.

Before developing the City wells, an exploratory test hole was sunk at each well site. An electrical survey of the test hole was made in order to supplement the driller's log, and drill-stem samples of water were obtained from selected sands and analyzed to serve as a guide for completing the well. The production wells were drilled to depths ranging from 1,434 feet to 2,580 feet and were cased, screened, and gravel-packed. The aggregate thickness of sand screened and developed in each well averaged about 400 feet. No sands were screened above 450 feet at Southwest, none above 1,160 feet at Central, none above 1,000 feet at East End, none above 700 feet at Northeast, and none above 600 feet at Heights. Each well is designed and equipped to produce approximately 3,000,000 gallons a day. Pumping tests have shown, however, that each of the new wells is capable of yielding considerably more than that amount. The new wells at Central and East End were screened below a thousand feet in order to take advantage of the deeper water-bearing beds that are less heavily drawn upon by other municipalities and private industries.

DEEP-WELL EXPLORATORY INVESTIGATIONS BY THE HOUSTON WATER DEPARTMENT

The most extensive deep-well exploratory program ever undertaken by the City was started in 1948, continued through 1949, and was terminated in the spring of 1950. One of the purposes of this program was to determine the maximum depths to which water of good quality occurs with a view of developing a water supply from deeper sands that previously had been undeveloped or lightly pumped. Investigations by the U. S. Geological Survey in the spring of 1948, based upon the study and correlation of electrical logs of oil tests in the area south, southeast, and east of Houston, led to the important discovery by test drilling of a section of potable-water sand between the depths of 2,200 and 2,600 feet in the East End well field. These deep sands were several hundred feet below any section previously tested or developed in the area. As a result of this discovery, four production wells that draw part of their water from the deeper sands were drilled at East End. By the end of 1949, 16 test holes had been drilled in four well fields. The depths of the test holes ranged from 2,495 to 2,848 feet. In addition to the four production wells at East End, two were put down at Central, six at Heights and four at Northeast.

In the exploratory investigations, each test hole was electrically logged and drill-stem samples of water were obtained in order to determine the quality of water in various sands and to determine the lowermost limits of potable water. Table II, page 13, shows the depths of the test holes, depths of water sampling, and results of analyses of the samples that were made in the laboratory of the U. S. Geological Survey. The 1948-49 program, however, was distinguished by other methods of study which previously had not been used by the City, and included caliper surveys in several wells, temperature surveys in three wells, and spinner surveys in one well (East End well 4). The caliper survey shows the diameter of the well at all points. It can be used as an aid for selecting the points of water sampling. Later, when casing has been inserted and cemented at the top of the sand and the sand has been underreamed, it can be used to determine the adequacy of the underreaming and thus assist in carrying out the most efficient development of the well. The temperature, and spinner surveys are made in a well after it is completed. The temperature survey serves as an indicator of the relative amounts of water being contributed by the different sands and the spinner survey gives an approximate measurement of the volume of water from each screen.

In the City exploration program the caliper and spinner surveys were particuarly useful. The following statement regarding the caliper surveys is quoted from the Annual Report of the Sanitary Engineering Section, Water Division, Utilities Department for 1949, by Clyde R. Harvill, Sanitary Engineer.

> "In the early part of the drilling program we experienced some difficulty in drill-stem testing, in obtaining a water sample satisfactory for chemical analysis. To meet this problem, the use of a caliper survey, run immediately after the electric log, was instituted. A caliper survey shows the actual diameter of the drilled hole and clearly demarks areas of caving. The use of this survey resulted in approximately a 30% reduction of drill-stem test failures-it took the guesswork out of selecting the proper size packer to seal off the formation and it allowed the selection of a formation sufficiently hard to hold the packer of the drill-stem testing tool. The water samples obtained after instituting this survey contained much less contamination from drilling mud and grease and were almost uniformly satisfactory for analysis".

For purposes of illustration, the results of the temperature and spinner surveys in East End well 4 are briefly described below. The test well was drilled in October and November 1948 to a depth of 2,819 feet. It was electrically logged, and a drill-stem test was made at a depth of 2,457-2,477 feet. The drill-stem sample proved to be water of good quality. From this information and the electrical log it was concluded that fresh water occurred in the sands to a depth of at least 2,530 feet. The well then was bottomed at 2,530 feet and the screen settings, shown in figure 3, were chosen for the production well. At the time of its completion the well was the deepest in operation in the Houston district.

The well was developed and a 96-hour production test was started on December 8, 1948. Near the end of the test on December 12, a temperature survey was made by the Halliburton Oil Well Cementing Company while the well was being pumped at a rate of 2,560 gallons a minute, and another temperature survey was run after the well had been shut down for 4 hours. On January 12 and 13, after the well had been idle for 1 month, additional temperature surveys were run by the Humble Oil and Refining Co. The results of the Halliburton and the Humble surveys, together with a temperature gradient determined by the latter company in the City of Houston test wells 8 and 9 near South Houston, are shown graphically in figure 3. The graph compiled on December 12 while the well was being pumped shows discernible breaks in the curve opposite at least four of the screen sections, indicating that these sections were contributing water to the well; however, the record does not show enough detail to definitely state that the remaining screen sections were not contributing.

The graphs that were recorded while the pump was idle on December 12 and January 13, however, show that, although the temperature dropped very little between the bottom of the well and the top of the uppermost screen at 1,000 feet, there was a decline of about 15° F. immediately above the top of that screen. This shows plainly that a flow of considerable volume comes from the lower sands, and under the impulse of differential pressure water is moving upward through the well and escaping into the upper sands.

A spinner survey was run in the well by Dowell Inc., on January 19, 1949, and was followed by a similar survey, which was made by the U. S. Geological Survey on January 28; both surveys were run while the well was idle. The results, shown graphically in figure 3, proved that on both occasions a large volume of water, perhaps in the order of magnitude of 600 to 800 gallons a minute, was entering the well through the two lowermost screens, moving upward through the well, and escaping into sands at all five of the upper screened sections. The movement was caused by differences in artesian pressure, the pressures being materially higher in the lower sands than in the upper sands.

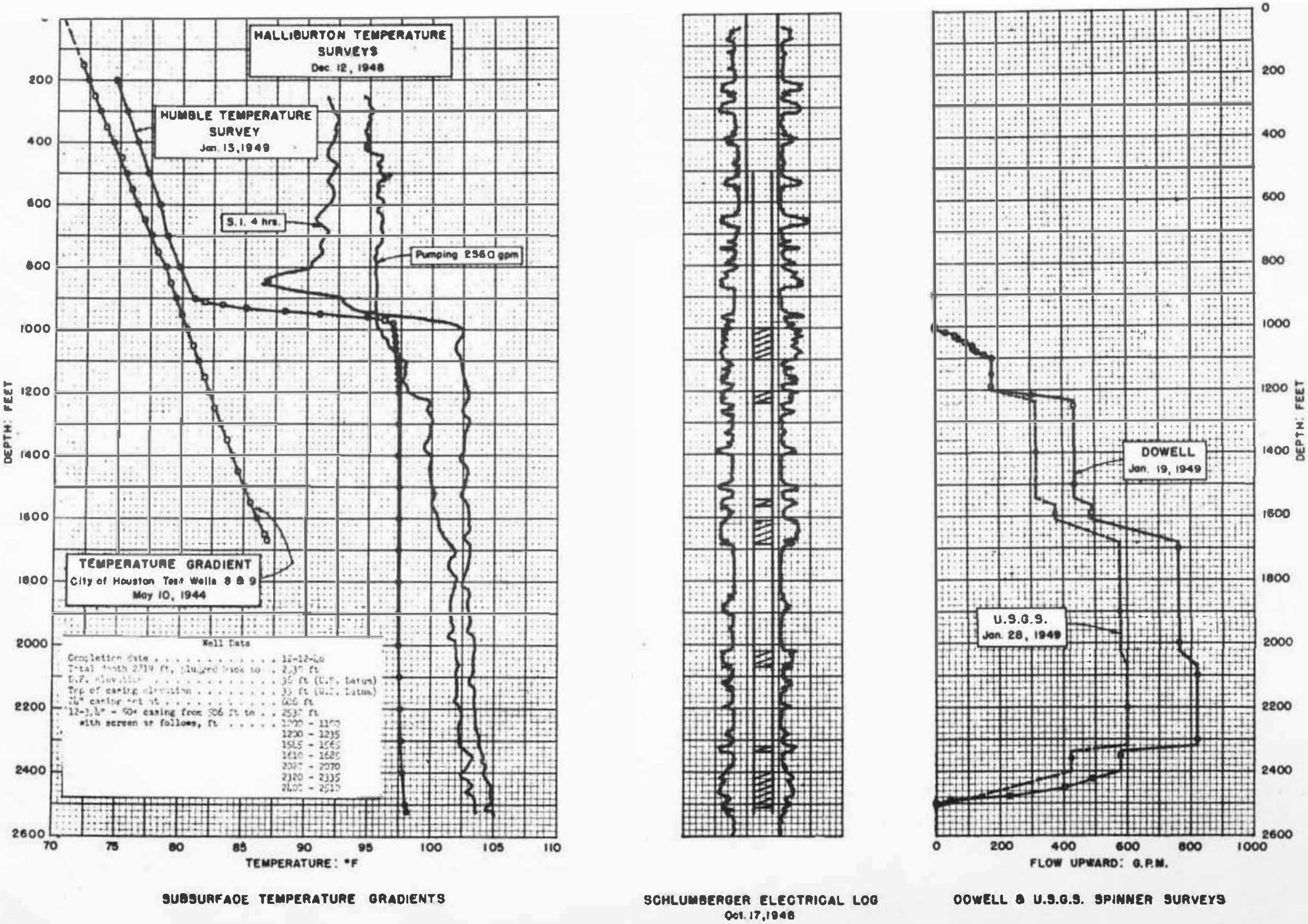

FIGURE 3.-Temperature, electrical, and spinner surveys in East End well 4, City of Houston, Texas.

(Reproduced by permission of Humble Oil and Refining Company, Houston, Texas)

The several detailed surveys described above, which have been sponsored by the engineers of the Utilities Department and financed by the City, have supplied valuable data for determining the extent of the ground-water reservoirs and for developing the greatest efficiency in the production wells.

VOLUME AND DISTRIBUTION OF PUMPAGE AND DECLINE OF ARTESIAN PRESSURES IN THE HOUSTON DISTRICT

Pumpage in the Houston, Pasadena, and Katy areas from all the pumping plants that yield more than 5,000 gallons a day has been compiled for the years 1930, 1935, 1937, and 1939 to 1949, inclusive. (See table 1).

In 1949 nearly all the ground water used in the Houston district was pumped from 475 wells, about 320 of which are in the Houston and Pasadena areas and the remainder in the Katy area. Accurate production figures were obtained from meter records for the municipal wells and most of the heavily-pumped industrial wells, which together contributed about 65 percent of the supply. Less accurate but reliable figures were obtained for about 20 percent of the supply by means of discharge ratings and the average length of time the pumps were operated. Records for the remaining 15 percent of the supply were not available and the pumpage was estimated.

In the Katy area the estimates of pumpage from the irrigation wells have been based on the number of acres irrigated from each well, the amount of current used by the electrically operated pumps, and systematic measurements of the discharge from several representative wells.

Table 1. Average daily pumpage in the Houston, Pasadena, and Katy areas (millions of gallons a day) a/

	1930	1935	1937	1940	1941	1942	1943	1944	1945	1946	1947	1948	1949
Houston Water Dept. (from City records)	25.8	24.5	25.2	28.8	27.2	30.5	35.2	39.5	43.2	51.3	55.8	60.9	60.4
Independent ublic supplies and small industrial wells	14	14	16	17	16	18	20	21	21	22	24	24	30
Pasadena industrial wells	10	10	29	33	34	36	39	47	48	50	55	61	60
Sub-total for Houston and Pasadena areas	50	49	70	79	77	85	94	108	112	123	135	146	150
Katy irrigation wells	18	14	30	45	23	38	52	55	50	60	75	120	98
Total for the district	68	63	100	124	100	123	146	163	162	183	210	266	248

a/ The rice-irrigation wells are pumped only during the season that begins about May 1 and lasts approximately 130 days. The pumpage in the Houston and Pasadena areas, although continuous, is much heavier in the summer than it is during the remainder of the year. Therefore, for convenience in compilation and in order that com arisons may be made, the withdrawals in all three areas are given as daily averages for the entire year. The City of Houston pumpage in 1946 includes 1,024 acre-feet (334,000,000 gallons) sold at the Southwest well field for the irrigation of rice land.

PUMPAGE AND DECLINE OF ARTESIAN PRESSURES IN THE HOUSTON AND PASADENA AREAS

PUMPAGE

In 1930 and 1931 the average pumpage in the Houston and Pasadena areas was about 50,000,000 gallons a day. This was reduced somewhat during the depression in 1932-35, but in 1936 the withdrawals were about the same as they were in 1930-31. In 1937 new development in the Pasadena industrial area brought the total to 70,000,000 gallons a day, an increase of 40 percent. The pumpage increased slightly from 1937 to 1941, but from 1941 through 1948 it increased steadily at an almost phenomenal rate. The 1949 pumpage for the Houston and Pasadena areas showed only a small increase over 1948 and for the Katy area there was a reduction of about 18 percent.

In 1949 there were 318 wells in service in the Houston and Pasadena areas, of which 39 were operated by the Houston Water Department, 64 by suburban communities and water districts, and the remainder by independent interests, mostly industrial plants. Industrial requirements for water are supplied largely from privately owned wells. The heaviest consumers are oil refineries, a paper mill, chemical plants, a steel mill, breweries, ice plants, railroads, packing plants, and launderies.

The combined withdrawals of ground water in the Houston and Pasadena pumping areas averaged about 150,000,000 gallons a day in 1949, as compared with 77,000,000 gallons in 1941. In 9 years, therefore, the pumpage practically doubled.

The estimated average daily withdrawal of ground water for public and industrial supplies in the Houston and Pasadena areas during 1949 is given in table 2. The table is subdivided to show separately pumpage by the Houston Water Department, by independent water-supply agencies, and by the different classes of industries that use more than 5,000 gallons a day.

Table 2. Estimated average daily pumpage for public and industrial supplies in the Houston and Pasadena areas in 1949

	Number of plants	Number of wells	Pumpage (million gallons a day)
Public supplies			
Houston Water Department	7	39	60.4
Independent public supplies	34	64	10.8
Industrial supplies			
Paper mill	1	9	18.0
Chemical plants	11	21	9.3
Oil refineries	8	31	21.8
Steel mill	1	8	6.5
Ice plants	17	22	4.5
Power plants	4	13	6.0
Tool companies	5	9	2.2
Railroads and allied plants	12	15	2.3
Meat packing plants	3	5	0.9
Laundries	8	8	0.4
Ship yards	1	2	0.2
Miscellaneous supplies			
Office buildings, hotels, theatres, country clubs, and plants using small supplies exceeding 5,000 gallons a day	59	72	6.1
Totals	171	318	149.7

Table 3. Average daily pumpage by well fields of the Houston Water Department

Well field	1935	1940	1941	1942	1943	1944	1945	1946	1947	1948	1949
				Thousands of gallons a day							
Central	5.122	5,997	5,380	6,320	8,408	9,367	8,642	7,337	7,503	9,021	7,683
Heights	5,159	5,242	5,220	5,460	5,743	6,408	7,925	8,930	8,576	8,376	9,293
Scott Street	7,822	7,587	7,600	7,620	8,350	7,657	5,777	6,550	7,138	6,509	5,498
South End	4,651	6,143	5,550	6,330	6,019	7,862	9,809	6,644	7,483	8,022	7,763
East End	-	1,517	1,350	1,600	1,724	2,789	3,220	3,688	3,756	4,194	5,783
Northeast	510	2,321	2,170	3,110	4,789	5,413	6,244	5,213	5,546	6,147	6,206
Magnolia Park	1,104	49	210	-	114	a/	-	-	-	-	-
Southwest	-	-	-	-	-	-	1,570	12,900	15,775	18,633	18,170
TOTAL	24,362	28,800	27,200	30,500	35,147	39,495	43,187	51,262	55,777	60,903	60,396

a/ Plant abandoned.

In 1949, the Houston Water Department operated 39 wells in seven widely-spaced fields within and adjacent to the city (see fig. 2). The daily pumpage for the year averaged 60,400,000 gallons as compared with 30,500,000 gallons a day in 1942, when the period of phenomenal increase in pumpage began. Figure 4 shows the average daily pumpage by the Houston Water Department and monthly precipitation at Houston for the period 1940 through 1949.

Table 3 gives the average daily pumpage from each municipal well field in 1935 and from 1940 to 1949, inclusive.

DECLINE OF ARTESIAN PRESSURES

The artesian pressures in observation wells of the Houston and Pasadena areas showed comparatively little net annual change from 1930 to 1936. A general decline occurred in 1937-38 resulting from the increase in pumping in the Pasadena area in 1937. During 1939-41 the decline continued at a somewhat slower rate, but during the 7 years starting with 1942, the average yearly rate of decline was greater than at any time during the period of record. The decline in pressures was especially rapid from the spring of 1946 to the spring of 1949. However, the records show that from the spring of 1949 to February 1950 the rate of decline decreased and several wells showed a small rise.

The declines of artesian pressures in wells that are screened opposite the heavily-pumped sands in six subdivisions of the Houston and Pasadena areas are given in table 4 for periods ranging from 1 year to 18 years. Following the table is a summary of the declines, with special reference to the large declines from 1946 to 1949, and the relatively small declines, or rises in some wells, between 1949 and 1950.

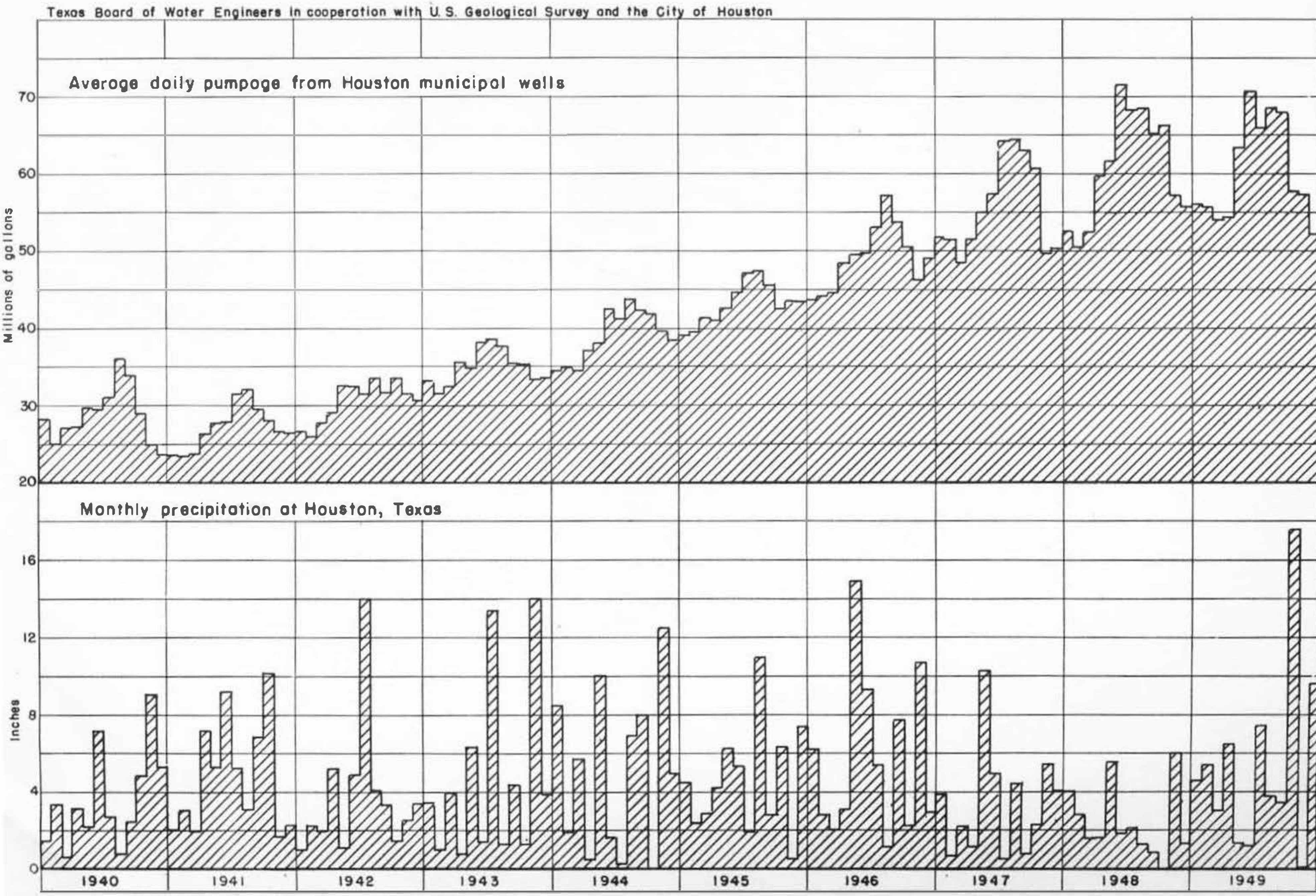

FIGURE 4.-Average pumpage from municipal wells and precipitation at Houston, Texas.

Table 4. Net decline or rise (+) of artesian pressures in wells screened opposite the heavily-pumped sands in the Houston, Pasadena, and adjacent localities, in feet, 1931-50 (based on spring measurements). (For location of wells, see figs. 1 and 2).

Well	Distance from Pasadena (miles)	Depth of well (ft.)	1931 to 1937	1937 to 1940	1940 to 1945	1945 to 1946	1946 to 1947	1947 to 1948	1948 to 1949	1946 to 1949	1940 to 1949	1937 to 1949	1931 to 1949	1949 to 1950
						Vicinity of Pasadena								
1182	½ N	685	--	--	73.8	+12.5	21.2	24.6	13.5	59.3	103.8	--	--	1.0
1170	1½ NW	836	--	51.0	65.5	+9.0	24.0	13.0	16.0	54.0	111.5	140.5	--	+3.0
1161	2 W	1,228	--	38.5	65.7	+5.5	18.1	13.4	15.5	47.0	108.2	128.4	--	1.5
1150	2½ NW	680	--	--	72.2	+7.9	18.2	15.3	16.9	50.4	114.8	150.6	--	--
1420	2½ NW	740	--	--	--	+7.4	19.4	14.9	16.4	50.7	--	--	--	6.2
1374	4 N	753	--	--	61.4	--	--	--	25.6	--	102.5	--	--	3.3
1229	4 S	1,680	--	--	44.9	6.3	11.4	+3.5	15.0	32.0	81.4	--	--	11.1
1230	4 S	1,419	--	--	49.5	3.4	14.8	9.3	16.6	39.8	94.0	--	--	11.6
1124	5½ E	1.329	--	--	49.2	.4	10.3	18.3	18.8	47.4	[illegible]	--	--	--
1126	5½ E	509	--	--	--	+9.2	11.8	11.5	--	--	--	--	--	--
936	6 N	619	--	--	31.7	2.3	6.7	10.3	11.4	30.8	64.8	--	--	6.3
1302	6½ S	832	--	27.3	41.2	4.8	8.2	--	--	--	--	--	--	--
933	7½ N	850	--	--	37.7	4.1	9.6	7.4	10.1	27.1	68.5	--	--	18.3
1100	7 E	900	--	--	35.6	+.6	6.9	9.6	19.0	35.5	70.3	--	--	14.1
1117	9 SE	526	--	--	28.5	.1	3.6	6.5	11.5	22.7	50.1	--	--	--
1121	9 SE	580	--	--	27.2	.7	7.4	--	--	--	--	--	--	--
943	9 NE	434	--	--	--	+1.3	3.8	8.5	14.3	26.6	--	--	--	4.0
1418	9½ S	1,348	--	--	--	4.7	7.6	6.4	13.8	27.8	--	--	--	--
947	10½ NE	312	--	--	12.9	2.0	1.7	4.3	7.0	13.0	27.1	--	--	2.6
1104	12 SE	570	--	--	29.0	1.0	5.8	7.8	14.9	28.8	56.6	--	--	4.7
1360	13½ SE	659	--	6.8	29.5	2.7	.3	6.1	--	--	--	--	--	.7
1019	14 E	450	--	.8	27.0	.0	4.3	8.7	14.8	28.3	56.5	--	--	--
						Eastern Houston								
811	4½ W	650	7.6	30.8	57.8	+12.1	22.5	11.8	14.6	49.0	94.7	118.0	122.3	1.0
878	5 W	905	10.5	37.7	54.7	+1.7	9.5	18.8	--	--	--	--	--	+3.5
913	5½ W	876	--	13.6	46.4	+1.7	16.2	6.1	13.3	35.6	80.3	99.2	--	--
759	5½ NW	569	14.8	32.3	47.2	+.9	15.6	10.9	13.1	40.0	86.4	110.2	125.0	--
879	5½ W	1,033	--	7.3	56.6	+7.9	15.4	8.2	11.3	35.0	83.8	--	--	3.9
876	6½ W	--	8.1	15.2	47.2	+4.4	15.7	8.2	11.2	35.2	78.1	96.6	104.7	3.6
757	6½ NW	676	12.0	29.7	42.1	1.9	14.4	10.9	11.7	37.0	81.0	105.7	114.4	2.5
751	7 NW	540	8.7	29.1	39.7	3.1	13.8	9.7	10.8	34.2	77.0	99.6	108.3	3.9
748	7½ NW	721	--	--	39.6	4.8	14.5	9.1	10.6	34.2	78.6	--	106.6	3.3
						Northern Houston								
663	10 NW	740	--	7.4	14.5	2.6	2.8	2.7	2.8	8.3	25.1	--	40.2	+3.3
1422	11 NW	--	--	--	--	5.2	15.2	11.8	12.1	35.0	--	--	--	.2
1398	11 NW	574	--	--	--	5.2	14.7	--	--	--	--	--	--	--
656	11½ NW	665	5.4	27.0	29.5	10.2	15.2	4.7	9.2	29.1	67.9	89.5	95.0	6.9
591	13½ NW	1.039	--	17.1	35.6	18.7	9.5	8.4	10.8	28.8	83.1	--	--	.3
1414	14 NW	834	--	--	--	11.7	9.2	8.3	11.6	29.1	--	--	--	--
538	15½ NW	481	--	--	--	7.5	9.2	8.8	8.9	26.9	--	--	--	1.7
						Central and western Houston								
853	9 W	650±	10.6	17.4	34.1	.4	.6	17.2	3.1	20.8	54.1	66.7	77.8	+7.7
854	9 W	919	--	6.0	15.1	2.3	4.8	8.5	5.9	7.3	30.7	66.6	--	+8.6
711	10 W	884	--	--	--	+3.3	17.4	11.3	11.9	40.6	--	--	--	--
619	10½ NW	625	13.5	18.4	35.1	+3.1	14.9	12.7	5.0	33.2	61.7	80.2	93.5	.3
623	11 NW	900±	--	6.0	26.5	2.9	5.0	7.5	5.2	17.7	47.1	--	--	--
602	13½ W	1,038	2.5	10.7	27.9	10.4	11.4	9.6	12.6	33.7	72.0	86.4	88.9	+7.4
1267	14 W	894	--	--	--	12.5	6.1	9.8	18.6	34.5	--	--	--	3.3
812	17 W	400±	--	--	--	6.6	8.4	9.8	9.5	27.8	--	--	--	2.2

Table 4. Net decline or rise (+) of artesian pressures in wells screened opposite the heavily-pumped sands in the Houston, Pasadena, and adjacent localities, in feet, 1931-50-Continued

Well	Distance from Pasadena (miles)	Depth of well (feet)	1931 to 1937	1937 to 1940	1940 to 1945	1945 to 1946	1946 to 1947	1947 to 1948	1948 to 1949	1946 to 1949	1940 to 1949	1937 to 1949	1931 to 1949	1949 to 1950
						West of Houston								
1417	15 SW	1,017	--	--	--	8.2	9.8	14.3	7.2	31.3	--	--	--	2.3
473	18½ W	416	--	--	13.5	7.0	7.7	9.1	9.6	26.4	46.0	--	--	.9
498	19½ W	707	--	3.7	14.0	6.3	7.5	9.4	+4.3	11.3	32.8	--	--	+1.9
490	23½ W	1.188	--	--	12.1	10.4	13.5	9.2	9.2	29.9	56.4	--	--	5.1
489	25½ W	472	--	--	6.6	3.5	3.8	6.9	7.7	18.1	29.1	--	--	+ .9
						North of Houston								
280	12 N	390	--	--	--	1.5	1.6	3.5	5.1	10.2	--	--	--	3.1
286	13½ N	250	--	--	--	3.1	2.3	3.6	5.0	10.9	--	--	--	+17.0
650	14 NW	468	--	5.8	19.0	8.8	6.1	6.2	7.7	20.0	47.3	--	--	--
287	14½ N	355	--	--	--	6.5	4.0	6.1	6.6	16.6	--	--	--	--
649	16 NW	367	--	4.8	14.2	9.5	5.6	6.7	8.2	30.3	43.3	--	--	--
291	17 N	1.308	--	--	--	2.2	1.8	3.8	3.8	7.4	--	--	--	1.9
1501	17 N	200±	--	--	--	1.3	.6	3.0	6.2	8.5	--	--	--	+ .8
290	17½ N	296	--	--	--	2.6	3.2	2.5	7.6	13.2	--	--	--	1.9
302	18 N	1,000±	--	2.7	8.4	8.1	4.5	5.3	6.6	16.4	31.8	--	--	5.8
456	20 NW	230	--	1.1	7.0	5.5	3.8	7.1	8.3	19.2	30.6	--	41.5	.5
264a/	21 NW	1,130	19.4	17.2	+1.1	6.6	2.3	5.5	5.6	13.3	18.8	--	55.6	.0
1506	21 NW	600±	--	--	--	9.5	3.5	7.0	--	--	--	--	--	.8
225a/	23½ NW	616	2.5	--	+3.6	21.5	4.2	6.8	6.3	17.3	35.2	--	--	.7
268a/	24½ N	793	--	--	20.1	28.6	9.4	4.8	--	--	--	--	--	1.6
269	24½ N	1,051	--	--	--	3.0	6.0	5.9	5.5	16.8	--	--	--	9.3
221a/	24½ NW	208	--	2.6	+7.8	10.8	1.3	5.9	7.1	14.3	17.3	--	--	+2.1
226a/	25 NW	740	--	--	--	12.0	3.7	5.8	--	--	--	--	--	+14.6
205	27 NW	625	--	2.3	--	--	4.5	5.6	--	--	--	--	--	--

a/ Water level affected by defective gas well in Bammel gas field.

Vicinity of Pasadena.- In 17 observation wells within a radius of 14 miles from Pasadena, declines of artesian pressures from 1946 to 1949 ranged from 13.0 feet to 59.3 feet and averaged 36.3 feet. The average decline by years was as follows: 1946-47, 11.0 feet; 1947-48, 10.9 feet; 1948-49, 14.4 feet. In seven of the wells that are within a radius of 4 miles from Pasadena, the declines from 1941 to 1949 ranged from 32.0 to 59.3 feet, and averaged 47.6 feet. In three of the wells within 2½ miles from Pasadena and near the center of the cone of depression there was an average decline of 139.8 feet between 1937 and 1949. From spring measurements in 1949 to February 1950 the average decline in 14 of the wells was 6.8 feet, but one well showed a rise of 3 feet. Of the 14 wells, nine are within a radius of 4 miles of Pasadena and showed declines that averaged 8.1 feet. Figure 5 shows the hydrographs of two of the wells in the last group, numbers 1170 and 1230.

Eastern Houston.- In eight observation wells in eastern Houston the declines in artesian pressures from 1946 to 1949 ranged from 34.2 feet to 49.0 feet and averaged 37.5 feet. The average decline by years was as follows: 1946-47, 16.0 feet; 1947-48, 9.4 feet; and 1948-49, 12.1 feet. From the spring of 1949 to February 1950 the average decline for six of these wells was 3.1 feet, and one well showed a rise of 3.5 feet. In six of these wells for which measurements are available for comparison, an average decline of 113.5 feet was recorded between 1931 and 1949. The hydrographs of three of the wells, numbers 751, 759, and 881, are shown in figure 6.

FIGURE 5.-Decline of artesian pressure in the Pasadena area, Texas.

mic 10-50

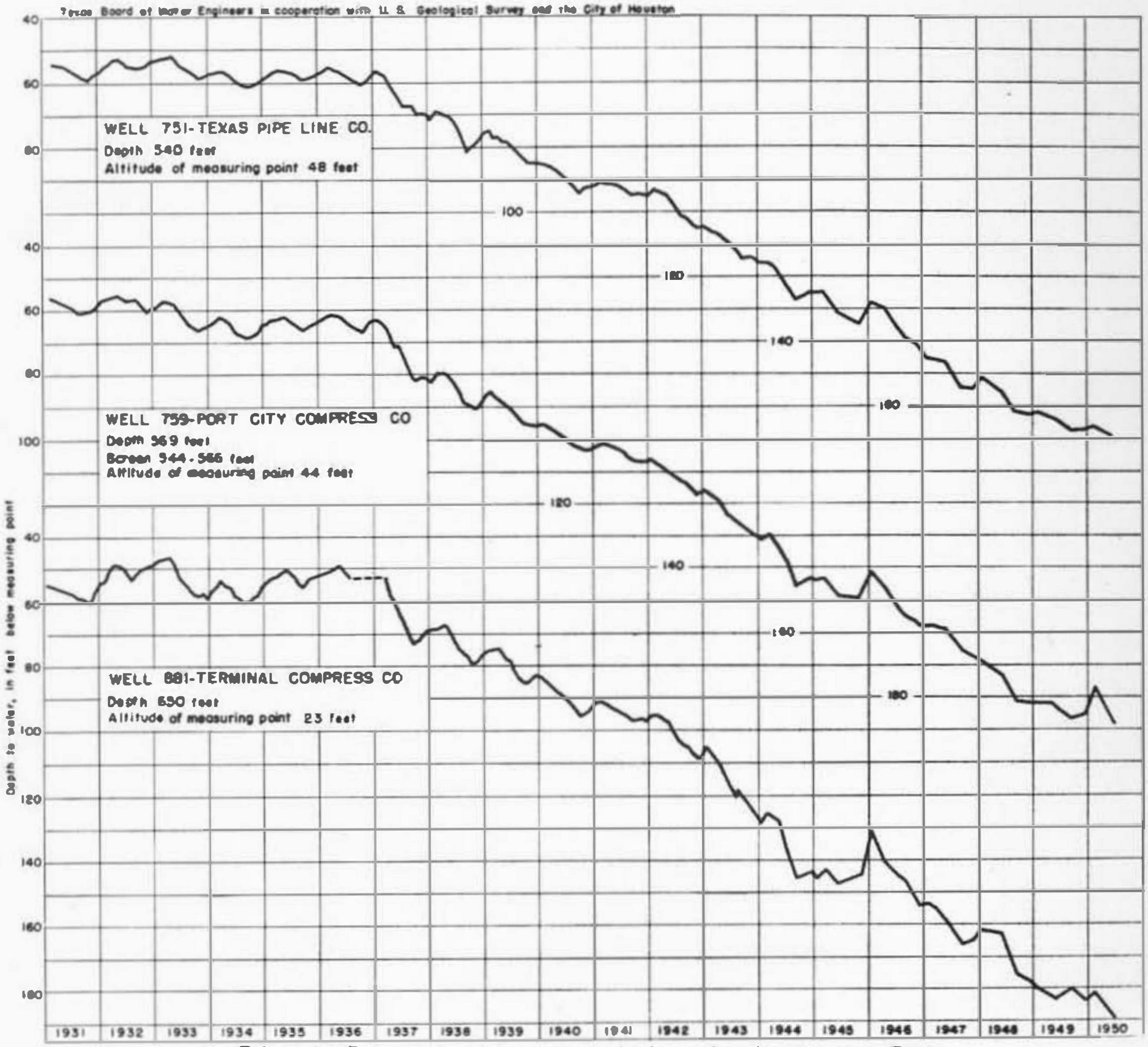

FIGURE 6.-Decline of artesian pressure in the eastern Houston area, Texas.

mlc 10-50

Northern Houston.- In six observation wells in northern Houston, the declines in artesian pressures between 1946 and 1949 ranged from 8.3 feet to 35.0 feet and averaged 26.9 feet. The average decline by years was as follows: 1946-47, 10.3 feet; 1947-48, 7.4 feet; and 1948-49, 9.2 feet. The average decline in four of the wells from 1949 to 1950 averaged 2.3 feet, and one well showed a rise of 3.3 feet. Measurements in two of these wells, numbers 663 and 656, show declines of 40.2 and 95.0 feet, respectively, between 1931 and 1939. The hydrograph of well 656 is shown in figure 7.

Central and western Houston.- Eight observation wells in central and western Houston show declines in artesian pressures between 1946 and 1949 ranging from 7.3 feet to 40.6 feet and averaging 28.3 feet. The average decline by years was as follows: 1946-47, 8.6 feet; 1947-48, 10.7 feet; and 1948-49, 9.0 feet. In three of the eight wells the declines from 1949 to 1950 were 0.3 foot, 2.2, and 3.3 feet; three wells showed rises of 7.4, 7.7, and 8.6 feet; and two wells did not have comparative measurements. From 1931 to 1949 the declines in three wells which have comparative measurements, numbers 602, 619, and 853 was 88.9, 93.5, and 77.8 feet, respectively. The decline in well 619 is shown by the hydrograph in figure 8.

West of Houston.- Five observation wells in the area west of Houston showed an average decline in artesian pressures between the spring measurements of 1946 and 1949 ranging from 11.3 feet to 31.3 feet and averaging 23.2 feet. The average decline by years was as follows: 1946-47, 8.5 feet; 1947-48, 9.8 feet; 1948-49, 5.9 feet. The decline in four of the wells between 1940 and 1949 averaged 41.1 feet. From 1949 to 1950 the decline in three of the wells was 0.9 foot, 2.3, and 5.1 feet, and two wells showed rises of 0.9 foot and 1.9 feet. The hydrographs of well 489 in figure 7 illustrates the fluctuation of artesian pressure in the area. The seasonal fluctuations shown by the hydrographs are believed to be due primarily to withdrawals for rice irrigation. The artesian pressures decline during the rice-pumping season and recover partially during the fall and winter.

North of Houston.- In the area north of Houston the decline in artesian pressures in 14 observation wells ranged from 7.4 to 30.3 feet and averaged 14.9 feet from 1946 to 1949. The average decline by years was as follows: 1946-47, 3.4 feet; 1947-48, 5.1 feet; 1948-49, 6.4 feet. Of these wells, 10 showed declines that averaged 2.6 feet and four showed rises that averaged 8.6 feet from 1949 to 1950. The declines in two of the wells, numbers 264 and 456, between 1931 and 1949 were 55.6 and 41.5 feet, respectively.

Wells screened opposite lightly pumped sands.- In observation wells that are screened opposite the lightly pumped, comparatively shallow sands the artesian pressures show trends similar to those that are screened in the deeper, more heavily pumped sands, but the average rate of decline is much less. In five widely separated observation wells the declines between the spring measurements in 1946 and 1949 ranged from 7.4 feet to 31.8 feet and averaged 15.6 feet. The average decline by years since 1946 in four of the wells was as follows: 1946-47, 4.1 feet; 1947-48, 2.8 feet; 1948-49, 7.8 feet. From 1949 to 1950, two of the wells showed declines of 3.2 and 3.5 feet while three wells showed rises of 1.1, 6.3, and 9.6 feet. In two of the wells there was an average decline of 33.7 feet during the 18-year period from 1931 to 1949. The hydrograph of well 604 (fig. 8) illustrates the fluctuations of artesian pressures in wells drawing from the lightly pumped sands.

Table 5 shows the declines in widely spaced wells that draw from the lightly pumped sands.

FIGURE 7.-Decline of artesian pressure in northern Houston and area west of Houston, Texas.

mic 10-50

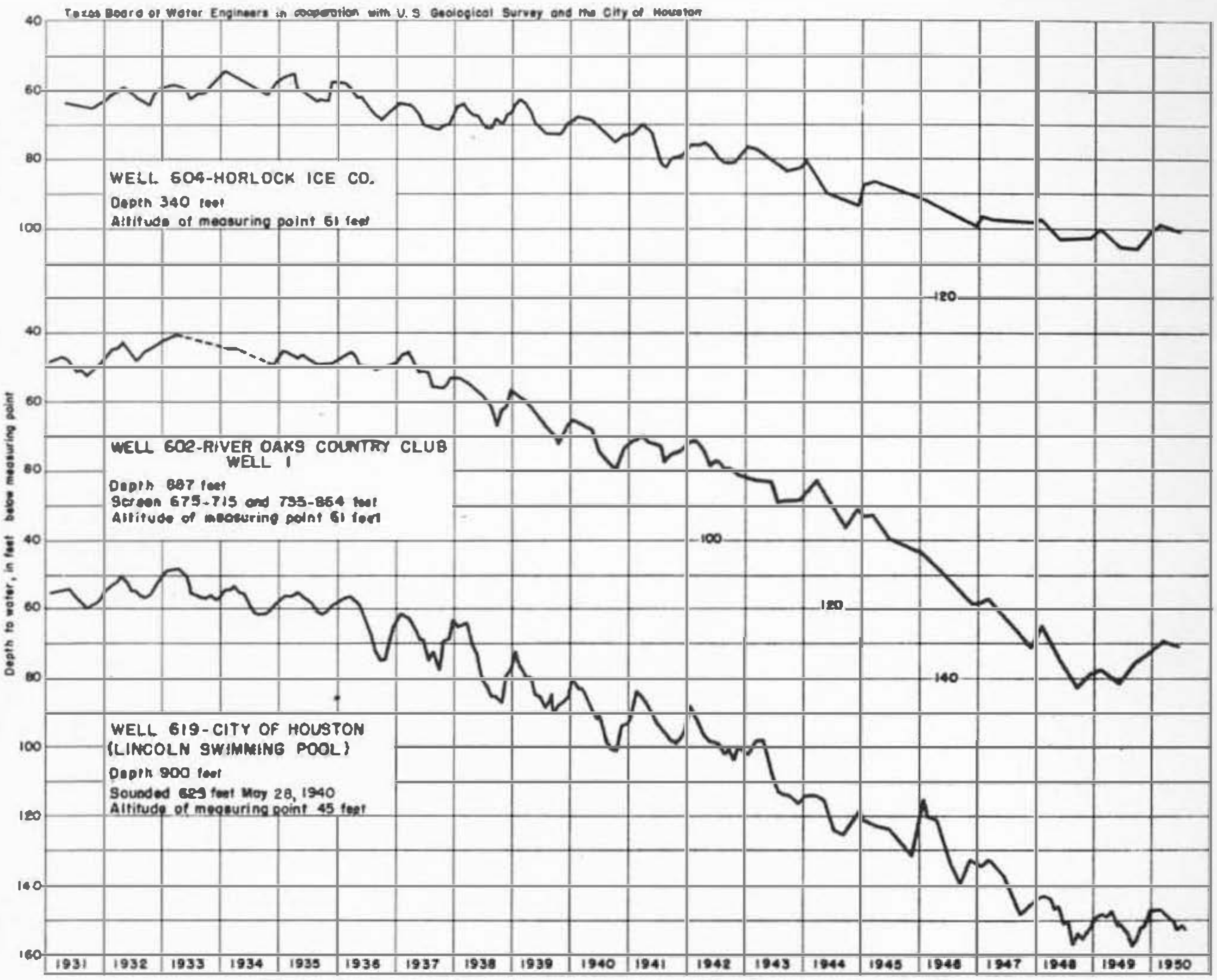

FIGURE 8.-Decline of artesian pressure in central and western Houston, Texas.

mk 10-50

Table 5. Net decline or rise (+) of artesian pressures in wells that draw from lightly pumped, comparatively shallow sands in the Houston, Pasadena, and adjacent localities, in feet, 1931-50 (based on spring measurements). (For location of wells, see figs. 1 and 2.)

Well	Distance from Pasadena (miles)	Depth of well (feet)	1939 to 1940	1940 to 1941	1940 to 1945	1945 to 1946	1946 to 1947	1947 to 1948	1948 to 1949	1949 to 1950	1946 to 1949	1940 to 1949	1937 to 1949	1931 to 1949	1949 to 1950
1234	4½ S	316	--	--	--	8.3	+13.7	--	--	+6.3	19.2	--	--	--	+6.3
934	7 N	135	--	18.1	32.5	3.7	2.3	3.3	5.8	3.17	11.4	46.4	--	--	3.2
909	8 SW	342	--	1.5	8.7	3.6	2.4	3.3	2.6	3.27	8.2	20.0	--	38.3	3.5
778	11 W	404	3.8	1.1	24.2	+10.5	8.3	4.4	19.2	--	31.8	44.6	--	--	+9.6
608	12 NW	350	4.4	4.1	21.3	2.8	4.8	--	--	--	--	--	--	--	--
604	12½ NW	340	4.9	2.2	18.3	5.8	3.3	.4	3.8	+1.66	7.4	32.6	32.9	29.2	+1.1

Houston municipal wells.- Table 6 shows the changes in artesian pressures based on spring measurements in the Houston municipal wells for the periods 1939-49, 1946-49, and 1948-49.

Table 6. Net decline or rise (+) of artesian pressures, in feet, in Houston municipal wells, 1939 to 1949 (based on spring measurements)

Plant	Office no.	City well no.	Date (1948)	Depth to water	Length of shut-down	Date (1949)	Depth to water	Length of shut-down	1948 to 1949	1946 to 1949	1939 to 1949
Central	617	F-1	Mar. 4	185.0	35 min.	Mar. 4	186.0	10 hrs.	1.0	--	92.7
	616	F-5	4	194.31	45 min.	3	191.98	12 hrs.	+2.3	44.8	98.9
	618	F-10	9	178.52	Unused	--	--	--	--	44.6	98.9
	624	F-11	4	183.81	55 min.	--	--	--	--	--	--
	625	F-12	4	184.0	30 min.	3	183.0	12 hrs.	+1.0	53.0	97.4
		C-16	9	190.30	Unused	--	--	--	--	--	--
		D-17	4	174.42	30 min.	4	177.17	3 days	2.8	--	89.6
		C-18	4	171.80	30 min.	4	170.36	35 min.	+1.4	40.1	--
		C-19	Apr. 17	206.60	1 hr.	4	205.0	45 min.	+1.6	--	--
East End	895	1	Mar. 7	199.15	45 min.	Feb. 23	207.90	5 days	8.8	31.3	110.4
		2	7	208.0	1 hr. 15 min.	Mar. 3	227.27	1 hr. 10 min.	19.2	42.8?	--
Heights	591	3	Feb. 4	164.35	Unused	Feb. 7	175.20	Unused	10.8	28.8	87.7
	589	5	Mar. 5	157.57	1 hr. 30 min.	--	--	--	--	--	--
	1410	6	5	164.85	1 hr. 10 min.	25	189.57	1 hr.	24.8	49.7	111.1
	1412	7	5	162.32	8 hr. 40 min.	25	179.80	50 min.	17.5	35.8	90.5
	1411	8	4	163.86	2 days	23	176.47	36 hrs.	12.6	26.7	84.6
Northeast	744	1	10	147.64	2 weeks	Mar. 1	160.72	24 hrs.	13.1	37.8	110.8
	1395	2	10	159.0	11 hrs. 30 min.	2	175.0	1 hr.	16.0	42.9	92.9
		3	11	147.62	4 hrs. 30 min.	2	163.84	1 hr. 50 min.	16.2	35.9	--
Scott Street	855	2	8	187.07	Unused	Feb. 23	194.22	Unused	7.2	40.4	99.4
	857	3	8	161.10	2 months	Mar. 2	189.0	50 min.	27.9	42.6	90.7
	858	4	10	180.0	45 min.	2	187.0	35 min.	7.0	39.4	93.5
	757	5	10	160.0	30 min.	2	179.0	40 min.	19.0	29.0	81.6
South End	795	2	8	128.96	6 days	--	--	--	--	--	--
	794	4	8	107.38	6 days	--	--	--	--	--	--
	793	5	9	194.72	50 min.	--	--	--	--	--	--
		7	9	197.65	1 hr. 10 min.	--	--	--	--	--	--

Table 6. Decline of artesian pressures, in feet, recorded in Houston municipal wells, Southwest field, 1945 to 1949 (based on spring measurements)

Well	Date (1948)	Depth to water	Length of shut-down	Date (1949)	Depth to water	Length of shut-down	1948 to 1949	1946 to 1949	1945 to 1949
1	Feb. 19	153.52	24 hrs.	May 20	172.79	30 min.	19.3	--	74.8
2	20	135.50?	20 hrs.	Mar. 3	167.28	1 hr.35 min.	31.8	--	72.4
3	20	148.71	21 hrs.	3	172.32	1 hr.50 min.	23.6	--	78.2
4	20	146.68	22 hrs.	3	169.85	45 min.	23.2	51.5	77.8
5	20	147.38	22 hrs.	3	169.28	1 hr.	21.9	57.9	77.7
6	19	139.28	6 hrs.	2	147.81	1 week	8.5	46.6	61.5
7	19	127.30	10 days	Feb. 10	144.02	3 days	16.7	--	17.9 a/
8	19	110.12	10 days	10	124.16	3 days	14.0	--	17.5 a/

a/ 1947 to 1949

Most of the measurements in the foregoing tables do not represent the actual static pressures because as a rule the pumps could not be shut down sufficient lengths of time to permit complete recovery; however, the computed average decline at each well field represents at least the magnitude of the decline in that field.

In the Central field, four of the wells showed an average decline of 94.6 feet between 1939 and 1949; four showed an average decline of 45.6 feet from 1946 to 1949; and two showed a very small decline and three others a small rise between 1948 and 1949. This change in the prevailing trend was due to a reduction in the rate of pumping for some time before the measurements were made in 1949; the average pumpage at the field was 9,152,000 gallons a day in February 1948, compared with 6,653,000 gallons a day in February 1949.

In the East End field, well 1 showed a decline of 110.4 feet between 1939 and 1949, a decline of 31.3 feet between 1946 and 1949, and a decline of 8.8 feet between 1948 and 1949. An increase in the rate of decline in the field is anticipated as a result of increased pumpage because four new wells have been added since 1946.

In the Heights field four of the wells had an average decline of 93.5 feet between 1939 and 1949; 35.2 feet between 1946 and 1949, and 16.4 feet between 1948 and 1949. It is expected this rate of decline will increase after the seven new wells in the field are put in operation.

In the Northeast field the decline in two wells averaged 101.8 feet between 1939 and 1949. In three wells the declines averaged 38.9 feet from 1946 to 1949 and 15.1 feet from 1948 to 1949. An increase in the rate of decline is expected when the eight new wells now constructed or planned are put in operation.

At the Scott Street field the declines in four of the wells averaged 91.3 feet from 1939 to 1949, 37.8 feet from 1946 to 1949, and 15.3 feet from 1948 to 1949.

In six wells in the Southwest field the decline in static pressures averaged 73.7 feet from 1945 to 1949, and in eight wells the decline averaged 19.9 feet from 1948 to 1949.

PUMPAGE AND DECLINE OF ARTESIAN PRESSURES IN THE KATY AREA

PUMPAGE

The Katy rice-growing area comprises parts of western Harris County, northern Fort Bend County, and eastern Waller County. In this area the land in rice production increased from about 20,000 acres in 1939 to nearly 48,000 acres in 1949. All the rice is irrigated from ground water pumped from wells that range in depth from 200 to 1,600 feet. Table 7 shows the number of wells that were used for rice irrigation; the number of acres irrigated; the amount of water pumped, in acre-feet; and the amount of water in acre-feet, including rainfall, applied to the land per acre per season in 1930, 1935, 1937, and 1939 to 1949, inclusive.

Table 7. Pumpage and rainfall in the Katy rice-growing area

	1930	1935	1937	1939	1940	1941	1942	1943	1944	1945	1946	1947	1948	1949
Number of wells	45	40	61	78	88	95	108	112	115	123	125	144	150	157
Number of acres irrigated a/	9,000	8,000	13,750	19,950	24,200	27,350	30,418	30,416	31,740	34,320	37,530	44,900	47,600	47,650
Amount of water pumped, in acre-feet b/	20,200	15,700	33,600	44,900	50,400	25,800	43,600	58,000	64,000	56,000	67,000	84,000	138,000	109,000
Amount of water pumped per acre, in acre-feet	2.2	2.0	2.4	2.2	2.1	0.9	1.4	1.9	2.0	1.6	1.8	1.9	2.9	2.3
Rainfall, in feet, May through Sept. c/	0.9	1.9	0.9	1.6	1.4	2.6	1.9	2.0	1.8	2.2	2.5	1.5	0.7	1.3
Total amount of water applied to the land (irrigation and rainfall), in acre-feet per acre	3.1	3.8	3.4	3.8	3.5	3.5	3.3	3.8	3.7	3.8	4.3	3.4	3.6	3.6

a/ Records of the American Rice Growers Co-operative Association.

b/ One-acre foot equals 325,829 gallons.

c/ 1930-45, average of rainfall at Hempstead, Houston, Seely and Sugarland.

1946, average rainfall at Addicks, Alief, Barker, Hempstead, Hockley, Houston, Katy, Pattison, Satsuma, Seely, and Sugarland.

1947-48, average of rainfall at Addicks, Alief, Barker, Cypress, Fairbanks, Gaston, Hempstead, Hockley, Houston, Katy, North Houston, Satsuma, Seely, and Sugarland.

1949, average of rainfall at Addicks, Alief, Cypress, Fairbanks, Gaston, Hempstead, Houston, Katy, North Houston, Satsuma, Seely, and Sugarland.

According to the records, the pumpage for irrigation, usually varies inversely as the rainfall during the rice-growing season; the amount of water applied to the land from the two sources remaining remarkably uniform. The rainfall in 1947 was below normal throughout the Katy area, but the number of acre-feet pumped per acre was about the average recorded for 11 previous years. The rainfall during the irrigation season in 1948 was far below normal, only 0.7 foot as compared with an average of about 2.0 feet for the 6-year period, 1940-45. The pumpage during 1948 was 2.9 acre-feet per acre, which was greater than it was in any previous year of record, and the total pumpage was by far the largest. The rainfall during the irrigation season in 1949 also was below normal, and the pumpage was 2.3 acre-feet per acre making the total pumpage for 1949 the second highest on record. Pumpage, in acre feet, is given in table 7. For comparison with municipal and industrial pumpage, withdrawals in the Katy area, expressed as a daily average amounted to 98,000,000 gallons a day in 1949 as compared to 123,260,000 gallons a day in 1948, 74,990,000 gallons a day in 1947, 58,000,000 gallons a day in 1946, 50,000,000 gallons a day in 1945, 45,000,000 gallons a day in 1940, and 14,000,000 gallons a day in 1935.

DECLINE OF ARTESIAN PRESSURES

The Katy rice-growing area occupies a part of the outcrop of the sands that furnish water to Houston. Any material change of artesian pressures or water levels in the wells of the area, therefore, is especially significant. Periodic measurements of depths to water were started in 1931-32 in nine selected wells, all of which were within a radius of 8 miles from Katy. Later the program was expanded as the irrigation development increased and spread to new territory, and during 1941-49, 35 observation wells were measured.

During most of the period of record the measurements have been confined to late February or March, about 6 months after the close of the pumping season, and before the start of the next, thereby giving the artesian pressures and water levels the maximum possible opportunity to recover from the effect of local withdrawals. The average annual declines shown by the early spring measurements reflect closely the areal declines.

A summary of the fluctuations in the observation wells for the period of record is given in table 8. Fluctuations of the artesian pressure in well 223 in Waller County, 6½ miles northwest of Katy, is shown graphically in figure 9.

Table 8. Net decline or rise (+) of artesian pressures or water levels, in feet, in wells in Katy area (based on spring measurements)

Well	Depth of well	1931 to 1933	1933 to 1939	1939 to 1940	1940 to 1945	1945 to 1946	1946 to 1947	1947 to 1948	1948 to 1949	1931 to 1941	1946 to 1949	1941 to 1949	1931 to 1949
						Harris County							
40	497	--	--	--	--	+1.4	0.0	3.3	4.7	--	9.0	6.3	--
134	274	--	--	3.8	3.3	.4	.0	1.3	--	20.3	--	--	--
136	138	2.6	6.7	4.7	3.8	.5	+ .1	1.7	3.7	17.0	5.4	6.6	23.6
139	134	--	6.2	4.0	3.6	.1	+ .5	2.9	5.4	--	7.8	8.9	--
140	359	--	--	3.9	3.2	.4	+ .4	2.9	5.5	--	8.0	9.0	--
160	499	--	--	3.5	+6.6	1.6	.7	3.8	6.0	--	10.4	7.8	--
182	239	--	--	6.3	+3.9	.0	.3	4.0	4.6	--	8.9	--	--
186	628	--	--	2.5	+2.3	.8	.0	3.5	3.9	10.1	7.4	5.4	15.6
352	470	--	--	3.5	4.7	.8	.0	2.2	3.1	--	5.2	6.8	--
357	--	2.0	3.8	1.7	12.7	.6	+ .6	3.0	--	17.1	--	--	--
362	500	2.9	4.8	3.1	3.3	.7	+ .5	3.4	10.6	12.6	10.0	12.1	24.8
367	535	--	--	2.5	2.1	.8	+ .2	2.9	6.1	--	8.8	10.5	--
370	625	--	--	2.2	--	--	--	--	5.1	--	--	11.8	--
371	374	--	--	1.3	2.7	.9	.1	3.4	5.7	--	9.0	11.7	--
380	50±	--	--	.4	.8	+ .9	+ .6	2.4	--	--	--	--	--
381	95	2.5	3.0	1.5	.2	+1.2	+ .9	2.1	6.2	8.0	7.4	5.5	13.4
382	185	--	--	2.8	1.6	1.8	.5	3.7	6.2	--	10.4	2.6	--
384	505	--	5.1	2.8	.8	1.8	4.0	2.8	.7	--	7.5	8.5	--
385	359	--	2.7	2.3	.6	.7	.6	1.8	6.4	--	8.8	9.5	--
399	326	--	--	1.8	2.7	.5	.0	1.8	4.4	--	6.1	5.7	--
480	512	--	--	--	--	2.2	2.0	5.8	6.9	--	13.9	19.1	--
						Fort Bend County							
7	653	.1	3.1	2.0	2.0	1.1	+ .1	2.1	3.5	6.8	5.6	7.2	14.0
11	170±	--	2.3	2.3	6.2	+ .4	+ .1	2.0	2.0	--	4.2	4.8	--
15	172	1.8	3.6	2.2	5.5	+1.1	.5	+4.8	3.5	9.8	+ .9	6.5	16.3
17	586	--	--	--	--	.9	+ .3	2.7	4.3	--	6.7	7.7	--
20	250	--	2.2	2.3	.7	.2	+2.8	8.6	--	--	--	--	--
21	--	1.3	1.8	1.9	.4	.0	.1	3.2	4.3	5.6	7.5	7.4	13.0
26	657	--	--	.3	+ .8	1.0	2.2	1.8	6.8	--	10.8	9.7	--
29	500	--	--	--	--	+ .7	--	--	--	--	--	--	--
30	334	--	--	--	--	+ .7	+ .6	1.1	3.1	--	3.6	1.7	--
33	346	--	--	1.7	3.4	.4	.4	1.2	2.1	--	4.3	6.3	--
						Waller County							
223	767	1.6	4.2	2.1	5.4	.8	+ .1	1.1	3.3	9.4	4.3	8.8	18.2
225	643	--	--	--	--	.8	+3.3	3.3	4.3	--	4.3	12.4	--
234-5	170±	2.3	6.6	3.5	2.5	1.0	.6	1.3	.9	13.9	4.8	6.7	20.6
239	--	--	--	--	--	+1.9	+4.5	4.2	5.8	--	5.4	9.0	--
240	290	--	--	--	--	.4	--	--	1.6	--	1.9	3.1	--
242	555	--	--	--	--	+1.1	+ .4	.6	1.3	--	1.5	5.9	--
245	482	--	--	--	--	2.4	+1.6	2.0	7.0	--	7.4	8.9	--
246	926	--	--	--	--	.4	--	--	4.0	--	5.3	9.0	--
247	641	--	--	2.0	5.1	.0	.6	1.7	2.8	--	5.2	8.8	--
252	246	--	--	--	3.9	1.0	.0	1.6	2.6	--	4.3	7.0	--

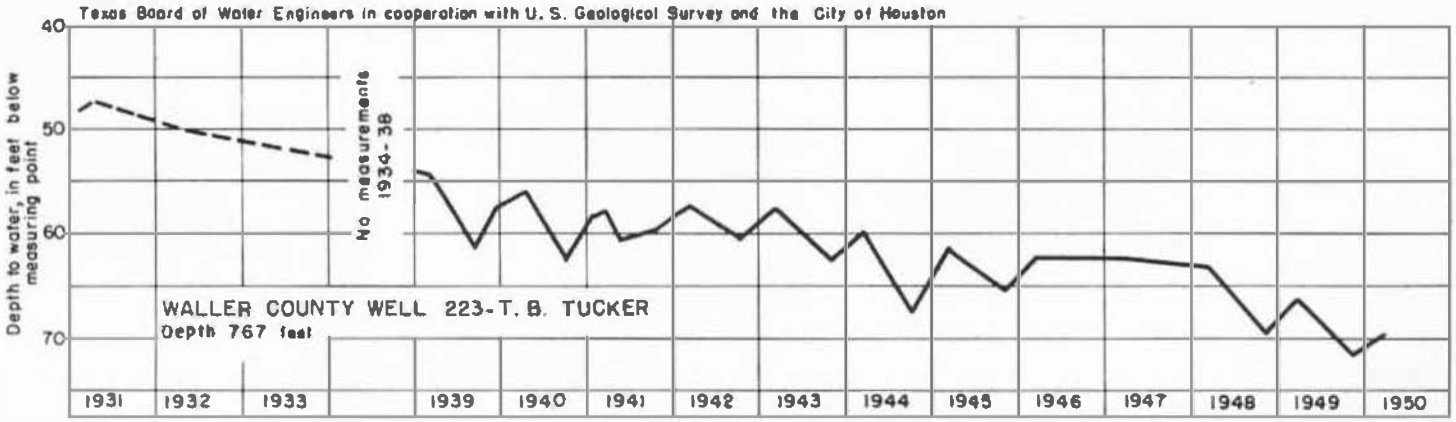

FIGURE 9.-Decline of artesian pressure in the Katy rice-growing area, Texas.

The records show that in the nine observation wells in the general vicinity of Katy net declines between 1931 and 1949 ranged from 13.0 feet to 24.8 feet and averaged 17.7 feet. About one-third of this decline, 5.5 feet, occurred between 1946 and 1949. Thirty-five observation wells, spaced at varying distances in the present enlarged area of pumping, showed an average decline of 8.0 feet between 1941 and 1949, of which 6.5 feet occurred between 1946 and 1949, and 4.1 feet between 1948 and 1949. The heavy decline between 1948 and 1949 was due to the unusually heavy pumping in 1948.

MAPS ILLUSTRATING DECLINE OF ARTESIAN PRESSURES IN WELLS FROM 1941 TO 1949

Maps have been prepared annually since 1940 illustrating the altitudes of water levels in wells based on spring measurements made in wells that penetrate the most heavily pumped sands of the Houston district. Many of these maps have been published in earlier reports. Figures 10 and 11 are maps drawn for the years 1941 and 1949. They show the position and areal extent of the cone of depression. That part of the area inside the -40 contour line bas been shaded for comparative purposes in order to illustrate the change in shape and size of the cone in the most intensively pumped parts of the district in Houston and along the Houston Ship Channel. The maps also show the approximate hydraulic gradient and the direction of movement of ground water which is approximately at right angles to the contours. Figure 12 illustrates the declines in artesian pressures from 1941 to 1949.

GEOLOGY AND ITS RELATION TO THE OCCURRENCE OF GROUND WATER

PHYSIOGRAPHY

The Houston district, in the West Gulf Coastal Plain, is divided physiographically into two parts by the Hockley escarpment, a southeast-facing feature that crosses central Waller County, northwestern Harris County, and southern Montgomery County. Barton [1] presented evidence that the scarp is a flexure scarp marking a deep-seated fault buried to some extent by later alluvial deposits. The importance of the fault in connection with artesian aquifers lies in the possibilities for the vertical rise of salt water along the fault plant into the upper fresh-water zones, or in the prevention of the movement of water down the dip from the outcrop into the ground-water reservoir in the Houston area. However, evidence has not been found during this investigation that such a fault extends upward into the late Miocene or Pliocene formations. Southeast of the Hockley escarpment a smooth, nearly featureless prairie rises gently from sea level to an altitude of about 160 feet at the foot of the scarp which is 80 miles inland. Only the few broad shallow valleys of the present streams and remnants of older stream channels break the monotony of this level depositional plain. West and northwest of the scarp a gently-rolling, stream-dissected plain has a southeastward slope of about 8 feet to the mile.

DRAINAGE

The Brazos River drains the extreme western part of the Houston district, the San Jacinto River drains the northeastern part, and Spring Creek, Cypress Creek, Buffalo Bayou and its tributaries, and Clear Creek drain the central and southern parts. The Brazos is an antecedent stream. According to Deussen [2] the Brazos antedates the deposition of the Tertiary plain, having been in existence on the Cretaceous plain when the shore line of the Gulf was far to the

1/ Barton, D. C., Surface geology of coastal southeast Texas: Bull. Amer. Assoc. Petrol. Geol., vol. 14, no. 10, pp. 1301-1320, 1930.

2/ Deussen, Alexander, Geology and underground water of the southeastern part of the Texas Coastal Plain: U. S. Geol. Survey Water-Supply Paper 335, 1914.

Texas Board of Water Engineers in cooperation with U. S. Geological Survey and the City of Houston

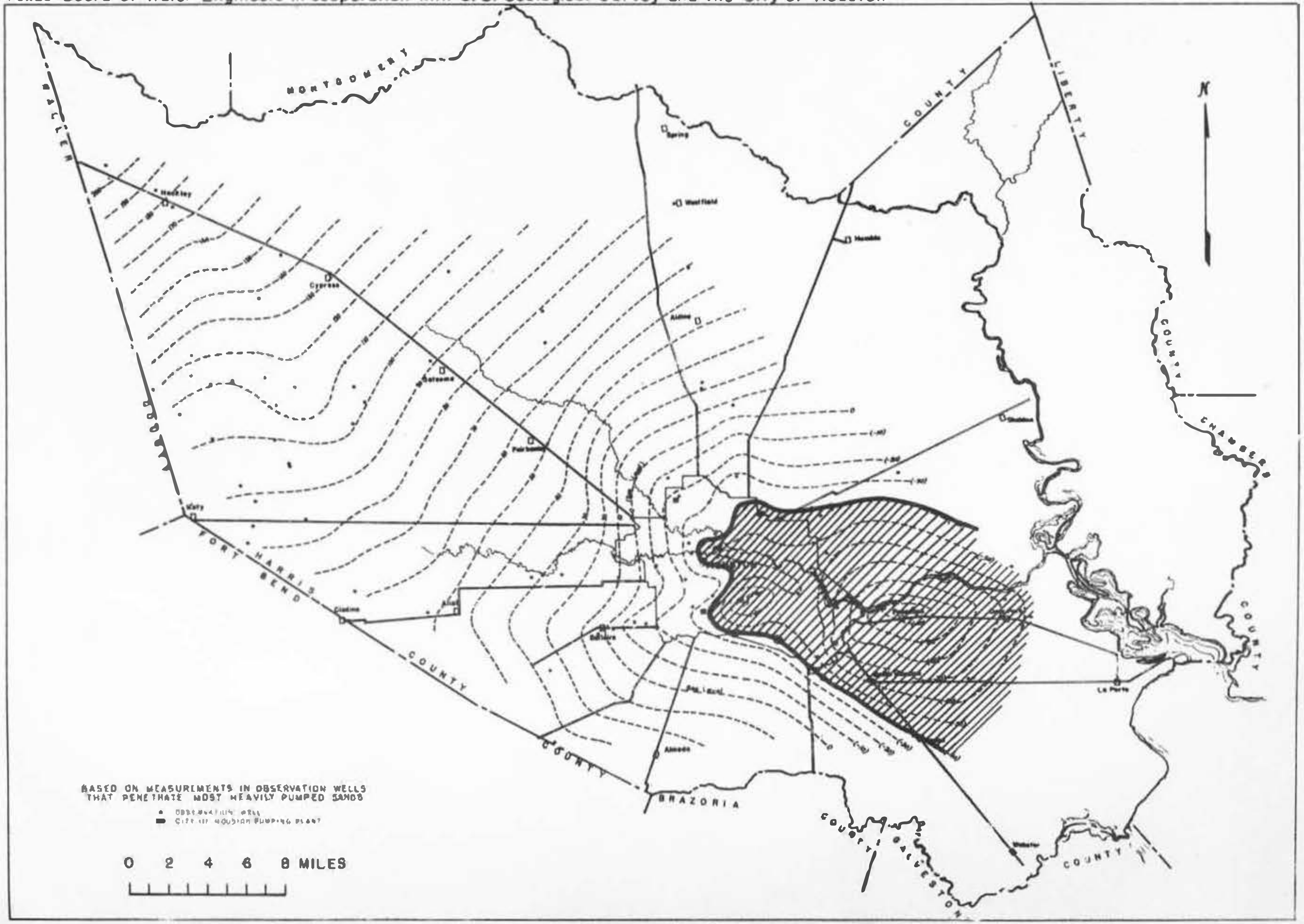

FIGURE 10.-Approximate altitudes of water levels, in feet, in wells in Houston district, Texas, January 1941.

Texas Board of Water Engineers in cooperation with U.S. Geological Survey and the City of Houston

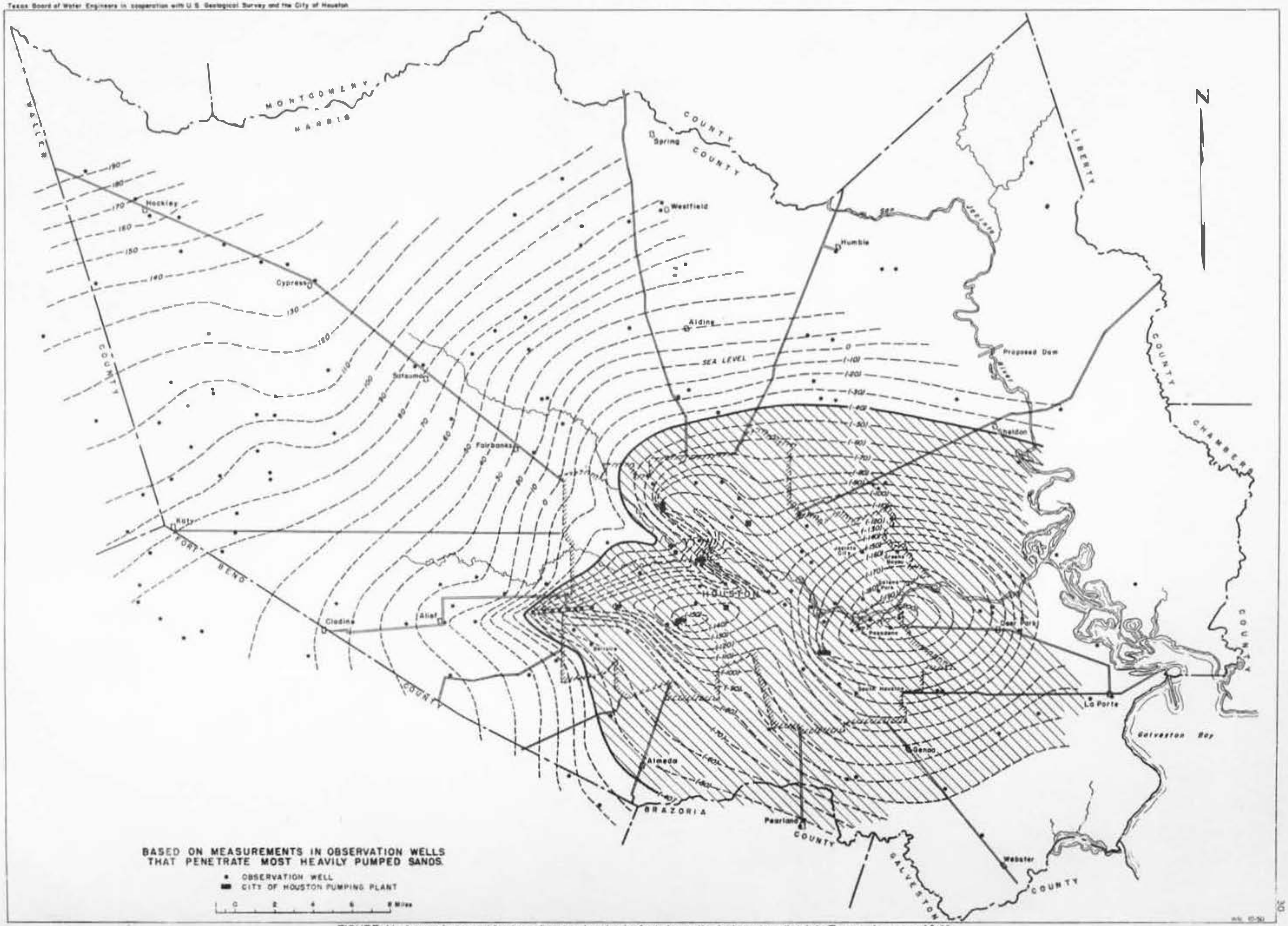

FIGURE 11.- Approximate altitudes of water levels, in feet, in wells in Houston district, Texas, January 1949.

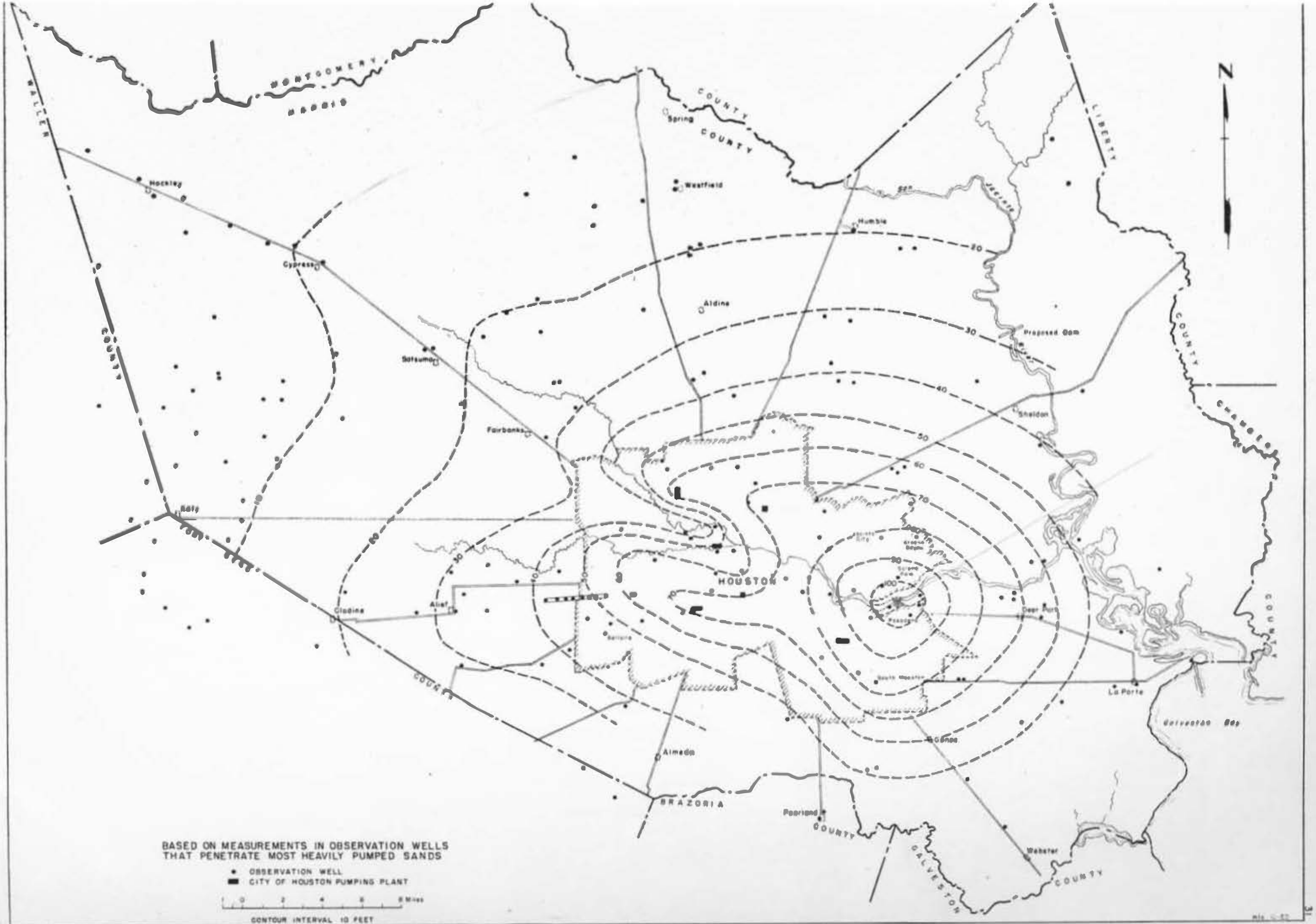

FIGURE 12-Declines of artesian pressure, in feet, from 1941 to 1949, Houston district, Texas.

north of its present position. In Tertiary time the Brazos extended its course as it contributed toward the building up of the Tertiary plain. During the late Tertiary and early Quaternary ages the river system brought in huge quantities of clay, silt, sand, and gravel from upstream sources; and these sediments were spread over the Houston district and adjacent territory as the courses of the streams shifted laterally over the nearly featureless coastal prairie. The stream channels were of such low gradient that they could not accommodate the flood waters and the sluggish streams overflowed, spread broadly, and meandered widely over the plain depositing a part of the load as alluvial fans which grew until they coalesced to form more or less continuous sheets of sediments.

The San Jacinto River is a consequent stream, having developed its course after the formation of the Tertiary plain. It has grown toward the interior by headwater erosion. The development of its drainage system began during Quaternary time (presumably late Pleistocene) and subsequently extended across the coastal prairies during Recent time. Buffalo Bayou, with its tributaries, and Clear Creek which bounds Harris County on the southeast developed during Recent time. These younger streams begin at the interior margins of the coastal prairie and include a number of creeks and bayous that are sluggish and contain brackish water in their lower reaches. Some of the smaller streams carry water only during and after heavy rains.

Discharge measurements of most of the streams in the Houston district and adjacent territory have been made and published annually in Water-Supply Papers by the Surface Water Branch, U. S. Geological Survey.

GEOLOGY AND STRUCTURE

The geologic formations from which the district obtains its water supply are as follows, from oldest to youngest: sands in the Lagarto clay of Miocene (?) age, the Goliad sand of Pliocene age, the Willis sand of Pliocene (?) age, the Lissie formation, and sands in the Beaumont clay of Pleistocene age (see table 9). The formations crop out in belts parallel to the coast as shown on the geologic map of Texas. (See fig. 13.) The dip of the beds is toward the southeast at an angle steeper than the slope of the land surface, and the formations are beveled at their outcrop by the land surface. Likewise, each formation is encountered at progressively greater depths toward the southeast as shown in plate 1. The estimated dip of the older beds is 50-60 feet to the mile and of the younger beds about 20 feet to the mile. The formations thicken considerably down dip. The rate of dip is variable owing to several salt-dome structures within or adjoining the district. Some of the salt domes, such as Pierce Junction and Blue Ridge a few miles south of Houston, and Barber's Hill about 20 miles east of Houston, are remarkable structural features consisting of upthrusts of large masses of salt piercing the younger formations from a deep-seated source, the geologic position of which is unknown. Plate 2, which is a northeast-southwest section approximately along the strike of the formations, shows the salt upthrusts that form the Blue Ridge and Barber's Hill salt domes and their relation to the nearby water-bearing strata.

Toward the interior successively older strata crop out, and the formation lowest in the geologic column has the highest topographic exposures. Such a structure together with the arrangement of the rocks, whereby permeable sands are interbedded with relatively impermeable clays and shales, makes an ideal condition for artesian water. Rain falling on the outcrops is conducted by slow percolation into the porous beds and is then transmitted down the dip to great depths beneath the surface.

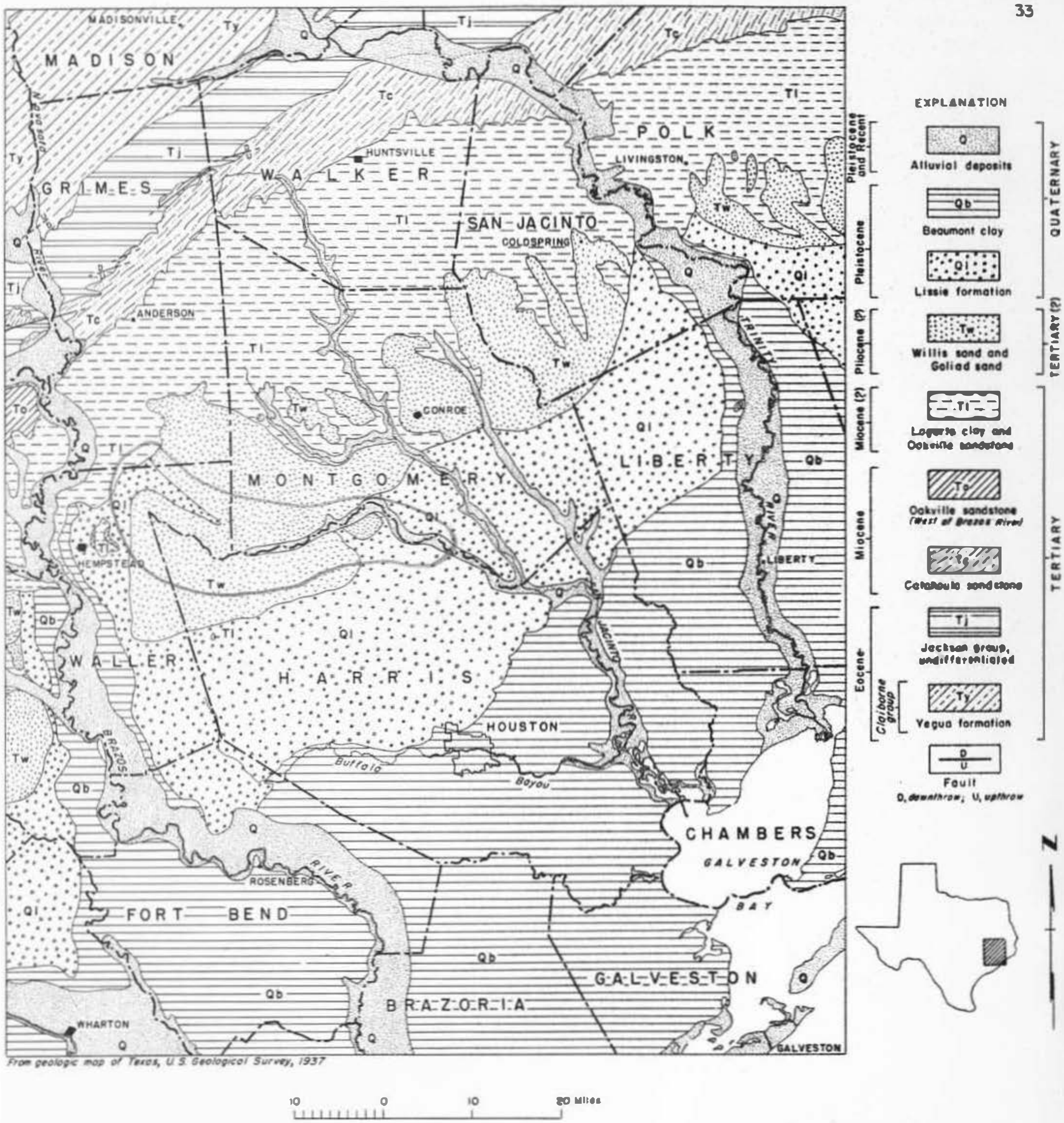

FIGURE 13.- Geologic map of a part of the Upper Gulf Coast, Texas.

Table 9. Outline of stratigraphy of the Houston district, Texas

System	Series	Formation	Approximate thickness (feet)	Lithologic character	Water-bearing properties
QUATERNARY	Recent		0-30	Fluviatile deposits of brown, red or black sandy clay and silt of low overflow stream terraces, and sand and gravel bars of present stream flood plains.	Not known to yield water to wells in material quantities. Test wells drilled in San Jacinto River flood plain by City of Houston yielded very small quantities of water.
	Pleistocene	Beaumont clay	0-800	Calcareous bluish-gray, red, brown, yellow, and purple clay containing lime nodules. Lenses of light-gray or bluish-gray fine-to medium-grained sand and sandy clay. Logs, peat, and plants, none of which are mineralized, are common; some shells are found in the clays. Several miles downdip from the outcrop very permeable sands occur which thicken toward the coast.	Upper sandy beds yield supplies of hard water to domestic and stock wells in the area south, southeast, and east of Houston. Basal 100 to 200 feet of the formation yields large supplies of good water for municipal and industrial uses along Houston Ship Channel and in Brazos and Galveston Counties. The water becomes salty near the coast.
		Lissie formation	0-1,600	Alternating beds of fine to coarse gray sand and thin lentils of fine gravel interbedded with gray, brown, blue, or red clayey sand and sandy clay. A few thin layers of lime-cemented sandstone may occur in the clay. Clay predominates in the upper part of the formation and sand in the lower part.	The thick sands in this formation yield large supplies of water to wells for rice irrigation in the outcrop areas, and to municipal and industrial wells in the Houston and Ship-Channel area and southward. Wells 100 feet deep or less generally yield very hard water, deeper wells yield softer water. The water becomes brackish downdip in north-central Brazoria and Galveston Counties and salty near the Gulf.
TERTIARY	Pliocene (?)	Willis sand	80-150	Reddish ferruginous fine to coarse sands, gravelly in places, disseminated clay and bentonitic material is present in varying amounts and acts as a binder to make the formation stand up in exposures. Basal 30 to 50 feet is mostly coarse quartz sand peppered with gravel, however gravel commonly occurs in small irregular lenses.	Yields abundant supplies of water of good quality, and together with the Lissie furnishes most of the water to wells for municipal, industrial, and rice-irrigation uses in the Houston district. Water generally is soft, even in shallow wells. South of Houston, in northern Brazoria and Galveston Counties, the water becomes brackish, and nearer the coast it becomes salty.
	Pliocene	Goliad sand	0-250	Chalky-white and pink bentonitic clays streaked with red and purple, and gravelly beds and lenses of lime-cemented sandstones. Sands are pinkish or whitish-gray and contain many black grains of chert giving a salt and pepper effect. The beds probably grade into and may be represented by basal Willis sands but cannot be positively separated from the Willis in well logs in the Houston district.	Sandy beds contribute large supplies of soft water to multiple-screened wells of City of Houston and many industrial plants. Water becomes salty south of Houston toward the coast.

Table 9. Outline of stratigraphy of the Houston district, Texas--Continued

System	Series	Formation	Approximate thickness (feet)	Lithologic character	Water-bearing properties
TERTIARY	Miocene (?) and Miocene	Lagarto clay and Oakville sandstone (undifferentiated)	1,100-2,000	Calcareous dull-yellow and gray to green clays and shales which are in general massive and tough and have a soapy feel. Several thick layers of medium-to coarse-grained gray or brown sand and many thin layers of hard lime-cemented sandstone are present in the clays and shales. Lower part of section includes cross-bedded light-gray massive sands and dirty-yellow or gray clays containing reworked Cretaceous fossils and volcanic ash.	The thick sands generally yield large quantities of soft water to wells in the Houston and Ship-Channel industrial areas. Thin sandstones may yield water that is rather highly mineralized in some areas. Salty water occurs in the formation in the La Porte-Baytown area in southeastern Harris County and downdip in Brazoria and Galveston Counties. The lower thick sands yield large quantities of water rather high in bicarbonate to some wells in Montgomery County, but generally the water in the immediate Houston area is comparatively highly mineralized and south of Houston is salty.
	Miocene	Catahoula sandstone	700-1,200	Argillaceous massive dark-brown, blue, and gray clays and silts, tuffaceous silts, and sands interbedded with sandstones. Sandstone beds are gray, brownish gray, and bluish gray and are medium-grained and cross-bedded; they consist of quartz grains with opaline cement. Conglomerate bed at base in some places.	Tests in north part of Houston indicate small amount of salty water in thin sandstones. Electrical logs indicate thick beds of sand containing potable water in Montgomery County and northern Waller County. Lower sandy beds generally yield fairly large quantities of hard but potable water to wells at Huntsville. Electrical logs of wells in Walker and Montgomery Counties and northern Harris and Waller Counties indicate the Catahoula may yield some potable water. Down dip at Houston the beds are 2,800 to more than 3,000 feet deep and contain highly mineralized waters.

Sediments making up these strata were derived largely from the limestones and marls of the Cretaceous formations, and from sands, gravels, silts, and clays of the older Tertiary formations. Redeposited Cretaceous fossils have been reported from the upper Miocene 3/. The sediments were laid down during several cycles of continental deposition and are largely fluviatile, deltaic, and lagoonal. Several series of coalescing river-built fans developed as depositional plains to form the Goliad, Willis, Lissie, and Beaumont formations. Doering 4/ presented evidence to indicate that the Goliad strata have been overlapped by the Willis in Montgomery County. Most of the sediments comprising the upper Miocene, Pliocene, and Pleistocene strata were transported and redeposited several times as the coastal plain was built up. Marine and lagoonal deposition together with wave and wind action were in progress along the coast.

3/ Sellards, E. H., Adkins, W. S., and Plummer, F. B., The geology of Texas, Univ. Texas Bull. 3232, pt.3, 1932, pp. 736-749.

4/ Doering, John, Post-Fleming surface formations of coastal southeast Texas and Louisiana, Bull. Amer. Assoc. Petrol. Geol., vol. 19, no. 5, (May 1935) pp. 651-688.

Owing to the mode of deposition, the formations are similar in lithology and origin and do not have persistent individual characteristics that can be traced downdip; and efforts to classify the sediments by mechanical analyses and by lithology according to groups that correspond to recognized formations in the outcrops have generally failed. White, Rose, and Guyton [5/], however, were able to recognize zones in the Houston district that are predominantly sand and zones that are predominantly clay. These zones are retained in this report and have been extended in more detail over a larger area by means of correlation on electrical logs of oil tests and water wells. The sand zones consist of extremely irregular and lenticular beds of gravel, sand, silt, and clay. The clay zones are made up of mottled calcareous massive clays that contain numerous thin beds and lenses of fine to medium-grained sands. Interfingering layers and lenses of massive clays grade laterally and vertically into the sand zones, and sands and gravels likewise grade into the clay zones. The thinner beds change character or pinch out within a few hundred feet. The lensing and intergrading within short distances is illustrated by plate 3, which is approximately a dip section extending a distance of 10.6 miles from the Northeast well field of the City of Houston south and southeastward to the East End well field.

Although the beds of clay are in general poorly stratified and persist only short distances, a few of the zones of clay beds have been traced across the district by means of electrical logs as shown in plates 1 and 2. A study of the electrical logs used in these sections together with many other logs, however, suggests that even though the clay zones appear to persist across the district, none of the individual beds of clay within the zones between the Lagarto clay and the Beaumont clay extends very far. If this condition exists, the clay zones are not extensive confining units within the Goliad, Willis and Lissie formations, which, therefore, may be considered a single aquifer. This is further suggested by the parallelism in fluctuations of artesian pressures in several observation wells, some of which are screened in the shallower sands and some in the deeper sands.

Plate 1 is a cross section down the dip of the formations from northern Montgomery County to the vicinity of Alta Loma, Galveston County, Texas, in which an attempt has been made to correlate the different zones with the surface outcrops of the formations; and also to correlate a few of the deeper formations that do not crop out in the area covered by the cross section. The so-called "Anahuac wedge" and the deeper rocks shown in the left-hand part of the section are based upon paleontological information supplied by various oil geologists. The correlations of the deeper beds have been shown on the section because they represent guides for making the shallower correlations and show the general thickening effect down dip that is characteristic of all the formations.

It is possible that some of the subsurface beds are not the equivalents of any outcropping beds. For example, the Goliad sand has not been mapped on the surface in Montgomery County, and evidence indicates that the strata have been overlapped by younger beds or wedge out similar to the deeper "Anahuac wedge". The so-called "Alta Loma" sand of Pleistocene age also may wedge out in subsurface and not appear in outcrop.

Plate 2 is a cross section approximately perpendicular to the section shown by plate 1. It extends from the Blue Ridge salt dome in Fort Bend County across the southeastern part of Houston to the Barber's Hill salt dome in Chambers County. These domes are roughly circular and the tops of the salt masses are about 1.5 miles across. The salt has pierced many thousand feet of overlying sediments and reaches to within a few hundred feet of the surface. No evidence has been found to indicate that the salt domes are an important source of contamination of the fresh-water sands, and it is believed that they are effectively sealed by impervious strata.

5/ White, W. N., Rose, N. A., and Guyton, W. F., Ground-water resources of the Houston district, U. S. Geol. Survey Water-Supply Paper 889-C, 1944.

The Lagarto clay and Oakville sandstone section probably includes zones 1 to 4 in plates 1 and 2. The Willis sand and Goliad (?) sand, the Lissie formation, and the Beaumont clay probably make up all or most of zones 5, 6, and 7. Most of the water wells in the Houston district draw from zones 3, 5, and 7. Down-dip from Houston, in extreme southeastern Harris County and northern Galveston County, the water in zones 3, 4, and 5 is too highly mineralized for public and most other uses. The shaded parts of the logs on plates 1 and 2 represent the part of the geologic section that contains potable water. It is interesting to note that in central and northern Montgomery County the base of the relatively potable water sands apparently lies at depths of 2,000 to 2,400 feet in the Catahoula sandstone or older formations, that the water in each formation becomes salty downdip, and that southward from the Harris-Galveston County line the gradient on the base of the potable water becomes very steep and the salty water lies at a depth of only about 800 feet in the "Alta Loma" sand at the south end of the section. The "Alta Loma" sand is an important aquifer along the Houston Ship Channel near Deer Park, Baytown, and La Porte; and it also furnishes water to the Galveston and Texas City municipal wells and many industrial wells between the Houston Ship Channel and Galveston.

Plate 3 is a cross section from the Northeast well field to the East End well field in Houston. The opportunity to construct this more detailed section was afforded by the recent drilling program of the City, which included electrical logging of the test hole drilled at the site for each production well. The drilling and logging of test holes at the sites for new industrial wells were also of valuable assistance. The lensing and intergrading of beds in short distances, making correlation of beds difficult or impossible, is illustrated by the section. No attempt has been made to give formation names or zone numbers to the beds. The shaded parts on the logs indicate places where drill-stem samples of water were taken, and the numbers indicate the chloride in parts per million.

SOURCE AND MOVEMENT OF GROUND WATER AND LOSSES FROM STORAGE

All the water pumped from wells in the Houston district comes from precipitation that enters the outcrops of the water-bearing sands northwest, north, and northeast of Houston. A large part of the rainfall on these areas is carried away by the streams, but a substantial part of it sinks into the soil, especially in sandy soil. During the late spring, summer, and early fall most of the water that enters the soil is lost by evaporation and transpiration. During the cool non-growing season, however, in large parts of these areas the water sinks downward through the permeable soil until less permeable underlying beds are encountered which slow the downward movement; and if the rainfall during this period is moderately heavy, a temporary shallow or perched water table is built up which frequently reaches nearly to the land surface. Later in the year a part of the soil moisture is lost by evaporation and transpiration, but a part of it percolates slowly downward to the permanent zone of saturation, the upper surface of which is the true water table. Thence the water moves laterally through the water-bearing beds into the artesian reservoir. The impulse which produces this movement and maintains pressure in the artesian reservoir is provided by gravity. The water at the outcrop is unconfined and the water table is higher than the water-bearing beds in the artesian area to the east and southeast which are confined between relatively impermeable silts and clays. The water at the outcrop, therefore, provides a hydraulic head just as a standpipe or elevated tank provides a head in a man-made water-supply system. If the man-made system is kept tightly closed the pressure per square inch at any point in the distribution system will be equal to the weight of a water column having a cross-sectional area of one square inch and a height equivalent to the difference in altitude between that point and the surface of the reservoir or stand pipe. If, however, a hydrant or faucet is opened and water is permitted to escape, the pressure at that point will be lowered and thereby a hydraulic gradient will be established toward it which will cause the water to flow. If many such outlets are opened the pressures may drop throughout the system and the flow from those outlets on higher grounds may cease, even if the water in the stand pipe or elevated tank is maintained at a constant level. There is still as much water in the system as ever, but a part of the pressure head has been lost by friction in the pipes which increases with the rate of movement of the water in them. If the water level at the source is permitted to drop, the rate of decline in pressure will be accelerated.

In the ground-water reservoirs of the Houston district water percolates through interstices in the sand and the frictional losses may be relatively high even though the rate of movement is very slow, perhaps only a few hundred feet a year. All ground-water reservoirs containing fresh water have natural outlets, otherwise there would have been no circulation previous to the drilling of wells. Some of the outlets to the artesian reservoirs in the Gulf Coastal Plain in Texas are believed to be along the continental shelf out in the Gulf at comparatively great distances from the outcrops. Other outlets probably are within the clays, silts, and sands that overlie the main artesian reservoir, through which natural discharge may occur by slow upward percolation and diffusion. Meinzer 6/ pointed out that although some rock strata are regarded as entirely impermeable under natural hydraulic gradients, there is evidence that water may move, with extreme slowness, through strata that have been regarded as totally impermeable. The quantitative importance of movement of water at right angles to the strata in the Texas Gulf Coast probably has been underestimated. The permeability of the materials measured at right angles to the stratification is likely to be very small. However, the other two factors to be considered - hydraulic gradient and cross-sectional area - are known to be relatively very great in the artesian reservoirs of the Gulf Coastal Plain.

Under natural conditions, before heavy withdrawals were made through wells, the underground movement toward the natural outlets was accompanied by some loss in head, but the loss per mile of travel down dip was comparatively small and the pressure remained high in large parts of the artesian reservoirs. In Houston, for example, the pressure in the early days of ground-water development was sufficient to raise the water 60 feet or more above the surface in wells ranging in depth from about 250 to 1,000 feet.

When wells are put down in an artesian area and allowed to flow or are pumped, the natural rate of movement toward the well is increased. This in turn increases the friction losses in the vicinity of the well and causes a cone of depression to form around it, which gradually spreads to adjacent areas. If many wells are put down and pumped, the cones of depression merge and eventually may form regional depressions of considerable depth. Figures 10, 11, and 12 illustrate the large depressions thus created in the Houston and Pasadena areas. These depressions are a pressure manifestation. The decline in pressure may cause a substantial drop in static and pumping levels over a wide area, but the sands are not unwatered unless the pumping levels are lowered below the top of the beds from which the wells draw water.

The artesian water-bearing beds in the Houston district are full of water, although this does not mean that the beds contain as much water as before the start of withdrawal. The ground-water aquifers are elastic and thus differ from man-made systems which are comparatively rigid. The mica, silts and clays that are associated with the water-bearing sands, and to some extent the sands and the water itself expand as the pressure declines and are compressed as the pressure increases. The ground water is stored and moves in the minute interstices between these particles and when the particles expand in response to reduction of pressure caused by pumping, a certain amount of water is driven out of storage and is discharged by the wells. The amount of water that is lost from storage per unit area per foot of decline in head in the artesian area, however, is small as compared with the loss accompanying a comparable decline of the water table at the outcrop, where water actually drains out of the pores. The

6/ Meinzer, O. E., and others, Hydrology, New York, McGraw-Hill Co., 1942.

loss in an artesian reservoir can be computed if the average decline of pressures in an area is known and the average coefficient of storage can be determined approximately. Such computations have been made using the map of water-level declines from 1941 to 1949, shown in figure 12. This required consideration of the territory enclosed within the 30-foot contour and its estimated extension to the east and south, comprising an area of about 740 square miles. From table 13 on page 47, after considering the full thickness of the sands and period of water-level decline, the figure 0.0015 was selected as the average coefficient of storage. The results indicate that within the 740 square miles, the average decline of artesian pressure was 57 feet and approximately 14¼ billion gallons of water was removed from storage during the period 1941-49. The withdrawal from storage was equivalent to about 4 percent of the total pumpage in the Houston and Pasadena areas during the 8-year period.

If the water-bearing beds on the outcrop are unwatered, a large quantity of water will be lost from storage as the water table declines, perhaps 20 percent of the volume of material unwatered. On this basis, if an average water-table decline of only 1 foot had occurred beneath 740 square miles of the outcrop during 1941-49, the volume of water removed from storage would have represented approximately 10 percent of the total pumpage from the Houston and Pasadena areas during the entire period or more than twice the computed loss from storage within the 740 square miles in the artesian reservoir which had a decline of 57 feet.

Records of water-level fluctuations on the outcrop, discussed in detail in another section of this report, indicate that the sands are still full of water and little or no loss from storage has occurred on the outcrop. Rejected recharge in the form of springs sustain the low flow for Spring Creek. Stream-flow data collected since 1939 show that there still is currently rejected recharge.

FLUCTUATIONS OF THE WATER TABLE IN OUTCROP AREAS

Systematic observation of water-table fluctuations on the outcrops of the water-bearing sands that supply an artesian reservoir is an important part of a ground-water investigation. This was recognized early in the Houston investigation and periodic measurements in selected shallow outcrop wells were made in 1931-34. In 1938 it was found that the program followed in the earlier years was inadequate, and since then more intensive studies have been made. Interpretation of the results of these studies, however, has been exceptionally difficult. It has been found that observation wells that are too shallow, or have leaky casings, tend to register fluctuations in the perched water table rather than in the true water table, whereas wells about 75 feet deep, or even less, may be affected to some extent by changes in artesian pressure and fail to correctly register changes in the true water table. Such is the case in nearly all the observation wells in the Katy rice-growing area, including wells that are used for domestic purposes as well as for irrigation.

Records have been obtained for about 20 wells that are believed to give correct information regarding changes in the true water table. Most of these wells are in northern Harris County and southern Montgomery County and are comparatively remote from heavy pumping. Four are in the rice-growing area near Hockley and Cypress and between Cypress and Katy.

Water-level measurements in nine representative water-table wells are given in table 10, page 43. The hydrographs of three of these wells together with monthly precipitation and accumulated departures from normal precipitation at the U. S. Weather Bureau Station at Conroe from 1939 through 1949, are shown in figure 14, on page 44.

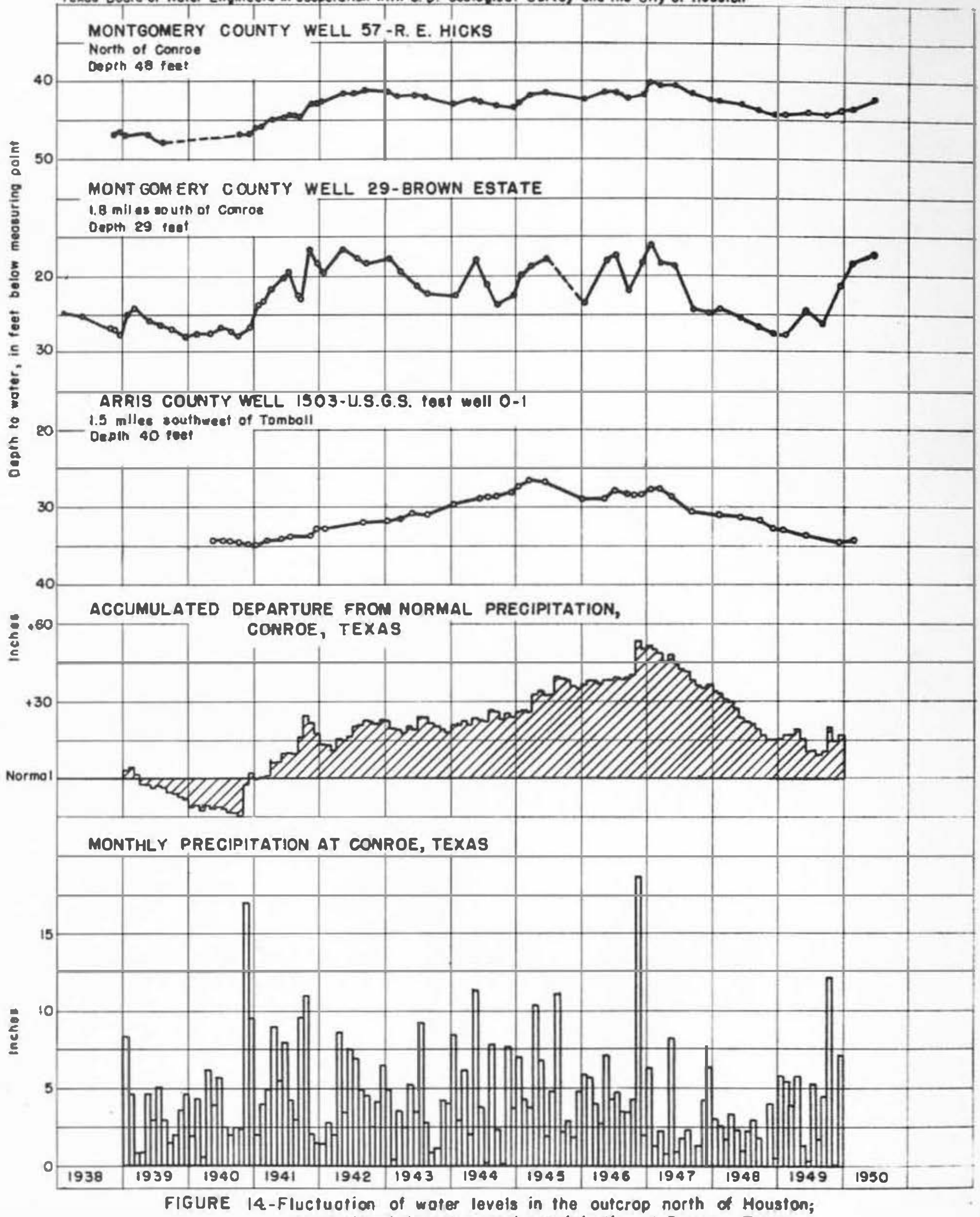

FIGURE 14.-Fluctuation of water levels in the outcrop north of Houston; accumulated departure and precipitation at Conroe, Texas.

mlc

The water levels in most of the water-table observation wells including those in the foregoing table show a small net rise between the start of the record in 1938-39 and comparable dates in 1948-49. Outstanding exceptions are the levels in two wells near Hockley, nos. 42 and 45, which show a net decline of about 9 feet between spring measurements in 1941 and February 1950. These two wells in recent years have been affected by pumping from nearby rice wells. Another water-table well (no. 171 Harris County), in the rice-growing district below the Hockley escarpment near Cypress, shows a net decline of 12 feet between 1947 and 1950; but the water table was higher in 1950 than it was in 1940. A fourth water-table well, (no. 380, 55± feet deep), in the rice-growing area, about 7 miles south of Cypress, showed a net decline of 1.7 feet between March measurements in 1940 and 1948. This well caved following the 1948 measurement and is no longer available for observation.

The records indicate that since 1938 the water table in shallow outcrop wells that are not influenced by nearby pumping from rice wells reflects closely the effects of precipitation on the outcrops. The rainfall at Conroe from 1939 through 1949 shows an accumulated departure of 17.2 inches above the average for the 28-year period of record. The precipitation in 1939 was 7.2 inches below the longtime average and the accumulated departure did not reach normal until December 1940. From that time through 1942 the departure rose to 22.8 inches above normal. The year 1943 was dry and the accumulated excess dropped to 18.0 inches. The precipitation was again heavy in 1944, 1945, and 1946, and the accumulated departure rose to 50.2 inches above normal. The years 1947 and 1948 were dry and at the end of 1948 the accumulated departure had dropped to 14.8 inches above normal. A similar pattern of rise and fall of the water table is reflected by the water-level measurements in the observation wells. (See fig. 14 and table 10.)

A careful study of the records leads to the conclusion that in the rice-growing areas on the outcrop of the Lissie and Willis formations the water table has declined considerably in some localities and only slightly in others. The available data are too meager, however, to warrant making any estimate of the amount of water lost from storage. For other parts of the outcrop of the sands that furnish the water supply for the Houston district and comprise by far the greater part of the outcrop, the data indicate no substantial lowering of the water table, but they are not adequate to enable a definite conclusion in this regard.

Further indication that the sands in most of the outcrop are full of water lies in the fact that there is still rejected recharge which sustains the low flow of Spring Creek. The discharge of Spring Creek, which crosses the outcrop of the Willis and Goliad sands and a part of the outcrop of the Lissie formation, has been measured on the outcrop of the Lissie near Spring, Tex., by the Surface Water Branch of the Geological Survey since April 6, 1939. The records of discharge reveal that there has been a continuous flow in the creek during the entire period of record; that the low-water flow below 200 second-feet correlates closely with the fluctuations in the water levels in several wells in the outcrop area for the period from 1939 through 1949; that the discharge of the creek also correlates closely with the precipitation during the same period; and that rejected recharge was measured at the gaging station throughout the dry periods of several months' duration in 1939, 1940, 1943, and 1947-49 when little or no surface runoff took place. It cannot be stated whether the pumping in the Houston area has had an appreciable effect on the amount of rejected recharge, owing to the fact that the minimum recorded flow of Spring Creek occurred in September 1940, during a period when the precipitation had reached its greatest accumulated departure below normal since the discharge measurements started in 1939. Since 1940 the precipitation has been so excessive that the accumulated departure above normal reached 50.2 inches in November 1947. Recharge to the water-bearing sands during the period of excessive precipitation undoubtedly has increased the rate of rejected recharge; on the other hand, the increased pumping in the Houston area may have tended to reduce the rate of rejected recharge. In either or both cases, the records show that there is still rejected recharge on the outcrop where it is crossed by Spring Creek.

CAPACITY OF THE SANDS TO TRANSMIT AND YIELD WATER

The amount of water that can be withdrawn perennially from an artesian ground-water reservoir depends largely upon the following properties or conditions of the water-bearing beds: (1) the capacity of the beds to serve as conduits from the outcrop or points of recharge to the places of withdrawal or discharge; (2) the amount of water available for recharge on the outcrop to replace the water that moves toward the areas of withdrawal or discharge; and (3) the amount of water obtained from storage in the reservoir as the artesian pressure declines. In the Houston district a large amount of investigational work has been done since 1939 to ascertain these properties of the water-bearing sands.

The capacity of the sands to serve as conduits from the outcrop to the places of withdrawal or discharge depends upon the transmissibility of the water-bearing beds, and the hydraulic gradient. The amount of water that is released from storage in the water-bearing beds as the artesian pressure declines depends on the coefficient of storage.

Computations of the pumping levels in the eight wells in the Southwest field were made in October 1949, using the coefficients of transmissibility and storage obtained from the pumping tests in November 1945 together with the average rate of pumping from each well from the start of operations as shown by records of the Houston Water Department. The computed pumping levels show a remarkably close agreement to the measured pumping levels in October 1949 as shown in the table that follows:

Computed pumping levels in wells in the City of Houston Southwest well field, based on average pumpage from each well for 1,410 days (47 months) in wells 1, 2, 3, 4, 5, 6, and 557 days (18 months) in wells 7 and 8.

Well No.	Computed pumping level below land surface, in feet (October 1949)	Measured pumping level below land surface, in feet (October 1949)	Difference, in feet
1	225.8	221.7	4.1
2	238.0	227.0	11.0
3	254.1	238.0	16.1
4	222.3	223.0	0.7
5	220.8	224.0	3.2
6	228.8	219.2	9.6
7	216.8	239.2	22.4
8	222.6	220.2	2.4

In the Southwest well field all the sands are screened between depths of about 550 and 1,500 feet, and, according to the electrical logs of the wells, the amount of sand in the screened section is fairly uniform from well to well.

On the basis of present information, and in view of the fact that most of the municipal and industrial wells in the Houston-Pasadena-Ship Channel areas have multiple screens in different sand zones, there is no practicable way of determining the amount of water withdrawn from each zone. It is believed, therefore, that the non-equilibrium formula can not be used generally with average coefficients to predict drawdowns over a wide area in the Houston district with a close degree of accuracy. However, the method has proved to be especially valuable for comparing the merits of different spacing of wells in a well field. It proved to be remarkably accurate in predicting the future drawdowns in the Southwest well field where good control was available.

The following table gives a summary of the results of tests from 1939 to 1949 to determine the coefficients of transmissibility and storage in the Houston district.

Table 13. Coefficients of transmissibility and storage obteioed from pumping tests on City of Houston wells, 1939-1949

Well field	Well No.	Depth of sands tested	Coefficient of transmissibility	Coefficient of storage	Classification of results of tests	Remarks
Central	C-16	1,144 to 1,517	60,000		Good	Recovery well C-16.
	C-20	1,015 to 1,940	140,000		Poor	Recovery well C-20.
	F-1	880 to 1,488	117,000		Fair	Recovery well F-1.
			134,000	0.00072	Fair	Recovery well F-10.
			121,000	.00038	Fair	Recovery well F-5.
	F-5	885 to 1,443	87,000		Fair	Recovery well F-5.
			114,000	.00051	Good	Pumping well F-10.
			104,000	.00038	Good	Pumping well F-1.
			122,000	.00089	Poor	Pumping well F-12.
			130,000	.00055	Fair	Recovery well F-10.
			121,000	.00048	Good	Recovery well F-1.
	F-10	880 to 1,497	117,000		Poor	Recovery well F-10.
	F-11	498 to 994	54,000		Good	Recovery well F-11.
	F-12	1,180 to 2,020	52,000		Good	Recovery well F-12.
Heights	5	408 to 1,860	82,000		Good	Recovery well 5.
	6	581 to 1,225	95,000		Good	Recovery well 6.
	7	561 to 1,454	105,000		Fair	Recovery well 7.
			134,000		Good	Recovery well 8.
	9	610 to 1,710	93,000		Fair	Recovery well 9.
	10	600 to 1,860	118,000		Poor	Recovery well 10.
	12	900 to 1,750	66,000		Fair	Recovery well 12.
	13	890 to 1,800	66,000		Good	Recovery well 13.
	14	950 to 1,790	87,000		Good	Recovery well 14.
East End	4	1,000 to 2,510	113,000		Good	Recovery well 4.
	5	1,470 to 2,560	82,000		Good	Recovery well 5.
	6	950 to 2,075	138,000		Good	Recovery well 6.
Northeast	1	1,013 to 1,872	57,000		Good	Recovery well 1.
	2	461 to 1,279	95,000		Fair	Recovery well 2.
	4	1,030 to 2,060	112,000		Poor	Recovery well 4.
	6	1,020 to 1,820	105,000		Good	Recovery well 6.
	7	1,001 to 1,880	155,000		Good	Recovery well 7.
Scott Street	2	1,326 to 1,502	120,000		Poor	Recovery well 2.
			147,000	.00055	Good	Pumping well 4.
	3		72,000		Good	Recovery well 3.
			67,000	.00079	Good	Recovery well 5.
	4	1,037 to 1,758	111,000		Good	Recovery well 4.
	5	470 to 949	55,000		Fair	Recovery well 5.
			47,000	.00025	Poor	Recovery well 1.
			94,000	.00108	Fair	Recovery well 3.
Southwest	2	675 to 1,478	156,000	.00089	Good	Pumping well 1.
	3	686 to 1,396	139,000	.0012	Good	Pumping well 1.
	4	692 to 1,490	141,000		Good	Recovery well 4.
			152,000	.0012	Good	Pumping well 1.
	5	653 to 1,379	145,000	.0011	Good	Pumping well 1.
	5		140,000	.00095	Good	Pumping wells 1 and 4.
	6	548 to 1,360	146,000	.0012	Good	Pumping wells 1 and 4.
	7	490 to 1,431	140,000	.0014	Fair	Pumping well 8.
	8	560 to 1,445	140,000	.0014	Fair	Pumping well 7.

QUALITY OF THE GROUND WATER

The value of a water supply for public and industrial uses and for irrigation is related directly to the character and quantity of dissolved mineral matter in the water. In selecting the sites for most industrial plants, for example, information relating to the chemical quality of the available water supplies is essential.

A large number of analyses of water from wells in the Houston district made by the Geological Survey, the City of Houston, and commercial laboratories are available in the files of the U. S. Geological Survey and the Texas Board of Water Engineers. Many of these analyses were published in 1944 in U. S. Geological Survey Water-Supply Paper 889-C (see Bibliography). The analyses show that in general most of the water pumped from wells in this district is of good quality and compares favorably with other public, industrial, and irrigation supplies throughout the United States.

In general, water of good quality can be obtained in the Houston district from all aquifers to relatively great depths. The shallow aquifers as a rule contain calcium bicarbonate type waters that are hard, whereas the deep aquifers contain sodium bicarbonate type waters that are soft. Waters from these aquifers contain only moderate amounts of mineral matter. An exception is the Willis sand which, in the outcrop, yields soft water of low mineral content. Water of high mineral content has been encountered in many of the deeper water wells and in oil tests. The mineral content of the ground water generally increases with depth and, therefore, determines the maximum depth to which wells will be drilled in the district. The higher mineralization of the water from the deeper sands is due largely to the increased amount of sodium chloride. The geologic structure has a definite influence upon the depths at which higher mineralization occurs. For example, on certain salt-dome structures, brackish or salty water has been encountered several hundred feet higher than in the adjacent territory. This fact is clearly brought out by plate 2, in which salt domes occur at each end of the section and cause a marked change in the quality of the ground water in their vicinity. On such subsurface structures as synclines, the fresh-water sands may extend to great depths.

The chemical character of ground water in supply wells, together with analyses of drill-stem samples in exploration holes, has been discussed in previous reports. Since the 1946 progress report was published, several test wells have been drilled by the City of Houston and analyses of the drill-stem samples obtained are tabulated in table 11. Most of the drill-stem samples were contaminated by drilling mud, and, therefore, the analyses may not represent the exact chemical constituents of the water in the aquifer.

Perhaps the most interesting discovery made in recent years based upon detailed studies of electrical logs of oil tests and confirmed by test drilling was the fact that potable water extends to a depth greater than 2,500 feet in the East End well field. A drill-stem sample from 2,536-2,570 feet in a test hole drilled at the site for production well 5 showed a chloride content of 198 parts per million. Four production wells have now been drilled at East End to tap a part or all of the deep sand discovered by the test drilling.

Plate 3 shows the depths at which drill-stem samples of water were obtained in seven test wells, four in the Northeast well field and three in the East End field. The numbers indicate the chloride content in parts per million.

Well field	Well	Date	Depth of test hole (feet)	Depth of sampling (feet)	Silica (SiO_2)	Calcium (Ca)	Magnesium (Mg)	Sodium and potassium (Na + K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Boron (B)	Dissolved solids	Total hardness as $CaCO_3$
Central	C-19	1948	2,515	1,925-1,970	44	3.2	3.5	256	a/ b/	65	201	4.0	0.0	0.97	670	22
				1,925-2,515	-	-	-	-	-	-	81	-	-	-	-	15
	C-20	1949	2,532	1,865-1,900	26	3.1	1.0	169	194	61	103	2.0	.5	.96	466	12
				2,184-2,220	14	14	1.7	488	b/	78	668	3.0	1.2	2.4	1,320	42
				2,498-2,532	8.0	101	14	1,220	112	3.1	2,020	.9	2.5	3.3	3,420	310
East End	3	1948	2,495	2,010-2,028	4.0	2.2	1.2	232	394	28	110	1.2	.0	-	601	10
				2,043-2,085	10	5.5	2.0	275	b-	98	225	2.2	.5	-	734	22
				2,320-2,350	16	4.5	1.7	250	372	29	152	2.4	.5	-	641	18
				2,469-2,495	10	7.1	.9	215	388	9.5	106	2.2	.0	-	578	21
	4	1948	2,815	2,457-2,477	54	6.1	3.5	198	281	32	133	1.6	.8	1.1	612	30
	5	1949	2,822	2,426-2,455	17	6.3	1.7	227	409	10	112	1.8	.0	.61	580	22
				2,536-2,570	15	7.2	1.8	293	446	3.3	198	2.8	.0	1.3	744	26
				2,599-2,638	13	71	13	851	162	68	1,320	1.6	2.0	2.4	2,420	230
	6	1949	2,807	2,028-2,076	20	3.5	1.7	247	430	4.2	101	1.2	.0	.03	618	16
				2,440-2,480	20	4.2	2.3	385	450	4.2	146	2.0	.2	.97	714	20
Heights	9	1949	2,498	1,680-1,720	48	1.1	.5	147	96	63	120	3.6	.0	1.0	432	4
				2,290-2,320	30	2.4	.7	304	463	7.3	191	3.6	.0	1.9	783	9
	10	1949	2,848	955-1,007	31	3.2	.7	60	61	36	36	.0	.0	.62	200	11
				2,323-2,380	71	9.1	9.0	179	226	39	148	3.6	.0	1.4	588	60
				2,541-2,586	46	4.4	1.5	960	210	27	1,340	1.2	6.5	2.1	2,490	17
	12	1949	2,523	1,745-1,758	32	1.6	.7	140	122	64	95	3.6	.0	1.3	404	7
				1,845-1,926	19	5.4	1.7	247	246	9.1	235	3.2	.0	1.3	685	20
				2,260-2,313	10	2.8	1.3	271	484	12	125	4.0	.5	.85	686	12
				2,475-2,522	10	38	9.0	1,030	464	12	1,400	2.0	.0	1.6	2,730	132
	13	1949	2,783	1,810-1,848	18	6.3	1.4	285	422	4.3	205	2.8	.0	.35	730	22
				1,962-2,024	44	12	.7	435	b/	60	478	3.6	.0	1.7	1,100	33
				2,520-2,562	25	24	4.8	788	329	16	1,080	2.4	.0	1.8	2,100	80
	14	1949	2,543	1,761-1,827	10	6.2	1.5	171	280	15	98	2.8	.0	.39	464	22
				2,260-2,320	16	6.5	.9	278	547	6.0	105	3.0	.0	.98	684	20
				2,475-2,543	20	27	16	1,250	489	1.4	1,710	1.6	.5	2.0	3,270	134
	15	1950	1,291	1,245-1,291	26	30	2.7	172	b/	32	58	.6	.0	.31	494	86
				2,260-2,301	10	2.8	.8	282	552	8.2	106	4.4	.0	.67	712	10
				2,705-2,810	16	52	17	1,390	384	21	2,010	1.6	.5	1.5	3,700	200
Northeast	4	1949	2,520	1,989-2,079	111	5.8	1.1	209	b/	174	66	-	.0	-	686	19
				2,470-2,520	10	30	6.8	686	227	7.2	992	-	1.8	-	1,850	103
	5	1949	2,502	1,907-1,957	80	4.6	.8	161	b/	54	85	-	.0	-	499	15
				2,025-2,057	18	63	3.9	353	b/	112	76	1.2	.0	.55	1,060	173
				2,427-2,502	9.8	106	26	1,150	132	7.9	1,950	1.2	3.5	1.9	3,320	372
	6	1949	2,815	1,892-1,935	18	3.4	.9	203	349	11	98	2.0	.0	.30	508	12
				1,979-2,071	18	14	4.2	220	224	98	170	2.2	.0	.89	682	52
				2,512-2,545	13	24	6.3	776	110	4.5	1,180	1.8	.0	2.4	2,060	86
				2,760-2,802	[illegible]	47	10	1,030	292	18	1,490	1.8	.0	1.9	2,760	158
	7	1949	2,518	1,862-1,934	16	3.7	.7	195	301	10	119	1.8	.0	.59	496	12
				1,945-1,987	13	2.6	.6	191	354	9.3	84	2.0	.0	.32	483	9
				2,433-2,518	9.2	12	2.6	457	278	10	560	2.6	.0	2.0	1,190	40
Southwest	8	1947	1,608	1,410-1,450	15	20	5.4	121	309	21	39	1.1	.2	-	375	72
				1,312-1,608	15	12	3.6	176	[illegible]	7.4	70	1.3	.2	-	474	45

a/ (CO_3) when present has been recomputed as (HCO_3).

b/ (OH and (CO_3) present. Probably drilling-mud contamination.

The possibility of salt-water encroachment has been discussed in several previous reports. Since 1931, samples of water have been collected periodically from 30 to 60 selected, widely spaced observation wells and analyzed primarily to determine if the chloride content has increased. Table 12 gives the well number, owner, screen setting, and the chloride content in parts per million for one sample each year from 33 of the wells. The locations of the wells are shown on figure 15. According to these analyses, the latest of which were made in March 1950, and other miscellaneous analyses not given in this report, there has been no significant change in the chloride of the ground water pumped in the Houston district. The occurrence of fresh water in the deep sands at the East End field and in the vicinities of South Houston, Pearland, and Almeda indicates that salt-water encroachment down the dip is not likely to invade wells in the heavily-pumped localities, at least for many years. However, since a hydraulic gradient now exists from the Gulf toward the pumped area slow encroachment may be taking place. In view of the tremendous importance of the quality of ground water in the Houston district, it seems advisable that periodic sampling from the present observation wells should be continued indefinitely, and other outpost observation wells should be installed to test the deeper sands in southeastern Harris County.

Table 12. Chloride content, in parts per million, by years in water samples from observation wells in the Houston district

Well	Owner	Screen record	1931	1936	1939	1940	1941	1942	1943	1945	1946	1947	1948	1949	1950
54	Fort Bend Utilities Co.	1,545-1,606	-	57	59	58	59	58	-	-	-	62	62	62	62
269	City of Houston test well 7	1,037-1,052	-	-	78	-	-	-	71	-	70	72	82	81	71
602	River Oaks Country Club	675- 864	35	34	37	36	28	30	41	-	-	40	44	56	-
620	Public Laundries	1,310-1,377	40	44	39	37	35	36	36	39	34	34	-	-	-
635	Houston Lighting & Power Co. (Gable Street)	747- 873	-	-	27	26	25	26	26	-	-	32	30	29	29
641	Rice Hotel Laundry	1,317-1,456	-	-	-	-	-	58	58	60	59	64	60	56	55
656	Texas Creosoting Co.	622- 666	35	27	26	28	27	28	28	26	30	-	32	33	29
669	Willborg's Laundry	903- 936	-	33	28	30	29	29	27	-	-	-	32	-	-
728	Burkhart Laundry	1,358-1,402	40	45	46	45	45	45	46	50	50	48	46	52	44
732	Gould Laundry	1,347-1,391	55	54	52	51	50	50	49	47	48	46	48	59	48
736	Houston Packing Co.	1,537-1,617	-	-	-	-	-	74	77	74	76	78	78	78	75
747	Southern Pacific Ry. Creosote Plant	739- 947	30	27	27	28	26	28	30	-	-	-	-	38	30
788	Shepherd Laundries	1,336-1,416	60	57	53	50	49	48	48	-	-	50	-	-	-
791	Warwick Hotel	408- 566	-	28	29	29	28	28	30	30	32	[illegible]	30	32	30
892	Lone Star Cement Co.	767-1,380	45	60	35	36	34	43	37	-	-	38	42	34	35
906	Garden Villas well 2	643- 905	38	36	38	33	36	36	37	-	-	39	40	34	35
1103	Southern Pacific Ry. Co. Strang Station	- 770	130	127	120	128	127	128	125	-	126	128	126	122	126
1107	City of La Porte well 2	425- 585	-	-	76	-	73	73	78	75	75	-	78	66	68
1124	Shell Oil Co. well 5	648-1,316	-	-	72	-	66	-	-	-	-	92	96	-	-
1130	Champion Paper & Fibre Co. D-2	1,006-1,458	-	-	40	-	37	40	41	40	41	46	40	44	45
1132	Champion Paper & Fibre Co. B-2	1,399-1,835	-	-	-	-	62	64	-	65	70	72	78	76	79
1137	Champion Paper & Fibre Co. A-3	1,393-1,923	-	-	63	-	82	81	94	87	87	80	74	82	80
1139	Sinclair Refining Co. well 9	889-1,186	-	-	-	-	41	43	44	38	42	46	44	43	45
1140	Sinclair Refining Co. well 8	1,358-1,697	-	-	36	38	36	37	40	42	38	42	38	39	35
1205a	City of South Houston well 4	- 771	45	-	-	-	-	42	-	-	39	44	42	45	43
1229	City of Houston test well 8	1,661-1,676	-	-	286	-	-	-	-	-	-	-	282	295	292
1230	City of Houston test well 9	1,399-1,414	-	-	208	-	-	-	-	-	-	-	214	192	188
1270	West University Place well 5	1,205-1,649	-	-	-	-	-	34	35	-	-	36	32	41	38
1302	City of Genoa	655- 832	83	77	76	77	74	-	76	-	76	82	84	77	81
1359	G. B. Whitcomb	- 563	45	43	44	44	42	42	45	44	48	-	-	48	46
1367	Humble Pipe Line Co. well 2	592- 659	-	-	90	92	93	-	93	93	94	98	96	94	96
1369	City of South Houston well 2	856- 916	-	-	46	-	45	-	43	-	-	-	48	-	-
1417a	Houston Lighting & Power Co. West Junction well 2	895-1,263	-	-	-	-	-	-	35	35	38	40	38	36	38

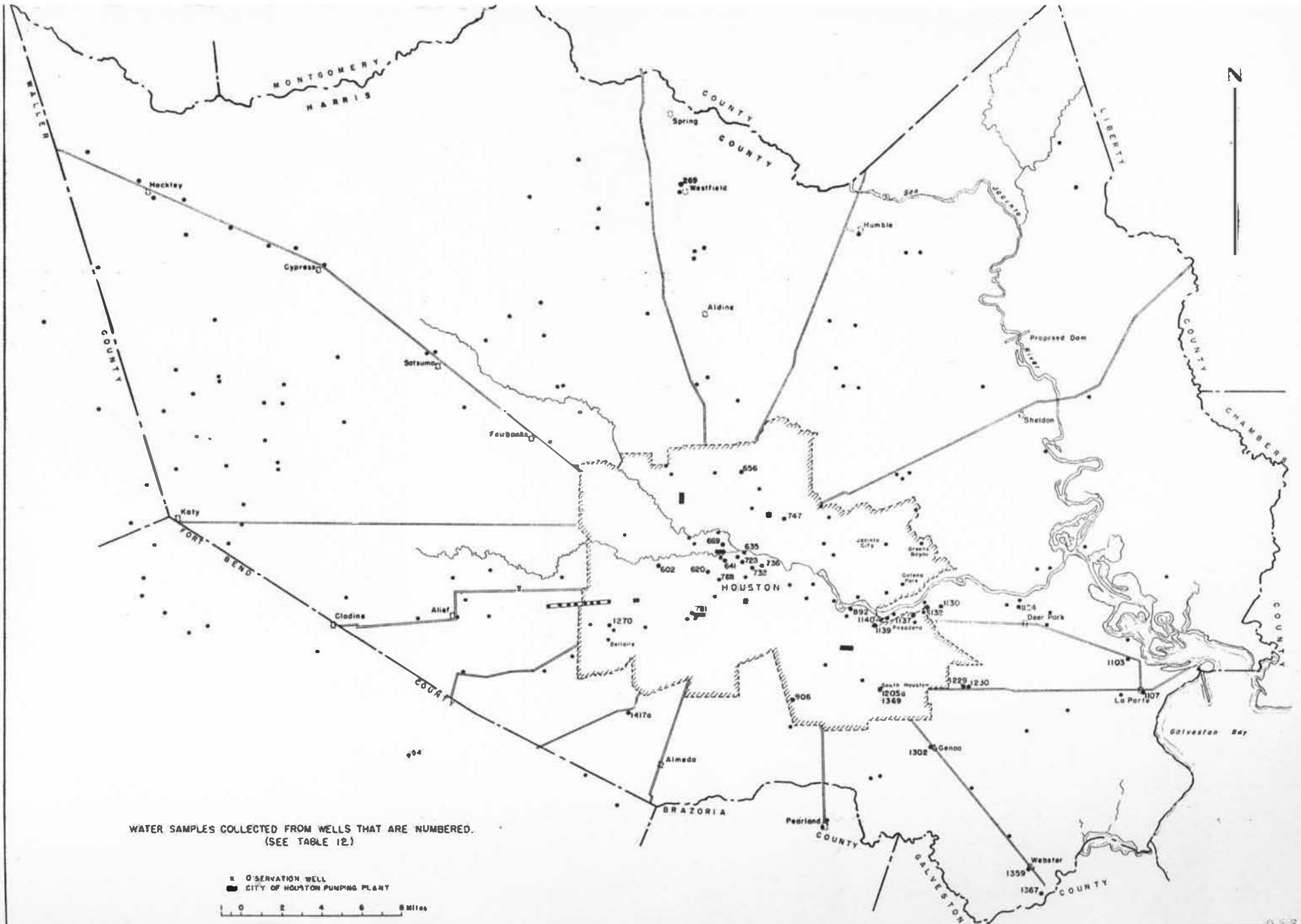

FIGURE 15.-Map showing location of wells sampled for quality of water analyses.

SUMMARY AND CONCLUSIONS

The water for all public supplies, nearly all the industrial supplies, and a large part of the irrigation supplies in the Houston district is drawn from wells, most of which range from 450 to 2,000 feet in depth. The phenomenal growth of Houston during the 20-year period 1930-50 has been accompanied by a corresponding increase in the quantity of water required for public and industrial supplies. In 1949 the pumpage in the Houston and Pasadena areas alone averaged 150,000,000 gallons a day, and was approximately three times as great as it was in 1930 and twice as great as in 1941.

As was to be expected, the increase in pumping caused pronounced declines in artesian pressures, the largest declines occurring since 1941. In observation wells for which comparable measurements are available the average decline in pressures from 1940 to 1950 was 90 feet in the Pasadena area, 85 feet in eastern Houston, 60 feet in north Houston, and 53 feet in central and western Houston. Materially greater declines occurred locally in the immediate vicinity of very heavily pumped wells or batteries of wells.

The pumpage from wells in the Katy rice-growing area in 1949 (109,000 acre-feet or an average of 98,000,000 gallons a day) was 3½ times the pumpage in 1930 and more than 4 times that in 1941. Some declines in water level and artesian pressure resulted from the pumpage in the Katy area, but the declines were relatively small and the pumping had little effect on the artesian reservoirs near Houston.

Despite the drop in artesian head, the evidence as a whole indicates that the ground-water reservoir in the Houston district is not yet overdrawn. This conclusion is based on the following facts:

Analyses of water samples collected periodically for 19 years from a large number of pumped wells widely spaced throughout the district show no significant changes of chloride content in any of the wells, regardless of depth. Recent geologic studies, based mostly on electrical logs of water wells and oil tests, show that the water-bearing beds contain potable water several miles down the dip to the south and southeast of Houston, much farther than was formerly supposed. Therefore, there is no immediate danger of contamination of the present well fields by the invasion of salt water from down dip. However, a hydraulic gradient exists from the southeast toward the pumped areas, and as a safeguard additional test wells should be put down between Houston and the Gulf to determine the location of the salt-water fresh-water interface and to observe the progress of any salt-water encroachment that may be occurring. There is some possibility that excessive pumping locally, particularly from the deepest fresh-water beds, might cause salt contamination from below, but this possibility is believed to be remote. The geologic studies, and recent exploratory drilling and research by the Houston Water Department, have shown that some parts of the Houston area are underlain by water-bearing beds at greater depths than previously had been supposed possible. This source of supply is practically untouched and represents an additional reserve, especially north and northeast of Houston.

For several years prior to 1949 the pumpage in the Houston and Pasadena areas increased each year, but the pumpage in 1949 was about the same as in 1948. At the end of this 2-year period the rate of decline of the artesian pressures was less than in preceding years. The data indicate that, if pumpage continues at the 1949 rate, approximate equilibrium of the artesian pressure will be established before the principal sands in the Houston district begin to be unwatered.

Observation wells in the outcrop of the aquifers, remote from pumping, have been measured for several years. The measurements show little or no net decline of the water table since 1938. This indicates that, during the period 1938-50, the water that moved from the outcrop into the artesian reservoir was replenished by precipitation on the outcrop. Spring Creek and its tributaries drain a part of the outcrop. Records of the low flow of Spring Creek show that there was rejected recharge on the outcrop in 1938 and there is still rejected recharge.

Questions frequently are asked as to what are the absolute limits of safe pumping in the Houston and Pasadena areas. These limits cannot be defined; it now appears that one important factor is the pumping levels at which the principal water-bearing sands will begin to be unwatered. In most of the district the pumping levels are still several hundred feet above those sands. The limit that should be sought is the practical limit; this is largely a matter of economics and requires thorough cost accounting. On the one hand, the increases in the cost of pumping that result from higher lifts must be considered, including replacement of power and pumping equipment, and losses incurred in replacing or abandoning wells in which the pumping levels are approaching the limits to which pumps of the required size can be lowered. On the other hand, consideration should be given to the cost of bringing in a supplemental supply of surface water from the San Jacinto or other nearby rivers, or ground water from areas outside those of heavy withdrawal, either north or northeast of Houston.

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Preliminary studies of the geology and ground-water resources of the Houston district were made and described in general by Singley 7/ and Taylor 8/. Hayes and Kennedy 9/ were the first to map and name the formations. In 1907 and 1908 Deussen 10/ studied the geology of a part of the Coastal Plain region, and gathered a large number of well records in the Houston district and took several samples of water for chemical analyses. These data together with other records and a description of the geology of southeastern Texas, were published in 1914.

Since 1930 the systematic ground-water investigation, carried out by the U. S. Geological Survey in cooperation with the Texas Board of Water Engineers and the City of Houston, has given special attention to the source and quantity of water available for practicable development. This report is the 22nd in a series of progress reports and technical papers describing the results of the cooperative investigation. Prior reports and papers are listed below.

Water-Supply Papers

Ground-water resources of the Houston district, Texas, by W. N. White, N. A. Rose, and W. F. Guyton: U. S. Geol. Survey Water-Supply Paper 889-C, 1944.

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Mimeographed progress reports

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Relation of phenomenal rise of water levels to a defective gas well in Harris County, Texas, by N. A. Rose and W. H. Alexander, Jr.: Bull. Amer. Assoc. Petrol. Geol., vol. 29, No. 3, pp. 253-279, Mar. 1945.

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Results of pumping test at new Southwest plant, Houston, Texas, by J. W. Lang and R. W. Sundstrom: U. S. Geol. Survey and Texas Board of Water Engineers, Dec. 1946.

Geology and ground-water resources of the Houston-Galveston area, Texas, by J. W. Lang. Abstract approved for publication in Proceedings, Tex. Acad. of Sci., Dec. 1949.

In addition, the following reports, covering counties that are adjacent to the Houston district, have been published or the field work has been completed and reports are awaiting publication by the U. S. Geological Survey and Texas Board of Water Engineers:

Ground-water resources of Brazoria County, Texas, by C. R. Follett, Nov. 1947.

Geology and ground-water resources of Walker County, Texas, by Allen G. Winslow.

Geology and ground-water resources of Fort Bend County, Texas, by C. R. Follett and J. W. Lang.

Geology and ground-water resources of Waller County, Texas, by T. R. Fluellen, Jr.

Ground-water resources of Chambers County, Texas, by W. W. Doyel.

The results of water-level measurements in observation wells in the Houston district from 1931 to 1945 have been published in U. S. Geol. Survey Water-Supply Papers 777, 840, 886, 909, 939, 947, 988, 1019, and 1026. Records for later years are in course of publication and are available for reference in the files of the U. S. Geological Survey at Houston and Austin, Texas, and Washington, D. C., and Texas Board of Water Engineers at Austin, Texas.

Table 10. Fluctuation of water levels in the outcrops of the water-bearing sands in the Houston district, Texas
Depth to water in feet below measuring point [a]

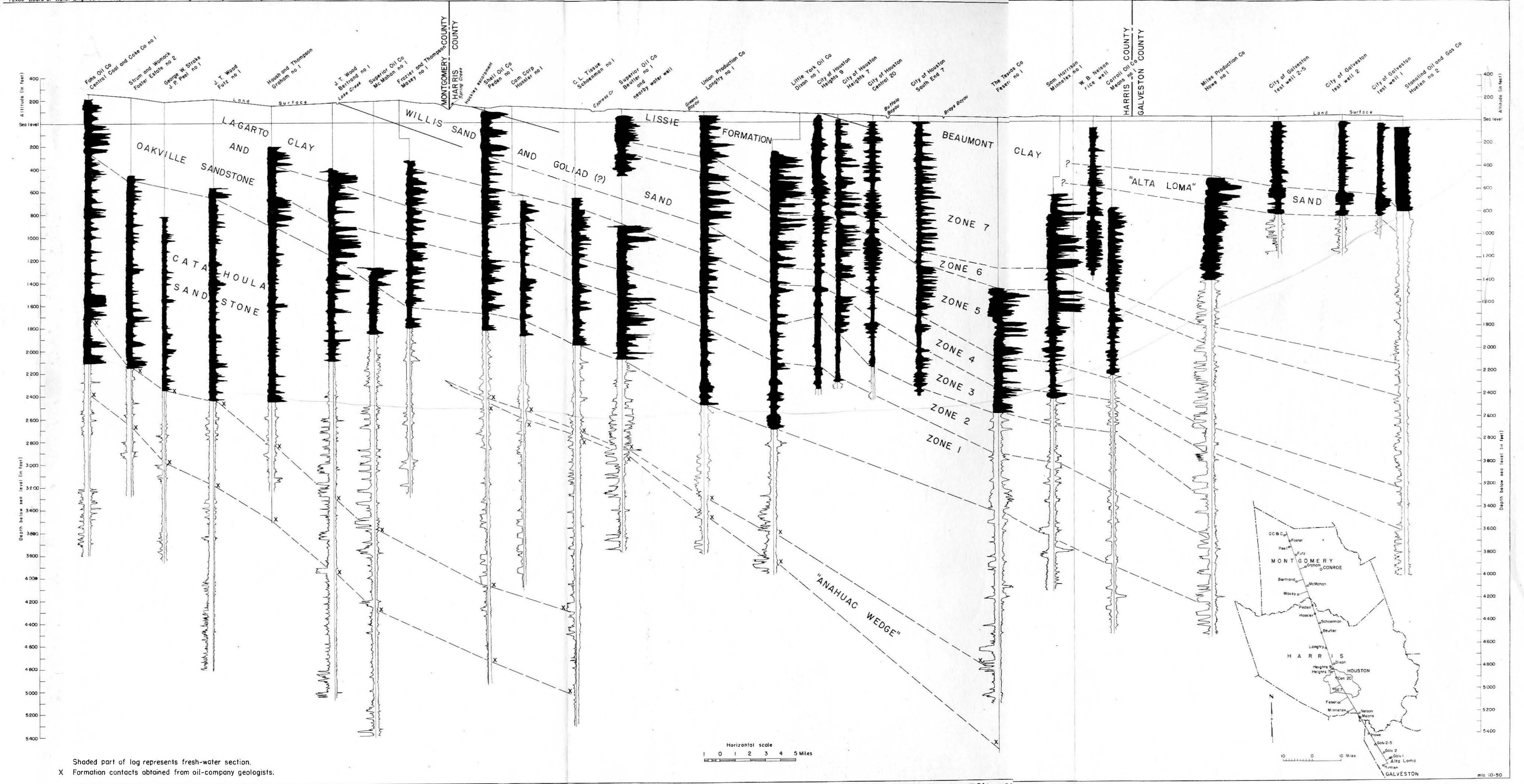
ll	Harris County						Montgomery County			
	11	171	95	194	1503 [b]	1504	29 [b]	45	46	57 [b]
th ..)	70	66	30	29	42	29	29	30	35	48
e										
. 1938	49.74	15.40	-	17.63	-	-	24.81	23.56	32.35	-
	-	11.30	-	15.16	-	-	25.14	23.70	32.19	-
.	-	16.86	-	19.28	-	-	26.98	26.17	32.79	46.84
.	-	17.41	-	21.71	-	-	27.30	25.53	32.73	46.39
. 1939	48.52	15.56	-	18.86	-	-	24.98	24.27	31.90	46.96
.	44.56	14.53	-	18.15	-	-	24.11	24.01	31.73	-
	44.51	17.37	-	17.70	-	-	25.85	24.56	33.01	46.84
.	44.55	20.66	-	16.17	-	-	26.15	25.55	32.92	47.70
t.	44.56	20.56	-	19.20	-	-	26.96	26.15	33.55	-
..	44.61	20.30	26.44	20.10	-	-	27.80	25.80	33.38	-
. 1940	44.88	19.61	26.77	20.05	-	-	27.54	25.40	32.44	-
	-	19.08	26.97	19.84	35.28	-	27.26	26.02	31.52	-
e	45.53	18.65	27.23	20.40	35.10	26.82	26.76	26.10	33.64	-
y	-	-	-	-	35.49	25.97	-	-	-	-
.	-	18.78	27.54	-	35.52	25.64	27.02	26.40	33.96	-
.	45.90	19.09	27.78	21.26	35.75	26.05	27.60	26.40	33.78	46.70
.	46.50	18.29	27.32	20.82	35.85	25.18	26.50	24.15	32.62	46.50
. 1941	45.70	17.18	25.42	17.65	35.69	22.62	23.75	25.30	32.68	45.78
.	-	16.51	24.67	16.45	35.51	22.48	23.10	23.86	30.90	45.65
.	44.85	-	-	-	35.15	21.96	-	-	-	-
.	-	11.75	23.20	14.10	-	-	21.53	25.32	33.30	44.83
	44.25	10.78	-	-	35.10	20.65	-	-	-	-
e	45.11	-	23.85	12.83	34.80	20.88	20.43	25.81	32.97	44.46
y	45.41	9.80	22.71	-	34.98	20.90	19.50	26.38	33.45	44.12
.	-	9.60	23.80	13.60	-	-	-	-	33.75	44.23
t.	-	9.73	23.47	14.03	34.65	23.24	23.03	25.20	33.05	44.32
.	-	9.40	17.72	9.66	34.43	20.62	16.46	22.59	31.52	42.97
.	45.20	9.49	12.79	11.18	33.91	20.81	18.21	23.10	32.97	42.75
. 1942	44.30	9.41	18.96	11.11	33.75	21.52	19.56	22.78	33.37	42.37
	-	8.91	15.48	10.90	33.35	21.85	16.76	23.60	32.82	41.40
y	44.81	8.68	16.91	-	33.01	22.51	17.87	21.02	33.04	41.35
.	-	-	-	-	32.97	22.64	-	-	-	-
t.	-	8.98	18.75	15.94	32.83	22.92	18.40	21.23	32.25	41.02
.	44.76	-	-	-	32.91	-	-	-	-	-
. 1943	44.45	9.98	14.66	14.56	32.83	23.36	17.73	19.16	32.29	41.11
.	44.65	-	15.55	12.25	32.37	23.19	19.31	20.43	31.96	41.83
.	44.71	9.93	-	-	-	-	-	-	-	-
e	44.60	9.80	18.76	15.54	31.97	23.64	21.35	23.46	32.12	41.83
.	44.79	10.17	18.91	15.13	32.01	22.99	22.13	22.63	32.35	41.96
. 1944	44.62	11.17	-	7.40	31.53	23.43	22.34	22.87	31.53	42.82
	44.15	9.58	10.40	9.00	29.72	21.20	17.88	21.29	31.30	42.37
y	-	-	17.26	13.50	29.64	21.80	21.05	22.98	31.73	42.78
t.	46.25	9.58	20.73	16.40	29.32	22.65	23.70	22.69	31.56	42.93
..	-	9.88	17.90	15.13	28.99	22.98	22.50	19.61	31.41	43.24
. 1945	43.63	9.57	13.17	-	28.11	21.77	19.98	18.75	30.98	42.63
.	43.91	9.19	13.54	9.96	27.57	21.08	18.88	18.93	31.16	41.86
e	47.02	8.36	15.47	10.42	27.70	20.38	17.96	19.96	31.27	41.46
. 1946	43.94	9.05	11.80	8.26	29.88	22.86	23.40	17.11	30.52	42.06
	43.78	8.09	10.09	9.13	28.83	21.43	18.01	16.63	30.56	41.35
y	43.56	7.45	10.37	7.16	28.06	20.24	17.21	15.75	30.65	41.32
t.	45.51	8.39	18.32	14.40	29.22	21.79	21.98	16.18	30.96	42.08
.	43.35	8.26	10.22	9.90	29.39	20.16	18.13	14.26	30.45	41.60
. 1947	43.43	8.02	6.76	8.12	28.51	19.49	15.98	12.73	30.04	40.09
.	42.68	8.10	9.68	9.39	28.61	20.52	18.21	12.50	29.96	40.39
e	-	7.77	13.41	11.61	29.32	21.74	18.74	13.24	29.92	40.24
t.	-	9.12	20.14	17.06	30.59	23.26	24.17	15.16	30.08	41.41
.	43.88	10.22	20.95	18.07	31.54	24.32	24.75	15.45	29.76	42.22
. 1948	43.63	10.87	17.11	14.66	31.81	24.45	24.05	15.05	29.66	42.24
e	43.67	10.92	18.44	15.79	32.17	24.46	25.02	22.71	30.14	42.98
t.	-	12.62	22.88	19.93	32.92	25.23	26.51	16.10	30.06	43.57
..	47.05	14.00	24.11	20.88	33.62	25.87	27.37	17.36	29.98	44.10
. 1949	44.46	13.62	24.56	21.40	34.02	26.14	27.42	16.82	29.88	44.22
e	48.67	13.41	20.91	19.68	34.73	24.50	24.62	16.98	30.23	43.91
t.	-	14.78	22.71	20.90	35.29	25.43	26.13	16.91	30.23	44.32
.	-	14.94	14.46	15.70	35.28	24.78	21.29	15.93	29.76	43.91
. 1950	-	15.09	8.80	14.88	35.25	23.38	18.33	14.88	29.46	43.16

Additional miscellaneous measurements are in files of the U. S. Geological Survey.

See hydrographs, figure 14.

Texas Board of Water Engineers in cooperation with U.S. Geological Survey and the City of Houston

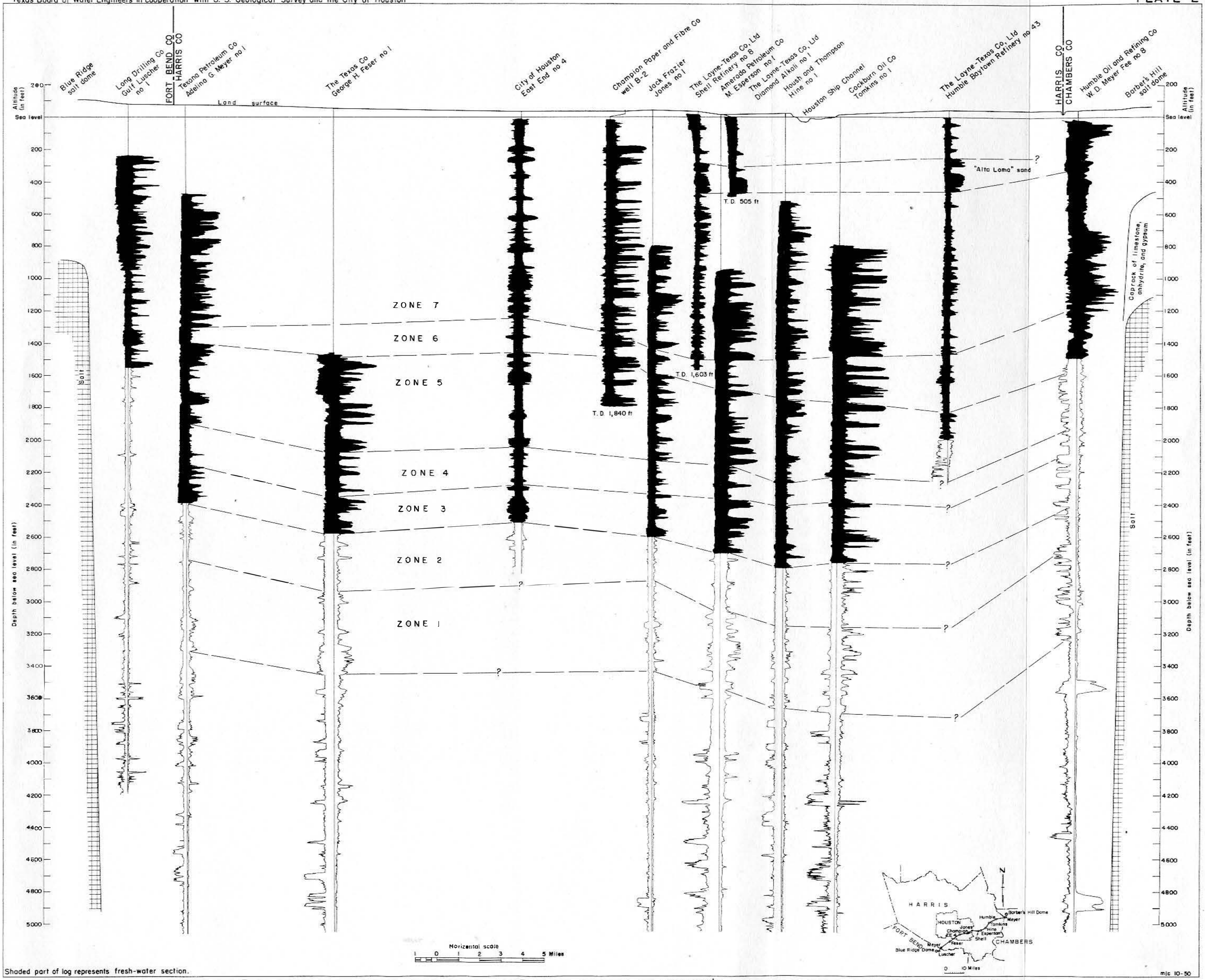
PLATE I



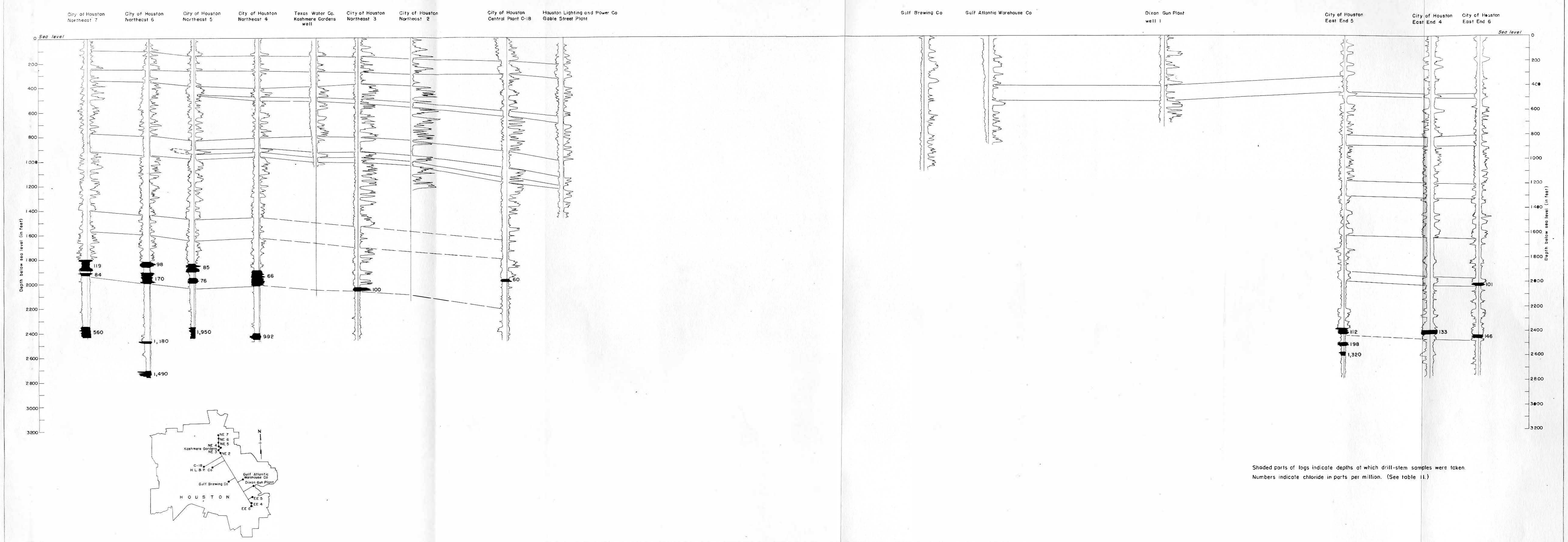
CROSS SECTION FROM NORTHERN MONTGOMERY COUNTY TO THE VICINITY OF ALTA LOMA, GALVESTON COUNTY, TEXAS.

Texas Board of Water Engineers in cooperation with U. S. Geological Survey and the City of Houston

PLATE 2



CROSS SECTION FROM BLUE RIDGE SALT DOME, FORT BEND COUNTY, TO BARBER'S HILL SALT DOME, CHAMBERS COUNTY, TEXAS.



CROSS SECTION FROM THE NORTHEAST WELL FIELD TO THE EAST END WELL FIELD, HOUSTON, TEXAS.

Horizontal scale
0 1,000 2,000 3,000 4,000 5,000 Feet

mlc 10-50