TEXAS STATE BOARD OF WATER ENGINEERS

Prepared in cooperation with the United States
Department of the Interior, Geological Survey

PROGRESS REPORT ON THE GROUND-WATER RESOURCES OF THE HOUSTON DISTRICT

By

W. N. White, N. A. Rose and W. F. Guyton

November 1940

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INTRODUCTION

Location of the area

The Houston district, as the term is used in this report, comprises an area between the Trinity and Brazos Rivers in Harris County and parts of Montgomery, Waller, and Fort Bend Counties. (See fig. 1, p. 36). In this district there are three areas in which large quantities of ground water are pumped: The Houston pumping area, which includes Houston and the areas immediately adjacent, except those to the east; the Pasadena pumping area, which includes the industrial section that extends along the ship-channel from the Houston city limits eastward to Deer Park; and the Katy pumping area, which is an irregularly shaped area of several hundred square miles in which water is pumped from wells for the irrigation of rice in Harris, Waller, and Fort Bend Counties, roughly centered around the town of Katy, 30 miles west of Houston. The present report does not cover the pumping areas in the vicinities of Baytown, Goose Creek, Alta Loma, and Texas City.

History of investigation and previous reports

An investigation of the supply of ground water available for the Houston district has been in progress since December 1930, when available funds have permitted, as part of a survey of the ground-water resources of Texas by the United States Geological Survey in cooperation with the State Board of Water Engineers. This investigation is under the general direction of O. E. Meinzer, geologist in charge of the division of ground water in the Geological Survey. The results of this investigation have been summarized in five mimeographed progress reports, the first of which was released to the public in October 1932, and the last in March 1939. These reports, with illustrations and records of several thousand wells, were bound together and released by the State Board of Water Engineers in 1939 under the title "Ground-water resources of the Houston-Galveston area and adjacent region, Texas." All periodic water-level measurements made before December 31, 1939, have been published by the Geological Survey 1/.

In the first progress report it was shown that the beds of sand that yield water to wells in the Houston district have an extensive outcrop area, that there is good evidence that the recharge to the water-bearing formations by penetration of the rain that falls on this area is heavy, that the sands have a large aggregate capacity to transmit water, and that under the conditions of pumping which existed at that time the artesian pressures in the Houston district were in a state of essential equilibrium. It was suggested, however, that any new supply wells drilled by the City should be located at considerable distances from the existing centers of pumpage.

The most significant fact brought out in the second report, December 29, 1933, was that there was a rise in the artesian head from the spring of 1931 to the spring of 1933 as a result of a moderate decrease in the rate of withdrawal from wells.

In the third report, March 1, 1937, the total pumpage and results of measurements of water levels in observation wells in the region were discussed in detail and the following conclusion was reached:

> No large increase in pumping over the volume of water pumped in 1936 should be made within the city limits or along the ship-channel between the city limits and Baytown. Any large increase in ground-water withdrawals in or near the existing deep depressions in artesian pressure in downtown Houston and in the east Houston-Pasadena district would be especially undesirable. New wells involving heavy withdrawals of water should be located at distances of several miles from these depressions.

The fourth and fifth reports, dated respectively July 1, 1938, and March 1, 1939, were devoted mostly to discussions of pumpage and of the decline in water levels that resulted from an increase of about 40 percent in the aggregate annual

1/ Water levels and artesian pressure in observation wells in the United States: U. S. Geol. Survey, Water-Supply Papers 777, 840, 845, and 886.

pumpage of the Houston and Pasadena areas about March 1, 1937, due to the development of a new industrial water supply at Pasadena.

The current phase of the investigation was begun in the fall of 1938 when $5,000 was allocated by the City of Houston for the investigation and was matched by Federal funds. Another appropriation of $5,000 was made in the spring of 1940 and was also matched with Federal funds. The report that follows is chiefly a discussion of results of the investigations made in the last two years. The authors are indebted to A. N. Sayre of the Geological Survey for his assistance in the compilation and critical review of the report.

Field operations

The field operations carried on in the Houston district from 1930 to 1938 have been described in previous reports. Since November 1938 periodic water-level measurements have been made in about 185 observation wells throughout the Houston district at intervals ranging from one to three months (see fig. 1 and 2, pp. 36 and 37). About 30 of the wells are located in the outcrop area along the Houston-Hempstead and Houston-Conroe Highways; 40 in the Katy pumping area; and 115 in the Houston and Pasadena pumping areas, including 24 Houston municipal wells. Automatic water-stage recorders are being maintained on seven of these wells. A map showing the approximate altitudes of water levels in wells drawing from the most heavily pumped sands of the district based on the water-level measurements has been prepared (see fig. 4, p. 39). Data have been collected on pumpage from wells throughout the district. Samples of water have been taken from selected wells about twice a year and analyzed. Records of approximately 300 wells and electrical logs of about 200 oil tests have been collected. These logs, together with other information, have been used in the preparation of geologic sections.

Twenty-one pumping tests have been made on Houston city-owned wells to determine coefficients of permeability and storage. By using average values obtained from these tests, computations have been made of theoretical water-level fluctuations that would result from various assumed pumping conditions. Forty-six shallow test wells have been put down since June 1940, in groups of two to six wells each at various places on the outcrop area and are being measured regularly in connection with studies of the recharge. Five of these sets of wells are along the Hempstead road, three in the Katy rice-growing area, two near Tomball, and two on the Conroe road.

As part of the investigation, 13 deep test wells have been put down by the City of Houston in unexplored parts of the district west, north, and southeast of Houston to obtain additional data concerning water-bearing sands and the quality of water they contain. Selected drill cores and drill-stem sand samples from the test wells have been tested for permeability, porosity, and mechanical composition; and water obtained from the drill-stem tests has been analyzed.

Considerable attention has been given to studies of the location of areas or beds of sand that contain salt water.

GEOLOGY

The Houston district lies within the West Gulf Coastal Plain. The Hockley escarpment, the most prominent of a series of southeast-facing escarpments that probably represent ancient shore lines, extends in a southwesterly direction across southern Montgomery County, northwestern Harris County, and central Waller County and divides the Coastal Plain in this district into two parts. The area south of the escarpment is a smooth, nearly featureless plain that rises from sea level on the Gulf to an altitude of about 165 feet near the foot of the Hockley escarpment, about six miles southeast of Hockley, which is nearly 80 miles inland (an average slope of about two feet a mile). The other area, lying west and northwest of the escarpment, rises at an average rate of about eight feet a mile and its surface is gently rolling. The district is bounded on the east by the Trinity River and on the west by the Brazos River. It is crossed by the San Jacinto River, Spring Creek, and a few other perennial streams. The smaller streams generally carry water only during and immediately after heavy rains. The tides reach inland from the Gulf to Houston through Galveston Bay and the Houston ship-channel.

Formations of Miocene, Pliocene, and Pleistocene age underlie the Houston district. They consist of beds of relatively impervious clay, shale, and gumbo interbedded with beds of permeable sand, sandstone, and gravel that yield large quantities of water. As shown on the accompanying section along A - A' (see fig. 3, p. 38) the formations dip southeastward so that successively younger formations crop out from the northwest to the southeast. Likewise, the formations are encountered by wells at progressively greater depths toward the southeast. In the section shown herewith the older formations dip about 35 feet to the mile, and the younger formations dip about 20 feet to the mile. There is, therefore, considerable thickening of the formations down the dip. In the area southeast of Houston the dips of all of the formations become considerably less. In or near the outcrop area sand predominates, and the clays generally are lenticular; but toward the Gulf the beds of sand become thinner, and the clay beds thicken and persist over large areas.

These formations were deposited during several cycles of marine and continental deposition and consist of zones that are predominantly clay alternating with zones that contain some clay but are predominantly sand. Because the sediments come from the same areas the beds in one zone are lithologically similar to those of adjacent zones. Thus far no fauna or flora of diagnostic value have been found in these sediments in the Houston district. Hence, if the section is to be subdivided it must be with the aid of other criteria, such as the character recorded on the electrical logs, the drillers' logs, the dip of the beds, and other less easily discernable characteristics. Although the geology of the area has been studied by several men [2], and the outcrop areas of the formations have been mapped, there is little agreement as to their correlation down the dip. There has not been sufficient opportunity for the study of these formations during the present phase of the investigation to permit their correlation from the outcrop to the wells. However, it has been found possible to separate the sediments penetrated by the wells into six zones. The separation of these zones is based chiefly on electrical logs of oil tests and water wells. Correlation of the zones were made along two lines (see fig. 3, p.38). Line A - A' extends approximately in the direction of the regional dip from a point four miles northwest of Hempstead, in Waller County, southeastward through Houston to a point three miles southeast of Pasadena. Line B - B' extends from the town of Clodine, on the Fort Bend-Harris County line, eastward through Houston to a point about ten miles east of the city limits. A brief description of the zones in the order of their deposition is given below.

Zone 1 ranges from 150 to 400 feet in thickness and consists dominantly of beds of sand although it contains some relatively thick beds and lenses of clay. At the outcrop the sand is generally cross-bedded, lenticular, and slightly cemented. The beds of sand in this zone yield water to shallow wells in the northern part of the district. In Houston the beds in the upper part of the zone yield potable water to several of the deep wells, but those in the lower part contain water with too much chloride for most uses. In the section along B - B' this zone has only been recognized in wells east of the City.

2/ Geologic map of Texas: U. S. Geol. Survey, 1937.

Deussen, Alexander, Geology and underground waters of the southeastern part of the Texas Coastal Plain: U. S. Geol. Survey, Water-Supply Paper 335, pp. 72-84, 1914

White, W. N., Livingston, Penn, and Turner, S. F., Ground-water resources of the Houston-Galveston area, Texas: U. S. Geol. Survey, Memorandum for the Press, October 17, pp. 4-7, 1932.

Doering, John, Post-Fleming surface formations of coastal southeast Texas and south Louisiana: Am. Assoc. of Petroleum Geologists, pp. 651-688, 1935.

Metcalf, R. J., Deposition of Lissie and Beaumont formations of Gulf Coast of Texas: Am. Assoc. of Petroleum Geologists, pp. 693-700, 1940.

Zone 2 is a thick bed of clay that is persistent over a wide area, although in most places it contains thin lenses of sand. It can generally be easily distinguished from the overlying and underlying zones of sand and therefore is an excellent key bed. It ranges in thickness from 150 to 225 feet. In section B - B' the lower portion of this zone grades into the underlying beds and no contact can be drawn.

Zone 3 includes the most productive water-bearing beds in the Houston, Pasadena, and Katy pumping areas. It ranges in thickness from 800 to 1,200 feet, and is made up chiefly of fine to coarse-grained sand but contains varying amounts of interbedded clayey sand, sandy clay, clay, silt, and gravel. These interfingering layers and lenses grade into one another laterally or vertically in short distances, and the thinner beds in many places change character entirely or pinch out within a few hundred feet; but some beds of clay and sandy clay as much as 250 feet thick may be traced for a considerable distance.

Zone 4 is a series of clay and sandy clay beds that contains numerous thin lenses and beds of sand. It has an average thickness of about 100 feet. A few logs show a predominance of sand in this zone, but it is unimportant as a source of ground water.

Zone 5 consists chiefly of thick beds of fine to medium-grained sand and thin beds and lenses of clay. Recent shells were fairly common in drill cuttings obtained from this zone. It ranges in thickness from 50 to 150 feet and is the principal water-bearing zone in Alta Loma, Baytown, and Texas City. Shallow domestic and industrial wells in the Houston and Pasadena pumping areas also draw water from it.

Zone 6 consists predominantly of calcareous clay containing numerous lime concretions and thin lenses and stringers of sand and sandy clay. The beds of sand supply water to very shallow domestic wells at Houston.

PUMPAGE

General statement

The water supplies of the Houston district are obtained almost entirely from wells. The estimated average quantities of water, in millions of gallons a day, pumped in the Houston, Pasadena, and Katy pumping areas in 1930, 1935, 1937, 1939, and 1940 are given in the following table:

Estimated average daily pumpage in the Houston, Pasadena, and Katy pumping areas (in millions of gallons a day) a/

	1930	1935	1937	1939	1940
Houston Water Department (from city records)	25.8	24.5	25.2	27.2	29.0
Houston independent public water supplies and industrial wells	14	14	16	16	17
Pasadena industrial wells	10	10	29	29	35
Total in the Houston and Pasadena pumping areas	50	49	70	72	81
Katy pumping area	18	14	30	40	45
Total	68	63	100	112	126

a/ For convenience in compiling, all figures are given as daily averages throughout the year.

Houston and Pasadena pumping areas

Nearly all of the water supply of the Houston and Pasadena pumping areas comes from approximately 225 wells for which pumpage records covering several years are available. Of these wells, 24 are operated by the Houston Water Department and 22 by suburban communities. Industrial requirements for water are supplied in large part from privately-owned wells. The heaviest industrial consumers are oil refineries, breweries, ice plants, railroads, laundries, and a large paper mill.

In 1930 the total combined withdrawals of ground water in the Houston and Pasadena pumping areas averaged about 50,000,000 gallons a day. In 1931-33, as the financial depression grew, the rate of pumping both from city and privately-owned wells gradually declined and reached a minimum in 1933, but the decline amounted to only 10 or 12 percent of the total in 1930. During the next three years the rate of withdrawal of ground water gradually increased and in 1936 the total pumpage was approximately the same as it was in 1930. About March 1, 1937 a battery of new wells was brought into operation by an industrial organization near Pasadena and pumped during the remainder of that year at an average rate of about 19,000,000 gallons a day. This represented an increase of about 40 percent over the average daily pumpage in the Houston and Pasadena pumping areas in 1936. In 1938 the average rate of withdrawal from the new wells at Pasadena was about 16,000,000 gallons a day, about 16 percent less than the average in 1937; and the total pumpage in the Houston and Pasadena areas was somewhat less than in 1937. In 1939 the total pumpage in these areas was slightly more than in 1937. In the late fall of 1939 and spring and summer of 1940 the demands by industries of Pasadena and by patrons of the Houston City Water Department increased materially, and it is estimated that the total pumpage during 1940 will average about 81,000,000 gallons a day. This represents an increase of about 32,000,000 gallons a day, or approximately 65 percent, over the pumpage in 1935. About 25,000,000 gallons of this increase has occurred in the Pasadena area.

Katy pumping area

The records of the American Rice Growers Cooperative Association show that in the Katy area about 9,400 acres of rice were planted in 1930, 8,000 acres in 1935, 13,750 acres in 1937, 16,370 acres in 1938, 19,950 acres in 1939, and 24,200 acres in 1940. All of this land was irrigated with water pumped from wells.

The wells are pumped during the rice-growing season which begins about the first of May and lasts about 130 days. The pumps are not operated continuously but only as water is needed. Hence, the number of days of pumping varies from season to season, depending on the rainfall, and averages about 100 days each year, from May 1 to September 15. In order that direct comparisons may be made with pumpage in the Houston and Pasadena areas the pumpage in the Katy area is calculated in gallons a day as though it were continuous during the entire year. In 1930, according to an inventory made in connection with the cooperative ground-water investigation, the total pumpage in the district, with about 45 wells in operation, amounted to about 20,000 acre-feet, the equivalent of a continuous draft of about 18,000,000 gallons a day. The estimates of pumpage since 1930 are based on records of the Rice Growers Association and the Houston Lighting and Power Company, on the results of measurements of discharge of water from the individual wells, and on records of the rainfall at Houston. The pumpage in 1935, with approximately 40 wells in operation, was about 14,000,000 gallons a day. In 1937 it was about 30,000,000 gallons a day from 61 wells; in 1938, about 25,000,000 gallons a day from 71 wells; in 1939, about 40,000,000 gallons a day from 78 wells; and in 1940, about 45,000,000 gallons a day from 88 wells (see fig. 1, p. 36). It is significant that the consumption in 1940 was more than three times that of 1935 and nearly twice that of 1938.

DECLINE OF WATER LEVELS IN WELLS

General conditions

In the early days of Houston, flowing wells could be obtained by drilling practically anywhere within the Houston district. The artesian pressure in some localities was sufficient to raise the water 15 to 30 feet above the surface. However, in 1931 the artesian head in the greater part of the Houston and Pasadena areas, as shown by water levels in unused wells, was between 50 and 80 feet below the surface, or from about sea level to 30 feet below sea level (see figs. 5-9, pp. 40-44), the decline in head having averaged about four feet a year between 1920 and 1931. As a result of a decrease in the rate of pumping in these areas between 1931 and 1933 the maximum observed water levels in the observation wells of the area showed a rise, on the average, of about 3-3/4 feet between the spring of 1931 and the spring of 1933. As the rate of pumping gradually increased between 1933 and 1936 the maximum levels gradually declined, the average decline amounting to a little more than five feet.

When additional pumping at the rate of 19,000,000 gallons a day was started at Pasadena about March 1, 1937, the levels began to decline almost immediately in observation wells near Pasadena. By October 1, 1937, the water levels near Pasadena had dropped about 45 feet in two of the observation wells (see fig. 5, well 1170, p. 40) and 35 feet in another. In more distant wells the water levels declined less rapidly, the magnitude of the decline and lag in its transmission in most cases depending on the distance from the center of pumping at Pasadena. In some wells in the central and western parts of Houston and elsewhere several months elapsed before the decline resulting from this new pumpage was noticeable. From the latter part of 1937 to the corresponding period in 1938 the water levels in the observation wells near Pasadena remained constant or rose slightly. This was due to a decrease in local pumping. In observation wells at Houston, and west and north of the city, however, the decline continued during 1938 and in some wells was more than it was in 1937. During 1939 and 1940 the rate of pumping at Pasadena again increased and the water levels there declined rapidly and persistently. In the wells in eastern and northern Houston and in the area north of Houston the decline in 1939 was more than it was in 1938, and the rate of decline has increased in 1940. In central and western Houston and the area west of the city the average decline in 1939 was about the same as in 1938, but the rate of decline has increased in 1940. A part of the increase in the rate of decline in Houston in 1940 has been due to increased pumpage from the municipal wells and a few privately-owned industrial wells in Houston. The trend of water levels in different parts of the Houston district from 1931 to the fall of 1940 is shown in the hydrographs of selected observation wells in figures 5 to 9 on pages 40 to 44 .

The approximate altitudes of water levels in wells that draw from the most heavily pumped sands are shown by contours for a large part of the district in figure 4, page 39 .

Decline in Houston, Pasadena, and adjacent localities from 1937 to 1940

The decline of water levels between 1937 and 1940 in privately-owned observation wells that have screens opposite the more heavily pumped sands in Houston, Pasadena, and adjacent localities, based on the highest observed levels from January to May, together with the decline from August 1939 to August 1940, is shown in the following table:

Decline of water levels in wells screened opposite the heavily pumped sands in Houston, Pasadena, and adjacent localities, in feet. 1937 to 1940

Well No.	Distance from Pasadena (miles)	Depth (feet)	Spring measurements				August measurements
			1937-38	1938-39	1939-40	1937-40	1939-40
			Vicinity of Pasadena				
1182	½ west	685	--	--	--	--	15.10
1187	1 west	800±	--	a/+0.13	18.93	--	15.37
1231	do.	800±	--	+1.47	19.34	--	14.64
1176	2 northwest	1,134	28.99	2.90	+1.48	30.41	4.91
1170	2 west	836	31.	+0.5	19.5	50.0	13.0
1161	2½ west	1,228	25.	3.5	10	38.5	18.35
1150	2½ northwest	680	--	--	--	37.	11.51
883	3½ west	841	--	--	11.24	--	13.08
1229	4 south	1,680	--	--	--	--	23.77
1230	do.	1,419	--	--	--	--	13.70
890	4½ west	1,284	22.12	--	--	38.61	--
1302	6½ south	832	18.	4.5	4.79	27.5	6.65
933	7 north	850	--	--	--	--	7.38
			Eastern Houston				
881	5 west	650	15.90	6.00	8.92	30.82	8.08
878	do.	905	24.64	4.54	8.63	37.81	--
913	5½ west	900±	--	6.38	7.17	--	8.54
759	5½ northwest	569	16.49	5.99	9.83	32.31	8.41
876	6½ west	--	--	5.57	9.65	--	4.85
757	6½ northwest	676	13.2	6.57	9.91	29.7	8.1
751	7 northwest	540	12.56	6.62	9.88	29.06	9.16
748	7½ northwest	721	--	--	--	--	9.53

a/ Plus indicates rise in the water levels

Decline of water levels in wells screened opposite the heavily pumped sands in Houston, Pasadena and adjacent localities, in feet. 1937 to 1940

Well No.	Distance from Pasadena (miles)	Depth (feet)	Spring measurements 1937-38	Spring measurements 1938-39	Spring measurements 1939-40	Spring measurements 1937-40	August measurements 1939-40
			Northern Houston				
662	10 northwest	834	12.20	7.21	15.65	35.06	--
663	do.	740	--	--	7.44	--	4.85
656	11½ northwest	665	10.79	6.13	10.11	27.03	7.18
585	12½ northwest	950	--	--	9.27	--	--
			Central and western Houston				
680	9½ northwest	1,280	13.20	+2.57	3.88	14.51	11.44
790	10½ west	606	+1.12	10.29	6.18	15.35	5.27
619	10½ northwest	625	2.18	8.71	7.51	18.40	10.83
788	11 west	1,416	--	--	3.90	--	--
623	11 northwest	900±	--	--	5.97	--	3.57
620	11½ west	1,379	--	--	2.52	--	5.94
787	12 west	700±	--	--	4.63	--	3.08
779	do.	584	--	--	4.82	--	--
780	do.	732	--	--	4.57	--	7.72
606	12 northwest	575	4.56	7.67	7.57	19.80	7.54
609	do.	825	--	--	7.09	--	8.46
602	13½ west	1,038	7.69	5.83	6.23	19.75	9.71
			Locality west of Houston				
804	14½ west	650±	6.20	6.15	5.09	17.44	--
783	15½ west	350±	2.67	5.17	4.34	12.18	4.75
809	16 west	1,100±	6.37	3.88	6.61	16.86	8.55

Decline of water levels in wells screened opposite the heavily pumped sands in Houston, Pasadena, and adjacent localities, in feet. 1937 to 1940

Well No.	Distance from Pasadena (miles)	Depth (feet)	Spring measurements 1937-38	Spring measurements 1938-39	Spring measurements 1939-40	Spring measurements 1937-40	August measurements 1939-40
			Locality west of Houston--Continued				
840	16 west	827	--	--	5.07	--	7.13
473	18½ west	416	--	--	3.94	--	3.93
498	19½ west	787	--	--	3.72	--	--
472	20 west	365	--	--	3.68	--	3.72
490	23½ west	1,272	--	--	--	--	3.52
489	25½ west	472	--	--	--	--	4.36
			Locality north of Houston				
650	14 northwest	468	--	--	5.84	--	5.13
649	16 northwest	367	--	--	4.84	--	4.44
302	18 north	1,000-	--	--	2.66	--	--
256	21 northwest	189	2.70	2.57	3.14	8.41	3.75
264	do.	900±	11.78	2.47	2.92	17.17	2.89
225	23½ northwest	616	--	--	2.54	--	5.22
268	24½ north	815	--	--	--	--	2.29
221	24½ northwest	208	--	--	2.63	--	4.86

The outstanding facts revealed by the above table are as follows:

Vicinity of Pasadena.-- In six observation wells near Pasadena for which comparable records are available the decline in water levels between 1937 and 1940 ranged from 27.5 to 50.0 feet and averaged 37.0 feet. The decline between August 1939 and August 1940 in 12 wells ranged from 4.91 to 23.77 feet and averaged 13.1 feet. (See fig. 5, p. 40.)

Eastern Houston.-- In five observation wells in eastern Houston the decline between 1937 and 1940 ranged from 29.06 to 37.81 feet and averaged 32.0 feet. The decline between August 1939 and August 1940 in seven wells ranged from 4.85 to 9.53 feet and averaged 8.1 feet. (See fig. 6, p. 41.)

Northern Houston.-- In two wells in northern Houston the decline was 27.03 and 35.06 feet between 1937 and 1940 and in two wells was 4.85 and 7.18 feet between August 1939 and August 1940. (See fig. 9, Well 656, p. 44.)

Central and western Houston.-- Observations in central and western Houston in five wells showed a decline between 1937 and 1940 ranging from 14.51 to 19.80 feet and averaging 17.5 feet, and a decline in ten wells between August 1939 and August 1940 ranging from 3.08 to 11.44 feet and averaging 7.4 feet. (See fig. 7 for hydrographs of wells in Central Houston, p. 42.)

Locality west of Houston.-- West of Houston the decline in three wells between 1937 and 1940 ranged from 12.18 to 17.44 feet and averaged 15.5 feet, and the decline in seven wells between 1939 and 1940 ranged from 3.52 to 8.55 feet and averaged 5.1 feet. (See fig. 8, Wells 809, 489, and 490, p. 43.)

Locality north of Houston.-- North of Houston the decline in two wells between 1937 and 1940 was 8.41 and 17.17 feet and the decline in seven wells between 1939 and 1940 ranged from 2.29 to 5.22 feet and averaged 4.1 feet. (See fig. 9, Wells 264 and 256, p. 44.)

Records of the water levels in observation wells that in general are considerably shallower than the wells listed in the last table and draw water from the more lightly-pumped sands are given below.

Decline in water levels in wells screened opposite the lightly-pumped sands in the Houston, Pasadena, and adjacent localities, in feet, 1937 to 1940

Well No.	Distance from Pasadena (miles)	Depth (feet)	Spring measurements				August measurements
			1937-38	1938-39	1939-40	1937-40	1939-40
1209	$4\frac{1}{2}$ south	650±	6.49	4.22	2.33	13.04	3.12
886	5 west	540	6.58	1.19	5.38	13.15	4.96
738	$8\frac{1}{2}$ northwest	205	3.03	0.40	2.06	5.49	2.42
778	$11\frac{1}{2}$ west	404	--	--	3.78	--	--
820	do.	310	0.60	3.89	2.43	6.92	2.80
608	12 northwest	350	--	--	4.40	--	4.82
604	$12\frac{1}{2}$ northwest	340	0.57	a/ +1.02	4.93	4.48	--

a/ Plus indicates rise in the water levels.

The decline in five of these wells between 1937 and 1940 ranged from 4.48 to 13.15 feet and averaged 8.6 feet; and the decline between August 1939 and August 1940 in five wells ranged from 2.42 to 4.82 feet and averaged 3.6 feet. This decline is smaller in magnitude than the decline in the deeper wells but has almost exactly the same trend. This indicates that, although clay beds of considerable thickness separate the shallow and deep water-bearing zones, a connection exists between them which permits some flow of water from one to the other.

In the table below the differences are shown between water-level measurements made in the Houston municipal wells during the winter and spring of 1939 and measurements made during the corresponding period in 1940. With each measurement is given the time the pump on the well was idle before the measurement was made.

Decline of water levels in Houston municipal wells, 1939 to 1940

Plant	Well	Date	Depth to water (ft.)	Time of shut down 1/	Date	Depth to water (ft.)	Time of shut down 1/	Decline from 1939 to 1940
Central	F-1	Feb. 25, 1939	93.30	30 min.	Feb. 27, 1940	103.89	30 min.	10.59
do.	F-5	do.	93.08	2½ days	Feb. 8, 1940	100.91	5½ days	7.83
do.	F-10	do.	83.22	3 days	do.	93.26	8½ days	10.04
do.	F-11	Jan. 16, 1939	86.0	45 min.	Feb. 27, 1940	93.0	30 min.	7.0
do.	F-12	Feb. 25, 1939	84.65	30 min.	do.	96.25	30 min.	11.60
do.	C-16	Jan. 16, 1939	97.83	30 min.	do.	101.33	30 min.	4.50
do.	D-17	Feb. 25, 1939	87.50	11 days	do.	101.03	120 min.	13.53
East End	1	Feb. 24, 1939	97.54	30 min.	do.	105.82	30 min.	8.28
Heights	6	do.	78.49	25 days	Feb. 28, 1940	87.41	29 days	8.92
do.	7	Mar. 21, 1939	89.31	30 min.	do.	96.96	30 min.	7.65
do.	8	do.	91.92	30 min.	do.	98.0	30 min.	6.08
Magnolia Park	2	Feb. 24, 1939	83.49	20 days+	Feb. 27, 1940	90.41	21 days	6.92
Northeast	1	do.	49.90	10 days	do.	62.89	60 days	12.99
do.	2	May 25, 1939	92.88	30 min.	May 9, 1940	102.1	30 min.	9.22
Scott Street	1	Feb. 24, 1939	102.51	90 days+	Feb. 27, 1940	116.54	90 days+	14.03
do.	2	do.	94.87	30 min.	do.	112.41	30 min.	17.54
do.	3	Feb. 25, 1939	98.31	30 min.	do.	116.97	30 min.	18.66
do.	4	do.	93.46	30 min.	do.	107.66	30 min.	14.20
do.	5	Feb. 24, 1939	97.36	30 min.	do.	111.84	1 day	14.48
South End	2	Dec. 14, 1938	82.07	30 min.	Feb. 28, 1940	87.23	35 min.	5.16
do.	4	do.	79.04	30 min.	do.	82.16	30 min.	3.12
do.	5	do.	114.19	33 min.	do.	116.71	33 min.	2.52

1/ Time pump was idle before measurement was taken.

Most of the water-level measurements in the last table do not reflect the true static levels because the wells were not allowed to remain unpumped long enough to permit the water levels to become static before the measurements were made and because no control was exercised over the rates or times at which the other wells in the fields were pumped. Hence, the water levels measured in a single well at two different times are not strictly comparable. However, if the measurements of all the wells at a plant are considered the individual discrepancies tend to be ironed out and the average of the individual declines gives the approximate magnitude of the decline at that plant. The average decline at each plant from 1939 to 1940 was as follows: Central, 9.3 feet; East End, 8.3 feet; Heights, 7.6 feet; Magnolia Park, 6.9 feet; Northeast, 11.1 feet; Scott Street, 15.8 feet; and South End, 3.6 feet.

Decline in the Katy pumping area

The irrigation wells in the Katy area range in depth from about 150 to about 900 feet. Nearly all of them are gravel-walled and screened so as to draw from all the water-bearing beds penetrated, including those near the surface in which the water is unconfined and there is a water table. According to a statement by Mr. John Cope, a prominent rice grower in the area, the water levels declined an average of about five feet between 1903 and 1931. As shown in the following table, the decline in 14 observation wells between March 1931 and March 1940 ranged from 4.5 to 14.0 feet and averaged 8.6 feet. Between March 1939 and March 1940 the decline in 31 wells ranged from 1.5 to 4.7 feet and averaged 2.6 feet (See fig. 8, well 205, p. 43).

Decline of water levels in wells in the Katy pumping area

Well No.	Depth of well (feet)	March 1931 to March 1940 (feet)	March 1939 to March 1940 (feet)	Well No.	Depth of well (feet)	March 1931 to March 1940 (feet)	March 1939 to March 1940 (feet)
		Harris County				Waller County	
134	274	--	3.8	223	767	8.5	2.0
136	138	14.0	4.7	235	--	12.3	3.5
139	134	a/10.2	4.0	247	641	--	2.0
140	359	--	3.9				
146	250	--	4.0				
182	239	--	2.8			Fort Bend County	
183	284	7.2	2.2				
186	628	9.3	2.5				
205	615	11.2	--	7	337	5.2	2.0
206	450+	7.6	3.6	11	170	a/4.7	2.3
352	470	--	3.5	15	172	7.6	2.2
357	--	7.5	1.7	19	545	7.5	2.0
362	500	10.9	3.1	20	250	a/4.6	2.3
367	535	--	2.5	21	--	4.5	2.0
370	625	--	2.2	26	657	--	2.0
381	95+	7.0	1.5	33	346	--	1.7
382	185	--	2.8				
384	505	a/ 7.8	2.8				
385	359	a/ 5.1	2.3				
399	326	--	1.8				
400	258	--	1.9				

a/ Decline between 1933 and 1940.

Fluctuation in water-table wells along the Hempstead and Conroe highways

Measurements of depths to water in about 70 shallow wells along the Hempstead and Conroe highways were made periodically during 1931 and 1932, and the measurements in about 30 of these wells have been made at intervals since that time. The water levels in nine of these wells are affected directly by changes in the levels of the perched water which occurs nearly everywhere in the outcrop area. They decline markedly during dry periods and rise quickly during and immediately after heavy rains, especially in winter. The water levels in the wells tapping only the true water table, on the other hand, fluctuate less with the rainfall, but are likely to be considerably affected by heavy pumping of wells in the outcrop area.

No decline of the water table has been found since 1931 in ten water-table wells along the Conroe highway, or in two wells near Houston and two wells northwest of Hockley along the Hempstead highway. There has been a decline in seven wells along the Hempstead highway which are near the northern part of the Katy pumping area. Practically all of this decline has occurred during the last two years. The water levels dropped considerably during the summer of 1939 and failed to rise as much during the winter of 1939-40 as during the corresponding period of 1938-39. They again declined considerably in 1940 and have not risen to the level they had at this time last year. The decline has ranged from one to five feet, with an average of about 2½ feet, and is apparently caused by pumpage from new rice-irrigation wells near the Hempstead highway and by increased pumpage in other parts of the rice-growing area.

CHEMICAL CHARACTER OF THE GROUND WATER

The character and quantity of dissolved mineral matter in a water supply largely determines its usefulness for public, industrial, and irrigation purposes. 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 show that most of the water pumped from wells is of good quality and compares favorably with other public, industrial, and irrigation supplies in the United States. Many of these analyses have been presented in the earlier mimeographed reports on the district.

In the Houston district, water of good quality is generally found in all aquifers to relatively great depths but water of objectionably high mineral content has been encountered in many of the deepest wells and oil tests. The higher mineral content of these deeper waters is due largely to increased amounts of sodium chloride. Samples of water with moderate mineral content and low chloride content have been collected from sands penetrated by wells at depths of about 2,000 feet in the City of Houston, about 1,900 feet at Pasadena, 1,850 feet in test well No. 8 put down by the City of Houston, 12 miles southeast of Houston near South Houston, and about 1,700 feet in test well No. 6 put down by the City of Houston near Clodine. However, samples of water having sufficient chloride to be objectionable were obtained from sands penetrated by wells at 2,100 feet in the City of Houston, at about 1,000 feet near Webster, 25 miles southeast of Houston, at about 1,000 feet at Baytown, 20 miles east of Houston, and at about 2,000 feet in test well No. 6 near Clodine. In test wells 8 and 9, near South Houston, water with low chloride content was found down to nearly 1,400 feet; but the water from 1,399 to 1,414 feet contained 208 parts per million of chloride; from 1,506 to 1,526, 652 parts per million chloride; and from 1,666 to 1,706, 290 parts per million chloride. However, at 1,832 to 1,850 in well No. 8 the chloride was only 89 parts per million, which is only slightly higher than the average of the Houston-Pasadena area. The electrical logs of oil tests that have been studied indicate that highly mineralized water occurs below 2,100 feet near Pasadena, 1,500 feet about 18 miles southeast of Houston, 1,800 feet about 11 miles south of Houston, 2,000 feet near South Houston, 2,200 feet near Aldine, 12 miles north of Houston, and 2,500 feet near Westfield, 20 miles north of Houston. These data show that water of low chloride content is likely to be found in the beds of sand from the surface to depths as great as

2,000 to 2,100 feet in Houston and to even greater depths in the area north of Houston, but that toward the south and southeast the depths to which water of low chloride content can be found become progressively less. They also tend to show that the deeper sands which supply fresh water in Houston contain water that is too highly mineralized for public, industrial, and irrigation uses at a comparatively short distance southeast of Houston. In localized areas near salt domes, such as Pierce Junction, Fairbanks, Eureka, and South Houston, highly mineralized water with high chloride content can probably be found at comparatively shallow depths. It is believed, however, that there is little likelihood of this highly mineralized water spreading into adjacent areas in which there is fresh water.

The possibility of salt-water encroachment has been discussed in previous reports. Since 1931 samples taken at regular intervals from selected widely-spaced wells in the district have been analyzed to determine whether there has been any increase in chloride content. According to these analyses, including the latest of May 1940, there has been no important change in the composition of the ground water in the formations from which the Houston district obtains its supply. It is possible, however, that there has been some encroachment in areas to the south or east of the Houston and Pasadena pumping areas where there are no wells drawing from the sands in which the encroachment may be occurring. Early in 1940 plans were made by the Water Department of Houston to put down additional test wells in those areas to obtain further information regarding the character of the water in the deeper sands, but this has not yet been done.

RESULTS OF EXPLORATORY WELL DRILLING

In the program of exploratory drilling carried out by the City of Houston during the summer of 1939, nine test wells were put down west of Houston along the Houston-Clodine road, two about 15 miles north of the city limits at Westfield, and two southeast of the city on the South Houston-La Porte highway, about three miles east of the town of South Houston. The main objects of the drilling program were as follows:

(1) West of Houston, to determine the thickness and character of the water-bearing sands, the chemical character of the water in them, and the static head down to a maximum depth of 2,000 feet.

(2) North of Houston, to determine the static head and obtain observation wells both in the sands at moderate depths, which are believed to correlate with the heavily-pumped sands at Houston, and in the deep sands which are undeveloped or very lightly drawn upon in Houston, and to determine the quality of the water in them.

(3) Southeast of Houston, to determine the static head in the fresh water-bearing sands and the position and thickness of sands containing salty or brackish water, and by using the test wells as observation wells to endeavor to obtain advance information on the possible encroachment of salt water from the direction of the Gulf.

The test wells were put down with a rotary drill. They were $5\frac{1}{2}$ inches in diameter and ranged in depth from 360 to 2,000 feet. The combined drilling footage of all the wells amounted to 16,646 feet and the average depth of the wells to 1,280 feet. All wells were electrically logged as soon as possible after the drilling was completed. Samples of cuttings were taken from the drilling mud after each 20 feet of drilling and in six of the wells cores of the sand were obtained in selected beds. In eight of the wells samples of sand and water were obtained by the drill-stem method; altogether 15 such samples were collected. Selected sand samples were analyzed and tested for permeability and porosity in a field laboratory. Six of the test holes were finished as observation wells by casing them with $3\frac{1}{2}$-inch (I. D.) casing and setting screens opposite selected beds of sand. Periodic water-level observations are made in them and the quality of the water is tested from time to time.

The test wells show that there is an average of 600 feet of water-bearing sands between the surface and a depth of 1,500 feet along the line of test wells from the western city limits of Houston to Clodine. A supply of water exists north of Houston in deep sands that are practically untouched by existing wells. The water contained in them at Westfield and Spring is well suited for domestic and industrial uses. The occurrence of fresh water in the deep sands in the vicinity of South Houston tends to show that salt-water encroachment from down dip through the sands tapped by wells in the heavily-pumped area may not be very serious so far as the immediate future is concerned, but more information is needed before a definite conclusion in that respect can be reached. (For more detailed information regarding the results of the test drilling see report of July 1940 by N. A. Rose, W. N. White, and Penn Livingston entitled "Exploratory well drilling in the Houston district, Texas.)

TRANSMISSIBILITY AND STORAGE CAPACITY OF THE WATER-BEARING BEDS

The amount of water that can be withdrawn from the water-bearing beds depends upon the amount of the rainfall that percolates into them in their outcrop areas, upon the capacity of the beds to transmit the water to the pumped areas, and upon the amount of water that is withdrawn from storage in the beds when the head declines. In all parts of the Houston district except the Katy area the water levels in the outcrops of the water-bearing sands are high enough so that some of the ground water is discharged by springs and seeps. It is evident therefore that the rainfall recharges the aquifers at a rate greater than the water is transmitted down the dip. In the Katy area the water levels have declined below the levels of the stream channels and none of the recharge returns to the surface as springs or seeps except possibly during or immediately after periods of heavy rainfall.

The rate at which water is transmitted depends on the thickness and permeability of the sands and the hydraulic gradient. The amount of water that is released from storage in an artesian aquifer depends on the elasticity of the water and the compressibility of the sands and their associated confining clays; in a non-artesian aquifer it depends on the effective porosity, or specific yield, of the aquifer. With comparable declines in head, the amount of water released from storage by lowering of the water table in the non-artesian aquifers is usually from 50 to 200 times as much as is released by the compression of the artesian aquifers.

Transmissibility

The coefficient of permeability of a given water-bearing material, as the term is used by the Geological Survey, is the rate of flow, in gallons a day, through a cross-sectional area of one square foot, under a hydraulic gradient of 100 percent, at a temperature of 60 degrees Fahrenheit. The coefficient of transmissibility of a given aquifer is the product of the thickness of the aquifer, in feet, multiplied by the average coefficient of permeability, corrected for the prevailing temperature of the water.

The average thickness of the beds of sand which furnish most of the supply for Houston and Pasadena has been estimated from drillers' logs and electrical logs as about 600 feet.

The coefficient of permeability of 15 samples, obtained from drill stem tests during the exploratory test well drilling, ranged from 41 to 811 and averaged about 275. (See detailed report on results of test drilling.)

In the fall of 1939 Mr. C. E. Jacob, of the Geological Survey, conducted 16 pumping tests at the Houston municipal well fields and five tests on the city-owned observation wells. Each test consisted of pumping a well a given length of time and upon stopping the pump, observing the rate of the recovery of the water level within the well. In many cases it was also possible to observe the interference in the recovery produced by stopping and starting pumps on nearby wells screened in the same sands. Mr. Jacob analyzed the results of these tests by means of the following equation developed by Theis:3/

$$s = \frac{114.6Q}{Pm} \int_u^\infty \frac{e^{-u}du}{u} \qquad \text{where } u = \frac{1.87r^2S}{Pmt}$$

where s is the drawdown, in feet at any point in the vicinity of a well pumped at a uniform rate; Q is the discharge of the well, in gallons a minute; P is the coefficient of permeability of the material in the aquifer, m is the thickness of the aquifer, in feet; r is the distance from the pumped well to the point of observation, in feet; S is the coefficient of storage; and t is the time the well has been pumped, in days. The average coefficient of permeability of the sand in the aquifers at Central, Heights, and Scott Street plants was calculated to be approximately 300. At the Northeast plant the permeability was computed as 240. In the observation wells put down by the city near Westfield, South Houston, and Alief the coefficients were found to be 150, 325, and 500, respectively. With an average coefficient of permeability of 300, as computed from these tests, and an average thickness of water-bearing beds of 600 feet, the coefficient of transmissibility, corrected for temperature, is computed to be 180,000 gallons a day.

Values for the coefficient of transmissibility of all the heavily-pumped water-bearing beds have been obtained from the applications of the Theis equation

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3/ Theis, C. V., The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using ground-water storage; Trans. Amer. Geophys. Union, pp. 519-524, 1935.

to drawdowns in eight selected wells over a period of three years, created by the increase in pumpage of 19,000,000 gallons a day at Pasadena in 1937. They range from 112,000 to 196,000 gallons a day and average 140,000 gallons a day.

The hydraulic gradient in the artesian beds in February 1940 was determined from the map, figure 4, page 39 . Water moves through the water-bearing beds in the direction of the hydraulic gradient, at right angles to the contours. The rate of inflow into the heavily-pumped area was calculated in accordance with Darcy's law, which states that the rate of flow of water through a given cross-sectional area of sand is directly proportional to the hydraulic gradient and the permeability. The contour 10 feet below sea level was chosen as the line along which the rate of inflow could be most readily and accurately determined. The length of this line was estimated as 45 miles, the average hydraulic gradient across this contour as 10 feet to the mile, and the average coefficient of transmissibility as 160,000 gallons a day (the average of the coefficients of transmissibility as computed from Jacob's permeability results, the three-year drawdown curves, and laboratory tests of samples of sand obtained during the test drilling by the City). On the basis of these estimates the inflow in February 1940 across the minus 10-foot contour was computed as 72,000,000 gallons a day.

Storage

The amount of water that is released from storage when the head in an artesian aquifer declines has been called the coefficient of storage, and has been defined as the amount of water, in cubic feet, that will be released from storage in each vertical column of the aquifer having a base one foot square when the artesian head is lowered one foot.[4/]

4/ Theis, C. V., The significance and nature of the cone of depression in ground-water bodies; Econ. Geol., vol. 33, No. 8, p. 894, December, 1938.

Using the Theis formula, Mr. Jacob obtained values for the coefficient of storage in 16 interference pumping tests. In 14 of the tests the values ranged from 0.000165 to 0.00108 and averaged about 0.0005 for thicknesses of sand from 157 to 400 feet. The other two tests were made on sets of wells that are screened chiefly opposite different beds of sand and therefore are not included in the average. The average thickness of the sands that were screened in the 14 tests was about 300 feet or only about half of the total thickness of the aquifers. As the coefficient of storage is considered approximately proportional to the thickness of the aquifer, a coefficient of 0.0005 for 300 feet is equivalent to 0.001 for a thickness of 600 feet, the approximate combined thickness of the heavily-pumped sands in the Houston and Pasadena areas.

Values for the coefficient of storage obtained by the application of the Theis equation to the three-year drawdowns in eight wells, mentioned on page 28, range from 0.0019 to 0.0054 and average 0.0033 for all the heavily-pumped water-bearing beds. It should be noted that in this case the head was lowered for the first time and the decline took place over a period of three years. Therefore, the average coefficient of storage calculated from these data should be larger than that calculated from data obtained from the short tests made in the thoroughly developed Houston well fields where the head has fluctuated many times through the range recorded in the tests.

Assuming that the average coefficient of storage lies between the values obtained from the pumping tests and those obtained from the three-year drawdowns and is about 0.002, and that the average decline during a period of one year from February 1939 to February 1940 was ten feet over an area of about 300 square miles within the minus 10-foot contour in figure 4, the amount of water taken out of artesian storage in this 300 square mile area during the one-year period was calculated to be about $3\frac{1}{2}$ million gallons a day, or somewhat less than 5 percent of the pumpage.

A large quantity of water was also drawn from artesian storage outside of the minus 10-foot contour, where considerable declines have taken place. However, the available data are not sufficient to permit estimates of the amount.

The decline in water levels in the Katy area involves unwatering by lowering the water table as well as removal of water yielded by compression. Hence although the water levels in the wells have declined less than in the Houston and Pasadena areas the decline represents more water taken from storage. The data indicate that a large part of the water that has been pumped has come from natural storage, but the data are insufficient to permit estimates of the amount.

Practical value of coefficients

The tests that have been made give a large range in the computed coefficients of permeability and storage, partly because of differences in the character and thickness of the different beds and of the same bed from place to place, and partly because of the imperfect conditions under which the tests were made and the inadequacy of the information as to the beds tapped by the pumped wells and the observation wells. The range in computed coefficients of storage is caused largely by the differences in the length of time covered by the different tests. In an area such as Houston, where the clays and sands are so closely inter-bedded and lenticular in extent and where sedimentation occurred under such varied conditions, it is practically impossible to obtain the average coefficient of permeability or the average coefficient of storage for the many aquifers drawn upon or for all parts of any one aquifer. Therefore, average values for the coefficients of permeability and storage computed from the available data should not be expected to give results which are more than approximately in the correct order of magnitude.

Use of coefficients in computing future declines of water tables

If the extent of the water-bearing beds and the coefficients of transmissibility and storage are known, computations can be made of the future declines of the water level that will result from increases in the rate of pumping. Although the available data are at present insufficient to permit a comprehensive analysis, the following curves (computed according to the Theis formula) are given as a simple approach to the problem. They show the drawdown that would occur at various distances from a pumped well after pumping 1, 3, and 10 years if the well taps an artesian aquifer of infinite areal extent having a coefficient of transmissibility of 160,000 gallons a day and a coefficient of storage of 0.002, if the well is pumped at a constant rate of one million gallons a day.

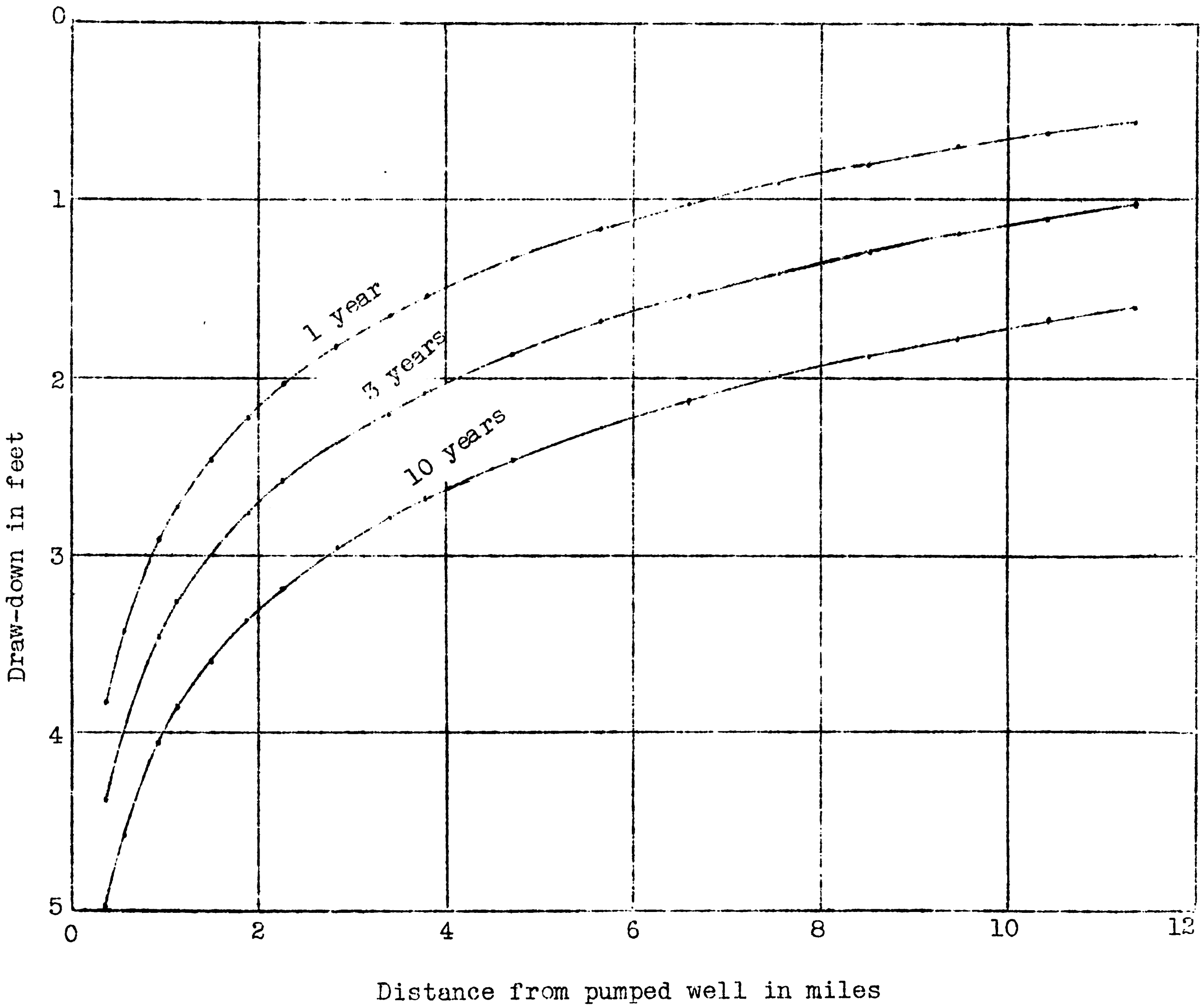


Figure 10. THEORETICAL DRAWDOWN (ACCORDING TO THE THEIS FORMULA) DUE TO PUMPING A WELL AT A CONSTANT RATE OF 1,000,000 GALLONS A DAY

(Aquifer having coefficients of transmissibility and storage of 160,000 gallons a day and 0.002 respectively)

The curves show that the decline in head in the aquifers near a pumping development begins immediately after pumping is started and is relatively large, the rate being rapid at first but gradually decreasing with time; whereas, the decline at a considerable distance from the development is smaller and does not begin for some time after pumping has been started.

SUMMARY

The aggregate annual pumpage in the Houston and Pasadena areas was nearly constant from 1930 to 1936, inclusive, but it increased about 60 percent between 1937 and 1940. In the Katy area the annual pumpage decreased slightly between 1930 and 1935, inclusive, but increased about 200 percent between 1936 and 1940. The total annual pumpage in the Houston district was nearly doubled in the five-year period.

From 1930 to 1937, inclusive, the water levels in the Houston and Pasadena areas remained practically constant, indicating that essential equilibrium in water levels had been reached for the amount of water pumped. As was to be expected, the increased pumpage in 1937 caused a marked decline in water levels, an increased hydraulic gradient, an expansion of the cone of depression, and the removal of water from artesian storage. Further increases in pumpage in 1939 and 1940 caused further decline and depletion. Since 1937 the head in the artesian aquifers has declined over a wide area, perhaps to the outcrop area. A part of the water that is pumped is taken from artesian storage in the pumping areas, but most of it is being drawn into these areas through the aquifers. The water that is drawn into these areas is replenished in large part by recharge on the outcrop area, but a substantial part of it is also drawn from storage in the artesian aquifers outside of the pumping areas. The evidence obtained to date indicates that the pumping has not yet drawn water from storage in the outcrop area.

In the Katy area, the decline in water levels has been less than in the Houston and Pasadena areas, but it represents in part an unwatering of the beds, and hence a larger proportion of the water derived from storage. If the present rate of pumping in the Katy area is continued the local ground-water reservoir will be seriously depleted.

If pumping at the present rate of 81,000,000 gallons a day in the Houston and Pasadena areas is continued, the artesian head will continue to decline for some years, although at a diminishing rate. If the rate of pumping is substantially decreased, the water levels will rise, but they will probably not return to the altitudes at which they stood when a similar pumping rate was maintained at an earlier time. Any increase over the present rate of pumping will cause further decline in water levels, withdrawal of additional water from artesian storage, further steepening of the hydraulic gradient, and increased flow of ground water into the pumping areas. The question as to further increase in the rate of pumping is partly a question of the maximum depth from which water can be economically pumped, but it also involves the further depletion of the storage in the ground-water reservoir, the possibility of withdrawing water at a more rapid rate than it can be replaced from rainfall in the outcrop areas, and the possibility of increasing the danger of encroachment of salt water. If it is desired to maintain the water levels at or near their present altitudes the present rate of pumping should be reduced and a supplementary supply of water should be developed.

Analyses of water samples taken periodically since 1931 from selected wells have thus far not given any evidence of intrusion of salt water into the fresh water-bearing sands of the area from down dip or from underlying salt-water sands. However, this intrusion may be occurring beyond the limits of observation wells. Further lowering of the head in the fresh water-bearing beds will increase the possibility of the intrusion.

Previous reports have indicated that additional supplies for the City of Houston could be obtained from wells west of Houston in the direction of Clodine. To obtain an additional supply from this area is now less promising because of the large increase in pumpage during the last two years in the nearby Katy area, with the resulting large withdrawal of water from storage. Although the information at hand indicates that a supplementary supply of ground water may be obtained in the area north of Houston, including the Aldine-Westfield locality, from sands which lie stratigraphically deeper than the heavily-pumped sands of the Houston and Pasadena areas, the information is insufficient to allow estimates to be made of the quantity and quality of the water. Additional test drilling would serve to show the character and extent of these sands and the quality of the water in them.

The need of watching the ground-water situation in the Houston district is probably greater now than ever before. The investigations described in this report should be continued, especially the obtaining of records of pumpage, water levels, and quality of water throughout the district. These data should be critically analyzed as they are collected.

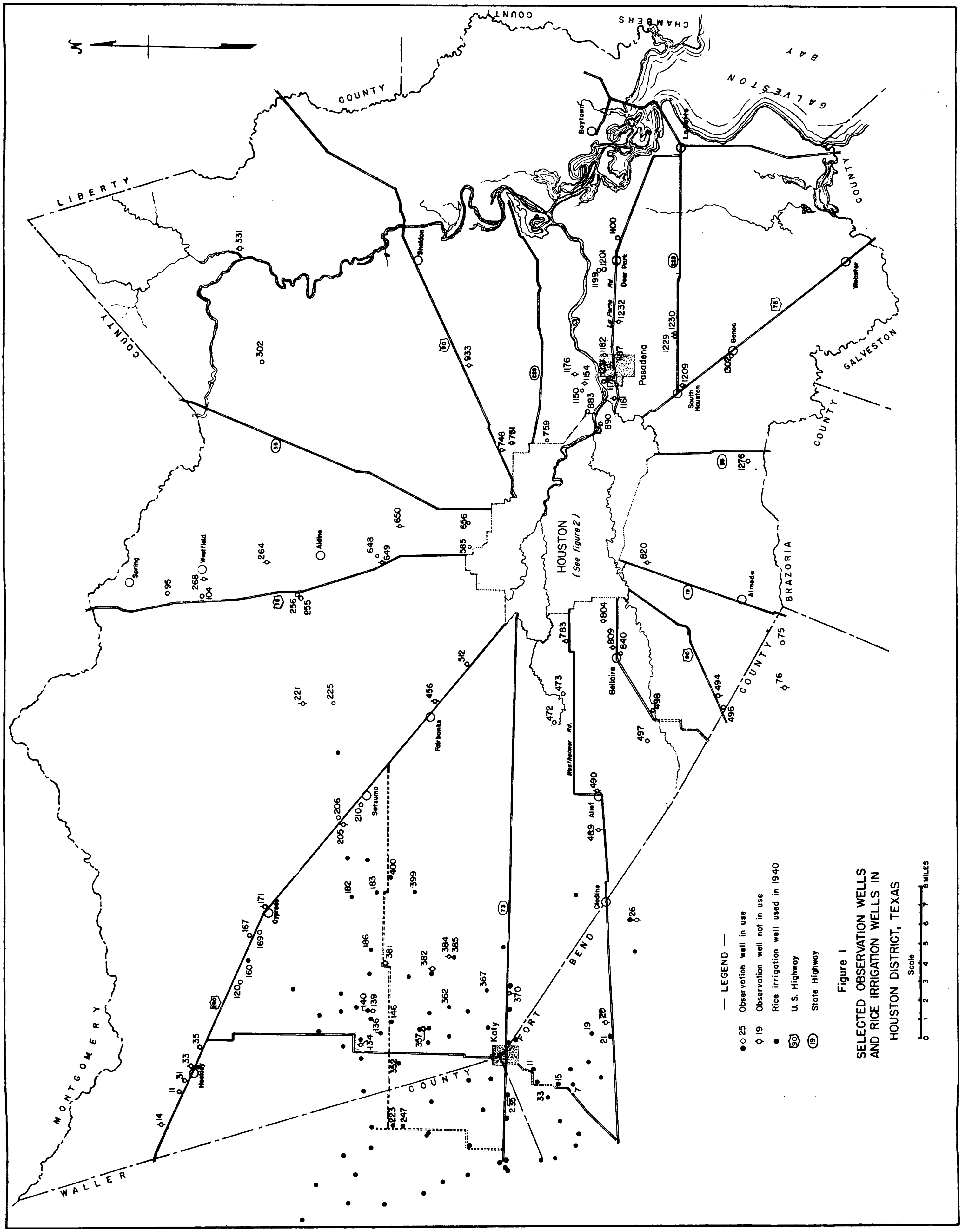


Figure 1
SELECTED OBSERVATION WELLS AND RICE IRRIGATION WELLS IN HOUSTON DISTRICT, TEXAS

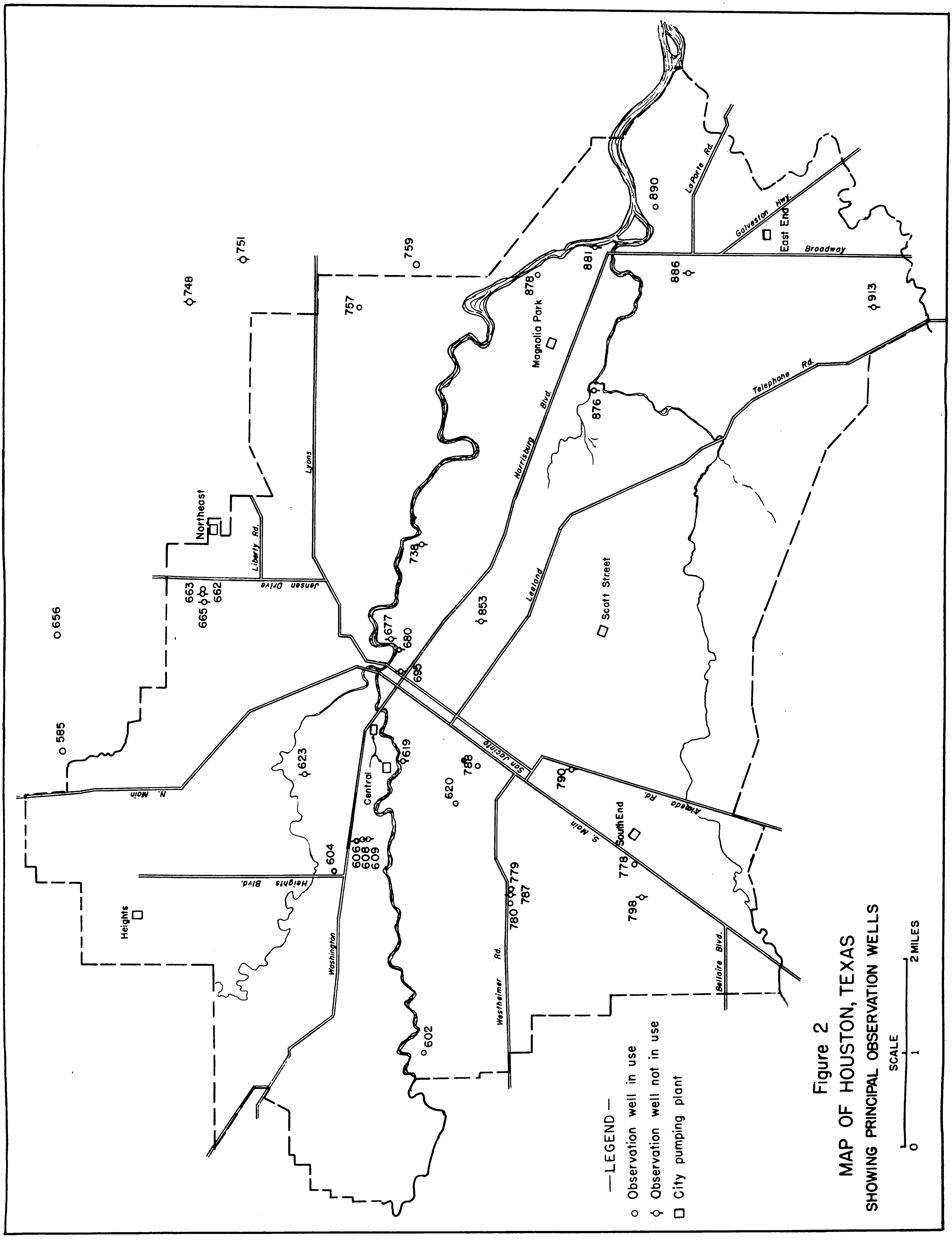
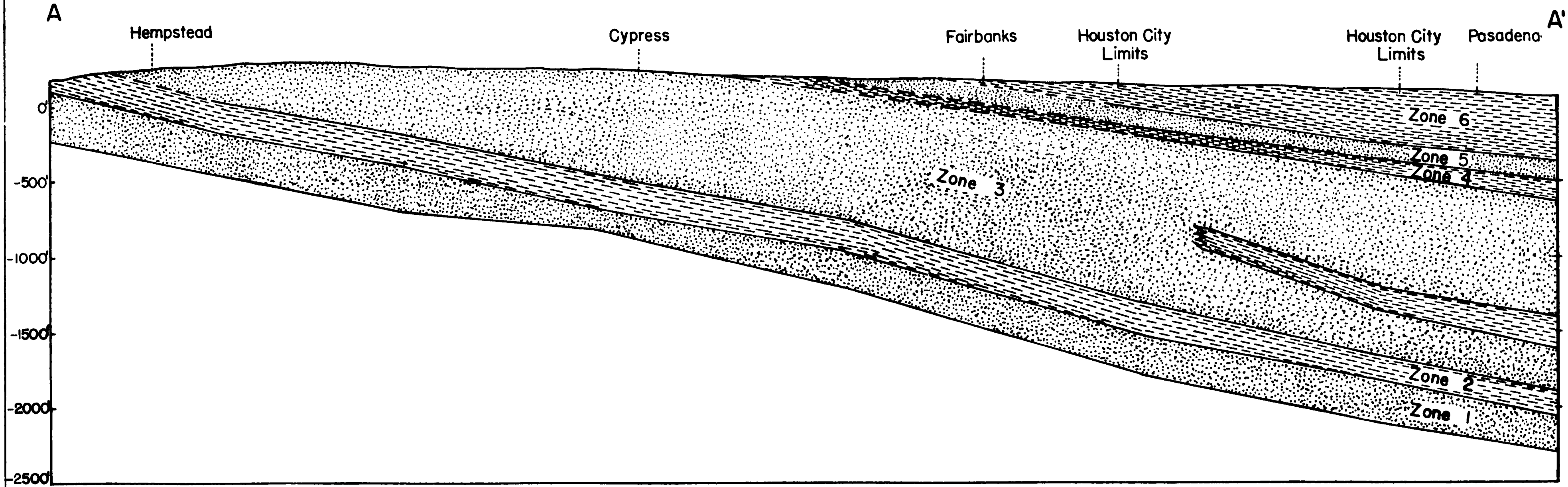
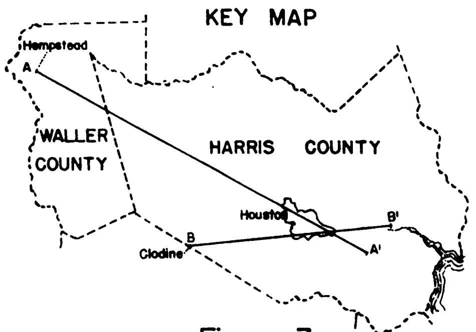


Figure 2
MAP OF HOUSTON, TEXAS
SHOWING PRINCIPAL OBSERVATION WELLS





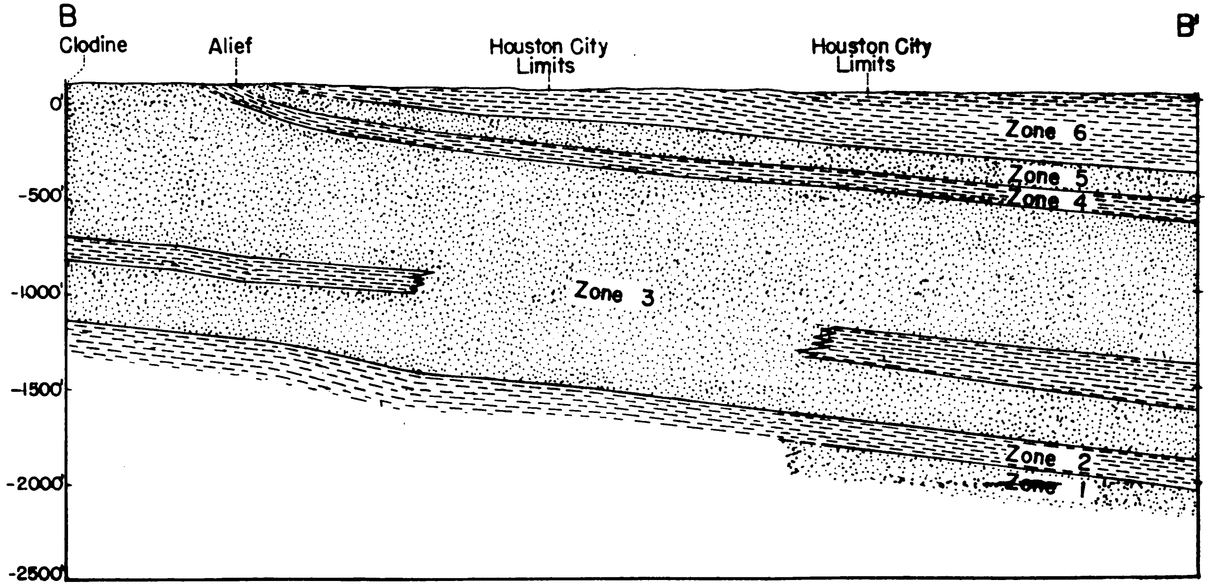


Figure 3
GENERALIZED GEOLOGIC SECTIONS IN WALLER AND HARRIS COUNTIES, TEXAS

LEGEND

Chiefly sand, contains beds and lenses of clay and sandy clay

Chiefly clay, contains beds and lenses of sand and sandy clay

Scale

0 3 6 9 Miles

11-12-40.

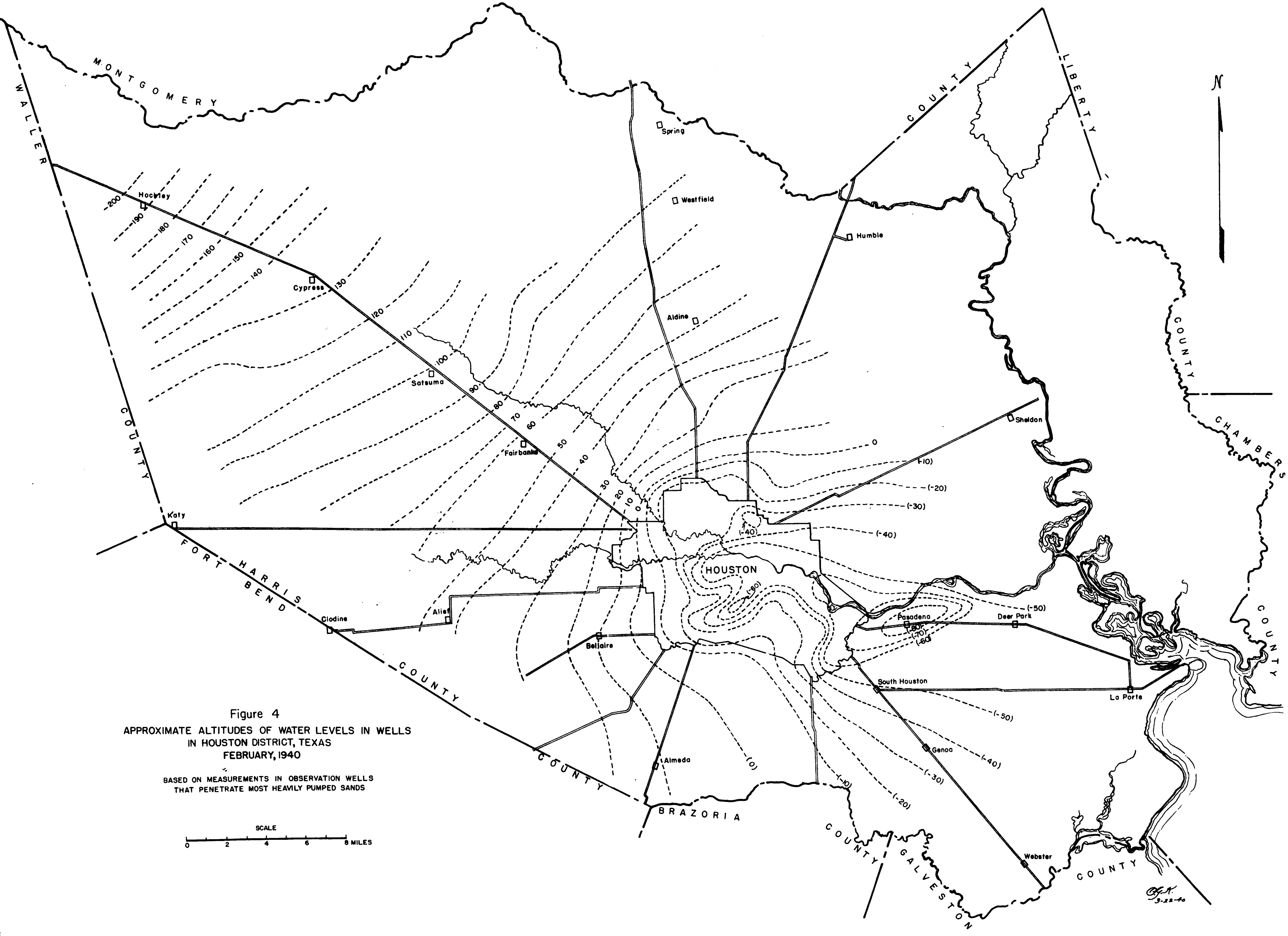


Figure 4

APPROXIMATE ALTITUDES OF WATER LEVELS IN WELLS
IN HOUSTON DISTRICT, TEXAS
FEBRUARY, 1940

BASED ON MEASUREMENTS IN OBSERVATION WELLS
THAT PENETRATE MOST HEAVILY PUMPED SANDS

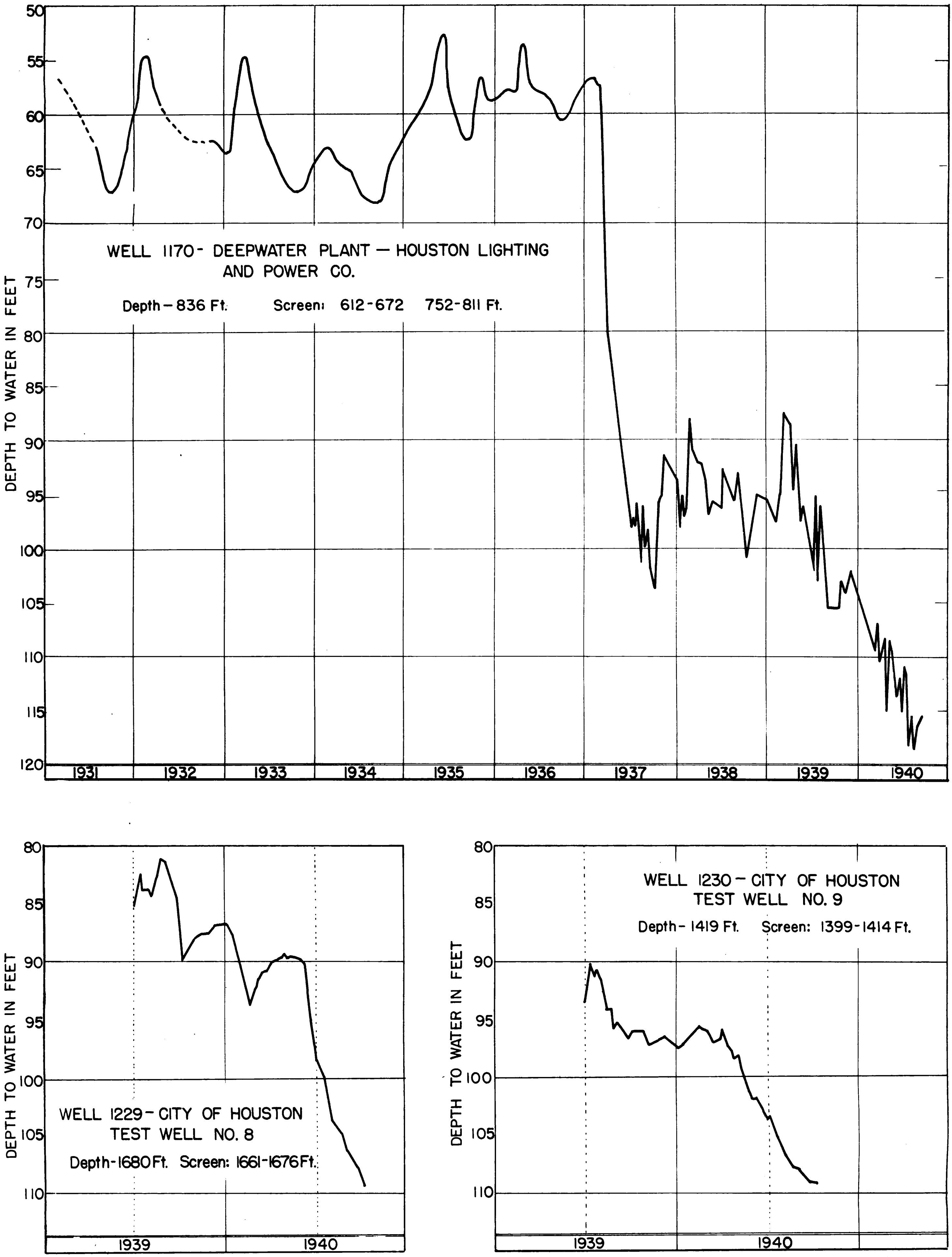


FIGURE 5. —FLUCTUATIONS OF WATER LEVELS IN WELLS IN PASADENA AREA

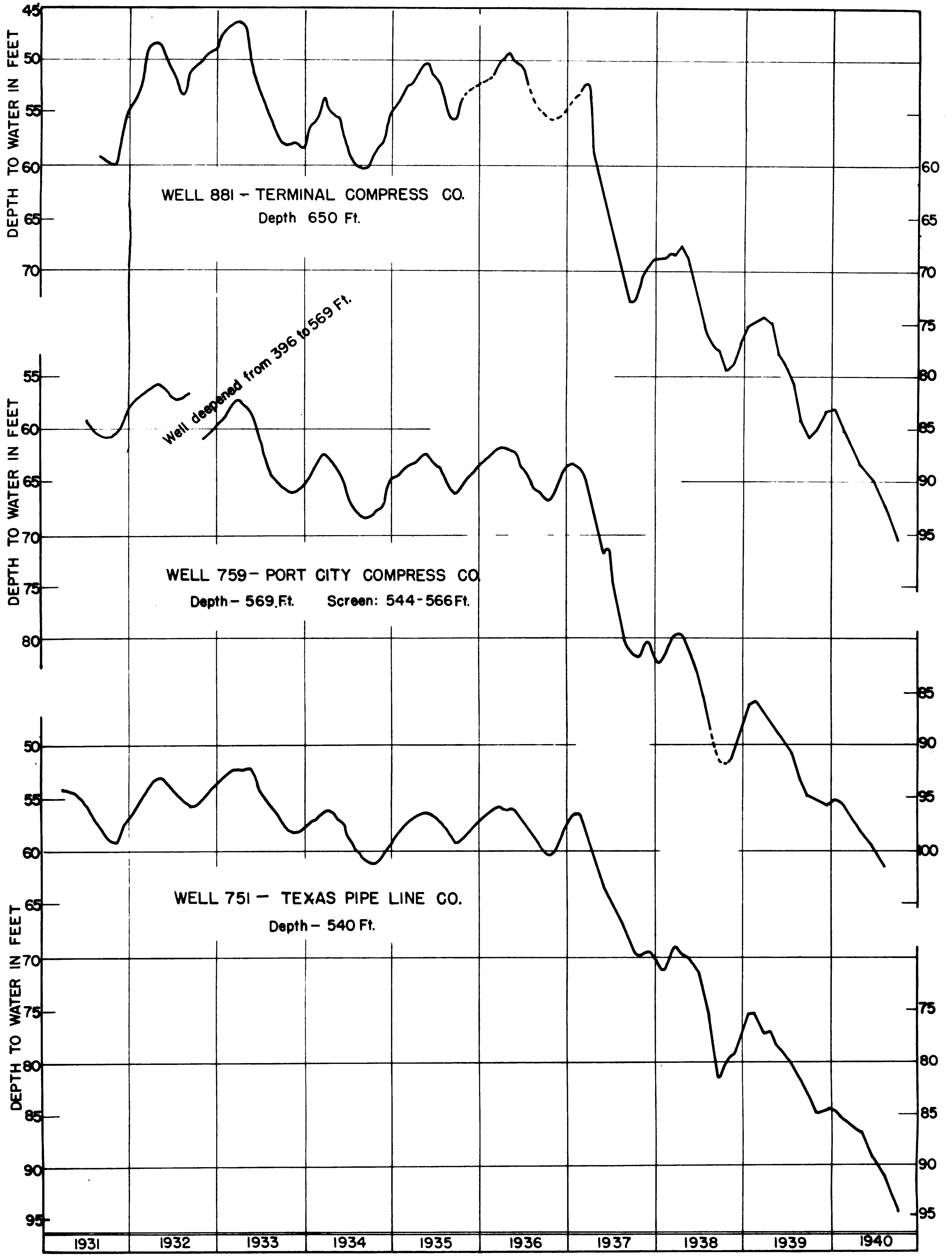


FIGURE 6.-FLUCTUATIONS OF WATER LEVELS IN WELLS IN EASTERN HOUSTON

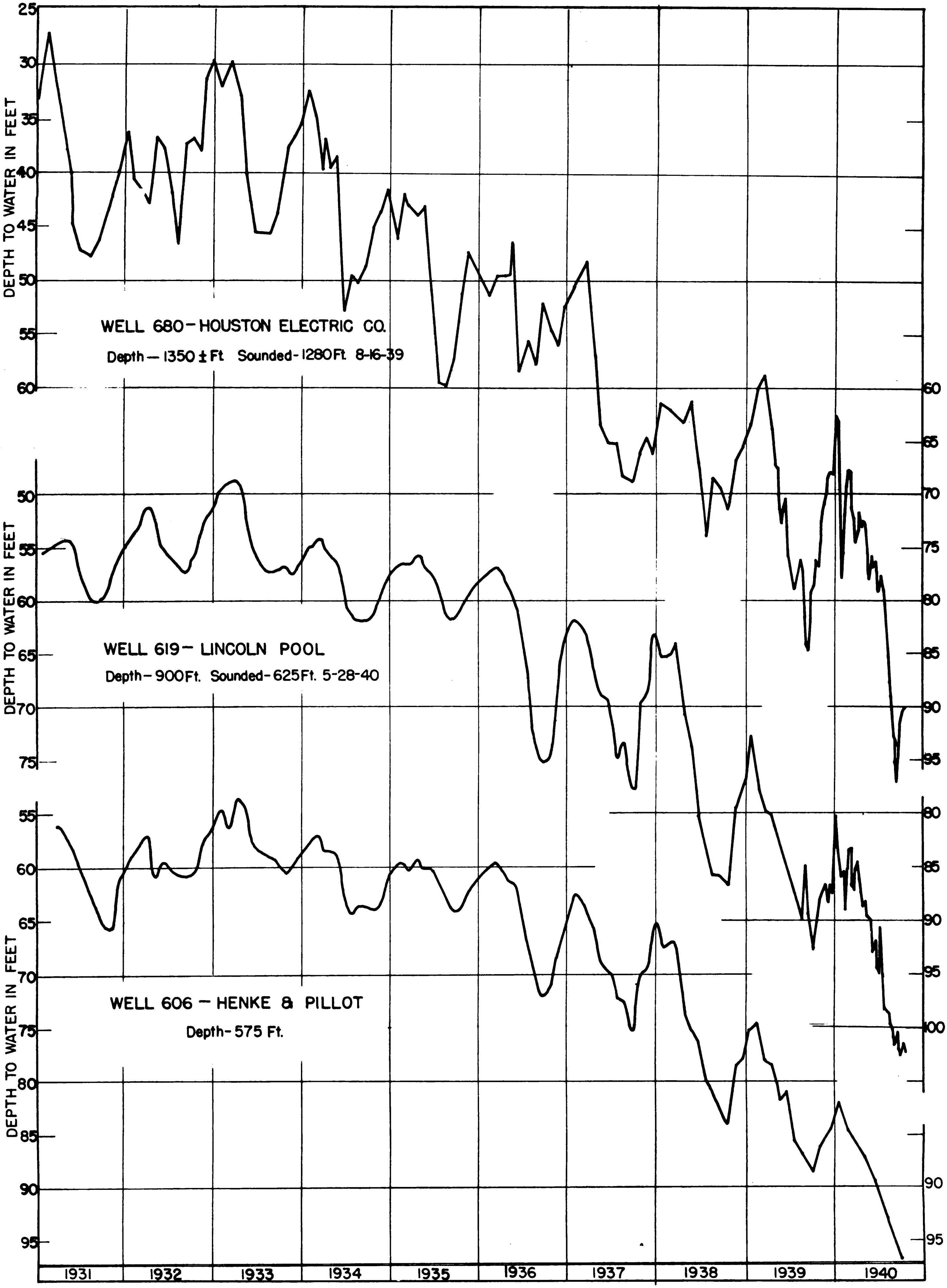


FIGURE 7. — FLUCTUATIONS OF WATER LEVELS IN WELLS IN CENTRAL HOUSTON

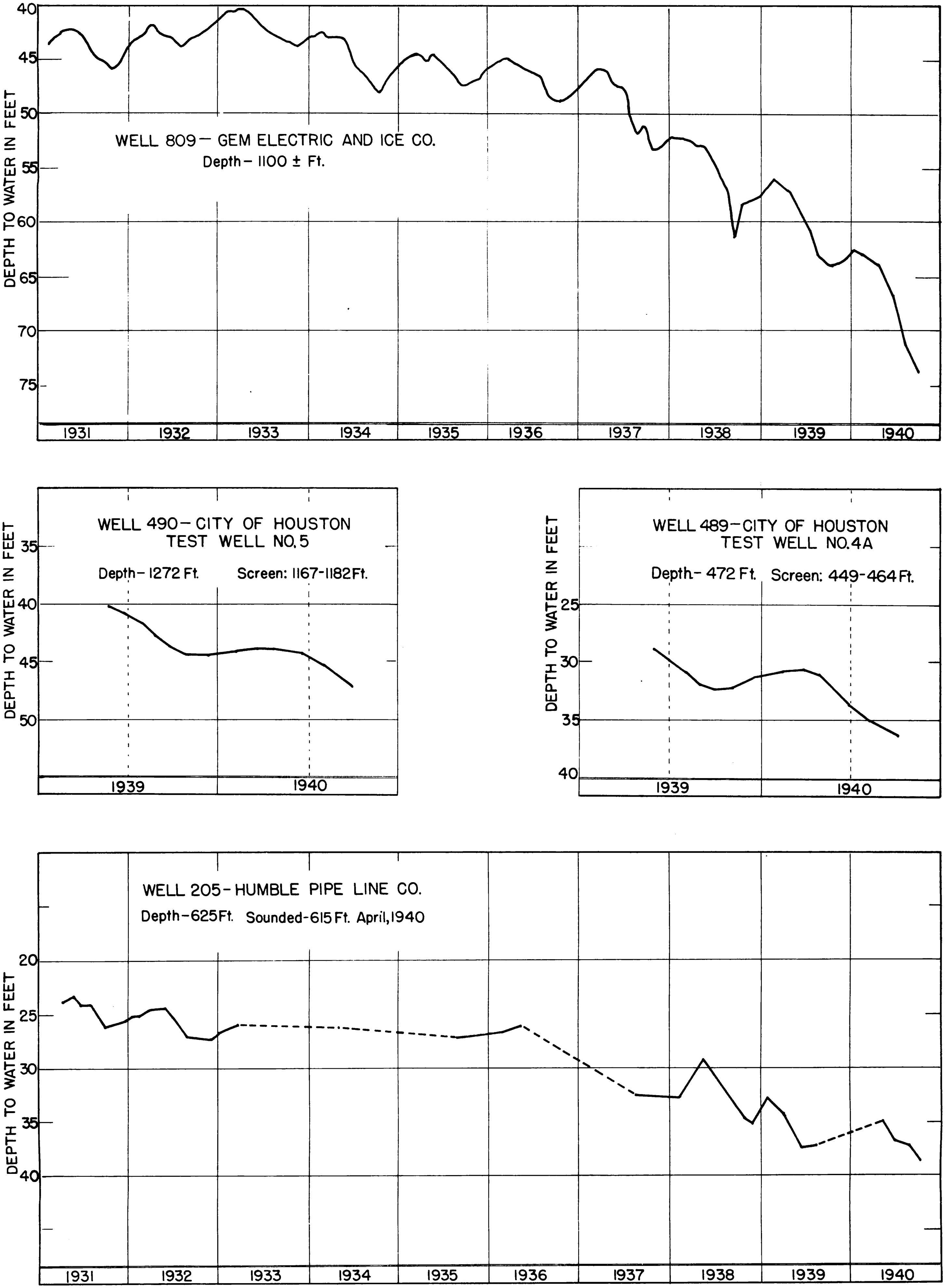


FIGURE 8.—FLUCTUATIONS OF WATER LEVELS IN WELLS WEST OF HOUSTON

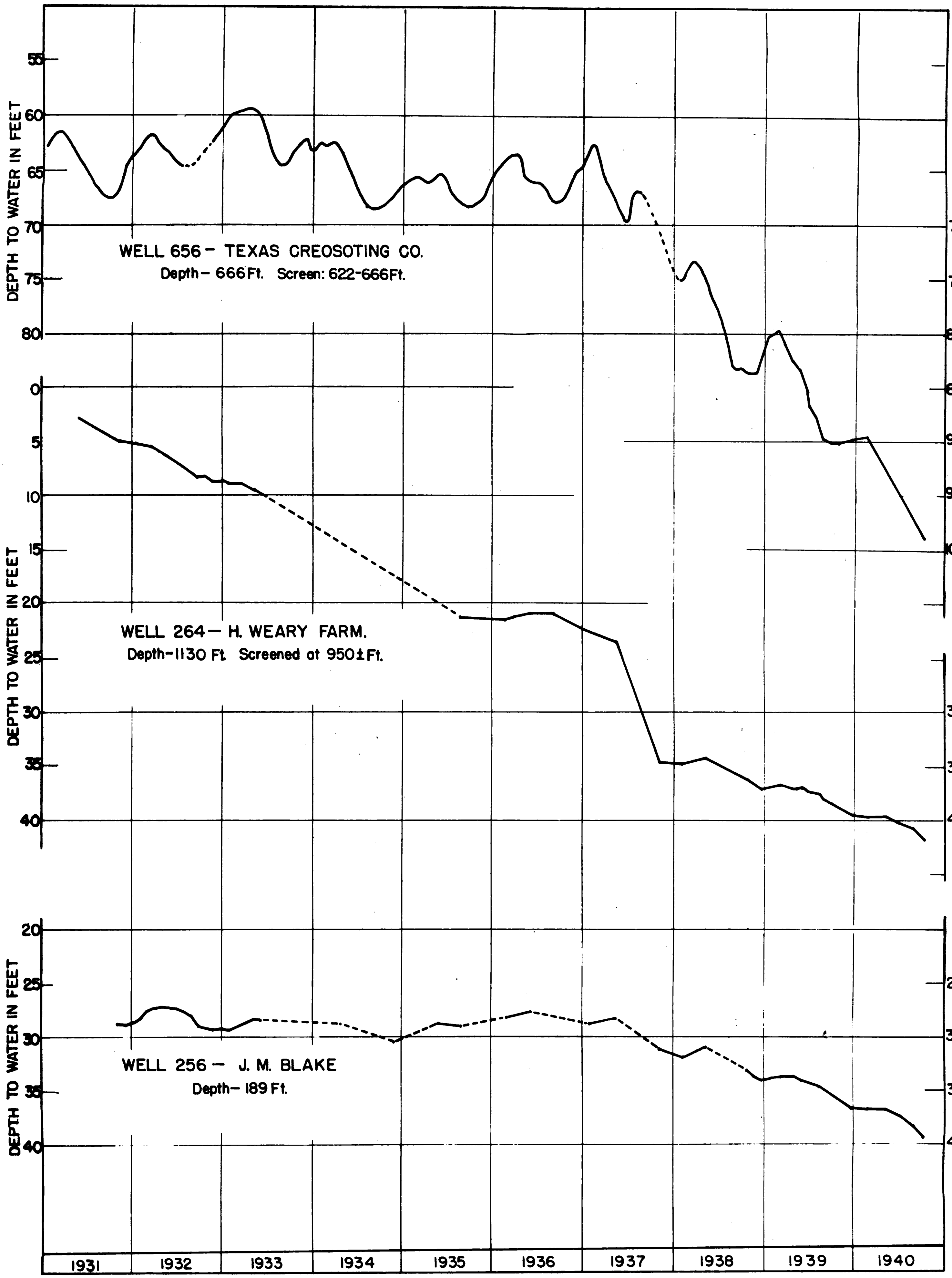


FIGURE 9. – FLUCTUATIONS OF WATER LEVELS IN WELLS NORTH OF HOUSTON