AMERICAN OIL COMPANY

PLANT ENGINEERING DEPARTMENT
TEXAS CITY, TEXAS

AMOCO

REFINERY GROUND SUBSIDENCE AT TEXAS CITY

REPORT NO. TR-58-1

FEBRUARY 1, 1958

Texas Board of Water Engineers in cooperation with the U. S. Geological Survey and the city of Galveston

Bulletin 5502 Plate 2

GEOLOGIC CROSS SECTION FROM FREEPORT, BRAZORIA COUNTY TO SOUTH TO SOUTHWESTERN JEFFERSON COUNTY, TEXAS

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TEXAS CITY, TEXAS

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I. INTRODUCTION AND SUMMARY

A. INTRODUCTION

The purpose of this report is to present the field data obtained since the January, 1954, survey (Engineering Department Memorandum on "Refinery Ground Subsidence", dated May 6, 1954) and the current ground subsidence trend with relation to well water pumpage rates in the refinery and surrounding areas. Data included in this study consists of published reports and unpublished field data of the U. S. Coast & Geodetic Survey, the U. S. Geological Survey, and the Texas Board of Water Engineers as well as previous Engineering Department reports and memoranda.

In addition, since the beginning of well water pumpage in 1933, the initiation of refinery settlement surveys in 1945, and the subsequent installation of Brazos River water facilities in 1948, considerable data relating to ground subsidence including settlement readings at key bench marks, well water pumpage, static levels in water wells, chloride content of water from wells, and river water usage have been recorded in various forms. A tabulation of these data have been included in this report for future reference in connection with refinery settlement and water supply studies.

Also, the continuance of investigations on the geology and ground-water resources in Galveston County by the U. S. Geological Survey in cooperation with the Texas Board of Water Engineers and releveling surveys by the U. S. Coast & Geodetic Survey on a periodical basis will aid greatly in predicting ground subsidence trends and the future development of water supplies for industrial and municipal growth in this county.

This report, which is composed of sections on ground subsidence, refinery and surrounding area water pumpage, and literature abstracts concerning land-surface subsidence at other locations, has been subdivided into the several important areas to assist the reader in locating the desired information. A large number of tables, curves, maps, sketches and photographs are included throughout the discussion and the literature abstracts.

B. SUMMARY

Based on all data obtained since the transferring of base reference points from USC&GS BM A-9 at La Marque to L-305 at Virginia Point in December, 1952, it appears that subsidence is continuing, although at a slower rate. As shown in Table 1 (page 6), the key refinery bench marks have settled on an average of 0.23 feet since December, 1952, or approximately 5/8 of an inch per year through July, 1957. This is considerably lower than the previous average settlement, which occurred between the years 1940 and 1952, and amounted to about 3½ inches per year. However, preliminary information on the adjusted 1953-54, USC&GS releveling indicates that the base monument L-305 has settled approximately 0.17 feet since the 1951 USC&GS releveling in this area. Therefore, future studies may reveal an increased subsidence rate in the refinery and surrounding area, following receipt of the official corrected and adjusted 1953-54, USC&GS data.

Presently the total subsidence in the refinery has reached a maximum of 4.67 feet at bench mark 17 and practically all bench marks located in the areas of maximum settlement are now in excess of four feet as illustrated on sketch No. 4944-7 (page 7).

Water levels in the refinery water wells have recovered to a large degree as a result of the reduced pumping rate, which averaged only 0.53 million gallons daily during 1957. Although well water pumpage in the Texas City area has been reduced by approximately 70 per cent since 1945, it appears that even the present pumpage is too great, particularly from the upper Beaumont clay. This coupled with a time lag effect may have considerable bearing on the present subsidence trend.

II DISCUSSION

A. GROUND SUBSIDENCE

II. DISCUSSION

A. GROUND SUBSIDENCE

At the beginning of refinery construction in 1933, the Galveston County Engineer established elevations of various primary bench marks. In 1938, the County Engineer ran a series of levels for Carbide and checked the elevation of the bench mark at the northeast corner of the refinery property within 0.08 feet of the original value which was considered satisfactory. Likewise, the annual plant survey of the same year disclosed that all bench marks checked within themselves. Annual plant surveys were conducted through 1940, but were then discontinued because of the press of war work and shortage of manpower. This factor delayed discovery of subsidence and thus limited the amount of early data.

The date subsidence began is not definitely known, but can be assumed to have started between late 1938, the last date all monuments checked, and early 1940, when unexplainable minor discrepancies began to occur in the field engineer's readings. Between 1940 and 1944 these discrepancies in elevations continued to increase, all of which indicated ground subsidence.

In early 1944, before subsidence was definitely known, studies were begun on the possibility of procuring an outside source of water to supplement existing wells, since increased area pumpage had lowered the static pumping levels to a point where the upper fine and low capacity sands were being depleted. This necessitated increasing the withdrawal from the lower level coarse sands which contained water of higher chloride content and poorer quality. Completion of this study culminated in the preparation of Engineering Department Report No. 24[1], in which it was recommended that procurement of outside water for industries in this area be encouraged.

In May, 1945, the field engineers ran a new series of levels from U. S. Coast & Geodetic Survey bench mark A-9, located approximately two miles west of the refinery on the G. H. & H. Railroad water tower foundation in La Marque, and established the fact that the No. 1 master bench mark at cracking unit No. 1 had declined 0.70 feet. Applying this factor to the remaining refinery bench marks resulted in a maximum settlement of 1.60 feet in the area of water wells Nos. 2 and 3 and extended the area of subsidence considerably. A simultaneous check made from USC&GS BM-K169 (Amoco BM-245) located southeast of the refinery property on a railroad culvert revealed no settlement. Also, to aid in obtaining future data, a new bench mark was established on the casing, set at two thousand feet, of the abandoned Pan American Production Company dry oil well, located immediately south of the refinery (Amoco BM-244). As a further check, the County Engineer was requested to make a similar level run from La Marque to the master bench mark, and his results verified the previous readings (Engineering Department Report No. 29[2]). Therefore, based on these results all subsequent refinery surveys between May, 1945, and December, 1952, were made using BM A-9 as a base reference point and the results are tabulated in Table 2.

As subsidence of the land-surface became unmistakably established, several theories were advanced as to the cause: (1) compression of clay type strata, which act as elastic media, due to dewatering of the clay resulting from a decrease in hydraulic pressure caused by excessive water withdrawal rates; (2) compaction of instable strata caused by excessive loading from tanks and equipment in the refinery area; and (3) squeezing out of the quick-sand layer in the upper strata due to high soil loading and/or high table water flows. Although it is possible that any one or all of these factors may contribute to land-surface subsidence all data collected thus far indicate that, subsidence is the result of excessive well water pumpage which has dewatered the underground structures at a rate much faster than the water in the sands and clays can be replenished.

As mentioned previously above and in Engineering Department Report No. 48[3] prior to December, 1952, all refinery releveling surveys were based on USC&GS BM A-9 at La Marque, since it was assumed that this bench mark was a stable reference point outside the cones of severe subsidence. However, the official corrected data received from USC&GS in November, 1952, on the 1951 releveling of the Katy to Galveston portion of line No. 241 (Smithville to Galveston, Texas) showed that bench mark A-9 (November, 1951) was not stable and had settled a total of 1.076 feet, 0.859 feet of which occurred between the 1943 and 1951 releveling of this line (see Figure 1) and 0.217 feet prior to 1943.

A study of the data on the 1951 USC&GS releveling survey indicated that USC&GS bench mark L-305 at Virginia Point, which had subsided 0.286 feet between 1943 and 1951 was the nearest relatively stable monument outside the area of severe subsidence. Therefore, it was decided to use L-305, located approximately five miles southeast of the refinery, as a base monument and encourage USC&GS to resurvey this bench mark as often as possible in order to assure reasonable validity as a base point.

The base monument was transferred from A-9 to L-305 and the key refinery bench marks corrected for the increased settlement of bench mark A-9, based on a correlation of the data obtained by the Carbide Surveys from Virginia Point in June, 1952, and January, 1953, and the Amoco Surveys from A-9 and check points inside the Carbide plant in October and December, 1952, as shown in Table 2. During 1953, 1954, and 1955, Carbide and Amoco alternated every six months in making subsidence survey checks from L-305 to a common tie point (Carbide bench mark N-3500 and W-1000), with each party completing the survey inside their respective plant. The January surveys were made by Carbide's field party and the July surveys by Amoco's field party. However, this was discontinued in 1956 and all subsequent surveys have been made on a yearly basis by Amoco's field party.

As shown in Table 1, a comparison of the December, 1952, and July, 1957, surveys based on bench mark L-305 at Virginia Point indicates that subsidence is 0.06 feet per year at six of the key bench marks which now represent the area of maximum subsidence. The other bench marks settled at an average of 0.03 to 0.05 feet annually and over in the Carbide plant the settlement rate averaged 0.06 feet per year. In summary, these key bench marks dropped an average of 0.230 feet since December, 1952, which gives an average settlement rate of 0.05 feet or about 5/8 of one inch per year. For the years 1940 to 1952 this average settlement amounted to 0.308 feet or about $3\frac{1}{2}$ inches per year. Thus a comparison of these two rates indicates there is a leveling-off in subsidence with the remaining settlement being caused by a time lag effect following the reduction in pumpage of large quantities of ground-water. However, it is possible that the sand and clay beds have been dewatered or depressured to such an extent, that even a small

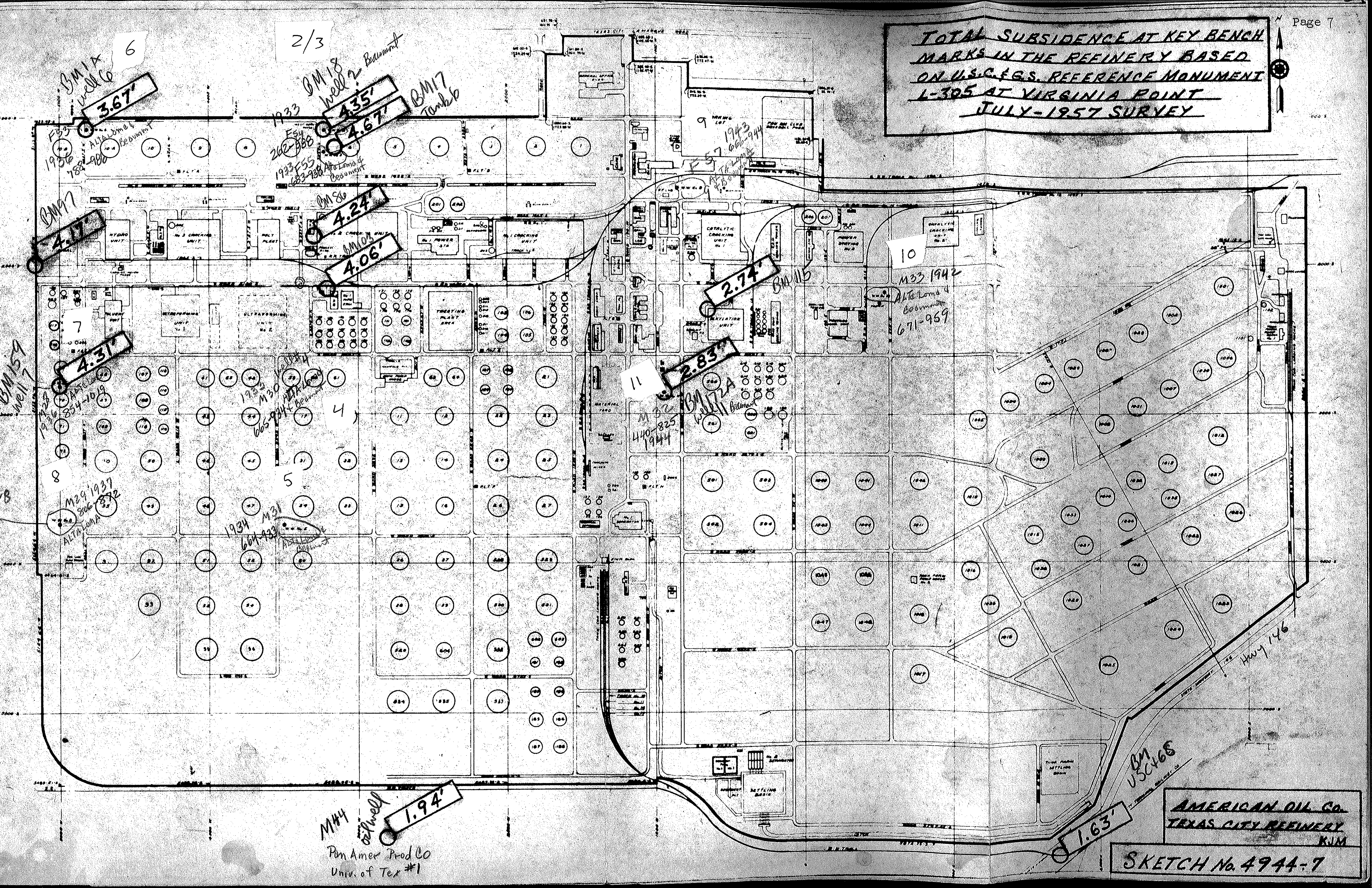
TABLE 1

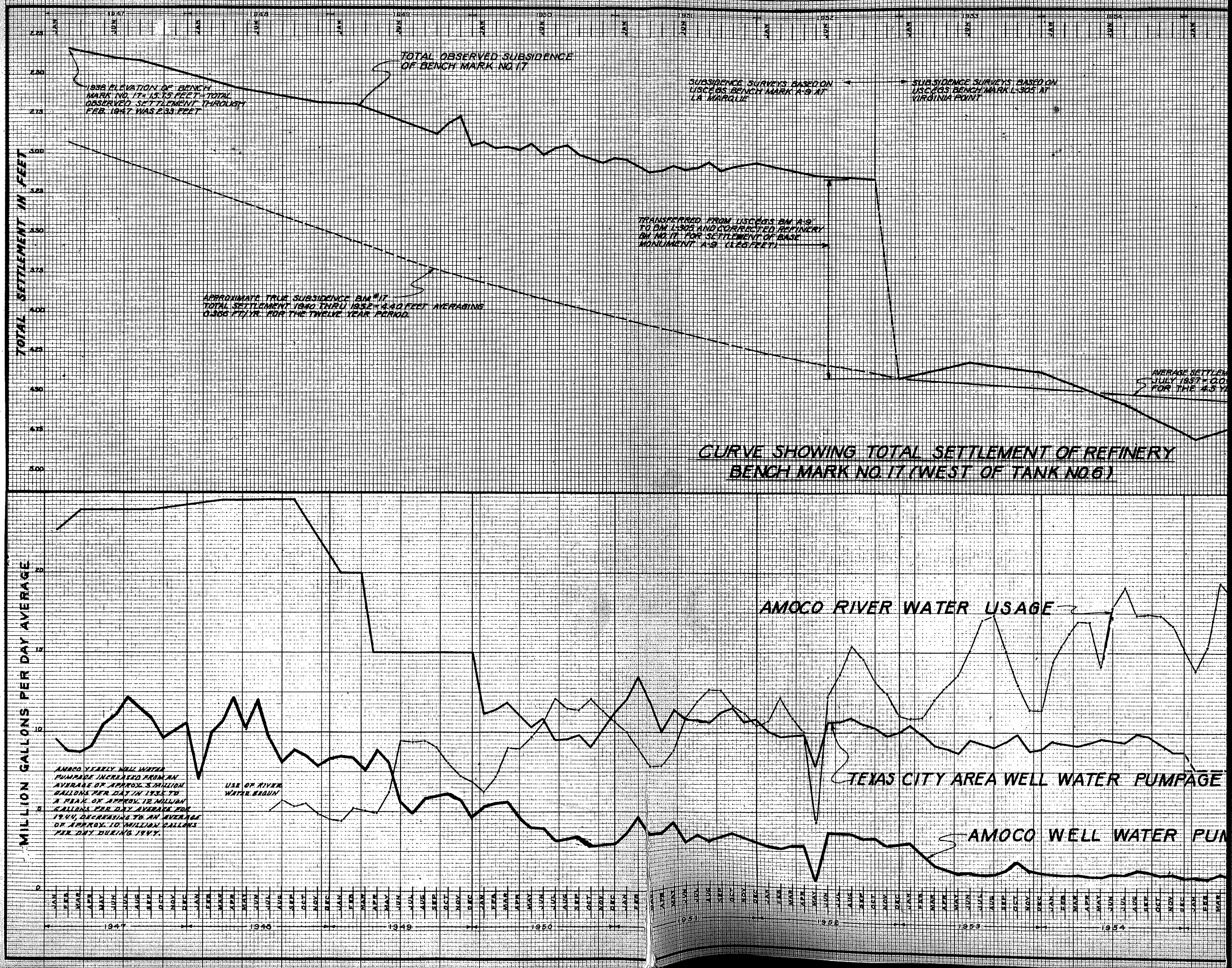
AMERICAN OIL COMPANY - TEXAS CITY, TEXAS

AVERAGE SUBSIDENCE RATES AT KEY BENCH MARKS

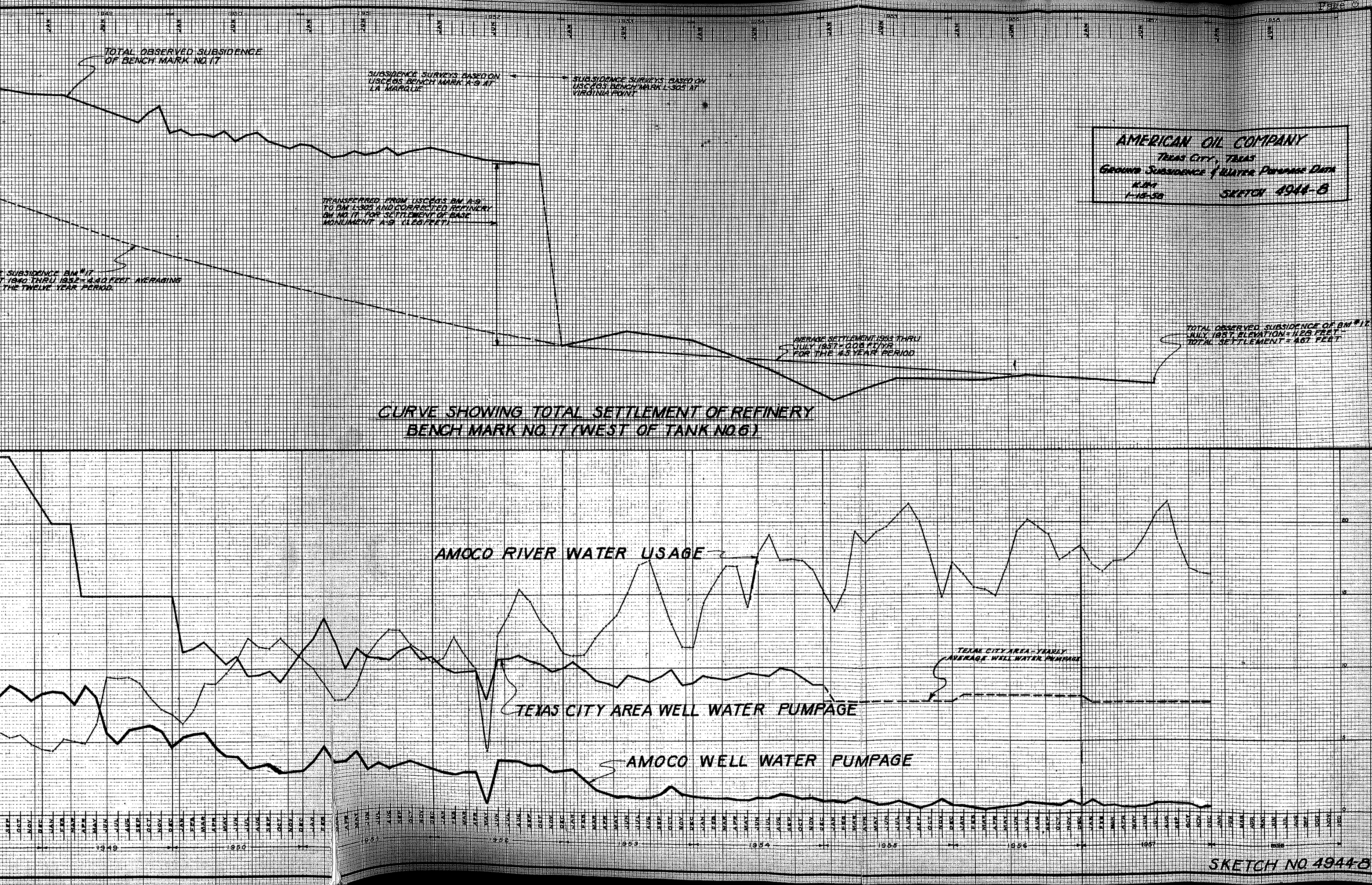
July 1940-1957

Bench Mark	Location	Total Settlement In Feet 1940-Dec. 52	Average Settlement Feet/Year 1940-Dec. 52	Incremental Settlement In Feet Dec. 52-July 57	Average Settlement Feet/Year Dec. 52-July 57
1A	Water Well No. 6 1085-S & 4825-W	3.46	0.288	0.210 3.67	0.0466
17	West Side Tank No. 6	4.40	0.366	0.270 4.67	0.0600
18	Water Well No. 2 House Found. 3245-W & 1065-S	4.09	0.341	0.260 4.35	0.0577
86	S. W. Corner Comp. Room No. 2 C. U.	3.99	0.332	0.250 4.24	0.0555
97	Monument 2000-S & 5155.45-W	3.91	0.326	0.260 4.17	0.0577
103	N. W. Corner Pump Room No. 2 Pipe Still	3.81	0.317	0.250 4.06	0.0555
151	Water Well No. 4 House Found. 2810-S & 3495-W	3.92	0.327	Water Well	Abandoned
159	Water Well No. 7 2810-S & 5000-W	4.02	0.330	0.290 4.31	0.0644
172A	Water Well No. 11 2850-S & 946-W	(1944) 2.69	0.336	(1944) 0.140 2.83	0.0311
115	N. W. Corner F-10 Alky Unit	(1943) 2.57	0.288	0.170 2.74	0.0377
244	Pan Am. Prod. Co. - Dry Oil Well	(1945) 1.71	0.244	0.230 1.94	0.0511
245	USC & GS B. M. on TCRRC & Galv. Hwy.	(1945) 1.49	0.213	0.140 1.63	0.0311
C & A Tie Pt.	Carbide B. M. N-3500 & W-1000	(1940) 3.52	0.293	0.290 3.81	0.0644
	AVERAGE	3.36	0.308	0.230	0.0511


TOTAL SUBSIDENCE AT KEY BENCH MARKS IN THE REFINERY BASED ON U.S.C.&G.S. REFERENCE MONUMENT L-305 AT VIRGINIA POINT JULY-1957 SURVEY
AMERICAN OIL Co.
TEXAS CITY REFINERY
KJM
SKETCH No. 4944-7
6
2/3
BM1X well 6
3.67'
BM18 well 2 Beaumont
4.35'
BM17 Tank 6
4.67'
1933 F54 262-888
1933 F55 683-938 Alta Loma & Beaumont
1936 F53 788-980 Alta Loma & Beaumont
9
1943 F57 666-944 Alta Loma & Beaumont
BM97
4.17'
BM86
4.24'
BM103
4.06'
10
M33 1942 Alta Loma & Beaumont 671-959
2.74'
BM115
7
BM159 well 7
4.31'
1936 M28 854-1019 Alta Loma
1933 M30 well 4 Alta Loma & Beaumont 665-934
4
11
2.83'
BM172A well 11 Beaumont
M32 440-825 1944
8
M29 1937 806-872 Alta Loma
5
1934 M31 664-933 Alta Loma & Beaumont
HYDRO UNIT
No. 3 CRACKING UNIT
POLY PLANT
No. 1 POWER STA
No. 1 CRACKING UNIT
CATALYTIC CRACKING UNIT No. 1
POWER STATION No. 2
CATALYTIC CRACKING UNIT No. 2
ALKYLATION UNIT
TREATING PLANT AREA
ULTRAFORMING UNIT No. 2
SETTLING BASIN
Hwy 146
BM USC 468
1.63'
M44 oil well
1.94'
Pan Amer Prod Co
Univ. of Tex #1



TOTAL SETTLEMENT IN FEET
TOTAL OBSERVED SUBSIDENCE OF BENCH MARK NO. 17
1936 ELEVATION OF BENCH MARK NO. 17 = 15.75 FEET — TOTAL OBSERVED SETTLEMENT THROUGH FEB. 1947 WAS 2.33 FEET
SUBSIDENCE SURVEYS BASED ON USC&GS BENCH MARK A-9 AT LA MARQUE
SUBSIDENCE SURVEYS BASED ON USC&GS BENCH MARK L-305 AT VIRGINIA POINT
TRANSFERRED FROM USC&GS BM A-9 TO BM L-305 AND CORRECTED REFINERY BM NO. 17 FOR SETTLEMENT OF BASE MONUMENT A-9 (1.26 FEET)
APPROXIMATE TRUE SUBSIDENCE BM #17 TOTAL SETTLEMENT 1940 THRU 1952 = 4.40 FEET AVERAGING 0.366 FT./YR. FOR THE TWELVE YEAR PERIOD.
CURVE SHOWING TOTAL SETTLEMENT OF REFINERY BENCH MARK NO. 17 (WEST OF TANK NO. 6)
MILLION GALLONS PER DAY AVERAGE
AMOCO RIVER WATER USAGE
TEXAS CITY AREA WELL WATER PUMPAGE
AMOCO WELL WATER PUM
AMOCO YEARLY WELL WATER PUMPAGE INCREASED FROM AN AVERAGE OF APPROX. 5 MILLION GALLONS PER DAY IN 1935 TO A PEAK OF APPROX. 12 MILLION GALLONS PER DAY AVERAGE FOR 1944, DECREASING TO AN AVERAGE OF APPROX. 10 MILLION GALLONS PER DAY DURING 1947.
USE OF RIVER WATER BEGUN
1947
1948
1949
1950
1951
1952
1953
1954


AMERICAN OIL COMPANY
TEXAS CITY, TEXAS
GROUND SUBSIDENCE & WATER PUMPAGE DATA
K.B.M.
1-15-58
SKETCH 4944-B
TOTAL OBSERVED SUBSIDENCE OF BENCH MARK NO. 17
SUBSIDENCE SURVEYS BASED ON USC&GS BENCH MARK A-9 AT LA MARQUE
SUBSIDENCE SURVEYS BASED ON USC&GS BENCH MARK L-305 AT VIRGINIA POINT
TRANSFERRED FROM USC&GS BM A-9 TO BM L-305 AND CORRECTED REFINERY BM NO. 17 FOR SETTLEMENT OF BASE MONUMENT A-9 (1.25 FEET)
SUBSIDENCE BM #17
1940 THRU 1952 = 4.40 FEET AVERAGING
THE TWELVE YEAR PERIOD.
AVERAGE SETTLEMENT 1953 THRU JULY 1957 - 0.08 FT/YR FOR THE 4.5 YEAR PERIOD
TOTAL OBSERVED SUBSIDENCE OF BM #17. JULY 1957 ELEVATION = 1.28 FEET - TOTAL SETTLEMENT = 4.67 FEET
CURVE SHOWING TOTAL SETTLEMENT OF REFINERY BENCH MARK NO. 17 (WEST OF TANK NO. 6)
AMOCO RIVER WATER USAGE
TEXAS CITY AREA - YEARLY AVERAGE WELL WATER PUMPAGE
TEXAS CITY AREA WELL WATER PUMPAGE
AMOCO WELL WATER PUMPAGE
1949
1950
1951
1952
1953
1954
1955
1956
1957
1958
SKETCH NO. 4944-B

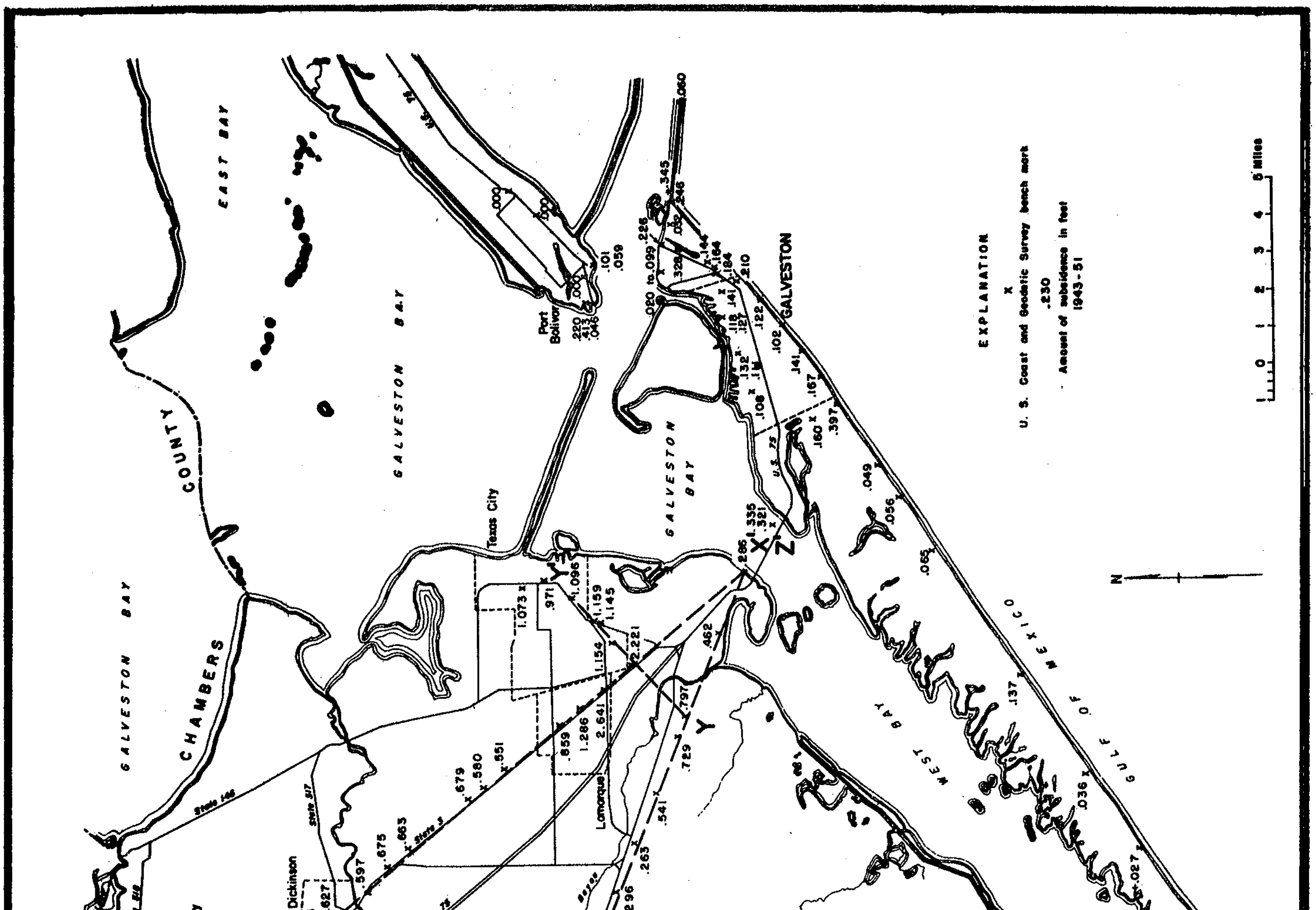


FIGURE 1 - LAND SURFACE SUBSIDENCE IN GALVESTON COUNTY, TEX. 1943-51.

amount of water pumpage still has considerable effect on the rate of stabilization of the sub-surface soils and the speed at which the sand and clay beds are recharged.

The total subsidence in the refinery has reached a maximum of 4.67 feet at bench mark 17 located on the west side of tank No. 6 in the vicinity of water wells Nos. 2 and 3. Also, as illustrated on sketch No. 4944-7, showing the location and total subsidence of the key refinery bench marks, practically all points in the areas of maximum settlement are now in excess of four feet.

Although a comparison of the December, 1952, and July, 1957, surveys indicated that subsidence is continuing at a slower rate in the areas of maximum settlement, wide fluctuations caused by plus readings followed by increases in subsidence rates have been reflected in the past intermediate survey readings between 1953 and 1957, as shown in Table 2. The readings taken for the July, 1954, and January, 1955, surveys indicated a marked increase in subsidence at all bench marks during 1954, varying from a total of 0.15 feet at bench mark Y-457 to a maximum of 0.42 feet at bench mark 17. Whereas, the following survey readings taken for the six month period ending in July, 1955, reflected an indicated rise at all locations varying, from a plus 0.10 feet at bench mark Y-457 to a maximum of plus 0.19 at several bench marks. The data taken since this time in March and July, 1956, showed very little change; however, the last survey during July, 1957, again indicated additional settlement with a maximum of 0.13 feet at one point and 0.09 feet at several other locations. Nevertheless these last figures still appear high when compared to the average settlement over the past 4.5 year period.

This wide variation in observed settlement readings taken since using L-305 as a base monument may be attributed to one or more of several factors, namely:

1. That the base monument L-305 during certain periods was settling relative to and at a faster rate than the surrounding bench marks.

2. During other periods the surrounding bench marks were settling at a faster rate than the base monument.

3. That these fluctuations may be the result of opposing forces set up in the sand and clay beds during the process of re-establishing the stability of the underground structure.

4. Possibly a faulting condition exists between the base monument and the surrounding bench marks.

5. There may have been some undetectable error in one of the recent surveys, possibly in transferring base monuments from A-9 to L-305.

The only apparent reason for the marked increase in observed settlement during the year 1954 except as mentioned above, was an increase of approximately 0.75 million gallons daily in the Texas City area shallow well pumpage from the Beaumont clay formation. Approximately 0.21 million gallons per day of this increase was a result of operating the No. 2 shallow well at the refinery in order to lower the Brazos river water solids content for boiler feed water purposes. However, the total well pumpage in the Texas City area decreased approximately 1.2 million gallons per day during 1954.

During the latter part of 1953 and early 1954, a U. S. Coast & Geodetic Survey party releveled the bench marks along line No. 111 (Galveston via La Porte to Houston) in the Texas City area including bench mark L-305 at Virginia Point and several other points along USC&GS level lines Nos. 110 and 241. Line No. 111 which extends along the Houston ship channel was releveled in an attempt to determine the amount of subsidence which had taken place in that area since 1943.

The preliminary information received thus far on the adjusted 1953-54 USC&GS releveling survey of this area indicates that bench mark L-305 has settled approximately 0.17 feet since 1951. However, since no official corrected and adjusted figures have been received to date from the U. S. Coast & Geodetic Survey, the significance of these data cannot be properly evaulated. As soon as the final data are received, a study will be made to determine the validity of the base monument L-305, and extent of subsidence in the surrounding area with relation to the refinery settlement. The results will be covered in a subsequent memorandum.

TABLE 2

AMERICAN OIL COMPANY - TEXAS CITY, TEXAS

GROUND SUBSIDENCE AT KEY POINTS - FEET *

BENCH MARK NO.	MARCH, 1956			JULY, 1956			JULY, 1957					
	Elev. This Survey	Increment Settlement	Total Settlement To Date	Elev. This Survey	Increment Settlement	Total Settlement To Date	Elev. This Survey	Increment Settlement	Total Settlement To Date	Elev. This Survey	Increment Settlement	Total Settlement To Date
1A	13.90	.05	3.60	13.92	+.02	3.58	13.83	.09	3.67			
17	11.31	.01	4.64	11.34	+.03	4.61	11.28	.06	4.67			
18	12.38	.03	4.30	12.42	+.04	4.26	12.33	.09	4.35			
86	13.76	.03	4.19	13.80	+.04	4.15	13.71	.09	4.24			
97	12.34	.01	4.07	12.31	.03	4.10	12.24	.07	4.17			
103	14.01	.03	4.00	14.04	+.03	3.97	13.95	.09	4.06			
159	13.84	.01	4.21	13.84	.02	4.23	13.74	.08	4.31			
172A	13.22	.03	2.78	13.25	+.03	2.75	13.17	.08	2.83			
115	14.16	.04	2.70	14.20	+.04	2.66	14.12	.08	2.74			
244	10.39	.05	1.91	10.43	+.04	1.87	10.36	.07	1.94			
245	6.26	.06	1.60	6.28	+.02	1.58	6.23	.05	1.63			
C & A Tie Pt.	9.84	.04	3.67	9.83	.01	3.68	9.70	.13	3.81			
A-9T	16.85	.06	1.37	16.89	+.04	1.33	16.83	.06	1.39			
Y-457	8.82	.02	.08	8.83	+.01	.07	Demolished					

* Elevations referred to U. S. Engrs. Datum and based on USC & GS BM L-305 (15.088' U.S.E. Datum).

ave chng -.03 +.02 -.08

TABLE 2

AMERICAN OIL COMPANY - TEXAS CITY, TEXAS

GROUND SUBSIDENCE AT KEY POINTS - FEET *

BENCH MARK NO.	JANUARY, 1954			JULY, 1954			JANUARY, 1955			JULY, 1955		
	Elev. This Survey	Increment Settlement	Total Settlement To Date	Elev. This Survey	Increment Settlement	Total Settlement To Date	Elev. This Survey	Increment Settlement	Total Settlement To Date	Elev. This Survey	Increment Settlement	Total Settlement To Date
1A	14.14	.00	3.36	13.98	.16	3.52	13.78	.20	3.72	13.95	+.17	3.55
17	11.59	.06	4.36	11.39	.20	4.56	11.17	.22	4.78	11.32	+.15	4.63
18	12.63	.07	4.05	12.47	.16	4.21	12.22	.25	4.46	12.41	+.19	4.27
86	14.01	.04	3.94	13.85	.16	4.10	13.62	.23	4.33	13.79	+.17	4.16
97	12.58	.02	3.83	12.39	.19	4.02	12.20	.19	4.21	12.35	+.15	4.06
103	14.25	.03	3.76	14.08	.17	3.93	13.86	.22	4.15	14.04	+.18	3.97
159	14.10	.01	3.95	13.92	.18	4.13	13.70	.22	4.35	13.85	+.15	4.20
172A	13.48	+.06	2.52	13.32	.16	2.68	13.12	.20	2.88	13.25	+.13	2.75
115	14.43	+.06	2.43	14.26	.17	2.60	14.05	.21	2.81	14.20	+.15	2.66
244	10.73	+.02	1.57	10.53	.20	1.77	10.32	.21	1.98	10.44	+.12	1.86
245	6.56	+.08	1.30	6.40	.16	1.46	6.21	.19	1.65	6.32	+.11	1.54
C & A Tie Pt.	10.06	.01	3.45	9.92	.14	3.59	9.69	.23	3.82	9.88	+.19	3.63
A-9T	17.02	+.04	1.20	16.95	.07	1.27	16.72	.23	1.50	16.91	+.19	1.31
Y-457	8.89	+.05	0.01	8.86	.03	0.04	8.74	.12	0.16	8.84	+.10	0.06

* Elevations referred to U. S. Engrs. Datum and based on USC & GS BM L-305 (15.088' - U.S.E. Datum).

+.005 -.15 -.21 +.19

AMERICAN OIL COMPANY - TEXAS CITY, TEXAS

GROUND SUBSIDENCE AT KEY POINTS - FEET *

BENCH MARK NO.	LOCATION	October - December, 1952 Based on Virginia Point			JUNE, 1953		
		Elev. This Survey	Increment Settlement	Total Settlement To Date	Elev. This Survey	Increment Settlement	Total Settlement To Date
1A	Water Well No. 6 1085-S & 4825-W	14.04	- -	3.40	14.14	+.10	3.36
17	West Side of Tank No. 6	11.55	- -	4.40	11.65	+.10	4.30
18	Water Well No. 2 House Foundation 3245-W & 1065-S	12.59	- -	4.09	12.70	+.11	3.98
86	SW Corner Comp. Room No. 2 C. U.	13.96	- -	3.99	14.05	+.09	3.90
97	Monument 2000-S & 5155.45-W	12.50	- -	3.91	12.60	+.10	3.81
103	NW Corner Pump Room No. 2 Pipe Still	14.20	- -	3.81	14.28	+.08	3.73
151	Water Well No. 4 House Foundation 2810-S & 3495-W	13.06	- -	3.92	13.18	+.12	3.80
159	Water Well No. 7 2810-S & 5000-W	14.03	- -	4.02	14.11	+.08	3.94
172A	Water Well No. 11 2850-S & 946-W	13.31	- -	2.69	13.42	+.11	2.58
115	NW Corner F-10 Alky Unit	14.29	- -	2.57	14.37	+.08	2.49
244	Pan Am Prod. Co. - Dry Oil Well	10.59	- -	1.71	10.71	+.12	1.59
245	USC & GS B. M. on TCRRC & Galv. Hwy.	6.37	- -	1.49	6.48	+.11	1.38
C & A Tie Pt.	Carbide B. M. N-3500 & W-1000 (Carbide-Amoco Tie Point)	9.99	- -	3.52	10.07	+.08	3.44
A-9	Transferred to R.R. Signal Foundation - La Marque	16.88	- -	1.34	16.98	+.10	1.24
Y-457	USC & GS - B. M. (Hwy. 146 & 3 at GH&H and SPRR)	8.86	- -	0.04	8.84	.02	0.06

* Elevations referred to U. S. Engrs. Datum and based on USC & GS BM L-305 (15.088' U.S.E. Datum).

+.10

TABLE 2

AMERICAN OIL COMPANY - TEXAS CITY, TEXAS

GROUND SUBSIDENCE AT KEY POINTS - FEET

BENCH MARK NO.	LOCATION	Original Elev. Of BM	Elev. In Oct.-Dec. 1952*	Correction Factor In Ft.	Adjusted Elev. Of BM**	Total** Adjusted Settlement
		A	B	C	D = B - C	A - D
1A	Water Well No. 6 1085-S & 4825-W	17.50	15.38	1.34	14.04	3.46
17	West Side of Tank No. 6	15.95	12.81	1.26	11.55	4.40
18	Water Well No. 2 House Found. 3245-W & 1065-S	16.68	13.85	1.26	12.59	4.09
86	SW Corner Comp. Room No. 2 C. U.	17.95	15.22	1.26	13.96	3.99
97	Monument 2000-S & 5155.45-W	16.41	13.84	1.34	12.50	3.91
103	NW Corner Pump Room No. 2 Pipe Still	18.10	15.46	1.26	14.20	3.81
151	Water Well No. 4 House Found. 2810-S & 3495-W	16.98	14.40	1.34	13.06	3.92
159	Water Well No. 7 2810-S & 5000-W	18.05	15.37	1.34	14.03	4.02
172A	Water Well No. 11 2850-S & 946-W	16.00	14.65	1.34	13.31	2.69
115	NW Corner F-10 Alky Unit	16.86	15.55	1.26	14.29	2.57
244	Pan Am Prod. Co. - Dry Oil Well	12.30	11.93	1.34	10.59	1.71
245	USC & GS B. M. on TCRRC & Galv. Hwy.	7.86	7.71	1.34	6.37	1.49
C & A Tie Pt.	Carbide B. M. N-3500 & W-1000 (Carbide-Amoco Tie Point)	13.51	11.33	1.34	9.99	3.52

* Based on original elevation of BM A-9 referred to U. S. Engrs. Datum (18.622 + 1.43 = 20.052 ft. U.S.E. Datum).

** Based on 1951 adjusted elevation (from USC & GS 1951-52 releveling referenced to the 1929 Sea Level Datum) of BM L-305 referred to U. S. Engrs. Datum (13.658 + 1.43 = 15.088 ft. U.S.E. Datum).

TABLE 2

AMERICAN OIL COMPANY - TEXAS CITY, TEXAS

GROUND SUBSIDENCE AT KEY POINTS - FEET

BENCH MARK NO.	OCTOBER, 1952			DECEMBER, 1952		
	Elev. This Survey	Incre- ment Settle- ment	Total Settle- ment To Date	Elev. This Survey	Incre- ment Settle- ment	Total Settle- ment To Date
1A	15.35	.05	2.15	15.38	+.03	2.13
17	12.81	.02	3.14	- -	- -	- -
18	13.85	.02	2.83	- -	- -	- -
86	15.22	.04	2.73	- -	- -	- -
97	13.82	.05	2.59	13.84	+.02	2.57
103	15.46	.04	2.55	- -	- -	- -
151	14.37	.04	2.61	14.40	+.03	2.58
159	15.35	.05	2.70	15.37	+.02	2.68
172A	14.61	.03	1.39	14.65	+.04	1.35
115	15.55	.05	1.31	- -	- -	- -
244	11.91	.03	0.39	11.93	+.02	0.37
245	7.63	.07	0.23	7.71	+.08	0.15
C & A Tie Pt.	11.32	.06	2.19	11.33	+.01	2.18

Prior to Dec., 1952, all refinery releveling surveys were based on USC & GS BM A-9 at La Marque. Releveling by USC & GS showed this bench mark had subsided 1.08' through Oct., 1951. Also, subsequent Amoco surveys indicated an additional .18' between Oct., 1951 and 1952, and .08' from Oct., 1952, to Dec., 1952. Therefore, the base monument was transfered from A-9 to L-305 at Virginia Point and the key refinery bench marks corrected for settlement of A-9 based on the 1951 USC & GS releveling; and a correlation of Carbide surveys from L-305 to BM K-169 and their plant in June, 1952, and Jan., 1953, and Amoco surveys from A-9 through the refinery to K-169 and Carbide-Amoco check point in Oct. and Dec., 1952. Thus a correction factor of 1.08' + .18' = 1.26' was applied to the key refinery points for settlement of A-9 through Oct., 1952, and a factor of 1.26' + .08' = 1.34' through Dec., 1952.

TABLE 2

AMERICAN OIL COMPANY - TEXAS CITY, TEXAS

GROUND SUBSIDENCE AT KEY POINTS - FEET *

BENCH MARK NO.	SEPTEMBER, 1951			OCTOBER, 1951			DECEMBER, 1951			MAY, 1952		
	Elev. This Survey	Increment Settlement	Total Settlement To Date	Elev. This Survey	Increment Settlement	Total Settlement To Date	Elev. This Survey	Increment Settlement	Total Settlement To Date	Elev. This Survey	Increment Settlement	Total Settlement To Date
1A	15.40	.05	2.10	15.43	+.03	2.07	15.43	.00	2.07	15.40	.03	2.10
17	12.86	.05	3.09	12.88	+.02	3.07	12.91	+.03	3.04	12.83	.08	3.12
18	13.90	.04	2.78	13.91	+.01	2.77	13.95	+.04	2.73	13.87	.08	2.81
86	15.27	.04	2.68	15.28	+.01	2.67	15.33	+.05	2.62	15.26	.07	2.69
97	13.84	.09	2.57	13.88	+.04	2.53	13.91	+.03	2.50	13.87	.04	2.54
103	15.50	.05	2.51	15.51	+.01	2.50	15.56	+.05	2.45	15.50	.06	2.51
151	14.44	.04	2.54	14.45	+.01	2.53	14.48	+.03	2.50	14.41	.07	2.57
159	15.41	.05	2.64	15.42	+.01	2.63	15.45	+.03	2.60	15.40	.05	2.65
172A	14.65	.05	1.35	14.67	+.02	1.33	14.69	+.02	1.31	14.64	.05	1.36
115	15.61	.05	1.25	15.64	+.03	1.22	15.65	+.01	1.21	15.60	.05	1.26
244	11.98	.04	0.32	11.98	.00	0.32	11.98	.00	0.32	11.94	.04	0.36
245	7.73	.01	0.13	7.71	.02	0.15	7.71	.00	0.15	7.70	.01	0.16
C & A Tie Pt.	- -	- -	- -	- -	- -	- -	11.40	.03	2.11	11.38	.02	2.13

* All elevations referred to U. S. Engineers Datum and based on U. S. Coast and Geodetic Survey Bench Mark A-9 at La Marque (18.622 + 1.43 = 20.052 ft. U.S.E. Datum).

TABLE 2

AMERICAN OIL COMPANY - TEXAS CITY, TEXAS

GROUND SUBSIDENCE AT KEY POINTS - FEET *

BENCH MARK NO.	MAY, 1951			JUNE, 1951			JULY, 1951			AUGUST, 1951		
	Elev. This Survey	Increment Settlement	Total Settlement To Date	Elev. This Survey	Increment Settlement	Total Settlement To Date	Elev. This Survey	Increment Settlement	Total Settlement To Date	Elev. This Survey	Increment Settlement	Total Settlement To Date
1A	15.44	.00	2.06	15.45	+.01	2.05	15.45	.00	2.05	15.45	.00	2.05
17	12.88	+.03	3.07	12.86	.02	3.09	12.87	+.01	3.08	12.91	+.04	3.04
18	13.91	+.01	2.77	13.90	.01	2.78	13.91	+.01	2.77	13.94	+.03	2.74
86	15.28	.00	2.67	15.28	.00	2.67	15.29	+.01	2.66	15.31	+.02	2.64
97	13.92	.01	2.49	13.93	+.01	2.48	13.93	.00	2.48	13.93	.00	2.48
103	15.52	.00	2.49	15.52	.00	2.49	15.53	+.01	2.48	15.55	+.02	2.46
151	14.46	+.02	2.52	14.46	.00	2.52	14.47	+.01	2.51	14.48	+.01	2.50
159	15.45	.02	2.60	15.46	+.01	2.59	15.46	.00	2.59	15.46	.00	2.59
172A	14.68	.00	1.32	14.69	+.01	1.31	14.70	+.01	1.30	14.70	.00	1.30
115	15.63	.00	1.23	15.64	+.01	1.22	15.66	+.02	1.20	15.66	.00	1.20
244	12.00	+.02	0.30	12.01	+.01	0.29	12.02	+.01	0.28	12.02	.00	0.28
245	7.71	+.02	0.15	7.75	+.04	0.11	7.76	+.01	0.10	7.74	.02	0.12

* All elevations referred to U. S. Engineers Datum and based on U. S. Coast and Geodetic Survey Bench Mark A-9 at La Marque (18.622 + 1.43 = 20.052 ft. U.S.E. Datum).

TABLE 2

AMERICAN OIL COMPANY - TEXAS CITY, TEXAS

GROUND SUBSIDENCE AT KEY POINTS - FEET *

BENCH MARK NO.	DECEMBER, 1950			JANUARY, 1951			MARCH, 1951			APRIL, 1951		
	Elev. This Survey	Increment Settlement	Total Settlement To Date	Elev. This Survey	Increment Settlement	Total Settlement To Date	Elev. This Survey	Increment Settlement	Total Settlement To Date	Elev. This Survey	Increment Settlement	Total Settlement To Date
1A	15.52	+.01	1.98	15.50	.02	2.00	15.42	.08	2.08	15.44	+.02	2.06
17	12.93	+.03	3.02	12.92	.01	3.03	12.84	.08	3.11	12.85	+.01	3.10
18	13.97	+.01	2.71	13.94	.03	2.74	13.88	.06	2.80	13.90	+.02	2.78
86	15.36	+.04	2.59	15.33	.03	2.62	15.26	.07	2.69	15.28	+.02	2.67
97	14.02	+.01	2.39	13.99	.03	2.42	13.90	.09	2.51	13.93	+.03	2.48
103	15.59	+.02	2.42	15.57	.02	2.44	15.50	.07	2.51	15.52	+.02	2.49
151	14.51	.00	2.47	14.50	.01	2.48	14.42	.08	2.56	14.44	+.02	2.54
159	15.55	.01	2.50	15.55	.00	2.50	15.45	.10	2.60	15.47	+.02	2.58
172A	14.70	+.03	1.30	14.71	+.01	1.29	14.65	.06	1.35	14.68	+.03	1.32
115	15.66	+.03	1.20	15.67	+.01	1.19	15.61	.06	1.25	15.63	+.02	1.23
244	12.06	+.01	0.24	12.03	.03	0.27	11.97	.06	0.33	11.98	+.01	0.32
245	7.74	+.02	0.12	7.73	.01	0.13	7.70	.03	0.16	7.69	.01	0.17

* All elevations referred to U. S. Engineers Datum and based on U. S. Coast and Geodetic Survey Bench Mark A-9 at La Marque (18.622 + 1.43 = 20.052 ft. U.S.E. Datum).

TABLE 2

AMERICAN OIL COMPANY - TEXAS CITY, TEXAS

GROUND SUBSIDENCE AT KEY POINTS - FEET *

BENCH MARK NO.	JULY, 1950			AUGUST, 1950			SEPTEMBER, 1950			NOVEMBER, 1950		
	Elev. This Survey	Increment Settlement	Total Settlement To Date	Elev. This Survey	Increment Settlement	Total Settlement To Date	Elev. This Survey	Increment Settlement	Total Settlement To Date	Elev. This Survey	Increment Settlement	Total Settlement To Date
1A	15.58	.03	1.92	15.58	.00	1.92	15.53	.05	1.97	15.51	.02	1.99
17	12.99	+.04	2.96	13.01	+.02	2.94	12.95	.06	3.00	12.90	.05	3.05
18	14.03	+.03	2.65	14.04	+.01	2.64	13.99	.05	2.69	13.96	.03	2.72
86	15.41	.00	2.54	15.41	.00	2.54	15.37	.04	2.58	15.32	.05	2.63
97	14.11	.04	2.30	14.11	.00	2.30	14.05	.06	2.36	14.01	.04	2.40
103	15.65	.01	2.36	15.66	+.01	2.35	15.61	.05	2.40	15.57	.04	2.44
151	14.58	.03	2.40	14.60	+.02	2.38	14.53	.07	2.45	14.51	.02	2.47
159	15.65	.03	2.40	15.65	.00	2.40	15.59	.06	2.46	15.56	.03	2.49
172A	14.73	+.02	1.27	14.73	.00	1.27	14.70	.03	1.30	14.67	.03	1.33
115	15.72	+.02	1.14	15.72	.00	1.14	15.66	.06	1.20	15.63	.03	1.23
244	12.09	+.01	0.21	12.10	+.01	0.20	12.08	.02	0.22	12.05	.03	0.25
245	7.79	+.03	0.07	7.80	+.01	0.06	7.75	.05	0.11	7.72	.03	0.14

* All elevations referred to U. S. Engineers Datum and based on U. S. Coast and Geodetic Survey Bench Mark A-9 at La Marque (18.622 + 1.43 = 20.052 ft. U.S.E. Datum).

TABLE 2

AMERICAN OIL COMPANY - TEXAS CITY, TEXAS

GROUND SUBSIDENCE AT KEY POINTS - FEET *

BENCH MARK NO.	MARCH, 1950			APRIL, 1950			MAY, 1950			JUNE, 1950		
	Elev. This Survey	Increment Settlement	Total Settlement To Date	Elev. This Survey	Increment Settlement	Total Settlement To Date	Elev. This Survey	Increment Settlement	Total Settlement To Date	Elev. This Survey	Increment Settlement	Total Settlement To Date
1A	15.57	.03	1.93	15.57	.00	1.93	15.59	+.02	1.91	15.61	+.02	1.89
17	13.00	+.01	2.95	12.98	.02	2.97	13.02	+.04	2.93	12.95	.07	3.00
18	14.02	+.01	2.66	13.99	.03	2.69	14.02	+.03	2.66	14.00	.02	2.68
86	15.39	.01	2.56	15.38	.01	2.57	15.41	+.03	2.54	15.41	.00	2.54
97	14.11	.04	2.30	14.10	.01	2.31	14.13	+.03	2.28	14.15	+.02	2.26
103	15.62	.02	2.39	15.63	+.01	2.38	15.65	+.02	2.36	15.66	+.01	2.35
151	14.59	+.02	2.39	14.56	.03	2.42	14.57	+.01	2.41	14.61	+.04	2.37
159	15.64	.04	2.41	15.64	.00	2.41	15.66	+.02	2.39	15.68	+.02	2.37
172A	14.68	.01	1.32	14.68	.00	1.32	14.70	+.02	1.30	14.71	+.01	1.29
115	15.66	.00	1.20	15.67	+.01	1.19	15.67	.00	1.19	15.70	+.03	1.16
244	12.04	+.01	0.26	12.03	.01	0.27	12.05	+.02	0.25	12.08	+.03	0.22
245	7.72	.01	0.14	7.73	+.01	0.13	7.77	+.04	0.09	7.76	.01	0.10

* All elevations referred to U. S. Engineers Datum and based on U. S. Coast and Geodetic Survey Bench Mark A-9 at La Marque (18.622 + 1.43 = 20.052 ft. U.S.E. Datum).

TABLE 2

AMERICAN OIL COMPANY - TEXAS CITY, TEXAS

GROUND SUBSIDENCE AT KEY POINTS - FEET *

BENCH MARK NO.	NOVEMBER, 1949			DECEMBER, 1949			JANUARY, 1950			FEBRUARY, 1950		
	Elev. This Survey	Increment Settlement	Total Settlement To Date	Elev. This Survey	Increment Settlement	Total Settlement To Date	Elev. This Survey	Increment Settlement	Total Settlement To Date	Elev. This Survey	Increment Settlement	Total Settlement To Date
1A	15.75	+.06	1.75	15.63	.12	1.87	15.61	.02	1.89	15.60	.01	1.90
17	13.19	+.04	2.76	13.01	.18	2.94	13.03	+.02	2.92	12.99	.04	2.96
18	14.22	+.05	2.46	14.01	.21	2.67	14.04	+.03	2.64	14.01	.03	2.67
86	15.58	+.04	2.37	15.42	.16	2.53	15.43	+.01	2.52	15.40	.03	2.55
97	14.31	+.08	2.10	14.15	.16	2.26	14.16	+.01	2.25	14.15	.01	2.26
103	15.80	+.05	2.21	15.65	.15	2.36	15.67	+.02	2.34	15.64	.03	2.37
151	14.74	+.06	2.24	14.59	.15	2.39	14.62	+.03	2.36	14.57	.05	2.41
159	15.83	+.06	2.22	15.69	.14	2.36	15.70	+.01	2.35	15.68	.02	2.37
172A	14.85	+.06	1.15	14.68	.17	1.32	14.73	+.05	1.27	14.69	.04	1.31
115	15.83	+.05	1.03	15.67	.16	1.19	15.71	+.04	1.15	15.66	.05	1.20
244	- -	- -	- -	12.08	.02	0.22	- -	- -	- -	12.03	.05	0.27
245	7.86	+.03	0.00	7.69	.17	0.17	7.76	+.07	0.10	7.73	.03	0.13

* All elevations referred to U. S. Engineers Datum and based on U. S. Coast and Geodetic Survey Bench Mark A-9 at La Marque (18.622 + 1.43 = 20.052 ft. U.S.E. Datum).

TABLE 2

AMERICAN OIL COMPANY - TEXAS CITY, TEXAS

GROUND SUBSIDENCE AT KEY POINTS - FEET *

BENCH MARK NO.	NOVEMBER, 1948			FEBRUARY, 1949			SEPTEMBER, 1949			OCTOBER, 1949		
	Elev. This Survey	Increment Settlement	Total Settlement To Date	Elev. This Survey	Increment Settlement	Total Settlement To Date	Elev. This Survey	Increment Settlement	Total Settlement To Date	Elev. This Survey	Increment Settlement	Total Settlement To Date
1A	- -	- -	- -	15.86	.10	1.64	15.66	.20	1.84	15.69	+.03	1.81
17	13.28	.09	2.67	13.27	.01	2.68	13.08	.19	2.87	13.15	+.07	2.80
18	- -	- -	- -	14.26	.31	2.42	14.08	.18	2.60	14.17	+.09	2.51
86	15.69	.15	2.26	15.63	.06	2.32	15.49	.14	2.46	15.54	+.05	2.41
97	14.53	.13	1.88	14.43	.10	1.98	14.24	.19	2.17	14.23	.01	2.18
103	15.93	.14	2.08	15.90	.03	2.11	15.72	.18	2.29	15.75	+.03	2.26
151	- -	- -	- -	14.87	.32	2.11	14.66	.21	2.32	14.68	+.02	2.30
159	16.10	.10	1.95	15.96	.15	2.10	15.78	.17	2.27	15.77	.01	2.28
172A	- -	- -	- -	14.87	.10	1.13	14.76	.11	1.24	14.79	+.03	1.21
115	15.85	.02	1.01	- -	- -	- -	15.74	.11	1.12	15.78	+.04	1.08
244	12.27	.00	0.03	- -	- -	- -	12.10	.17	0.20	- -	- -	- -
245	7.87	+.02	+0.01	- -	- -	- -	7.81	.06	0.05	7.83	+.02	0.03

* All elevations referred to U. S. Engineers Datum and based on U. S. Coast and Geodetic Survey Bench Mark A-9 at La Marque (18.622 + 1.43 = 20.052 ft. U.S.E. Datum).

TABLE 2

AMERICAN OIL COMPANY - TEXAS CITY, TEXAS

GROUND SUBSIDENCE AT KEY POINTS - FEET *

BENCH MARK NO.	FEBRUARY, 1947			JUNE, 1947			AUGUST, 1947			APRIL, 1948		
	Elev. This Survey	Increment Settlement	Total Settlement To Date	Elev. This Survey	Increment Settlement	Total Settlement To Date	Elev. This Survey	Increment Settlement	Total Settlement To Date	Elev. This Survey	Increment Settlement	Total Settlement To Date
1A	16.20	.01	1.30	16.18	.02	1.32	16.10	.08	1.40	15.96	.14	1.54
17	13.62	.02	2.33	13.56	.06	2.39	13.54	.02	2.41	13.37	.17	2.58
18	14.66	.01	2.02	14.61	.05	2.07	14.57	.04	2.11	- -	- -	- -
86	16.07	.02	1.88	15.99	.08	1.96	15.97	.02	1.98	15.84	.13	2.11
97	15.00	.02	1.41	14.89	.11	1.52	14.87	.02	1.54	14.66	.21	1.75
103	16.30	.02	1.71	16.22	.08	1.79	16.20	.02	1.81	16.07	.13	1.94
151	15.25	.11	1.73	15.20	.05	1.78	15.19	.01	1.79	- -	- -	- -
159	16.54	.03	1.51	16.41	.13	1.64	16.41	.00	1.64	16.20	.21	1.85
172A	14.97	.05	1.03	14.97	.00	1.03	14.97	.00	1.03	- -	- -	- -
115	15.94	.05	0.92	15.94	.00	0.92	15.93	.01	0.93	15.87	.06	0.99
244	12.28	.00	0.02	12.28	.00	0.02	12.28	.00	0.02	12.27	.01	0.03
245	7.86	.01	0.00	7.86	.00	0.00	7.86	.00	0.00	7.85	.01	0.01

* All elevations referred to U. S. Engineers Datum and based on U. S. Coast and Geodetic Survey Bench Mark A-9 at La Marque (18.622 + 1.43 = 20.052 ft. U.S.E. Datum).

TABLE 2

AMERICAN OIL COMPANY - TEXAS CITY, TEXAS

GROUND SUBSIDENCE AT KEY POINTS - FEET *

BENCH MARK NO.	FEBRUARY, 1946			MAY, 1946			AUGUST, 1946			NOVEMBER, 1946		
	Elev. This Survey	Increment Settlement	Total Settlement To Date	Elev. This Survey	Increment Settlement	Total Settlement To Date	Elev. This Survey	Increment Settlement	Total Settlement To Date	Elev. This Survey	Increment Settlement	Total Settlement To Date
1A	16.40	.05	1.10	16.38	.02	1.12	16.31	.07	1.19	16.21	.10	1.29
17	13.84	.06	2.11	13.80	.04	2.15	13.71	.09	2.24	13.64	.07	2.31
18	14.85	.05	1.83	14.80	.05	1.88	14.74	.06	1.94	14.67	.07	2.01
86	16.23	.06	1.72	16.18	.05	1.77	16.13	.05	1.82	16.09	.04	1.86
97	15.22	.05	1.19	15.19	.03	1.22	15.06	.13	1.35	15.02	.04	1.39
103	16.46	.05	1.55	16.41	.05	1.60	16.35	.06	1.66	16.32	.03	1.69
151	15.48	.07	1.50	15.43	.05	1.55	15.38	.05	1.60	15.36	.02	1.62
159	16.72	.06	1.33	16.70	.02	1.35	16.60	.10	1.45	16.57	.03	1.48
172A	15.07	.06	0.93	15.08	+.01	0.92	15.06	.02	0.94	15.02	.04	0.98
115	16.04	+.03	0.82	16.04	.00	0.82	15.99	.05	0.87	15.99	.00	0.87
244	12.27	.03	0.03	12.28	+.01	0.02	12.29	+.01	0.01	12.28	.01	0.02
245	7.82	.06	0.04	7.84	+.02	0.02	7.87	+.03	+0.01	7.87	.00	+0.01

* All elevations referred to U. S. Engineers Datum and based on U. S. Coast and Geodetic Survey Bench Mark A-9 at La Marque (18.622 + 1.43 = 20.052 ft. U.S.E. Datum).

TABLE 2

AMERICAN OIL COMPANY - TEXAS CITY, TEXAS

GROUND SUBSIDENCE AT KEY POINTS - FEET *

BENCH MARK NO.	LOCATION	Elevation in 1938 or as Noted	Original Elevation	MAY, 1945		NOVEMBER, 1945		
				Elev. This Survey	Total Settlement To Date	Elev. This Survey	Increment Settlement	Total Settlement To Date
1A	Water Well No. 6 1085-S & 4825-W	17.50	17.50	16.61	0.89	16.45	.16	1.05
17	West Side of Tank No. 6	15.95	15.95	14.38	1.57	13.90	.48	2.05
18	Water Well No. 2 House Found. 3245-W & 1065-S	16.68	16.68	15.11	1.57	14.90	.21	1.78
86	SW Corner Comp. Room No. 2 C. U.	17.95	17.95	16.52	1.43	16.29	.23	1.66
97	Monument 2000-S & 5155.45-W	16.41	16.41	15.48	0.93	15.27	.21	1.14
103	NW Corner Pump Room No. 2 Pipe Still	18.01	18.01	16.82	1.19	16.51	.31	1.50
151	Water Well No. 4 House Found. 2810-S & 3495-W	16.98	16.98	15.75	1.23	15.55	.20	1.43
159	Water Well No. 7 2810-S & 5000-W	18.05	18.05	17.08	0.97	16.78	.30	1.2[illegible]
172A	Water Well No. 11 2850-S & 946-W	(1944)	16.00	- -	- -	15.13	- -	0.87
115	NW Corner F-10 Alky Unit	(1943)	16.86	- -	- -	16.01	- -	0.85
244	Pan Am Prod. Co. - Dry Oil Well	(1946)	12.30	- -	- -	12.30	.00	0.00
245	USC & GS B. M. on TCRRC & Galv. Hwy.	(1945)	7.86	7.86	0.00	7.88	+.02	+0.02
C & A Tie Pt.	Carbide B. M. N-3500 & W-1000 (Carbide-Amoco Tie Point)	13.51	13.51	- -	- -	- -	- -	- -

* All elevations referred to U. S. Engineers Datum and based on U. S. Coast and Geodetic Survey Bench Mark A-9 at La Marque (18.622 + 1.43 = 20.052 ft. U.S.E. Datum).

II DISCUSSION

B. REFINERY AND SURROUNDING AREA WATER PUMPAGE

II. DISCUSSION

B. REFINERY AND SURROUNDING AREA WATER PUMPAGE

Refinery Pumpage and River Water Usage

The increased development of ground water resources in the Texas City and surrounding area during the 1930's resulted in large scale well pumpage which brought about an increasing decline in artesian pressures in the water-bearing formations and an accompanying increase in the salinity of the water. This in turn dewatered the underground structures and lowered the hydraulic gradient to the extent that probably compaction of the less permeable clays began and settlement of the land-surface resulted.

As mentioned in Engineering Department Report No. 48[3], well water pumpage in the refinery during 1940, prior to the first evidence of subsidence, averaged approximately 8 million gallons daily while the total local area usage was approximately 11 million gallons daily. However, by 1945, the refinery pumpage had reached a peak of 13 million and the total Texas City-La Marque pumpage exceeded 23 million gallons daily. In 1948, the pumpage in this area reached a peak of 26 million and the Amoco and Carbide combined consumption almost 18 million gallons per day. Therefore, in view of the resultant severe subsidence experienced in both plants, Brazos River water was made available in 1948.

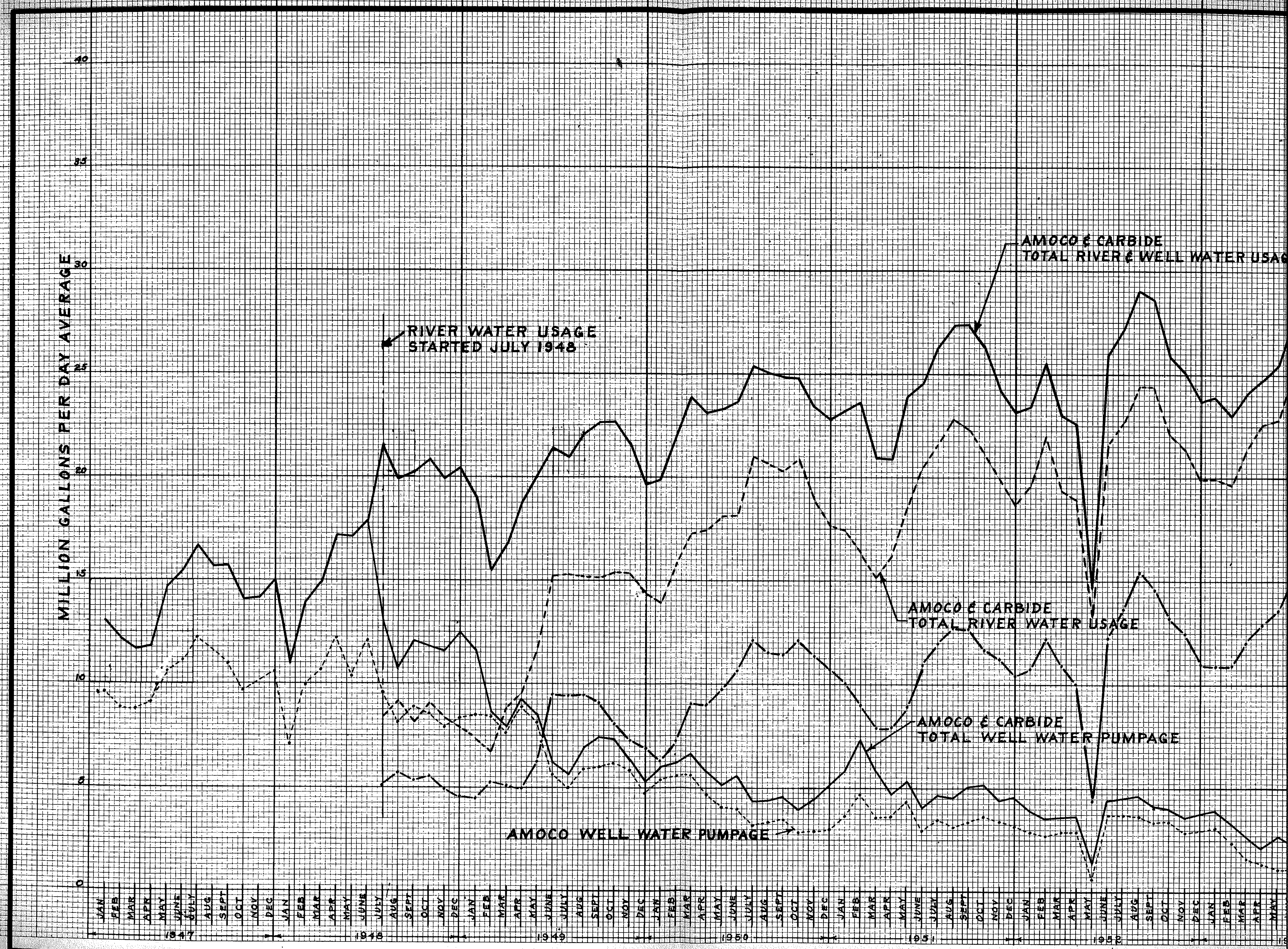
Following the installation of river water facilities for fire, service, and cooling water purposes, the total refinery well pumpage decreased from an average of approximately 10 million in 1948, to less than 3 million gallons daily in 1952, compared to a total pumpage of approximately 11 million gallons per day for the Texas City area as shown on sketch No. 4944-8 (page No. 8). Also, additional reductions in refinery pumpage have been realized since 1952, by the installation of additional treating facilities for boiler feed water and the conservation of well water wherever possible, including the use of river water for all air conditioning systems. Over the past five year period (1953 through 1957) the refinery pumpage has averaged only 0.9 million and in 1957 decreased to 0.53 million gallons daily as shown on sketch No. 4944-9 and Table 4. Carbide's pumpage for the corresponding period averaged approximately 0.7 million decreasing to 0.58 million gallons per day in 1957, while the total Texas City area pumpage averaged 9 million for this period and decreased to approximately 8 million gallons daily during 1957. Of the total refinery water requirements during the past year, which averaged approximately 18.5 million gallons per day, less than 3 per cent was supplied from water wells as compared to the approximately 97 per cent river water usage.

Surface water is supplied to the refinery and other Texas City industries via a 50 mile long canal from the Brazos River. Included in the distribution facilities constructed in 1948 by the Galveston County Water Company are a 1,000 acre reservoir, an all electric unattended pumping station located east of the Carbide plant, and approximately three miles of 42", 30", and 24" diameter water piping. Present capacity of these facilities is 50 million gallons daily.

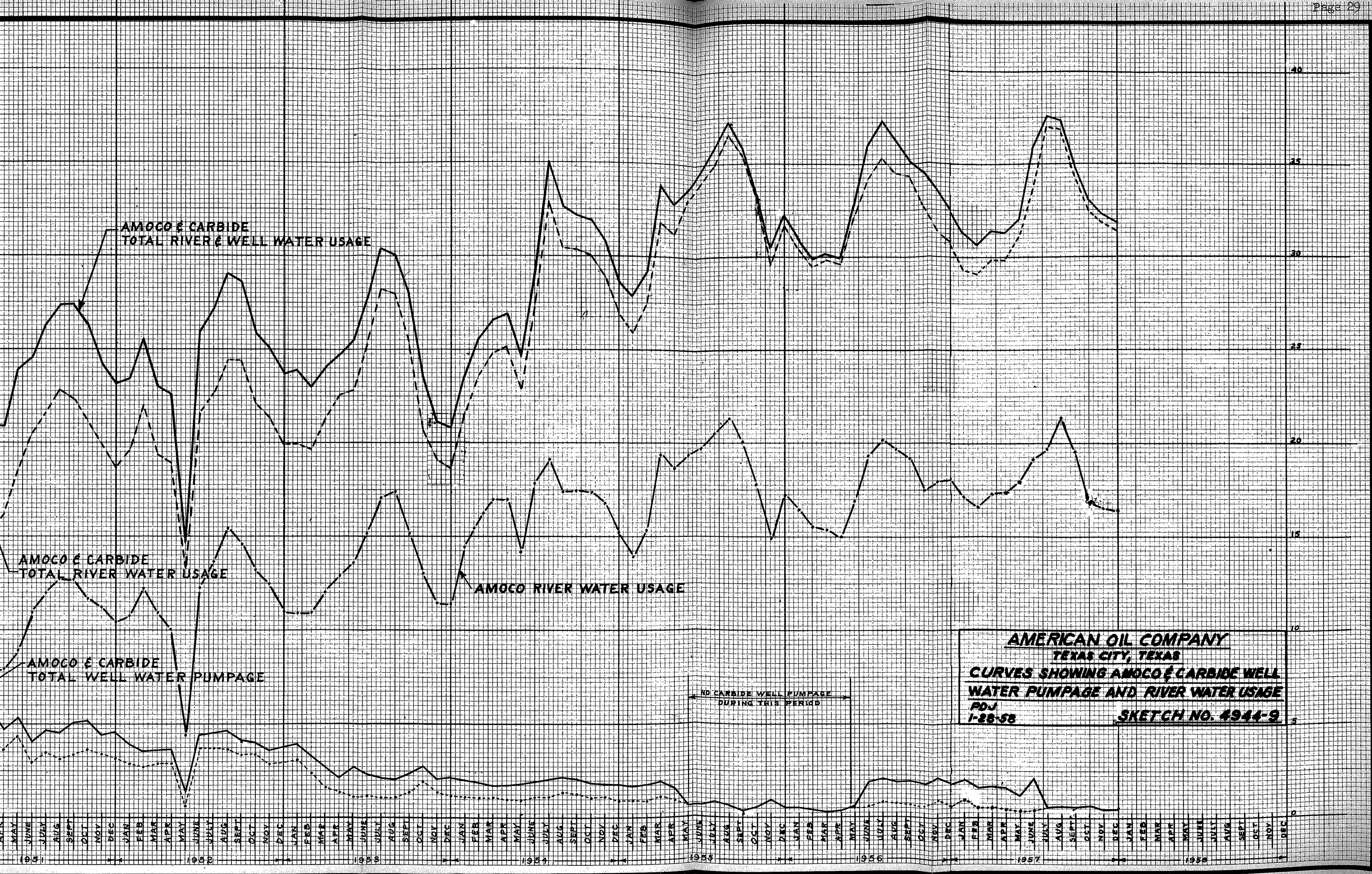
As indicated in the following tabulation river water consumption by Amoco and Carbide, respectively, has increased to 18 million and 14 million gallons daily. Monsanto's consumption increased to 5.5 million gallons daily in 1957 but the other relatively small users of river water--Sid Richardson, Wah Chang (Tin Processing), Texas City Chemicals, and Kelso--accounted for a total of 1.5 million gallons per day in 1955 and only 0.8 million gallons in 1957.

RIVER WATER - GALVESTON COUNTY WATER COMPANY - MILLION GALLONS DAILY

YEAR	1948	1950	1955	1957
AMERICAN OIL COMPANY	5.0	11.0	18.0	18.2
CARBIDE & CARBON CHEMICALS	3.0	9.0	14.0	14.2
MONSANTO	0.0	0.0	5.0	5.5
OTHERS	0.0	1.0	1.5	0.8
TOTAL RIVER WATER	8.0	21.0	38.5	38.7



MILLION GALLONS PER DAY AVERAGE
40
35
30
25
20
15
10
5
0
AMOCO & CARBIDE
TOTAL RIVER & WELL WATER USAG
RIVER WATER USAGE
STARTED JULY 1948
AMOCO & CARBIDE
TOTAL RIVER WATER USAGE
AMOCO & CARBIDE
TOTAL WELL WATER PUMPAGE
AMOCO WELL WATER PUMPAGE
JAN FEB MAR APR MAY JUNE JULY AUG SEPT OCT NOV DEC
1947
1948
1949
1950
1951
1952



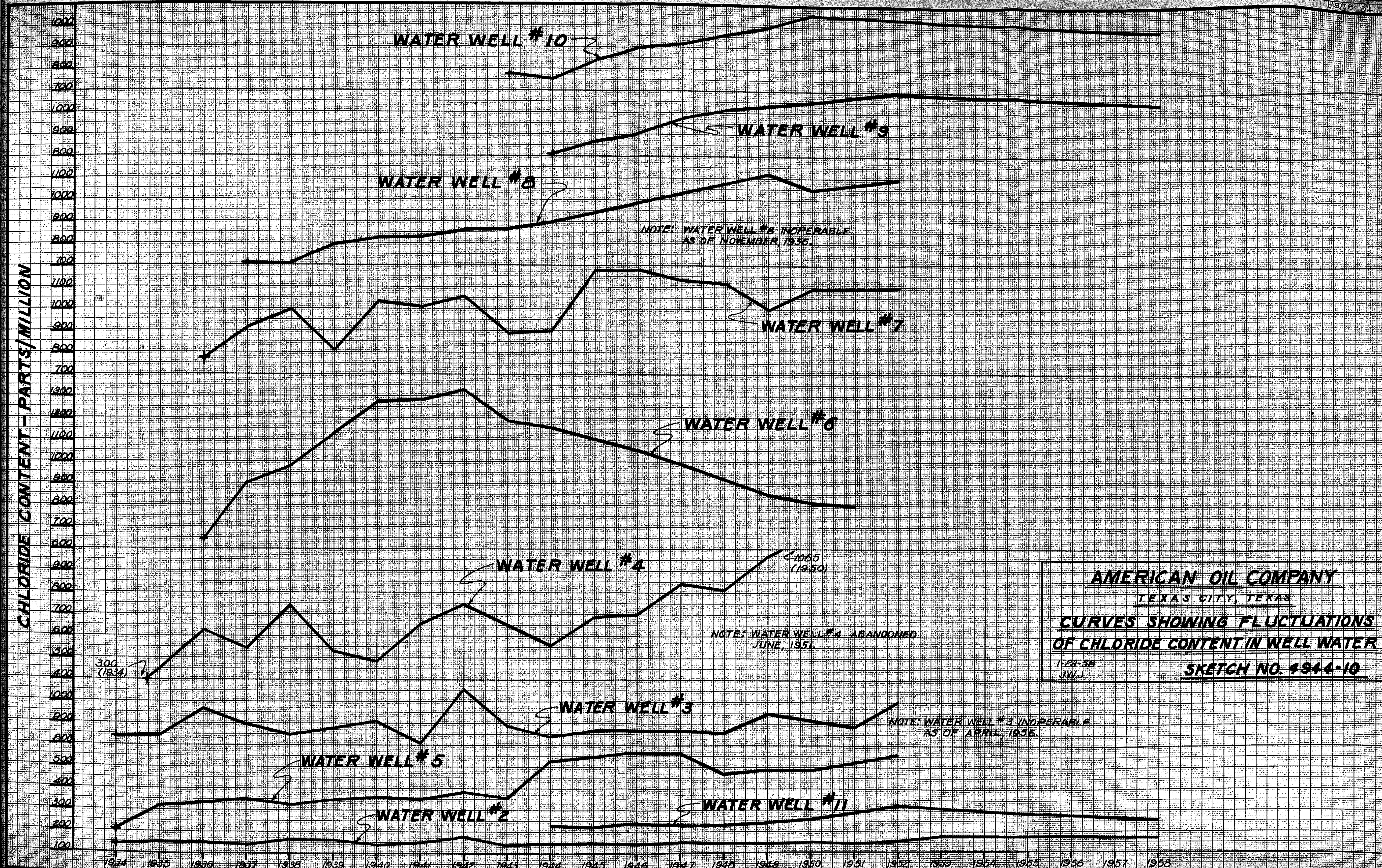
AMERICAN OIL COMPANY
TEXAS CITY, TEXAS
CURVES SHOWING AMOCO & CARBIDE WELL WATER PUMPAGE AND RIVER WATER USAGE
PDJ
1-28-58
SKETCH NO. 4944-9
AMOCO & CARBIDE TOTAL RIVER & WELL WATER USAGE
AMOCO & CARBIDE TOTAL RIVER WATER USAGE
AMOCO RIVER WATER USAGE
AMOCO & CARBIDE TOTAL WELL WATER PUMPAGE
NO CARBIDE WELL PUMPAGE DURING THIS PERIOD
40
35
30
25
20
15
10
5
0
1951
1952
1953
1954
1955
1956
1957
1958

Attached Table 7 and the river water versus well water curves included on sketch No. 4944-9 show a complete summary of the surface water rates for the refinery and graphically compare well water pumpage within the Amoco and Carbide plants to river water consumption. Future water requirements will undoubtedly be supplied by this system also and it is predicted that even the domestic and municipal water supply in Galveston County will be switched from wells to the Brazos River water source sometime in the future.

Chloride Content Trend as Ground-Water Pumpage Increases

Water samples from the refinery wells have been taken periodically since the drilling of each well to determine the chloride trends and quality of the water in various wells. Curves showing fluctuations of chloride content of the water from the refinery wells are shown on sketch No. 4944-10 and tabulated in Table 6. Samples of the water from the shallow wells Nos. 2 and 11 screened in the sands of the Beaumont clay have shown very little change in chloride content since 1934, as compared to the wide fluctuating increases indicated by the deep wells screened in the "Alta Loma" sands over the past years during periods of heavy pumpage. Although large reductions in refinery and total area pumpage have taken place since 1948, in the Texas City area there has been very little overall change in the quality of water. However, recent samples taken in January of this year from both the shallow wells Nos. 2 and 11 (170 PPM and 253 PPM, respectively) and deep wells Nos. 9 and 10 (1046 PPM and 982 PPM, respectively) indicate a slight decrease in chlorides since the last analyses were made.

According to reports by the U. S. Geological Survey[4], salt water was present in the lower part of the "Alta Loma" sand in the Alta Loma and Texas City areas and throughout that sand on Galveston Island when the first supplies were developed. Encroachment either from below or from down dip has occurred with the lowering of the artesian pressure in the Alta Loma and Texas City areas. The salt water apparently is in the form of a wedge, thickening down dip and occupying only the lower part of the formation up dip. Salt water is present also in the sands underlying the "Alta Loma", except in the extreme northern and northwestern parts of Galveston County. The encroachment appears to have occurred simultaneously from


AMERICAN OIL COMPANY
TEXAS CITY, TEXAS
CURVES SHOWING FLUCTUATIONS OF CHLORIDE CONTENT IN WELL WATER
1-28-58
JWJ
SKETCH NO. 4944-10
CHLORIDE CONTENT - PARTS/MILLION
WATER WELL #10
WATER WELL #9
WATER WELL #8
NOTE: WATER WELL #8 INOPERABLE AS OF NOVEMBER, 1956.
WATER WELL #7
WATER WELL #6
WATER WELL #4
1065 (1950)
300 (1934)
NOTE: WATER WELL #4 ABANDONED JUNE, 1951.
WATER WELL #3
NOTE: WATER WELL #3 INOPERABLE AS OF APRIL, 1956.
WATER WELL #5
WATER WELL #11
WATER WELL #2
1934 1935 1936 1937 1938 1939 1940 1941 1942 1943 1944 1945 1946 1947 1948 1949 1950 1951 1952 1953 1954 1955 1956 1957 1958

down dip and from beneath and can be expected to continue. A ground-water divide between Texas City and Alta Loma has acted as a partial barrier to the movement of salty water from the east. However, this divide has been partially removed or reduced in height as a result of the large reduction of pumping in the Texas City area.

The city of Galveston has obtained water of relatively low salinity by tapping the thinner and shallower section of the sand north of Alta Loma. Nevertheless, the old well field adjacent to this area has been encroached upon by salt water which is too salty for human consumption. Water from these two well fields is blended together in order to increase production and retain a slight ground-water divide between the fields and delay the ingress of salt water into the new wells.

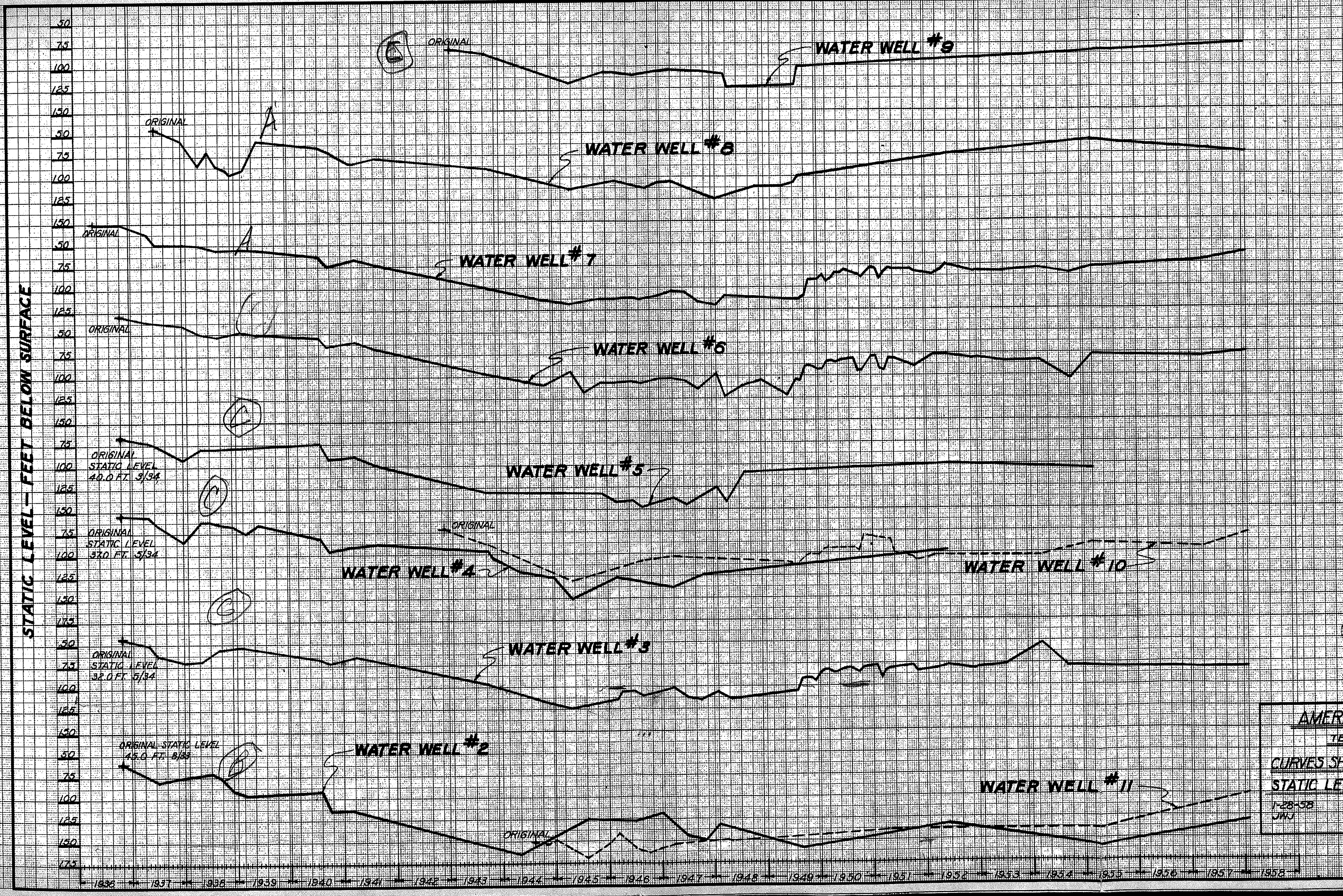
Fluctuation of Static Levels in Water Wells

Originally all water wells in Galveston County had sufficient artesian pressures to cause free flow although as large scale withdrawals began the water levels in wells declined as the pumpage increased. Since 1948, the water levels in many wells in the county have risen as a result of the decrease in pumpage and others have tended to become stabilized.

Water levels in the refinery wells started dropping as pumpage began in 1933; however, the largest declines took place between about 1936 and 1948 as a result of the continued increase in refinery pumpage and the rapid industrial development of the Texas City area. During this period water levels in the refinery shallow wells declined an average total in excess of 100 feet and those in the deep wells declined an average total of approximately 80 feet. Following the decrease of well pumpage at the end of World War II in 1945, and the introduction of Brazos River water in 1948, the levels in both the shallow and deep wells through January of this year have risen on an average of approximately 35 to 40 feet and the average total decline since 1936, is now on the order of 30 to 70 feet in the deep and shallow wells, respectively. Also, the No. 9 well which was placed in service during 1943, had an original static level of 80 feet below the surface. The latest January, 1958, measurement showed the present static level to be 76 feet or a rise of 4 feet since the original level. At present this is the only refinery water well which is pumped on a continuous basis and it is used to supply all drinking and sanitary water requirements. Curves showing fluctuations of static levels in the refinery water wells are shown on sketch No. 4944-11 and tabulated in Table 9.

As mentioned previously above, the reduction of pumpage in the Texas City area, and the use of the newly developed surface water facilities in 1948 resulted in a definite improvement of static levels and particularly those wells screened opposite the "Alta Loma" sand. The recovery was noticed over a large area extending out from Texas City. However, because wells at Alta Loma and Texas City in Galveston County, and at Baytown, La Porte, Pasadena, and Deer Park in Harris County, all withdraw water from the "Alta Loma" sand, the artesian pressures have been influenced to varying degrees by pumping throughout the region. Profiles prepared by the U. S. Geological Survey to illustrate the piezometric surface of the "Alta Loma" sand in Galveston and Harris Counties, as it is believed to have been prior to any significant water pumpage and as it existed in 1941, 1948, and 1952 are shown in Figure 5.

Although the greatest number of wells in Galveston County withdraw water from the sands of the upper Beaumont clay, the pumpage from this formation has not been as great as that from the "Alta Loma" sand. However, because of the low permeability and lenticular character of the sands of the Beaumont clay, the decline in water levels has been much greater in proportion to the quantity of water pumped. Pumping tests have been made on wells in the Texas City area by the U. S. Geological Survey to determine the coefficients of transmissibility and storage. Results of these tests indicated that the productivity of the Beaumont clay is too low to permit large-scale pumpage, in relatively small areas, without excessive declines in water levels. Whereas, the "Alta Loma" sand permits the lateral movement of water to points of discharge with a much lower hydraulic gradient and less loss in artesian pressure at the points of pumpage.


STATIC LEVEL—FEET BELOW SURFACE
WATER WELL #9
ORIGINAL
WATER WELL #8
ORIGINAL
WATER WELL #7
ORIGINAL
WATER WELL #6
ORIGINAL
WATER WELL #5
ORIGINAL STATIC LEVEL 40.0 FT. 3/34
WATER WELL #4
ORIGINAL STATIC LEVEL 37.0 FT. 5/34
WATER WELL #10
ORIGINAL
WATER WELL #3
ORIGINAL STATIC LEVEL 32.0 FT. 5/34
WATER WELL #2
ORIGINAL STATIC LEVEL 45.0 FT. 8/35
WATER WELL #11
ORIGINAL
1936
1937
1938
1939
1940
1941
1942
1943
1944
1945
1946
1947
1948
1949
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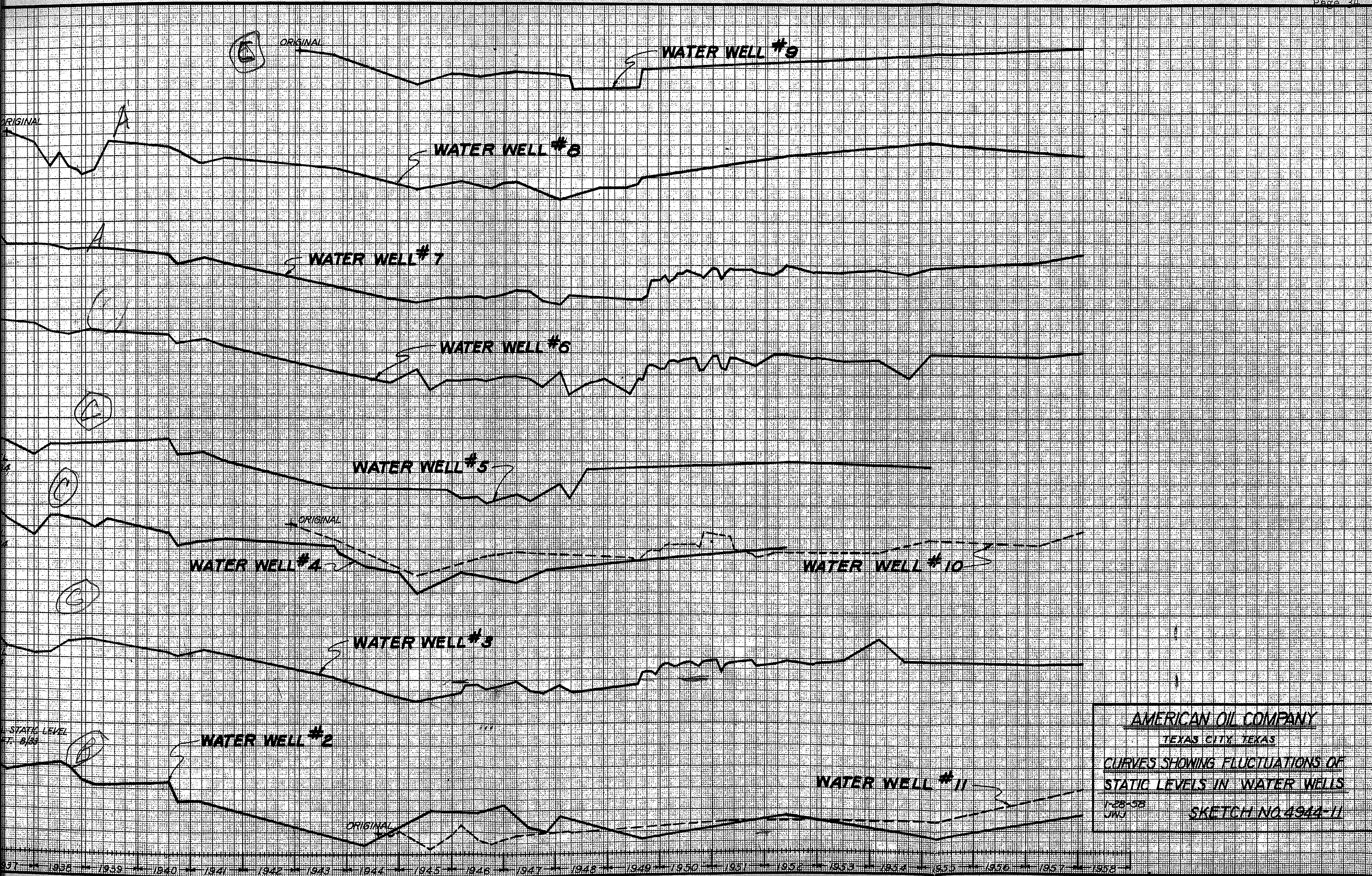
ORIGINAL
WATER WELL #9
ORIGINAL
WATER WELL #8
WATER WELL #7
WATER WELL #6
WATER WELL #5
ORIGINAL
WATER WELL #4
WATER WELL #10
WATER WELL #3
STATIC LEVEL
FT. 8/33
WATER WELL #2
ORIGINAL
WATER WELL #11
1938 1939 1940 1941 1942 1943 1944 1945 1946 1947 1948 1949 1950 1951 1952 1953 1954 1955 1956 1957 1958
AMERICAN OIL COMPANY
TEXAS CITY, TEXAS
CURVES SHOWING FLUCTUATIONS OF
STATIC LEVELS IN WATER WELLS
1-28-58
JWJ
SKETCH NO. 4944-11

Based on a recent report prepared by the U. S. Geological Survey and Texas Board of Water Engineers(5), substantial recoveries of water levels were observed in many wells of the Houston-Pasadena area between 1954 and 1955, as a result of the introduction of San Jacinto River water during May, 1954, to the Houston municipal mains.

Water levels in wells of the Baytown-La Porte and eastern Houston ship channel areas which are screened in the "Alta Loma" sands have continued to decline at a slow rate and in 1955, the levels in these wells were in excess of 150 to 200 feet, respectively, below the ground surface.

Present Condition of Refinery Water Wells

Of the refinery's ten water wells drilled between 1933 and 1944, only seven are in an operable condition at the present time. The four original wells (Nos. 2, 3, 4, and 5) were placed in service during 1934, supplemented by two additional wells (Nos. 6 and 7) in 1936, one (No. 8) in 1937, two (Nos. 9 and 10) in 1943, and one (No. 11) in 1944. Over the past years of operation severe difficulty has been experienced in these wells because of sand erosion necessitating the replacement of numerous pump bowls, impellers, and shafts; and electrolytic pit type corrosion in the pumping equipment requiring replacement of the pump discharge columns, oil tubing, etc. Also, the well liners and/or screens for wells Nos. 3, 4, 5, and 10 have been severely attacked by electrolytic corrosion requiring rehabilitation and extensive repairs, except in the No. 4 well which was abandoned in May, 1951, since the liner and screen were deteriorated beyond economical repair. The No. 3 well was rehabilitated in 1947 by replacement of the well liner; however, in April, 1956, this well was removed from service because of excessive sanding. Removal of the pump revealed that the 8" suction nozzle and approximately 23 feet of suction piping had eroded from the pump and remained in the well. In addition, exploratory work indicated that the 16" surface casing had failed at the 292' and 355' levels, apparently the result of severe electrolytic corrosion. In November, 1956, while in temporary service because of the loss of the Brazos River water supply, the No. 8 well began excessive sanding. Inspection revealed that the surface casing had failed at the 365' and 412' levels.

Presently the remaining refinery wells, except water well No. 9 which is used for drinking and sanitary water purposes spared by No. 10 well, are maintained on an emergency standby basis to supplement river water in case of failure. However, based on the poor condition and evidence of severe corrosion existing in the wells, it is very likely that several of them would fail if pumped for any length of time under maximum conditions occurring with a failure of Brazos River water. Therefore, since the total refinery water requirements are increasing and the reliable capacities of existing wells becomes less each year including the excessive maintenance required in maintaining old water wells on a standby basis; studies are in progress to determine the necessary steps that should be taken to insure an adequate and continuous water supply in view of the possible failure of the river water system.

Surrounding Area Water Pumpage

The Houston-Galveston region, including the Baytown-La Porte area, contains the most heavily industrialized areas of the Texas Gulf Coast, and is one of the most heavily concentrated regions of ground-water pumpage in the United States. The majority of the industry and population, and much of the rice irrigation in the region is dependent on ground-water for its water supply, and during 1954, an average total of about 388 million gallons of water daily was pumped from wells. Table 3 shows the estimated average daily withdrawal of ground-water for public, industrial, and rice irrigating supplied for the years 1952 to 1957, and the locations of heavy concentrated pumpage are indicated on Figure 2.

According to recent data supplied by the U. S. Geological Survey, the average daily pumpage in the Houston district, which includes the Houston, Pasadena, and Katy areas reached an all-time high in excess of 338 million gallons during 1954. However, the increase in pumpage over that of 1953 was confined to the Katy rice irrigation area, where a record high of about 67,000 acres was irrigated. The completion of Lake Houston Dam on the San Jacinto River in May, 1954, and the resulting increased use of surface water in the heavily industrialized Houston-Pasadena area permitted the first decrease in ground-water pumping in that area since 1941. During 1956, the total average daily pumpage decreased over that in 1954 to approximately 298 million as a result of the reduced pumpage for irrigation purposes.

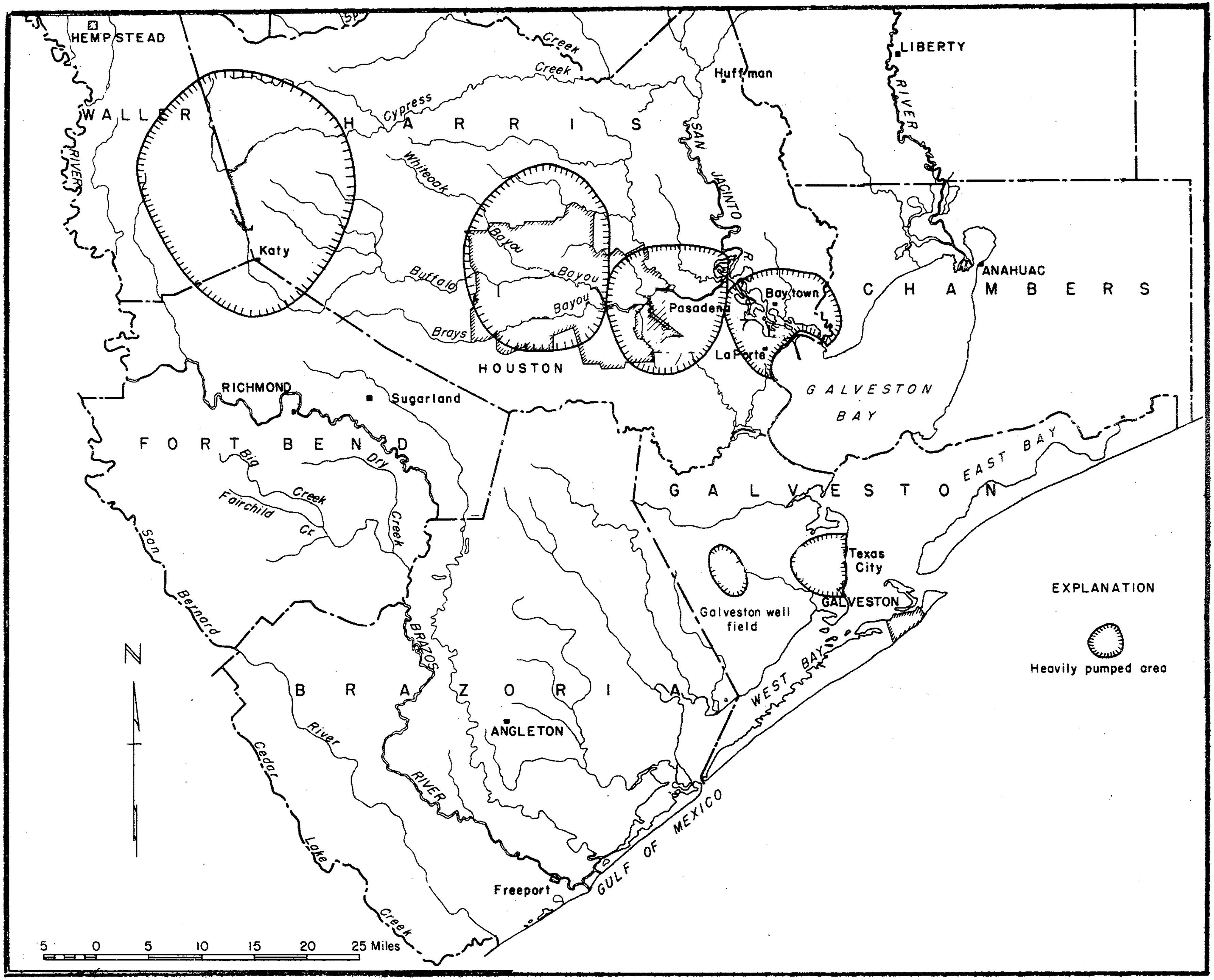

FIGURE 2 - HEAVILY PUMPED AREAS - HOUSTON-GALVESTON REGION

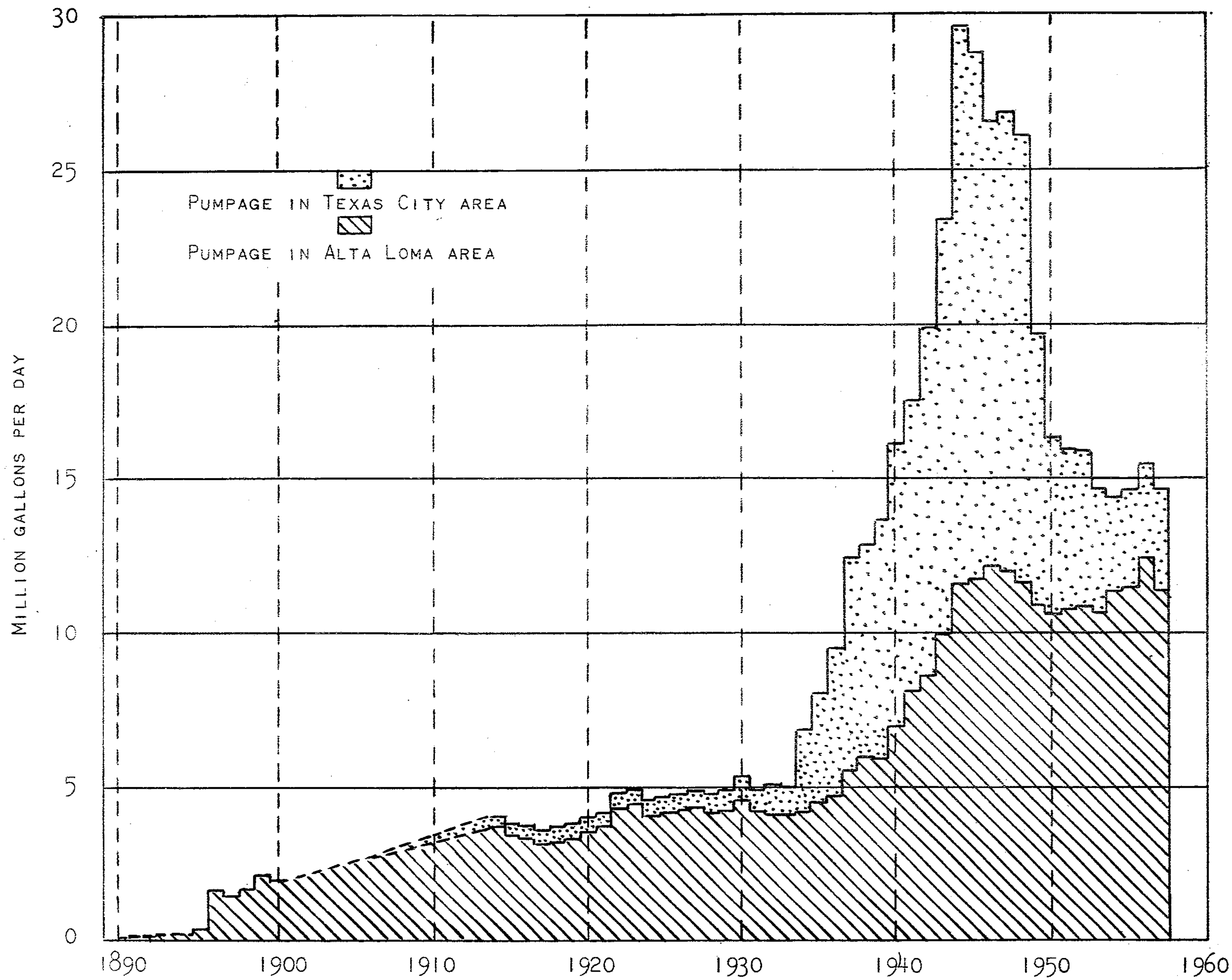

FIGURE 3 - AVERAGE DAILY PUMPAGE FROM THE "ALTA LOMA" SAND IN THE ALTA LOMA AND TEXAS CITY AREAS, 1890-1957.

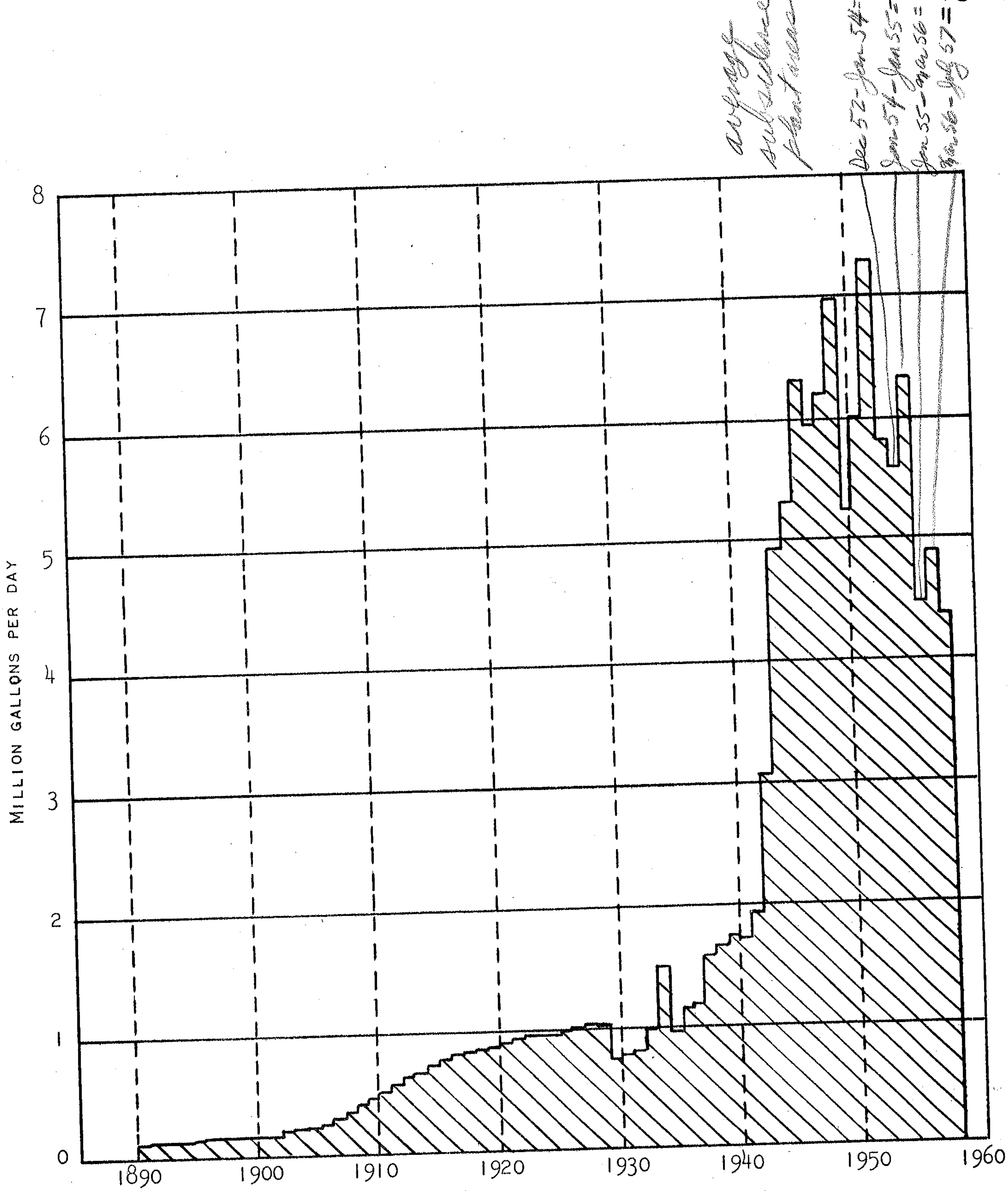

FIGURE 4 - ESTIMATED AVERAGE DAILY WITHDRAWAL OF WATER FROM THE UPPER PART OF THE BEAUMONT CLAY IN THE TEXAS CITY AREA, 1890-1957.

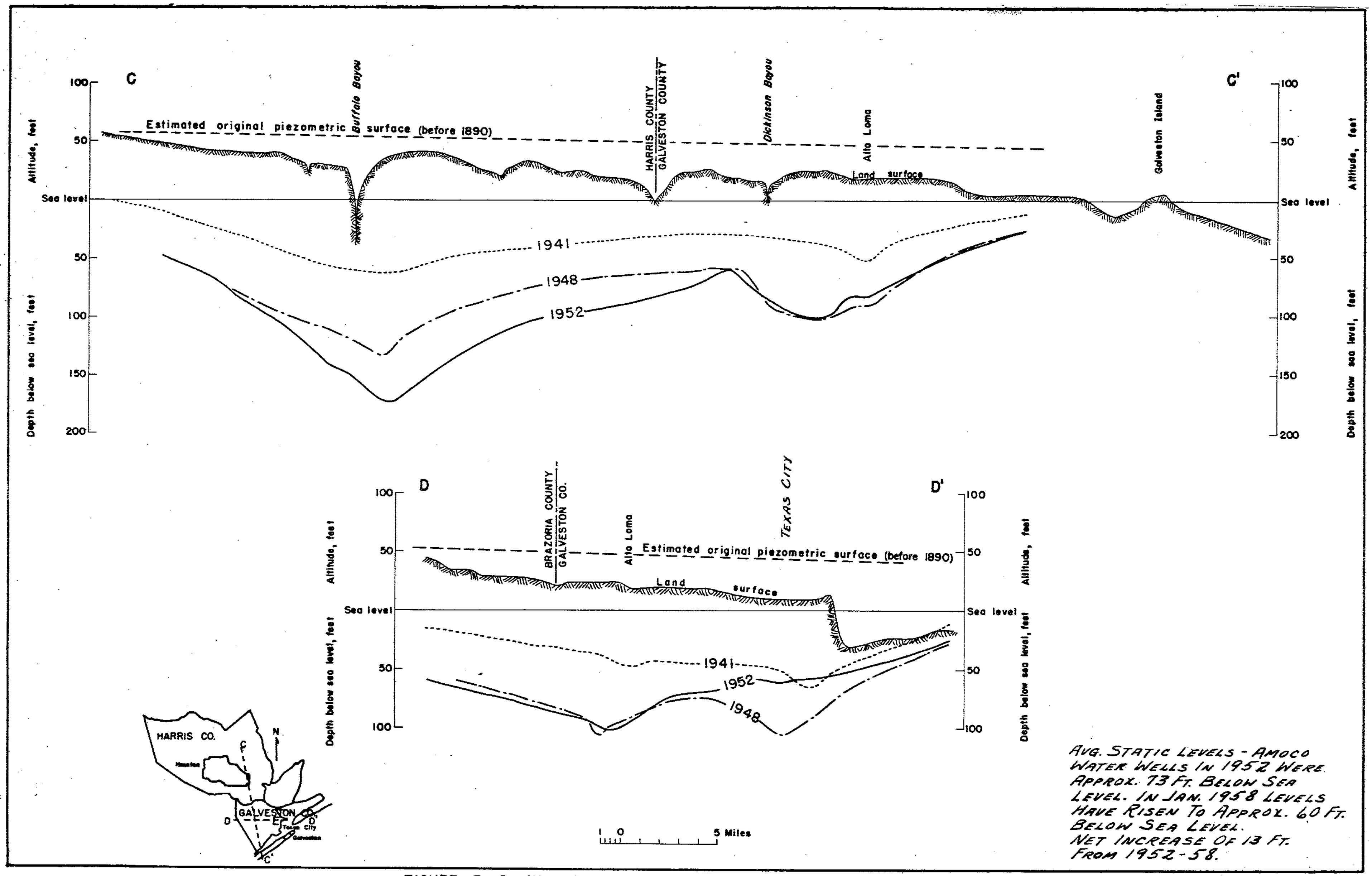

FIGURE 5 - Profiles of the piezometric surface in the "Alta Loma" sand.

Well water pumpage in the Baytown-La Porte areas, the majority of which is pumped from the "Alta Loma" sands at a depth of approximately 500 feet, increased from a total average of approximately 25 million in 1952 to 28 million gallons daily during 1956. Although the Baytown industrial pumpage decreased, there was a greater increase in the public supply and irrigation demands as shown in Table 3.

Prior to 1948, the water for all public and nearly all industrial requirements in Galveston County was derived from wells, with the greatest concentrated areas of pumpage being around Alta Loma and Texas City. The average daily pumpage in these areas increased from about 6 million gallons in 1938 to almost 18 million gallons in 1940 and reached a peak of approximately 35 million in 1945. Between 1945 and 1948, the rate of pumpage remained fairly constant, at which time surface water was diverted from the Brazos River for industrial supplies in the Texas City area and well pumpage was reduced about 30 per cent. Since 1948, well water pumpage for industrial use has continually decreased as a result of the increased usage of river water, although considerable industrial expansion and growth has taken place over this period as indicated in Table 4 and shown graphically on Figures 3 and 4. During the past year an average total of approximately 44 million gallons of water daily was consumed by industries in the Texas City area. Of this total slightly less than 12 per cent was supplied from water wells and the remaining approximately 88 per cent from river water. Although this percentage of ground-water pumpage appears small, every effort should be made to reduce pumpage wherever possible by industry and including municipal requirements to assure the future availability of usable ground-water supplies and to prevent land-surface subsidence.

Presently the greatest concentrated pumpage in Galveston County is by the City of Galveston from their deep well field in the Alta Loma area, which has averaged approximately 11.3 million gallons daily over the past five year period in comparison to 9.6 million for the Texas City-La Marque area and a total Galveston County pumpage of approximately 24 million gallons per day as indicated in Table 5.

TABLE 3

HOUSTON - GALVESTON REGION

WATER WELL PUMPAGE - MILLION GALLONS PER DAY AVERAGE

	1952	1953	1954	1955	1956	1957
HOUSTON DISTRICT						
Houston Area	97.0	99.6	95.9	86.0	100.0	--
Pasadena Area	83.0	87.0	83.0	80.0	73.0	--
Katy Area (Rice irrigation)	128.0	120.0	160.0	104.0	125.0	--
Total - District	308.0	306.6	338.9	270.0	298.0	--
BAYTOWN - LA PORTE AREA						
Industrial	20.1	17.8	15.2	17.7	18.0	--
Public	2.7	3.0	4.1	4.5	4.5	--
Irrigation	2.0	2.0	2.5	3.0	5.4	--
Total - Area	24.8	22.8	21.8	25.2	27.8	--
GALVESTON COUNTY						
Industrial	10.84	10.04	9.57	6.16	6.37	5.63
Public	14.02	14.24	15.24	15.02	16.17	15.43
Irrigation	-	-	2.00	1.70	1.40	1.20
Total - County	24.86	24.28	26.81	22.88	23.94	22.26

TABLE 4

TEXAS CITY - LA MARQUE & ALTA LOMA AREAS

WATER WELL PUMPAGE - MILLION GALLONS PER DAY AVERAGE

	1940	1945	1950	1955	1957
TEXAS CITY - LA MARQUE AREA					
American Oil	8.05	11.47	3.98	0.77	0.53
Amoco Chemicals	0.43	0.38	0.46	0.20	0.20
Carbide	0.00	3.28	1.20	0.28	0.59
Monsanto	0.00	0.99	0.65	Discontinued - 1953	
Republic	1.07	2.61	2.75	2.35	2.35
Sid Richardson	0.86	2.03	Discontinued - 1951		
Texas City Refining	0.00	0.82	0.40	1.27	1.43
Texas City Terminal	0.23	0.23	0.12	0.10	0.10
Tin Processing	0.00	1.33	0.97	0.81	0.05
Total Industrial	10.64	23.14	10.53	5.78	5.25
City of Texas City	0.25	0.71	1.04	1.68	2.10
WCID #3 La Marque	0.05	0.05	0.64	1.00	0.78
WCID #4 Texas City Heights	0.05	0.05	0.20	0.25	0.26
Total Public	0.35	0.81	1.88	2.93	3.14
Total Area Pumpage	10.99	23.95	12.41	8.71	8.39
ALTA LOMA AREA					
City of Galveston	6.92	11.66	10.50	11.41	11.32

TABLE 5

GALVESTON COUNTY, TEXAS

AVERAGE DAILY WATER WELL PUMPAGE IN MILLIONS OF GALLONS*

CONSUMER \ FORMATION	1952		1953		1954		1955		1956		1957	
	Beaumont	Alta Loma	Beaumont	Alta Loma	Beaumont	Alta Loma	Beaumont	Alta Loma	Beaumont	Alta Loma	Beaumont	Alta Loma
American Oil	0.440	2.480	0.430	1.090	0.640	0.440	0.188	0.582	0.003	0.577	0.006	0.528
Amoco Chemicals	0.275	- -	0.180	- -	0.200	- -	0.200	- -	0.200	- -	0.200	- -
Carbide	0.850	- -	0.960	0.092	0.855	0.006	0.276	0.007	0.730	- -	0.585	- -
Monsanto	0.180	- -	- -	- -	- -	- -	- -	- -	- -	- -	- -	- -
Republic	0.720	1.800	0.720	2.000	0.865	1.730	0.620	1.730	0.620	1.730	0.620	1.730
Texas City Refining	0.288	0.865	0.288	0.865	0.400	0.865	0.400	0.865	0.430	1.000	0.430	1.000
Texas City Terminal	0.163	- -	0.093	- -	0.100	- -	0.100	- -	0.100	- -	0.100	- -
Tin Processing	0.692	- -	1.238	- -	1.380	- -	0.815	- -	0.600	- -	0.055	- -
City of Texas City	1.407	- -	1.510	- -	1.730	- -	1.685	- -	1.935	- -	2.095	- -
City of Galveston	- -	10.729	- -	10.504	- -	11.265	- -	11.408	- -	12.220	- -	11.320
WCID No. 1 Dickinson	0.207	- -	2.221	- -	0.237	- -	0.204	- -	0.306	- -	0.394	- -
WCID No. 2 League City	0.095	- -	0.113	- -	0.115	- -	0.127	- -	0.175	- -	0.165	- -
WCID No. 3 La Marque	0.400	0.723	0.450	1.000	0.490	1.000	0.330	0.670	0.014	0.840	0.014	0.767
WCID No. 4 Texas City	0.148	- -	0.182	- -	0.186	- -	0.250	- -	0.250	- -	0.260	- -
WCID No. 7 Hitchcock	0.041	0.190	- -	0.160	- -	0.110	- -	0.225	- -	0.290	- -	0.268
WCID No. 12 Kemah	0.060	- -	0.070	- -	- -	0.080	- -	0.080	- -	0.099	- -	0.100
Galveston County Memorial Hospital	0.020	- -	0.030	- -	0.030	- -	0.035	- -	0.035	- -	0.035	- -
Irrigation	- -	- -	- -	- -	0.500	1.500	0.400	1.300	0.200	1.200	0.200	1.000
Falstaff Brewing Company	- -	2.000	- -	2.000	- -	2.000	- -	0.300	- -	0.300	- -	0.300
High Grade Packing Company	0.090	- -	0.090	- -	0.090	- -	0.085	- -	0.085	- -	0.085	- -
Total Formation Pumpage	6.076	18.787	6.575	17.711	7.818	18.996	5.715	17.167	5.683	18.256	5.244	17.013
Total County Pumpage	24.863		24.286		26.814		22.882		23.939		22.257	

*All pumpage figures shown in this table are not necessarily accurate since some owners do not meter the water and only an approximation is possible.

TABLE 6

AMERICAN OIL COMPANY

TEXAS CITY, TEXAS

CHLORIDE CONTENT OF WATER FROM WELLS (PPM)

YEAR	WATER WELL									
	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7	No. 8	No. 9	No. 10	No. 11
1934	137	840	300	210	--	--	--	--	--	--
1935	150	844	450	318	--	--	--	--	--	--
1936	153	967	624	333	640	770	--	--	--	--
1937	144	895	540	350	900	910	702	--	--	--
1938	165	844	740	324	978	990	702	--	--	--
1939	162	876	528	348	1130	804	795	--	--	--
1940	140	910	483	360	1270	1029	822	--	--	--
1941	150	804	654	351	1280	1005	829	--	--	--
1942	174	1052	744	383	1324	1052	860	--	--	--
1943	135	885	--	354	1185	885	864	--	777	--
1944	144	834	552	528	1155	897	894	810	750	228
1945	150	867	687	546	1101	1173	939	867	837	222
1946	142	--	699	561	1050	1176	--	900	894	243
1947	153	867	840	564	990	1128	--	969	912	234
1948	147	858	822	462	--	1113	--	1011	954	231
1949	144	945	969	486	849	993	1119	1026	996	243
1950	150	--	1065	483	813	1089	1044	1044	1059	252
1951	143	882	--	--	--	--	--	--	--	--
1952	156	1000	--	554	800	1092	1092	1090	--	320
1953	180	--	--	--	--	--	--	--	--	--
1958	170	--	--	--	--	--	--	1046	982	253

TABLE 7

AMERICAN OIL COMPANY - TEXAS CITY, TEXAS

BRAZOS RIVER WATER USAGE

MILLION GALLONS PER DAY AVERAGE

MONTH	YEAR									
	1948	1949	1950	1951	1952	1953	1954	1955	1956	1957
JANUARY	--	4.45	6.25	10.00	10.70	10.81	14.44	13.85	16.45	17.19
FEBRUARY	--	5.21	7.21	8.96	12.21	10.87	15.97	15.38	15.50	16.66
MARCH	--	5.04	9.00	7.84	10.82	12.10	16.90	19.46	15.33	17.30
APRIL	--	4.91	8.93	7.84	9.98	12.83	16.90	18.51	14.98	17.39
MAY	--	6.23	9.70	8.90	4.34	13.52	14.17	19.30	16.81	17.98
JUNE	--	9.45	10.56	10.83	12.23	15.22	17.85	19.74	19.35	19.20
JULY	5.05	9.39	12.04	11.95	13.60	17.03	19.10	20.50	20.16	20.69
AUGUST	5.70	9.40	11.50	12.70	15.40	17.30	17.33	21.29	19.54	21.39
SEPTEMBER	5.28	9.01	11.33	12.59	14.54	15.08	17.40	19.92	19.17	18.58
OCTOBER	5.50	8.13	12.06	11.60	13.10	13.00	17.30	17.51	17.47	16.85
NOVEMBER	4.93	7.25	11.27	11.23	12.45	11.47	16.72	14.82	17.84	16.51
DECEMBER	4.50	6.87	10.70	10.40	10.88	11.28	15.10	17.25	18.04	16.44
AVERAGE	5.16	7.11	10.05	10.40	11.69	13.38	16.60	18.13	17.55	18.01 (18.03)

TABLE 8

AMERICAN OIL COMPANY - TEXAS CITY, TEXAS
MONTHLY WELL WATER PUMPAGE - MILLION GALLONS PER DAY AVERAGE

YEAR →	1955			1956			1957			1958		
MONTH ↓	Shallow Wells #2 & 11	Deep Wells #3-10*	Total Pumpage	Shallow Wells #2 & 11	Deep Wells #3-10*	Total Pumpage	Shallow Wells #2 & 11	Deep Wells #3-10*	Total Pumpage	Shallow Wells	Deep Wells	Total Pumpage
JANUARY	0.518	0.455	0.973	0	0.519	0.519	0.062	0.875	0.937			
FEBRUARY	0.475	0.502	0.977	0	0.433	0.433	0	0.499	0.499			
MARCH	0.506	0.604	1.110	0	0.326	0.326	0	0.526	0.526			
APRIL	0.181	0.615	0.796	0	0.369	0.369	0.002	0.425	0.427			
MAY	0	0.619	0.619	0.003	0.509	0.512	0.003	0.369	0.372			
JUNE	0.057	0.637	0.694	0.002	0.549	0.551	0	0.412	0.412			
JULY	0.025	0.709	0.734	0	0.802	0.802	0	0.579	0.579			
AUGUST	0	0.702	0.702	0.002	0.746	0.748	0	0.593	0.593			
SEPTEMBER	0	0.445	0.445	0.002	0.664	0.666	0	0.560	0.560			
OCTOBER	0	0.602	0.602	0.003	0.543	0.546	0	0.548	0.548			
NOVEMBER	0.498	0.489	0.987	0.017	0.940	0.957	0	0.469	0.469			
DECEMBER	0	0.605	0.605	0.001	0.519	0.520	0	0.487	0.487			
YEARLY AVERAGE	0.188	0.582	0.770	0.003	0.577	0.580	0.006	0.528	0.534			

* Well No. 4 abandoned June, 1951.

TABLE 8

AMERICAN OIL COMPANY - TEXAS CITY, TEXAS
MONTHLY WELL WATER PUMPAGE - MILLION GALLONS PER DAY AVERAGE

YEAR →	1951			1952			1953			1954		
MONTH ↓	Shallow Wells #2 & 11	Deep Wells #3-10*	Total Pumpage	Shallow Wells #2 & 11	Deep Wells #3-10*	Total Pumpage	Shallow Wells #2 & 11	Deep Wells #3-10*	Total Pumpage	Shallow Wells #2 & 11	Deep Wells #3-10*	Total Pumpage
JANUARY	0.660	2.900	3.560	0.400	2.460	2.860	0.300	2.790	3.090	0.600	0.430	1.030
FEBRUARY	0.660	4.040	4.700	0.500	2.210	2.710	0.250	2.080	2.330	0.680	0.350	1.030
MARCH	0.580	2.940	3.520	0.540	2.310	2.850	0.010	1.590	1.600	0.700	0.340	1.040
APRIL	0.540	3.040	3.580	0.590	2.250	2.840	0.240	1.040	1.280	0.590	0.400	0.990
MAY	0.560	3.740	4.300	0.370	0.170	0.540	0.400	0.680	1.080	0.550	0.430	0.980
JUNE	0.500	2.410	2.910	0.530	3.060	3.590	0.520	0.620	1.140	0.610	0.490	1.100
JULY	0.560	2.860	3.420	0.530	3.070	3.600	0.470	0.550	1.020	0.660	0.460	1.120
AUGUST	0.570	2.590	3.160	0.320	3.300	3.620	0.490	0.540	1.030	0.690	0.630	1.320
SEPTEMBER	0.530	2.760	3.290	0.360	2.920	3.280	0.620	0.760	1.380	0.700	0.550	1.250
OCTOBER	0.610	2.910	3.520	0.400	2.900	3.300	0.640	1.200	1.840	0.630	0.430	1.060
NOVEMBER	0.650	2.700	3.350	0.400	2.450	2.850	0.670	0.630	1.300	0.670	0.410	1.080
DECEMBER	0.540	2.680	3.220	0.360	2.600	2.960	0.500	0.630	1.130	0.610	0.340	0.950
YEARLY AVERAGE	0.580	2.960	3.540	0.440	2.480	2.920	0.430	1.090	1.520	0.640	0.440	1.080

* Well No. 4 abandoned June, 1951.

TABLE 8

AMERICAN OIL COMPANY - TEXAS CITY, TEXAS
MONTHLY WELL WATER PUMPAGE - MILLION GALLONS PER DAY AVERAGE

YEAR →	1947			1948			1949			1950		
MONTH ↓	Shallow Wells #2 & 11	Deep Wells #3-10	Total Pumpage	Shallow Wells #2 & 11	Deep Wells #3-10	Total Pumpage	Shallow Wells #2 & 11	Deep Wells #3-10	Total Pumpage	Shallow Wells #2 & 11	Deep Wells #3-10	Total Pumpage
JANUARY	0.865	8.150	9.015	0.861	6.202	7.063	0.895	7.543	8.438	0.795	4.549	5.344
FEBRUARY	0.900	7.900	8.800	0.644	9.205	9.849	0.993	7.075	8.068	0.849	4.658	5.507
MARCH	1.290	7.450	8.740	1.134	9.386	10.520	0.954	6.714	7.668	0.806	4.773	5.579
APRIL	0.870	8.050	8.920	1.101	11.124	12.225	1.007	7.804	8.811	0.697	3.959	4.659
MAY	1.390	9.250	10.640	0.988	10.358	11.346	1.055	7.020	8.075	0.790	3.259	4.049
JUNE	1.300	9.800	11.100	1.140	10.883	12.023	0.918	4.715	5.633	0.801	3.197	4.998
JULY	1.030	11.100	12.130	0.905	8.605	9.510	0.914	3.980	4.894	0.683	2.525	3.208
AUGUST	1.280	10.300	11.580	1.014	7.118	8.132	0.895	4.967	5.862	0.646	2.672	3.318
SEPTEMBER	1.330	9.700	11.030	0.992	7.816	8.808	0.858	5.116	5.974	0.522	2.965	3.487
OCTOBER	1.220	8.400	9.620	0.925	7.573	8.498	0.827	5.409	6.238	0.632	2.180	2.812
NOVEMBER	1.100	8.900	10.000	0.892	6.930	7.822	0.769	5.013	5.782	0.619	2.305	2.924
DECEMBER	1.170	9.300	10.470	0.985	7.245	8.230	0.801	3.904	4.705	0.598	2.366	2.964
YEARLY AVERAGE	1.145	9.025	10.170	0.965	8.537	9.502	0.907	5.772	6.679	0.703	3.284	3.987

TABLE 8

AMERICAN OIL COMPANY - TEXAS CITY, TEXAS
MONTHLY WELL WATER PUMPAGE - MILLION GALLONS PER DAY AVERAGE

YEAR →	1943			1944			1945			1946		
MONTH ↓	Shallow Wells #2	Deep Wells #3-10	Total Pumpage	Shallow Wells #2 & 11	Deep Wells #3-10	Total Pumpage	Shallow Wells #2 & 11	Deep Wells #3-10	Total Pumpage	Shallow Wells #2 & 11	Deep Wells #3-10	Total Pumpage
JANUARY	0.630	7.870	8.500	0.550	10.000	10.550	1.470	9.730	11.200	0.750	7.800	8.550
FEBRUARY	0.440	7.160	7.600	0.380	10.220	10.600	1.580	9.590	11.170	1.312	9.908	11.220
MARCH	0.590	7.210	7.800	0.615	10.085	10.700	1.220	11.180	12.400	1.037	1.055	11.587
APRIL	0.470	8.130	8.600	0.450	11.150	11.600	1.425	10.515	11.938	1.119	10.700	11.819
MAY	0.450	6.950	7.400	0.610	11.340	11.950	1.433	11.050	12.483	1.310	9.800	11.110
JUNE	0.640	8.560	9.200	0.520	13.580	14.100	1.005	12.500	13.505	1.522	9.580	11.102
JULY	0.700	8.900	9.600	0.690	13.510	14.200	0.940	11.780	12.720	1.118	9.480	10.598
AUGUST	0.730	9.770	10.500	0.810	12.190	13.000	0.802	10.280	11.082	0.892	8.375	9.267
SEPTEMBER	0.680	9.270	9.950	0.680	11.520	12.200	0.906	9.290	10.196	0.850	9.750	10.600
OCTOBER	0.585	9.415	10.000	0.630	11.370	12.000	0.801	9.630	10.431	0.978	8.860	9.838
NOVEMBER	0.445	10.055	10.500	0.630	11.070	11.700	0.551	9.880	10.431	0.833	7.659	8.492
DECEMBER	0.405	9.843	10.258	0.770	10.230	11.000	0.529	9.641	10.170	0.828	8.401	9.229
YEARLY AVERAGE	0.564	8.594	9.158	0.611	11.355	11.966	1.055	10.422	11.477	1.046	9.238	10.284

Well No. 9 completed January, 1943.

Well No. 11 completed December, 1944.

TABLE 8

AMERICAN OIL COMPANY - TEXAS CITY, TEXAS
MONTHLY WELL WATER PUMPAGE - MILLION GALLONS PER DAY AVERAGE

YEAR →	1939			1940			1941			1942		
MONTH ↓	Shallow Wells #2	Deep Wells #3-8	Total Pumpage	Shallow Wells #2	Deep Wells #3-8	Total Pumpage	Shallow Wells #2	Deep Wells #3-8	Total Pumpage	Shallow Wells #2	Deep Wells #3-8	Total Pumpage
JANUARY	0.320	5.780	6.100	0.300	7.400	7.700	0.050	7.150	7.200	0.565	7.235	7.800
FEBRUARY	0.335	5.856	6.191	0.425	7.275	7.700	0.680	6.720	7.400	0.565	7.235	7.800
MARCH	0.282	6.318	6.600	0.340	7.610	7.950	0.745	6.855	7.600	0.565	7.335	7.900
APRIL	0.302	5.898	6.200	0.440	7.360	7.800	0.565	6.985	7.550	0.565	7.635	8.200
MAY	0.325	6.275	6.600	0.430	8.170	8.600	0.565	7.235	7.800	0.565	7.635	8.200
JUNE	0.370	6.380	6.750	0.485	7.215	7.700	0.565	7.635	8.200	0.565	7.135	7.700
JULY	0.400	7.500	7.900	0.395	8.505	8.900	0.565	7.535	8.100	0.565	7.785	8.350
AUGUST	0.335	7.845	8.180	0.385	8.415	8.800	0.565	7.185	7.750	0.565	8.835	9.400
SEPTEMBER	0.405	7.995	8.400	0.495	8.405	8.900	0.565	7.635	8.200	0.565	6.035	6.600
OCTOBER	0.370	7.830	8.200	0.200	8.000	8.200	0.565	7.635	8.200	0.565	8.235	8.800
NOVEMBER	0.330	7.320	7.650	0	7.200	7.200	0.565	7.335	7.900	0.565	8.835	9.400
DECEMBER	0.510	7.590	8.100	0	7.200	7.200	0.565	7.535	8.100	0.565	8.335	8.900
YEARLY AVERAGE	0.359	6.882	7.241	0.325	7.729	8.054	0.546	7.287	7.833	0.565	7.690	8.255

Well No. 10 completed November, 1942.

TABLE 8

AMERICAN OIL COMPANY - TEXAS CITY, TEXAS
MONTHLY WELL WATER PUMPAGE - MILLION GALLONS PER DAY AVERAGE

YEAR →	1935			1936			1937			1938		
MONTH ↓	Shallow Wells #2	Deep Wells #3, 4 & 5	Total Pumpage	Shallow Wells #2	Deep Wells #3-7	Total Pumpage	Shallow Wells #2	Deep Wells #3-8	Total Pumpage	Shallow Wells #2	Deep Wells #3-8	Total Pumpage
JANUARY	0.370	1.830	2.200	0.370	2.330	2.700	0.580	5.720	6.300	0	5.800	5.800
FEBRUARY	0.370	2.330	2.700	0.370	2.530	2.900	0.730	5.470	6.200	0.285	5.715	6.000
MARCH	0.370	2.430	2.800	0.370	2.830	3.200	0.610	5.100	5.710	0.355	6.065	6.400
APRIL	0.370	2.330	2.700	0.370	2.930	3.300	0.515	5.885	6.400	0.350	5.850	6.200
MAY	0.370	2.530	2.900	0.370	3.730	4.100	0.520	5.630	6.150	0.302	5.498	5.800
JUNE	0.370	2.230	2.600	0.370	3.730	4.100	0.618	6.982	7.600	0.195	5.885	6.080
JULY	0.370	3.530	3.900	0.370	4.330	4.700	0.390	6.410	6.800	0.435	6.765	7.200
AUGUST	0.370	3.530	3.900	0.370	4.730	5.100	0.365	6.435	6.800	0.165	6.985	7.150
SEPTEMBER	0.370	3.030	3.400	0.370	5.530	5.900	0.420	5.980	6.400	0.460	5.740	6.200
OCTOBER	0.370	3.030	3.400	0.370	4.430	4.800	0.295	6.005	6.300	0.465	6.185	6.650
NOVEMBER	0.370	2.530	2.900	0.370	4.330	4.700	0.190	5.960	6.150	0.265	5.535	5.800
DECEMBER	0.370	2.430	2.800	0.370	5.480	5.850	0	6.250	6.250	0.275	5.775	6.050
YEARLY AVERAGE	0.370	2.647	3.017	0.370	3.190	4.280	0.436	5.985	6.421	0.294	5.981	6.275

Well No. 2 completed August, 1933.
Well No. 3 completed November, 1933.
Well No. 4 completed December, 1933.
Well No. 5 completed January, 1934.
Well No. 6 completed May, 1936.
Well No. 7 completed April, 1936.
Well No. 8 completed June, 1937.

AMERICAN OIL COMPANY - TEXAS CITY, TEXAS

TABLE 9

STATIC LEVELS IN WATER WELLS - FEET BELOW SURFACE

Date	Well No. 2		Well No. 4		Well No. 8		Well No. 9		Well No. 11	
	Level This Survey	Total Level Decline To Date	Level This Survey	Total Level Decline To Date	Level This Survey	Total Level Decline To Date	Level This Survey	Total Level Decline To Date	Level This Survey	Total Level Decline To Date
8/33	45.0*	- -	- -	- -	- -	- -	- -	- -	- -	- -
5/34	- -	- -	37.0*	- -	- -	- -	- -	- -	- -	- -
10/36	60.0	15.0	54.0	17.0	- -	- -	- -	- -	- -	- -
4/37	75.0	30.0	56.0	19.0	- -	- -	- -	- -	- -	- -
6/37	81.0	36.0	66.0	29.0	44.0*	- -	- -	- -	- -	- -
12/37	75.0	30.0	84.0	47.0	62.0	18.0	- -	- -	- -	- -
4/38	- -	- -	62.0	25.0	84.0	40.0	- -	- -	- -	- -
6/38	71.0	26.0	62.0	25.0	70.0	26.0	- -	- -	- -	- -
8/38	76.0	31.0	65.0	28.0	86.0	42.0	- -	- -	- -	- -
10/38	- -	- -	- -	- -	91.0	47.0	- -	- -	- -	- -
11/38	91.0	46.0	67.0	30.0	96.0	52.0	- -	- -	- -	- -
2/39	96.0	51.0	75.0	38.0	90.0	46.0	- -	- -	- -	- -
5/39	- -	- -	66.0	29.0	58.0	14.0	- -	- -	- -	- -
7/40	92.0	47.0	82.0	45.0	65.0	21.0	- -	- -	- -	- -
9/40	115.0	70.0	96.0	59.0	69.0	25.0	- -	- -	- -	- -
2/41	114.0	69.0	91.0	54.0	84.0	40.0	- -	- -	- -	- -
3/41	- -	- -	- -	- -	84.0	40.0	- -	- -	- -	- -
8/41	- -	- -	88.0	51.0	78.0	34.0	- -	- -	- -	- -

TABLE 9

AMERICAN OIL COMPANY - TEXAS CITY, TEXAS

STATIC LEVELS IN WATER WELLS - FEET BELOW SURFACE

Date	Well No. 2 (Bean - F54)		Well No. 4 (B+AL M30)		Well No. 8 (AL M-29)		Well No. 9 (AL+B F57)		Well No. 11 (B. M32)	
	Level This Survey	Total Level Decline To Date	Level This Survey	Total Level Decline To Date	Level This Survey	Total Level Decline To Date	Level This Survey	Total Level Decline To Date	Level This Survey	Total Level Decline To Date
1/43	- -	- -	- -	- -	- -	- -	80.0*	- -	- -	- -
9/43	156.0	111.0	96.0	59.0	90.0	46.0	85.0	5.0	- -	- -
10/43	- -	- -	105.0	68.0	- -	- -	- -	- -	- -	- -
4/44	165.0	120.0	120.0	83.0	- -	- -	- -	- -	- -	- -
7/44	- -	- -	- -	- -	- -	- -	- -	- -	151.0*	- -
10/44	- -	- -	- -	- -	- -	- -	- -	- -	158.0	7.0
12/44	- -	- -	127.0	90.0	- -	- -	- -	- -	148.0	+3.0
4/45	- -	- -	150.0	113.0	113.0	69.0	119.0	39.0	- -	- -
7/45	125.0	80.0	127.0	90.0	- -	- -	- -	- -	170.0	19.0
12/45	- -	- -	- -	- -	- -	- -	107.0	27.0	153.0	2.0
2/46	- -	- -	127.0	90.0	105.0	61.0	107.0	27.0	142.0	+9.0
6/46	128.0	83.0	- -	- -	- -	- -	109.0	29.0	159.0	8.0
9/46	- -	- -	- -	- -	113.0	69.0	- -	- -	163.0	12.0
12/46	118.0	73.0	- -	- -	106.0	62.0	106.0	26.0	157.0	6.0
3/47	132.0	87.0	138.0	101.0	106.0	62.0	104.0	24.0	153.0	2.0
6/47	145.0	100.0	- -	- -	- -	- -	- -	- -	- -	- -
10/47	150.0	105.0	123.0	86.0	119.0	75.0	106.0	26.0	- -	- -
1/48	132.0	87.0	- -	- -	126.0	82.0	- -	- -	- -	- -

TABLE 9

AMERICAN OIL COMPANY - TEXAS CITY, TEXAS

STATIC LEVELS IN WATER WELLS - FEET BELOW SURFACE

Date	Well No. 2 F54		Well No. 4		Well No. 8		Well No. 9		Well No. 11	
	Level This Survey	Total Level Decline To Date	Level This Survey	Total Level Decline To Date	Level This Survey	Total Level Decline To Date	Level This Survey	Total Level Decline To Date	Level This Survey	Total Level Decline To Date
3/48	- -	- -	- -	- -	- -	- -	109.0	29.0	149.0	+2.0
4/48	- -	- -	- -	- -	- -	- -	124.0	44.0	151.0	0.0
10/48	- -	- -	- -	- -	112.0	68.0	- -	- -	- -	- -
4/49	- -	- -	- -	- -	111.0	67.0	- -	- -	- -	- -
7/49	- -	- -	- -	- -	107.0	63.0	122.0	42.0	- -	- -
8/49	147.0	102.0	- -	- -	99.0	55.0	101.0	21.0	- -	- -
10/50	- -	- -	106.0	69.0	- -	- -	- -	- -	- -	- -
4/51	- -	- -	- -	- -	- -	- -	- -	- -	139.0	+12.0
5/52	133.0	88.0	97.0	60.0	75.0	31.0	- -	- -	- -	- -
4/55	159.0	114.0	- -	- -	64.0	20.0	- -	- -	139.0	+12.0
1/58	131.0	86.0	- -	- -	75.0	31.0	76.0	+4.0	100.0	+51.0

* Original Static Level.

TABLE 9

AMERICAN OIL COMPANY - TEXAS CITY, TEXAS

STATIC LEVELS IN WATER WELLS - FEET BELOW SURFACE

Date	Well No. 3 F55 (B+AL)		Well No. 5 M-31 (B+AL)		Well No. 6 F53 (B+AL)		Well No. 7 M-28 (AL)		Well No. 10 M33 (B+AL)	
	Level This Survey	Total Level Decline To Date	Level This Survey	Total Level Decline To Date	Level This Survey	Total Level Decline To Date	Level This Survey	Total Level Decline To Date	Level This Survey	Total Level Decline To Date
3/34	- -	- -	40.0*	- -	- -	- -	- -	- -	- -	- -
5/34	32.0*	- -	- -	- -	- -	- -	- -	- -	- -	- -
4/36	- -	- -	- -	- -	- -	- -	25.0*	- -	- -	- -
10/36	43.0	11.0	67.0	27.0	30.0*	- -	26.0	1.0	- -	- -
4/37	51.0	19.0	72.0	32.0	36.0	6.0	37.0	12.0	- -	- -
6/37	63.0	31.0	76.0	36.0	- -	- -	49.0	24.0	- -	- -
12/37	70.0	38.0	92.0	52.0	40.0	10.0	49.0	24.0	- -	- -
4/38	69.0	37.0	79.0	39.0	49.0	19.0	50.0	25.0	- -	- -
8/38	56.0	24.0	79.0	39.0	53.0	23.0	56.0	31.0	- -	- -
1/39	53.0	21.0	- -	- -	48.0	18.0	54.0	29.0	- -	- -
5/39	- -	- -	- -	- -	51.0	21.0	56.0	31.0	- -	- -
7/40	68.0	36.0	74.0	34.0	56.0	26.0	63.0	38.0	- -	- -
9/40	72.0	40.0	92.0	52.0	64.0	34.0	74.0	49.0	- -	- -
3/41	65.0	33.0	94.0	54.0	60.0	30.0	67.0	42.0	- -	- -
8/41	- -	- -	99.0	59.0	68.0	38.0	73.0	48.0	- -	- -
11/42	- -	- -	- -	- -	- -	- -	- -	- -	72.0*	- -
9/43	97.0	65.0	130.0	90.0	97.0	67.0	99.0	74.0	89.0	17.0
10/44	117.0	85.0	- -	- -	109.0	79.0	114.0	89.0	- -	- -

TABLE 9

AMERICAN OIL COMPANY - TEXAS CITY, TEXAS

STATIC LEVELS IN WATER WELLS - FEET BELOW SURFACE

Date	Well No. 3		Well No. 5		Well No. 6		Well No. 7		Well No. 10	
	Level This Survey	Total Level Decline To Date	Level This Survey	Total Level Decline To Date	Level This Survey	Total Level Decline To Date	Level This Survey	Total Level Decline To Date	Level This Survey	Total Level Decline To Date
4/45	124.0	92.0	- -	- -	94.0	64.0	118.0	93.0	130.0	58.0
7/45	- -	- -	- -	- -	118.0	88.0	- -	- -	- -	- -
11/45	- -	- -	132.0	92.0	107.0	77.0	112.0	87.0	- -	- -
2/46	114.0	82.0	142.0	102.0	107.0	77.0	112.0	87.0	- -	- -
3/46	106.0	74.0	- -	- -	- -	- -	- -	- -	- -	- -
6/46	106.0	74.0	141.0	101.0	106.0	76.0	111.0	86.0	- -	- -
8/46	111.0	79.0	148.0	108.0	108.0	78.0	113.0	88.0	113.0	41.0
12/46	- -	- -	142.0	102.0	103.0	73.0	109.0	84.0	110.0	38.0
3/47	102.0	70.0	137.0	97.0	103.0	73.0	105.0	80.0	108.0	36.0
6/47	112.0	80.0	145.0	105.0	109.0	79.0	106.0	81.0	109.0	37.0
9/47	114.0	82.0	- -	- -	114.0	84.0	116.0	91.0	- -	- -
1/48	106.0	74.0	126.0	86.0	97.0	67.0	120.0	95.0	- -	- -
3/48	115.0	83.0	142.0	102.0	123.0	93.0	109.0	84.0	- -	- -
7/48	- -	- -	109.0	69.0	112.0	82.0	- -	- -	- -	- -
8/48	- -	- -	- -	- -	109.0	79.0	- -	- -	- -	- -
10/48	- -	- -	- -	- -	107.0	77.0	113.0	88.0	- -	- -
11/48	- -	- -	- -	- -	106.0	76.0	- -	- -	- -	- -
5/49	- -	- -	- -	- -	122.0	92.0	- -	- -	110.0	38.0

TABLE 9

AMERICAN OIL COMPANY - TEXAS CITY, TEXAS

STATIC LEVELS IN WATER WELLS - FEET BELOW SURFACE

Date	Well No. 3		Well No. 5		Well No. 6		Well No. 7		Well No. 10	
	Level This Survey	Total Level Decline To Date	Level This Survey	Total Level Decline To Date	Level This Survey	Total Level Decline To Date	Level This Survey	Total Level Decline To Date	Level This Survey	Total Level Decline To Date
7/49	105.0	73.0	- -	- -	104.0	74.0	114.0	89.0	113.0	41.0
8/49	92.0	60.0	- -	- -	106.0	76.0	113.0	88.0	- -	- -
9/49	91.0	59.0	- -	- -	91.0	61.0	110.0	85.0	103.0	31.0
10/49	91.0	59.0	- -	- -	89.0	59.0	92.0	67.0	102.0	30.0
11/49	94.0	62.0	- -	- -	91.0	61.0	92.0	67.0	102.0	30.0
12/49	86.0	54.0	- -	- -	93.0	63.0	92.0	67.0	102.0	30.0
1/50	82.0	50.0	- -	- -	93.0	63.0	87.0	62.0	96.0	24.0
2/50	82.0	50.0	- -	- -	84.0	54.0	89.0	64.0	93.0	21.0
3/50	85.0	53.0	- -	- -	83.0	53.0	87.0	62.0	95.0	23.0
4/50	84.0	52.0	- -	- -	85.0	55.0	84.0	59.0	94.0	22.0
5/50	82.0	50.0	- -	- -	83.0	53.0	84.0	59.0	94.0	22.0
6/50	81.0	49.0	- -	- -	82.0	52.0	81.0	56.0	94.0	22.0
8/50	80.0	48.0	- -	- -	81.0	51.0	84.0	59.0	94.0	22.0
9/50	85.0	53.0	- -	- -	95.0	65.0	86.0	61.0	98.0	26.0
10/50	79.0	47.0	- -	- -	94.0	64.0	89.0	64.0	81.0	9.0
12/50	78.0	46.0	- -	- -	78.0	48.0	78.0	53.0	82.0	10.0
1/51	77.0	45.0	- -	- -	78.0	48.0	79.0	54.0	83.0	11.0
2/51	92.0	60.0	- -	- -	93.0	63.0	91.0	66.0	- -	- -

TABLE 9

AMERICAN OIL COMPANY - TEXAS CITY, TEXAS

STATIC LEVELS IN WATER WELLS - FEET BELOW SURFACE

Date	Well No. 3		Well No. 5		Well No. 6		Well No. 7		Well No. 10	
	Level This Survey	Total Level Decline To Date	Level This Survey	Total Level Decline To Date	Level This Survey	Total Level Decline To Date	Level This Survey	Total Level Decline To Date	Level This Survey	Total Level Decline To Date
3/51	83.0	51.0	- -	- -	94.0	64.0	83.0	58.0	- -	- -
4/51	81.0	49.0	- -	- -	80.0	50.0	78.0	53.0	85.0	13.0
5/51	80.0	48.0	- -	- -	81.0	51.0	79.0	54.0	101.0	29.0
9/51	78.0	46.0	- -	- -	88.0	58.0	79.0	54.0	105.0	33.0
10/51	84.0	52.0	- -	- -	90.0	60.0	83.0	58.0	108.0	36.0
2/52	82.0	50.0	- -	- -	77.0	47.0	86.0	61.0	110.0	38.0
4/52	79.0	47.0	- -	- -	- -	- -	80.0	55.0	103.0	31.0
5/52	77.0	45.0	99.0	59.0	77.0	47.0	75.0	50.0	- -	- -
11/52	82.0	50.0	- -	- -	81.0	51.0	83.0	58.0	103.0	31.0
12/52	79.0	47.0	- -	- -	80.0	50.0	82.0	57.0	103.0	31.0
6/53	77.0	45.0	- -	- -	84.0	54.0	83.0	58.0	105.0	33.0
2/54	53.0	21.0	- -	- -	83.0	53.0	80.0	55.0	104.0	32.0
8/54	79.0	47.0	- -	- -	104.0	74.0	85.0	60.0	97.0	25.0
2/55	- -	- -	106.0	66.0	78.0	48.0	79.0	54.0	91.0	19.0
3/57	82.0	50.0	- -	- -	80.0	50.0	72.0	47.0	95.0	23.0
1/58	80.0	48.0	- -	- -	75.0	45.0	63.0	38.0	80.0	8.0

* Original Static Level.

III CONCLUSIONS AND RECOMMENDATIONS

III. CONCLUSIONS AND RECOMMENDATIONS

Presently all indications are that subsidence is continuing in the refinery and surrounding area, although at a slower rate since 1952, than over the previous twelve year period. In addition, preliminary information on the adjusted 1953-54, USC&GS releveling indicates that the base monument L-305 has settled approximately 0.17 feet since 1951, which on further study may reveal an increased subsidence rate in the refinery.

Although ground-water pumpage in the Texas City area has been reduced by approximately 70 per cent since 1945, it appears that even the present pumpage is too great especially from the upper Beaumont clay. This coupled with a possible time lag following reductions in large-scale pumpage may have considerable effect on the present trend. Furthermore, it is possible that the continued extremely heavy pumpage in the Houston District may effect the subsidence trend in this area.

According to geological data there is a tendency for clays to be compacted naturally with age and the upper part of the Beaumont clay is a relatively young geologic unit which offers greater opportunity for compaction than the older formations. Also, this formation consists mainly of clay with relatively thin beds of sand and the average sand-clay ratio is of the order of 1 to 8. Whereas, the average sand-clay ratio in the "Alta Loma" sand is of the order of 6 to 1. Therefore, because of the natural tendency of the clays to be compacted, the high clay ratio in the upper Beaumont clay, and since the clays are more likely to be compacted than the sands, subsidence has probably resulted from excessive pumpage in this formation with the pumpage from the "Alta Loma" sand contributing to a lesser degree.

Therefore, based on the above it is recommended that:

1. Amoco eliminate well pumpage by installing the necessary filtration and treating equipment for drinking and sanitary water purposes.

2. Suggest and encourage all industries in the Texas City area to eliminate pumpage where possible, especially from the shallow Beaumont clay formation.

3. Initiate studies to determine more accurately the effects of the extremely heavy pumpage in the Houston district on subsidence in the Texas City area.

4. Investigate further the possible effect of pumpage from the "Alta Loma" sands in the Alta Loma, Baytown-La Porte, and Houston Ship Channel areas on subsidence in the Texas City and surrounding area.

5. Reinstate the subsidence survey checks on a six month basis.

6. Investigate the surrounding area to determine, if possible, a more stable reference point on which to base refinery surveys. Also, request USC&GS to resurvey the Virginia Point bench mark at least on a two year basis in order to assure reasonable validity as a base monument.

7. Since the City of Texas City obtains all water for public supply from shallow wells it is suggested that they be encouraged to drill any new additional wells as remote from the severe subsidence area as possible and tap the "Alta Loma" sands.

8. Establish a committee composed of representatives from each industry in the Texas City area including a representative from the cities of Texas City, La Marque, and Galveston to aid in reducing well pumpage and long-range planning of water requirements for the area as a whole.

PREPARED BY: K. J. Miller
K. J. MILLER

CHECKED BY: J. B. Wallace
J. B. WALLACE

APPROVED BY: C. J. Houlgrave
C. J. HOULGRAVE

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LITERATURE ABSTRACTS

REFINERY GROUND SUBSIDENCE - 1957

LITERATURE ABSTRACTS

SECTION	DESCRIPTION
A	Geology and Ground Water Resources of Galveston County, Texas
B	Land-Surface Subsidence and Its Relation to the Withdrawal of Ground Water in the Houston-Galveston Region, Texas
C	Salt Water and Its Relation to Fresh Ground Water in Harris County, Texas
D	Ground Subsidence at Long Beach, California
E	Mexico City Is Sinking

LITERATURE ABSTRACT A

GEOLOGY AND GROUND WATER RESOURCES OF GALVESTON COUNTY, TEXAS

PLANT ENGINEERING DEPARTMENT

LITERATURE ABSTRACT - A

GEOLOGY AND GROUND WATER RESOURCES OF GALVESTON COUNTY, TEXAS

BY: BEN M. PETITT, JR. AND ALLEN G. WINSLOW

The following is an excerpt of the United States Geological Survey Bulletin No. 5502 prepared for the Texas Board of Water Engineers in 1955 and designed to compile a complete history of the ground water resources of Galveston County including the Texas City industrial area. Much of the data have been supplied by American Oil Company and Union Carbide Chemicals Corporation in cooperation with the overall problem of ground subsidence and excessive water well pumpage during the past two decades.

PHYSIOGRAPHY AND DRAINAGE OF GALVESTON COUNTY

Galveston County, occupying part of the Gulf Coastal Plain of Texas, may be divided into two units - the land surface and the bay. The land surface is divided into three areas - the mainland lying west of Galveston Bay, Galveston Island, and Bolivar Peninsula, which extends in a southwesterly direction from Chambers County. The bay area includes East Bay, West Bay, and a part of Galveston Bay.

The mainland of Galveston County is an almost featureless plain which slopes southeastward at a rate of slightly less than 1 foot per mile. The land surface is highest in the northwestern part where the altitude is approximately 40 feet. The surface is drained by sluggish, low-gradient streams, the principal ones being Clear Creek, Dickinson Bayou, and Highland Bayou. All streams are affected by tidewater in their lower reaches.

Galveston Island and Bolivar Peninsula are long, narrow sandbars, making up the outer coastline of Galveston County. These sandbars have an average width of about 2 miles and an altitude of generally less than 15 feet. However, a hill marking the pressure of a salt dome rises to an altitude of 25 feet at High Island on the extreme northeastern end of Bolivar Peninsula. Galveston Island extends northeastward from the Brazoria County line for a distance of about 28 miles and is separated from Bolivar Peninsula by Bolivar Roads, the outlet from Galveston Bay to the Gulf of Mexico. Bolivar Peninsula extends from Bolivar Roads northeastward into Chambers County.

Galveston Bay is a shallow, rather flat bottomed depression containing numerous small, low-lying islands and shell reefs. The Bay has been divided into three parts: Galveston Bay proper, West Bay, and East Bay. Galveston Bay lies north of the city of Galveston and extends northward into Chambers County. West Bay forms a narrow arm approximately 3 miles wide, extending southwestward into Brazoria County. East Bay is a narrow northeastward-extending arm paralleling the coast and ending near High Island.

Texas Board of Water Engineers in cooperation with the U. S. Geological Survey and the city of Galveston — Bulletin 5502

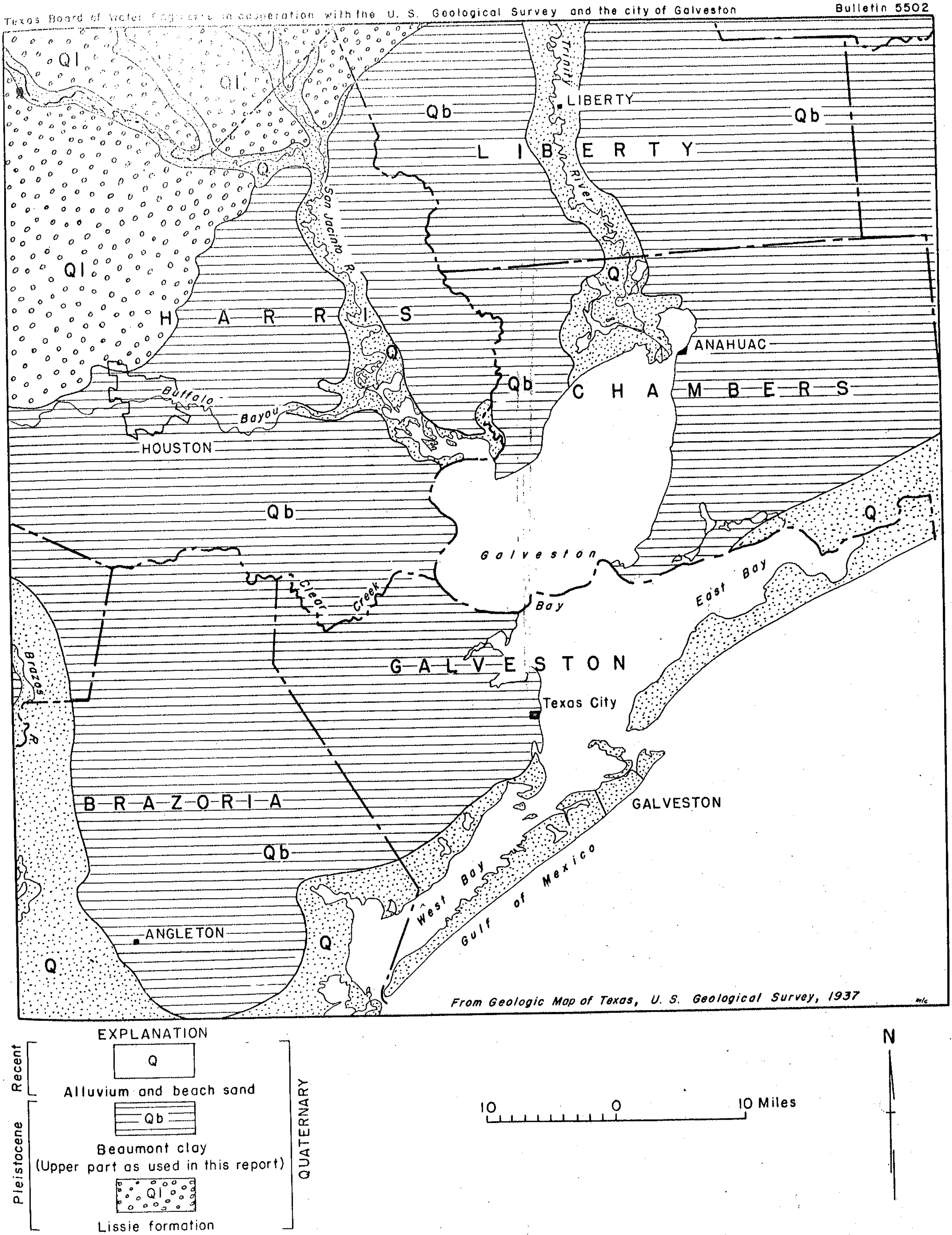

FIGURE 3.- Geologic map of Galveston County, Tex., and surrounding area.

GENERAL GEOLOGY

Galveston County is underlain by sequences of unconsolidated sands and clays. The sediments are mostly of alluvial or deltaic origin. Some of the material has been reworked by littoral currents to form beach deposits. The strata crop out in belts roughly parallel to the coast and dip gently toward the coast (fig. 3). The dip of the beds is greater than the slope of the land surface; so that the formations lie at progressively greater depths toward the southeast (pl. 1). The formations extend out under the Gulf of Mexico, but their Gulfward extent is not knows. Inasmuch as the edge of the continental shelf is about 100 miles offshore, the sands probably pinch out or grade into shale before reaching the floor of the Gulf along the continental slope.

Successively older strata crop out inland from the Gulf, and the outcrops of older formations are at successively higher altitudes (pl. 2). These facts, coupled with the occurrence of permeable sands interbedded with relatively impermeable clays in the formations, provide ideal conditions for the occurrence of artesian water. Rain that falls on the outcrops of the sand beds is the principal source of recharge to the underground reservoir.

The geologic formations that contain fresh water in Galveston County are, from oldest to youngest, the Lissie formation, the "Alta Loma" sand at the base of the Beaumont clay, and the upper part of the Beaumont clay, all of Pleistocene age; and beach and dune sands and coastal marsh deposits of Recent age (table 2).

GEOLOGIC FORMATIONS AND THEIR WATER-BEARING PROPERTIES

Lissie Formation

The Lissie formation is relatively unimportant as an aquifer in Galveston County. The water is generally of poor quality, although some potable water is believed to occur in the upper part of the formation in the northern part of the county. In this report the name Lissie, as used by Doering (1935), is employed. Recent work by Bernard (1950), and work in progress, indicate that the correlation of the Lissie with the Pleistocene section of southwestern Louisiana is uncertain.

According to Plummer (in Sellards, Adkins, and Plummer, 1932, p. 784), the Lissie formation was laid down principally as flood-plain and deltaic deposits on a nearly featureless coastal plain. During Pleistocene time, large streams carried tremendous quantities of sand, gravel, clay, and silt from the upland areas and deposited these sediments as the streams shifted laterally over the coastal plain. This type of deposition resulted in a series of alternating beds of sand, sandy clay, and clay. The sands are fine to coarse in texture and are generally gray in the subsurface sections, but they are red, orange, or buff colored on the outcrop. Although the individual sand bodies consist of lenses which cannot be traced long distances, zones which can be recognized in electric logs as predominantly clayey or predominantly sandy may be traced relatively long distances.

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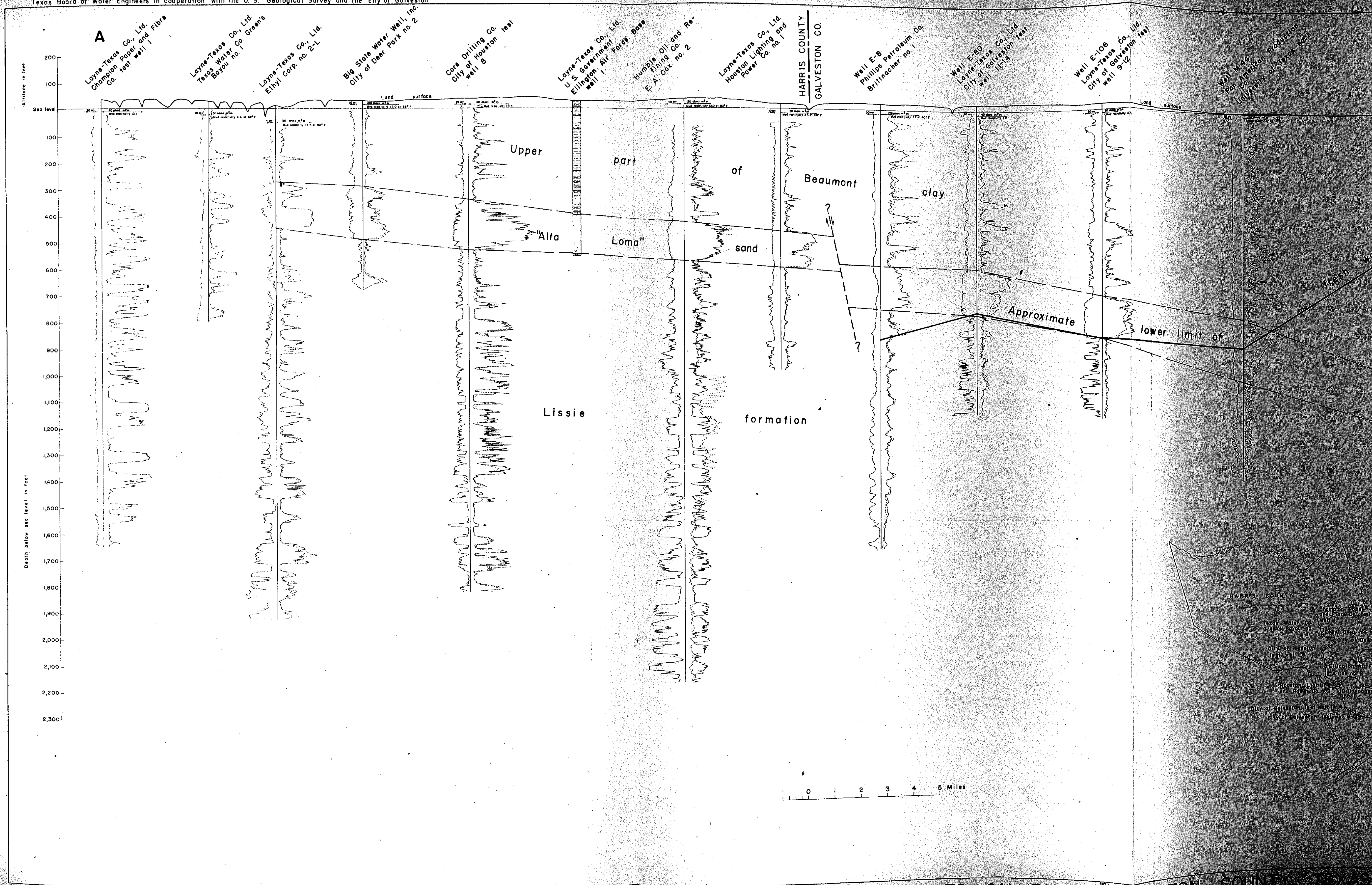
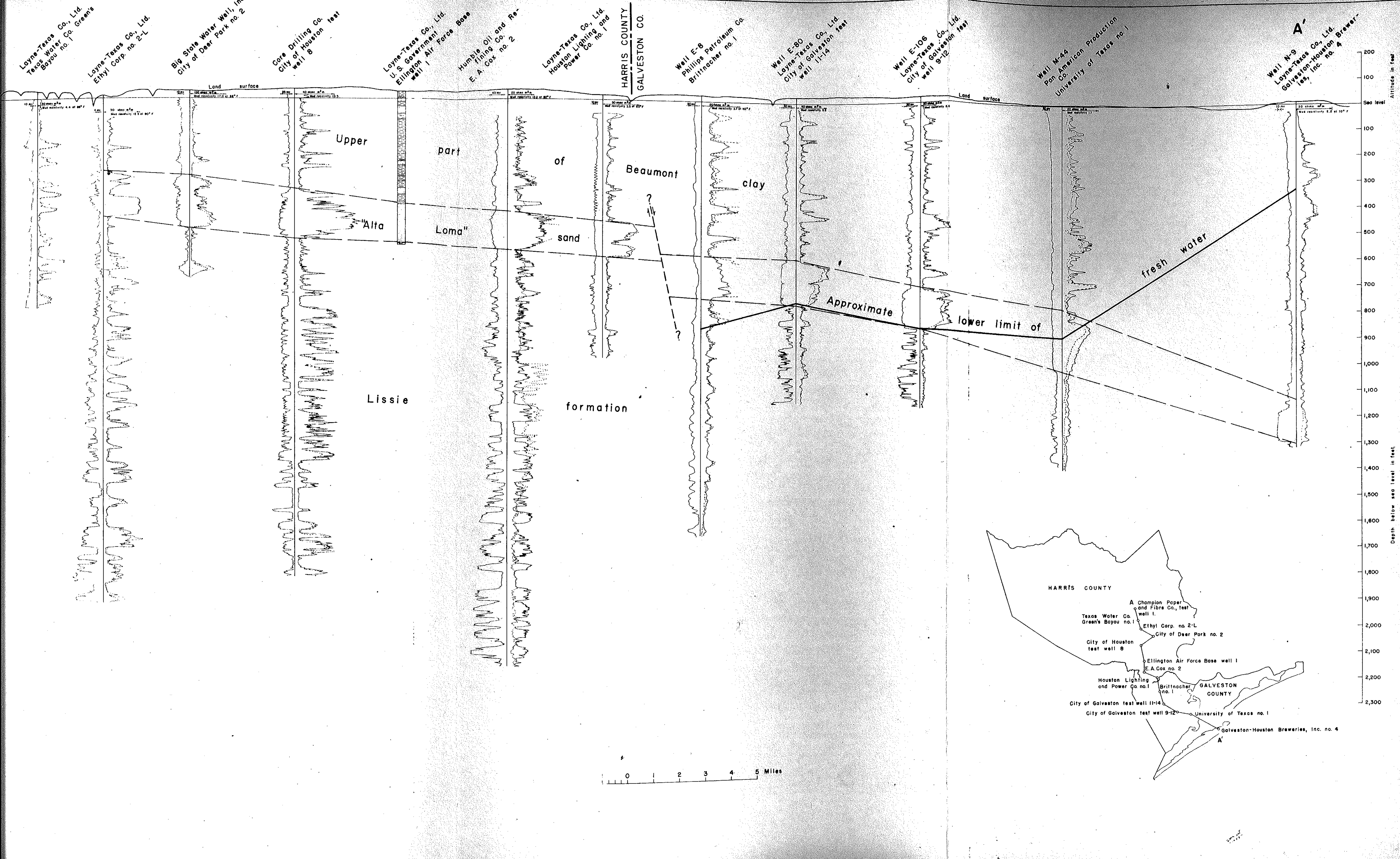


GEOLOGIC CROSS SECTION FROM PASADENA, HARRIS COUNTY, TO GALVESTON, GALVESTON COUNTY, TEXAS



GEOLOGIC CROSS SECTION FROM PASADENA, HARRIS COUNTY, TO GALVESTON, GALVESTON COUNTY, TEXAS

TABLE 2. - OUTLINE OF STRATIGRAPHY OF GALVESTON COUNTY, TEXAS

SYSTEM	SERIES	FORMATION		APPROXIMATE THICKNESS (FEET)	LITHOLOGIC CHARACTER	WATER-BEARING PROPERTIES
Quaternary	Recent			0 - 50±	Beach and dune sand and coastal marsh deposits.	Yield small supplies of water of good to poor quality to wells on Galveston Island and Bolivar Peninsula.
	Pleistocene	Beaumont clay	Upper part	400 - 1,150	Calcareous red, yellow and brown clay which produces a black or gray soil. Lenses of fine-grained sand and sandy clay. Some shell beds and nodules of calcium carbonate.	Yields moderate to large supplies of water of good to poor quality to wells throughout most of the county. The sands have relatively low permeabilities but are heavily pumped in the Texas City area. South of the Texas City area the water becomes brackish, especially in the lower part of the formation.
			"Alta Loma" sand	80 - 370	Fine-to medium-grained massive gray to tan well-sorted sand. Mainly quartz grains, but chert and limestone fragments are common. Probably an extensive beach deposit. May be correlated for long distances in a belt parallel to the coast.	Relatively highly permeable sand. Yields abundant supplies of water to wells wherever it is tapped; however, in the southern part of the county the water is brackish. Salt-water encroachment has occurred in the Texas City and Alta Loma areas.
		Lissie formation		1,100+	Alternating beds of sand, sandy clay, and clay. Sands are fine to coarse in texture and lenslike in structure. Largely fluviatile and deltaic deposits.	Not an important aquifer in Galveston County. Yields potable water to wells only in the extreme northern part. Contains brackish and salty water throughout most of the county. Yields large supplies of water of good quality to wells in the Houston area.

GEOLOGIC FORMATIONS AND THEIR WATER-BEARING PROPERTIES (continued)

Lissie Formation (continued)

The Lissie formation lies unconformably on older formations and is in turn overlain, probably unconformably, by the "Alta Loma" sand at the base of the Beaumont clay. The thickness of the Lissie in Galveston County was not determined, but it is probably greater than 1,100 feet. The Lissie crops out in northern Harris County, where it receives recharge from rain-fall. In southern Harris County the Lissie is overlapped by the "Alta Loma" sand and the upper part of the Beaumont clay. The Lissie is encountered in wells in northern Galveston County at a depth of about 600 feet.

The Lissie formation is the oldest formation containing potable water in Galveston County. The Lissie yields large supplies of potable water to wells in much of Harris County and is the most important aquifer in the heavily industrialized Houston district. A few wells in extreme northern Galveston County tap the upper part of the Lissie; however, throughout most of the county the formation contains highly mineralized water.

Beaumont Clay (Alta Loma Sand)

Immediately overlying the Lissie formation in Galveston County is a bed of sand 84 to 370 feet thick called the "Alta Loma" sand. Deussen in describing wells in Galveston County included the sand with the Lissie formation. Other writers (White, Livingston, and Turner, 1932), believed the sand to be basal Beaumont, and that usage is followed in this report. Bernard described a sand in the sub-surface in Orange County which is probably the equivalent of the "Alta Loma". This sand is tentatively correlated by Bernard with the basal part of the Prairie formation of Louisiana, but later information suggests that the Louisiana classification may have to revised extensively, so that any correlation between Pleistocene units in Texas and Louisiana is highly tentative at present.

Although the "Alta Loma" sand has not been identified in the outcrop, it appears to be a definite stratigraphic unit and can be mapped from well logs over long distances in its sub-surface position. The sand differs both lithologically and hydrologically from the underlying Lissie formation and the overlying part of the Beaumont clay, and ultimately it may prove to deserve ranking as a separate formation. It is the principal aquifer in Galveston County.

The name "Alta Loma" sand was suggested because of the occurrence of the sand in sub-surface section near the town of Alta Loma in Galveston County in the vicinity of the Galveston well field. Extensive test drilling by the city of Galveston has yielded much hydrologic and lithologic information concerning the formation in the Alta Loma area. The sand is well known also in the eastern Ship Channel area of the Houston district and in southeastern Harris County.

The "Alta Loma" sand probably represents a beach sand laid down unconformably on the Lissie formation. Its distribution suggests littoral deposition roughly parallel to the present shoreline. It extends as a belt along the coast from at least as far southwest as Freeport in Brazoria County, northeast to Galveston Bay, where it swings inland around and roughly parallel to the bay; thence, it extends northeast along the coast of Chambers, Jefferson, and Orange

GEOLOGIC FORMATIONS AND THEIR WATER-BEARING PROPERTIES (continued)

Beaumont Clay (Alta Loma Sand) (continued)

Counties into Louisiana. The sand is much more uniform than other individual sand bodies in the Pleistocene section of the Texas Gulf Coast, and may be correlated in electrical logs of wells for long distances, especially along the strike (pl. 2). Owing to the comparatively narrow belt like distribution of the formation, correlation up the dip cannot be carried as far as correlation along the strike. Inland from the coast, the formation probably changes from the beach sand facies to a lagoonal type of deposit which commonly occurs on the shoreward side of such deposits along the present Gulf Coast. The apparent change in facies, shown on cross section (A-A', pl. 1) between the Ethyl Corp. No. 2L well and the Texas Water Co. Greens Bayou No. 1 well seems to confirm this interpretation.

The "Alta Loma" sand has not been identified in the outcrop and, indeed, if the apparent facies change just described is extensive, the sand itself probably does not crop out. However, its equivalent, a lagoonal, deltaic, or flood-plain deposit, probably crops out. But, owing to the similarity of this part of the formation to the underlying sands of the Lissie, it would be very difficult to distinguish the two formations in the outcrop. If the beach facies of the formation were present at the surface, it probably could be identified.

The position and thickness of the "Alta Loma" sand throughout most of Galveston County have been well established through a study of the many well logs. However, in the area east of Dickinson identification is uncertain because the vertical continuity of the sand is broken by beds of clay as indicated by electric logs of oil tests. In the northeastern part of the county the sand has not been mapped because of lack of well logs. For the remainder of the county, maps showing the elevation of the top of the sand and the approximate thickness have been prepared (figs. 4 and 5). In the extreme northern part of the county the sand is encountered in wells at a depth of about 400 feet, whereas the top of the sand in well N-9 on Galveston Island is at about 1,180 feet. The dip of the formation averages about 20 feet per mile on the mainland and steepens to about 30 feet per mile southward to Galveston Island. However, this steepening may not represent the true dip, as the sand thins in this direction. The dip in Harris County, as shown in the cross section, is about 10 feet per mile, the change in dip occurring at about the Harris-Galveston County line where there appears to be a fault (pl. 1). The dip in the northern part of this section probably is slightly steeper than that shown because the section is not strictly a dip section.

The "Alta Loma" sand extends out under the Gulf of Mexico, but its actual extent in this direction is not known. The electrical log of an oil test drilled about 7 miles offshore from Freeport shows a sandy section from about 1,070 feet to about 1,390 feet. If this section correlates with the "Alta Loma" and if the strike may be assumed to be approximately parallel to the shoreline, the dip of the top of the formation is about 12.5 feet per mile. Another well drilled about 8 miles off Galveston Island shows a sandy section from about 1,110 feet to about 1,430 feet, which if correlated with the "Alta Loma" as shown in the log of the

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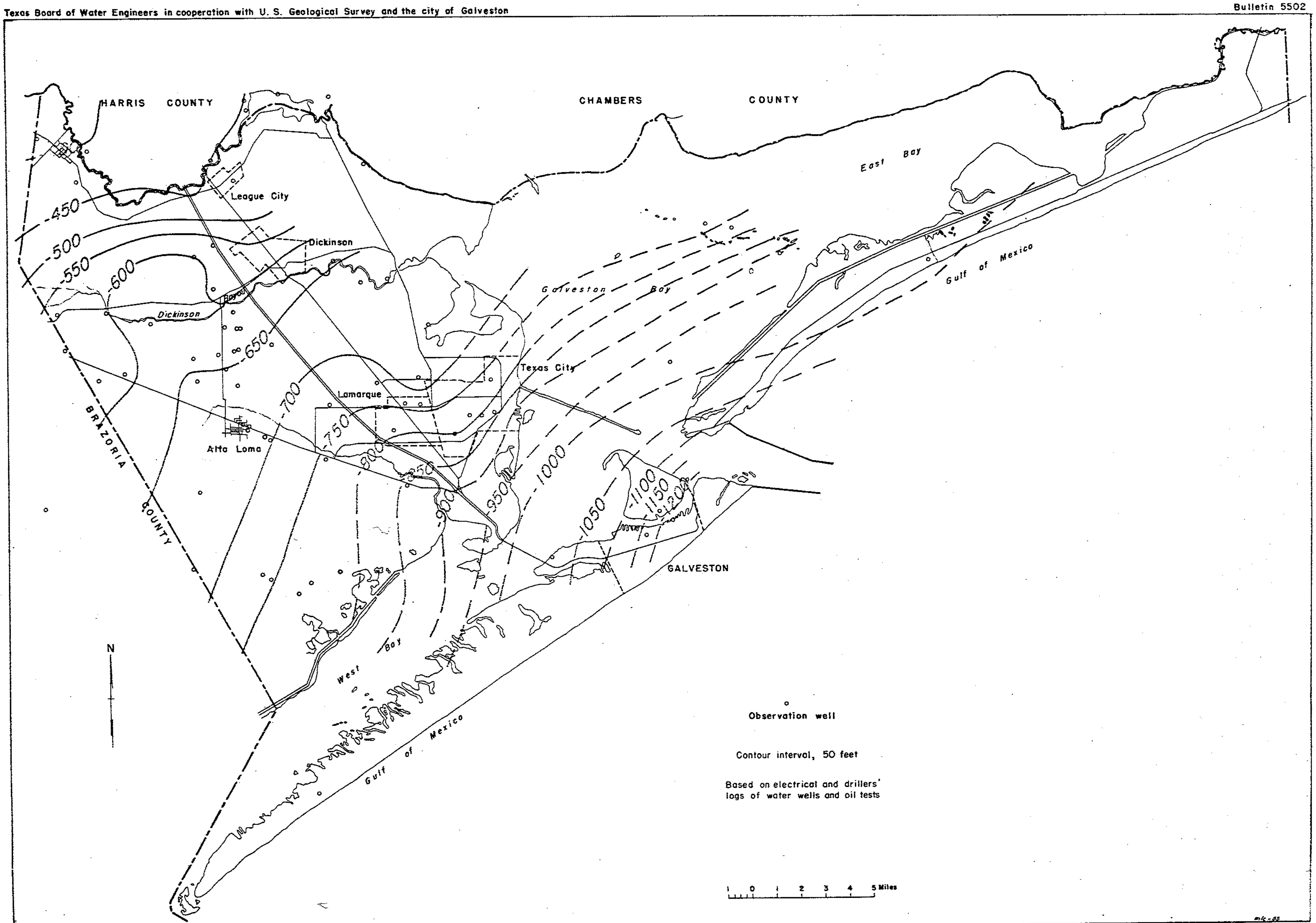

FIGURE 4.- Map showing approximate altitude of top of the "Alta Loma" sand in Galveston County, Tex.

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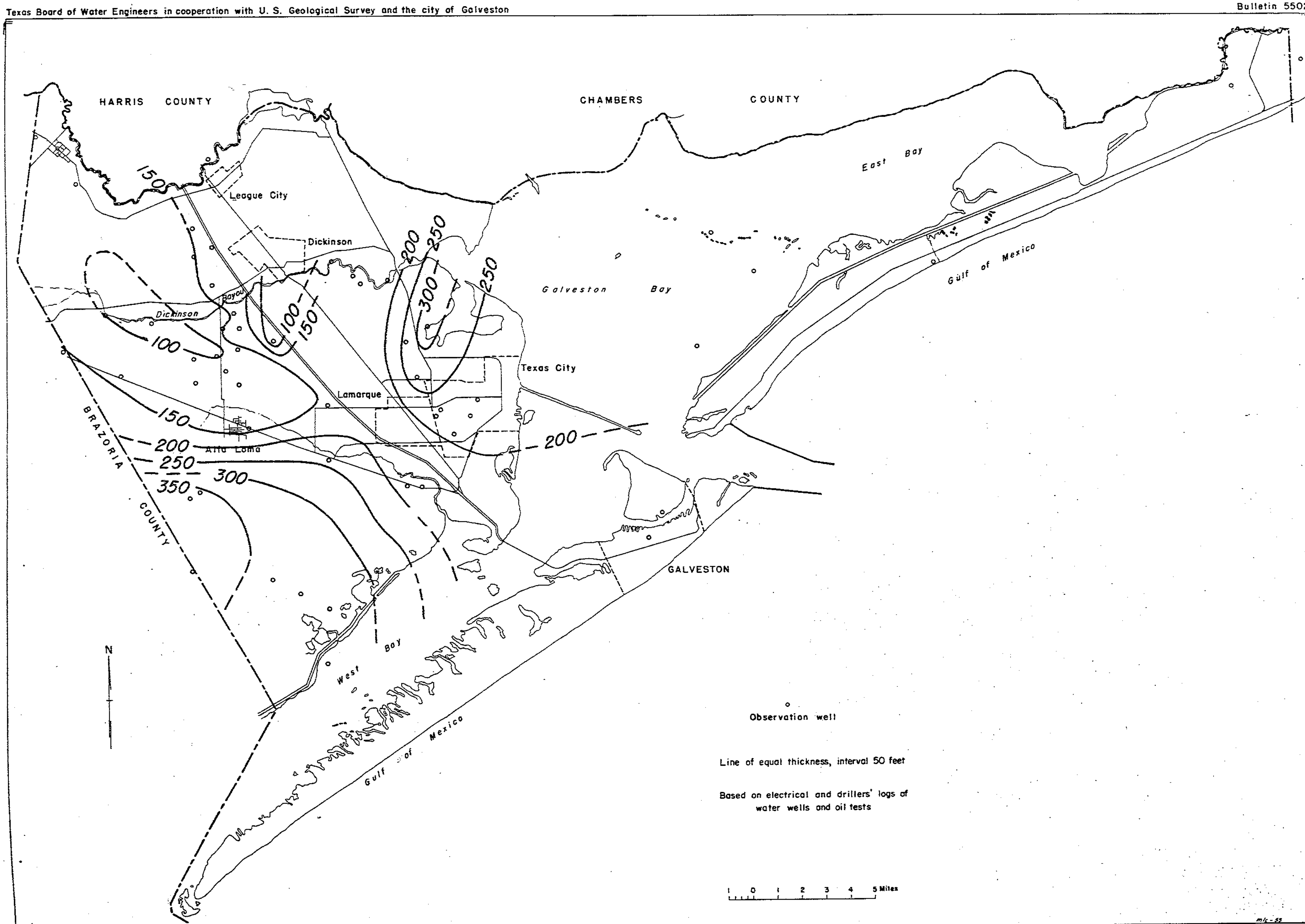

FIGURE 5.- Isopachous map showing approximate thickness of the "Alta Loma" sand in Galveston County, Tex.

GEOLOGIC FORMATIONS AND THEIR WATER-BEARING PROPERTIES (continued)

Beaumont Clay (Alta Loma Sand) (continued)

Humble-Houston Farms Development Co., No. 2 well (pl. 2) indicates a dip of about 18 feet per mile for the top of the formation. Correlation of the "Alta Loma" in the Sun-Stage 340 well (pl. 2) with a sandy section from about 1,360 to about 1,490 feet in an oil test drilled about 10 miles off Bolivar Peninsula shows a dip of about 23 feet per mile for the top of the formation.

Considering the foregoing discussion, and admitting that the correlations are questionable, it appears that the rate of dip, at lease for a short distance under the Gulf, is on the order of 20 feet per mile. However, it seems probable that the rate of dip farther offshore would become less and possibly would approach zero.

Regardless of the possible structural relationship of the beds under the Gulf, and considering the facies changes observed in older beds on the Gulf Coast, it seems probable that the "Alta Loma" sand may pass into a marine facies and then grade into shale without ever cropping out on the floor of the Gulf.

The "Alta Loma" sand in Galveston County consists of a massive gray to tan, fine-to-medium-grained well-sorted sand. The size of most of the sand grains is between 0.1 and 0.3 millimeter. Quartz is by far the most common constituent, but chert and limestone fragments are common and shell fragments and reworked fossils of Cretaceous age have been reported.

Figure 5 is an isopachous map showing the approximate thickness of the "Alta Loma" sand in Galveston County. The most striking feature revealed by this map is the thickening of the formation both toward the east and the southwest from Alta Loma. The thickening has special significance in connection with occurrence of salt water; which is discussed in a later section of this report.

The "Alta Loma" sand is one of the most permeable aquifers of the Texas Gulf Coast. In Galveston County permeabilities ranging from 580 to 700 gallons per day per square foot (Meinzer units) and averaging 645 gallons per day per square foot have been determined from pumping tests made at Alta Loma and at Texas City. Similar permeabilities have been determined for the sand in Harris County. According to N. A. Rose, a permeability of 2,000 Meinzer units was determined from the results of a pumping test in Orange County.

Wells that obtain water from the "Alta Loma" sand generally yield between 500 and 3,000 gallons a minute within practical limits of drawdown. The newer wells of the city of Galveston near Alta Loma are capable of yielding more than 1,000 gallons a minute. Wells drawing water from this aquifer in the Texas City area commonly yield between 1,200 and 1,500 gallons a minute. On Galveston Island the well at the Galveston-Houston Breweries, Inc., which yields mineralized water used only for cooling purposes, had a yield of 2,200 gallons a minute when drilled.

GEOLOGIC FORMATIONS AND THEIR WATER-BEARING PROPERTIES (continued)

Upper Part of Beaumont Clay

The name Beaumont clay was first used by Hayes and Kennedy in describing the clay deposits lying between the sandy Lissie formation and the coastal deposits of Recent age in Jefferson County, Tex. The name has been widely used in describing the formation along the Gulf Coast in both Texas and Louisiana. It is used in this report to include the sediments between the base of the "Alta Loma" sand and the coastal deposits of Recent age. The Beaumont clay has been mapped in Jasper, Newton, and Orange Counties, Tex., by Bernard; but he substituted the name Prairie formation, after Fisk's classification, for the Beaumont clay in Louisiana.

According to Plummer the Beaumont clay was deposited largely by rivers in the form of deltas and natural levees. Between the deltas and natural levees, lagoonal and, in some places, marine deposition occurred. The resulting formations show a rapid lateral change of facies of the sediments. A small foraminiferal fauna, indicating marine or brackish-water deposition, was picked from a set of drill cuttings from a well at Dickinson. The sediments of the upper part of the Beaumont are much finer-grained than those of the Lissie formation or the "Alta Loma" sand.

In Galveston County the upper part of the Beaumont clay consists principally of calcareous red, yellow, or brown clay which weathers to bluish gray or black. The clay strata are interbedded with fine-grained grayish sand and sandy clay and a few beds of shells. Nodules of calcium carbonate are common. The individual sands are, for the most part, extremely lenticular and can be traced only short distances. Some of the sand is so fine that it is difficult to screen it properly in wells. Pumping tests at Texas City have indicated permeabilities ranging from 173 to 423 and averaging 300 gallons per day per square foot. In Galveston County the clays predominate in the uppermost part of the formation, whereas the lower beds of the upper part are more sandy. The typical Beaumont clay (upper part of the Beaumont as used in this report) crops out in southeastern Harris County and in all of Galveston County, except for a narrow strip along the coast, where it is mantled by marsh deposits and beach and dune sand. The upper part ranges in thickness from about 400 feet in northern Galveston County to about 1,150 feet on Galveston Island. The average dip is about 20 feet per mile throughout the county, but it appears to be greater in the southern part (pl. 1).

Although the greatest number of wells in Galveston County withdraw water from wells that are screened opposite sands in the upper part of the Beaumont clay, the pumpage from this aquifer has not been as great as that from the "Alta Loma" sand. The upper part of the Beaumont is an important source of water throughout the county, and in the Texas City area it is at present the only formation that yields water containing less than 1,000 parts per million (ppm) of dissolved solids.

Large wells that obtain water from sands of the upper part of the Beaumont clay usually yield between 100 and 600 gallons a minute; all wells yield relatively small quantities of water with corresponding large drawdowns as compared to the large wells drawing from the "Alta Loma" sand.

GEOLOGIC FORMATIONS AND THEIR WATER-BEARING PROPERTIES (continued)

Recent Beach and Dune Sand and Marsh Deposits

The Recent beach and dune sand deposits and silts and clays of the marsh deposits in Galveston County overlie the Beaumont clay in a narrow strip bordering the north shore of West Bay and on Galveston Island and Bolivar Peninsula. These sands are thin, reaching a maximum thickness of about 50 feet on Galveston Island. They are of very little importance as an aquifer in the county, although a few domestic and stock wells (K-2, K-4, H-4, Q-7, and Q-18) draw small quantities of water of rather poor quality from the sands on Bolivar Peninsula and on Galveston Island.

GROUND WATER HYDROLOGY

The Shape of the Piezometric Surface and Its Relation to the Movement of Water

Maps of Galveston County and parts of Harris and Chambers Counties have been prepared periodically, illustrating the altitude of water levels in wells based on measurements made during the spring in wells screened opposite the "Alta Loma" sand. Maps for the years 1941, 1948, and 1952 (figs. 19 to 21) show the position and areal extent of the cones of depression as they existed at those times.

These maps of the piezometric surface indicate the direction of movement of water, which is normal to the isopiestic (contour) lines. They also indicate the altitude to which the water level in each well screened opposite the "Alta Loma" sand would have risen at the time shown.

The contour map of the piezometric surface of the "Alta Loma" sand for 1941 (fig. 19) shows three prominent cones of depression. These cones are centered at Baytown, Texas City, and Alta Loma. Although the oldest of the cones is at Alta Loma, the one at Baytown was the largest in 1941.

By 1948, the shape of the piezometric surface had changed materially. Additional declines of 50 feet at Baytown, 70 feet in the Pasadena-Deer Park area, 46 feet in the Alta Loma area, and 33 feet in Texas City area had been observed. The pumping along the Houston Ship Channel between Pasadena and Deer Park had become sufficient to create a separate cone of depression. The same was true in the vicinity of La Porte. Owing to this pumping, a ground-water divide had been formed a short distance north of Alta Loma. Another divide which previously had been formed between Alta Loma and Texas City was moving slowly toward Alta Loma. The greatest movement of water toward Alta Loma at that time appeared to be largely from the south and west.

Between 1948 and 1952 more changes occurred. The recovery of water levels resulting from a large reduction in pumpage at Texas City in 1948 was sufficient to remove almost completely the cone of depression that had been formed there. Pumpage along the Houston Ship Channel, between Pasadena and Deer Park, had become so great that the individual cones of depression existing at

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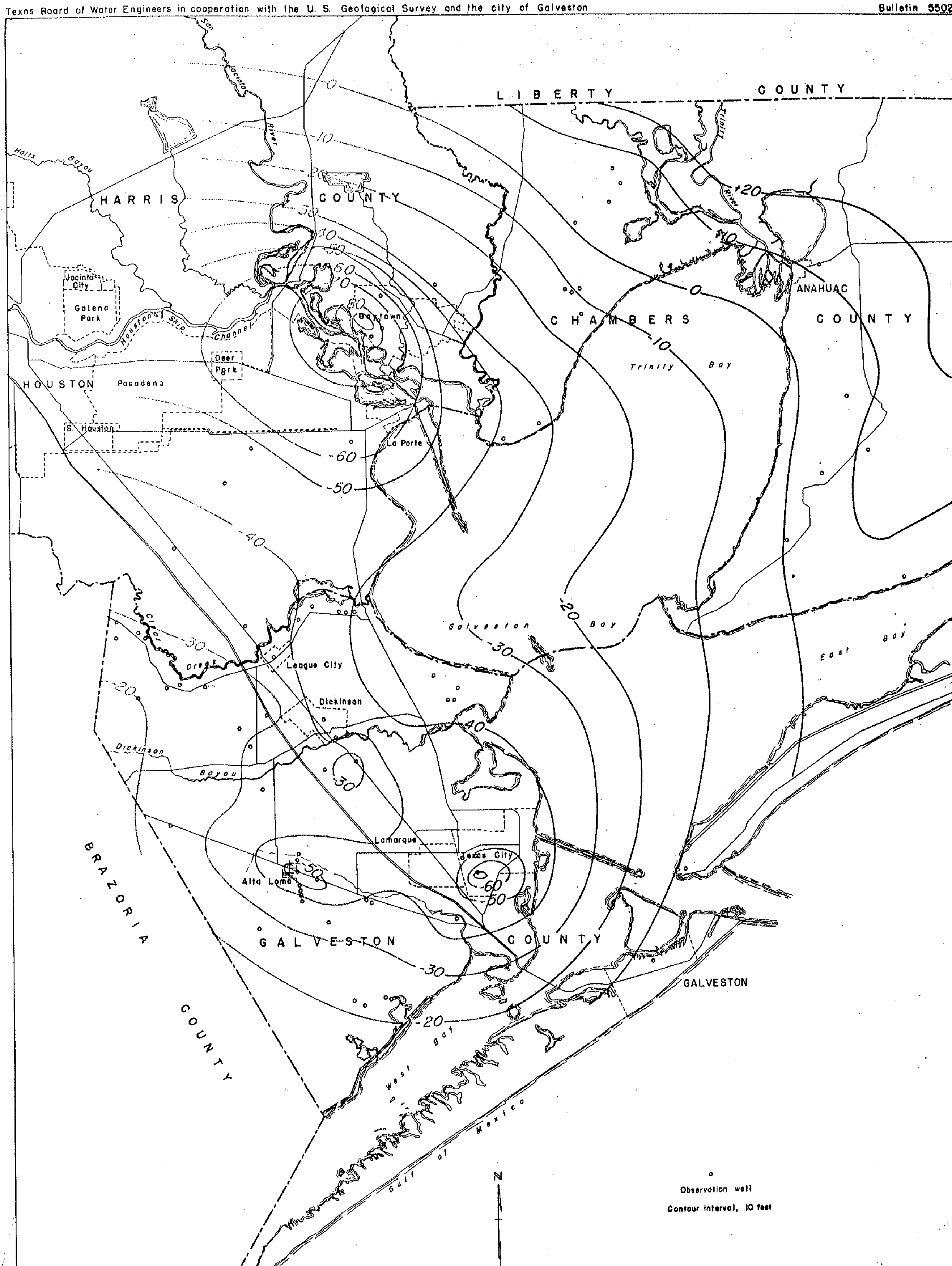

FIGURE 19.- Approximate altitudes of water levels, in feet, in wells screened in the "Alta Loma" sand in Galveston, Harris, and Chambers Counties, Tex., May 1941.

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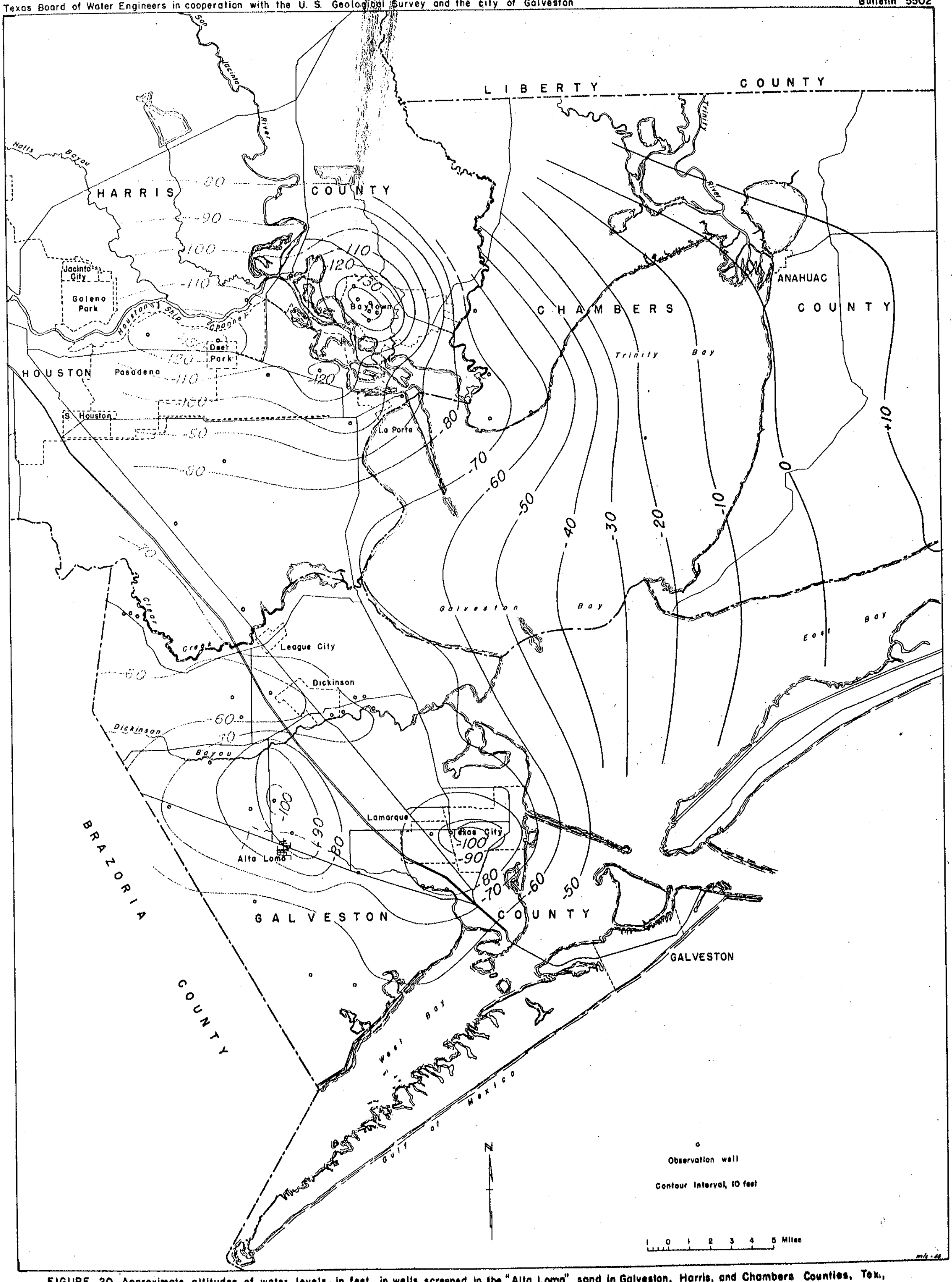

FIGURE 20.-Approximate altitudes of water levels, in feet, in wells screened in the "Alta Loma" sand in Galveston, Harris, and Chambers Counties, Tex., May 1948.

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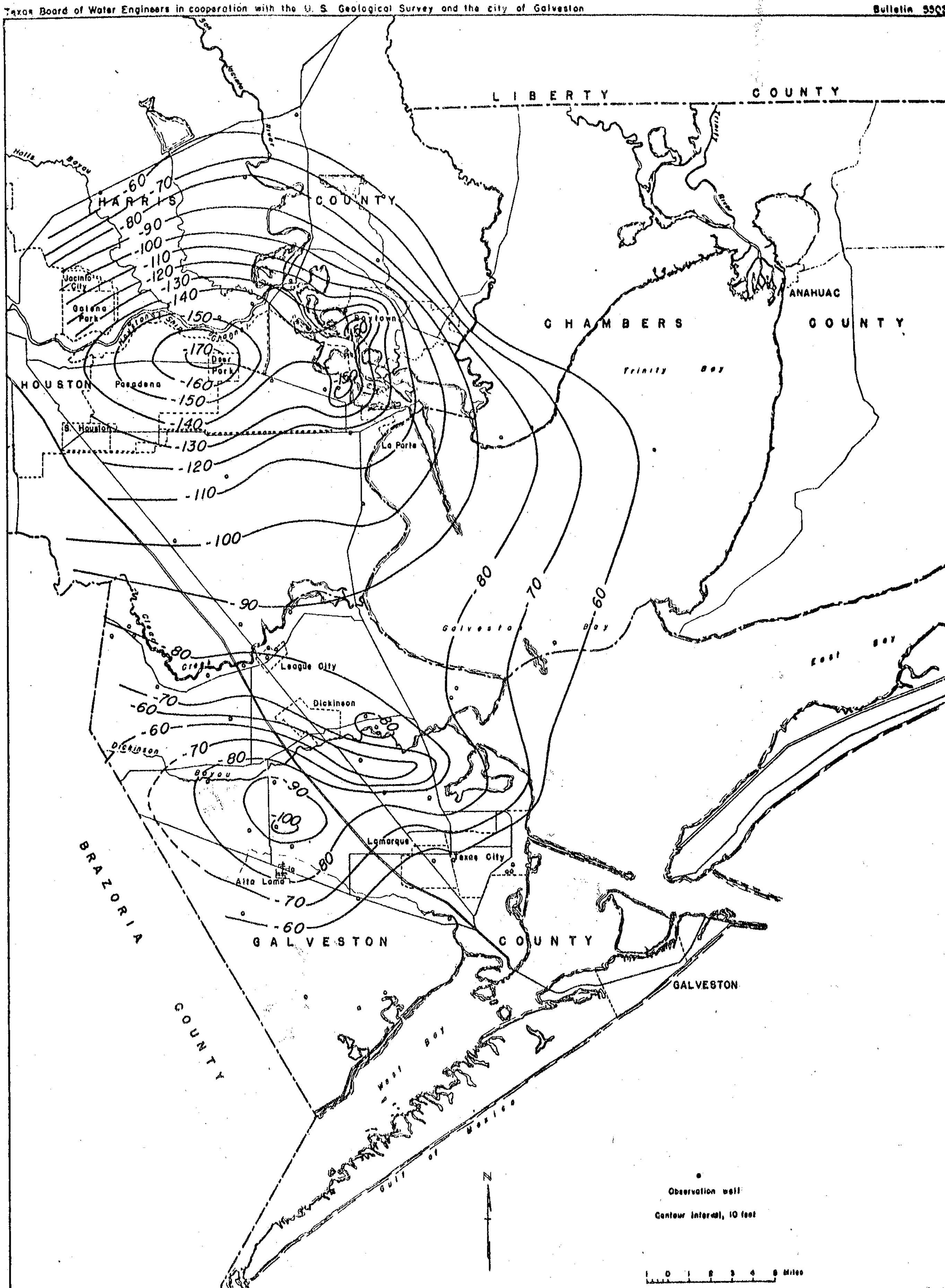
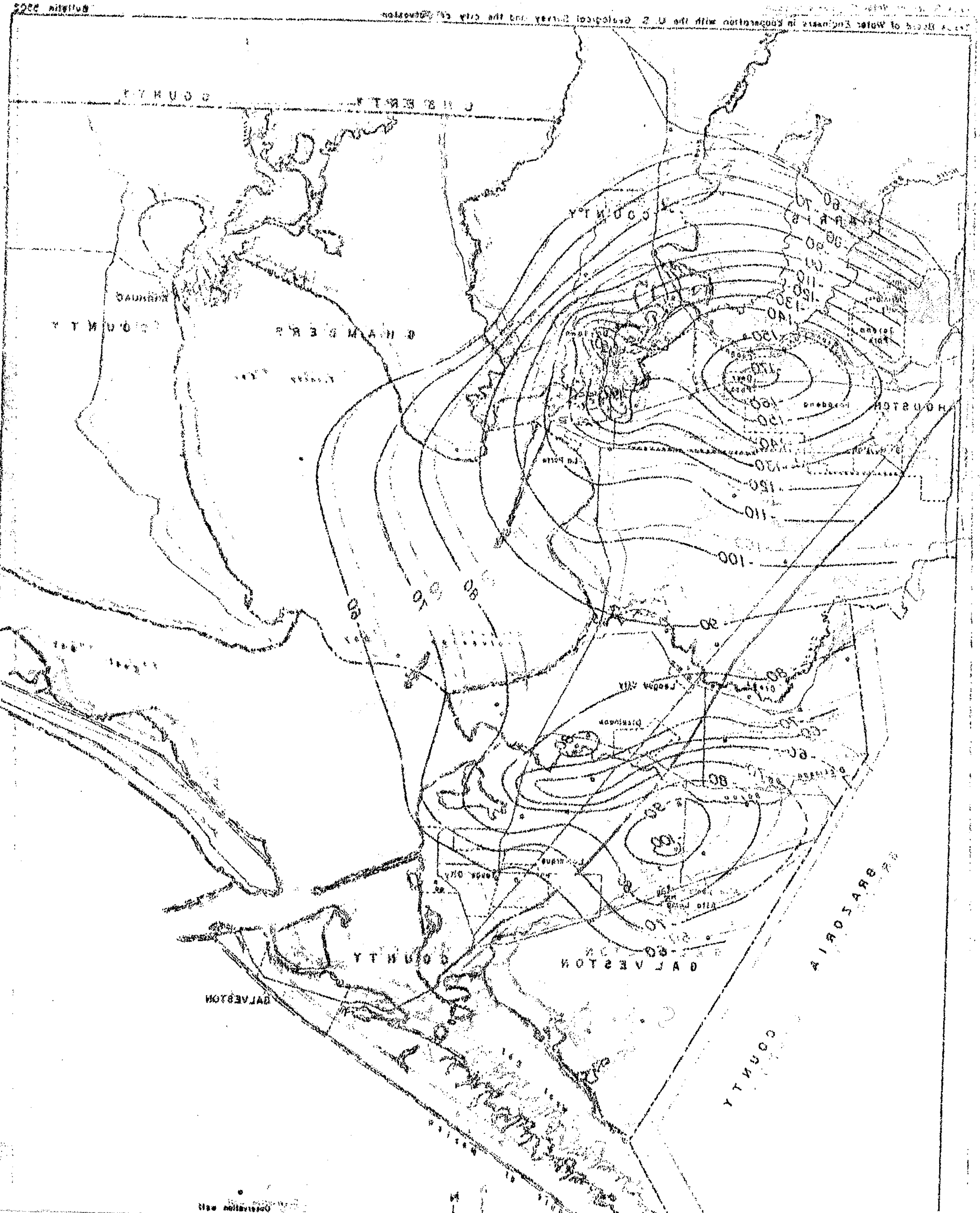


FIGURE 21.-Approximate altitudes of water levels, in feet, in wells screened in the "Alta Loma" sand in Galveston, Harris, and Chambers Counties, Tex., May 1952.



GROUND WATER HYDROLOGY (continued)

The Shape of the Piezometric Surface and Its Relation to the Movement of Water (continued)

Baytown and La Porte became subsidiary cones on the larger cone centered at Deer Park. The influence of this large cone extended well into Galveston County. The ground-water divide north of Alta Loma had become sharply accentuated. It appears that water may now move toward Alta Loma from almost any direction except that the movement of water from the north probably will be reduced ultimately as the ground-water divide is lowered.

QUALITY OF WELL WATER

Beaumont Clay (Alta Loma Sand)

The "Alta Loma" sand is the principal aquifer in Galveston County. Water of good quality is available in relatively large quantities on most of the mainland. Salt water is known to occur in the lower part of the "Alta Loma" sand in the southern part of the county and throughout the sand beneath Galveston Island.

Many samples of water from wells screened in the "Alta Loma" have been collected and analyzed, and many of the wells have been resampled periodically to show the trend of increase in salinity and the position of the salt-water interface. The analyses show that the water varies greatly in the amount of dissolved mineral matter present. Chloride and bicarbonate are the predominant anions. Sulfate is present only in very small quantities. All the waters in which the concentration of the chloride ion is high are sodium chloride waters. The hardness of the water is of the carbonate or "temporary" type. Sodium and calcium are the predominant cations.

Analyses of representative waters from the "Alta Loma" sand are shown graphically in figure 26. The heights of the several sections of the diagrams correspond to the quantities of the constituents reported in the table of analyses.

The most notable characteristic of the water from the "Alta Loma" sand is that the concentration of bicarbonate is relatively constant regardless of the increase in dissolved solids, and the increase in the dissolved solids is largely due to the increase in sodium, potassium, and chloride ions.

The earliest analyses of water from the "Alta Loma" taken on Galveston Island showed the presence of highly mineralized water, although the salinity did not approach that of sea water. In the Alta Loma-Texas City area the chloride content increases down the dip of the formation and vertically downward in the sand section. From a study of the electrical logs of wells (pls. 1 and 2) and analyses of water samples, it appears that the salt water is lying in a wedge in the lower part of the sand at Alta Loma and Texas City. Inasmuch as the sand thickens down dip and along the strike in both directions from Alta Loma, a higher percentage of salty water is drawn into the wells that penetrate the thicker sections; whereas, the wells that penetrate only the thinner sections yield water lower in chloride content.

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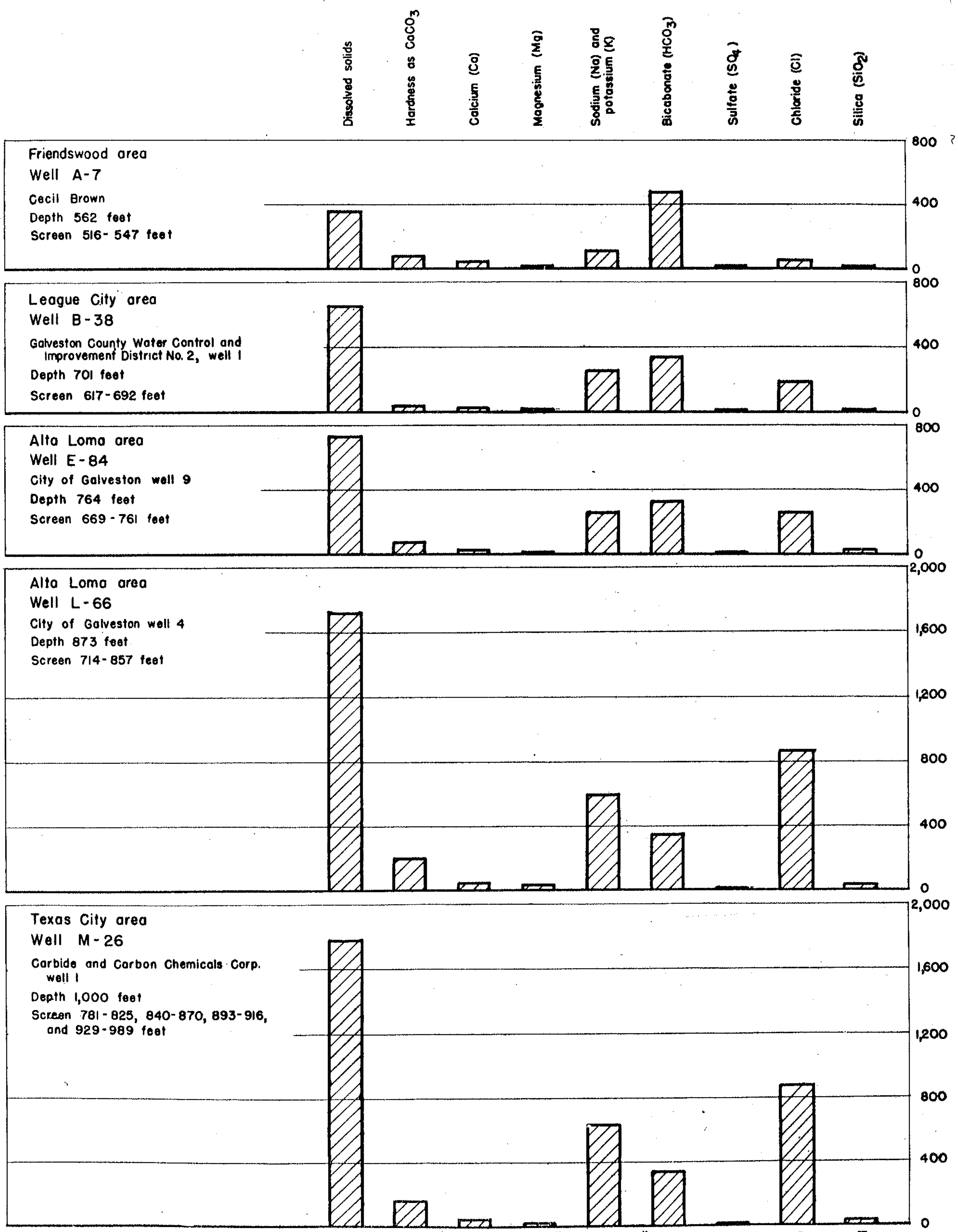

FIGURE 26.- Quality of water from typical wells in the "Alta Loma" sand in Galveston County, Tex.

QUALITY OF WELL WATER (continued)

Beaumont Clay (Alta Loma Sand) (continued)

The water in the "Alta Loma" sand up the dip from Galveston County is of excellent quality. The chloride content in wells along the Houston Ship Channel averages about 40 ppm. A well at the Humble pump station (Harris County well 1367), just north of the Galveston County line near League City, yields water from the "Alta Loma" sand containing about 96 ppm of chloride. The chlorograph of this well shows no appreciable increase in chloride content from 1939 to 1951. This stability is in direct contrast to the trends shown by the chlorographs of wells at Alta Loma and Texas City where there has been salt-water encroachment. This evidence, together with a study of electrical logs of wells in the area, indicates that the salt-water wedge in the deeper part of the "Alta Loma" sand does not extend as far north as the League City area (fig. 30).

Wells in the Friendswood area tap the part of the "Alta Loma" sand that is farthest up dip in Galveston County, and consequently the water is the least highly mineralized in this area. Water from both wells A-7 and B-3 had a chloride content of 39 ppm in 1939. In 1951 the wells yielded water having 42 and 38 ppm of chloride, respectively, thus indicating that there has been no salt-water encroachment in this area.

In the League City area, down dip from the Friendswood area, the water in the "Alta Loma" sand is a little more highly mineralized. Water from well B-45 had a chloride content of 74 ppm in 1941, as compared to 75 ppm in 1951. Water from other wells tapping the "Alta Loma" sand in this area had a range in chloride content of 86 to 108 ppm in 1939. The available evidence indicates that there has been no salt-water encroachment in this area.

In the Dickinson area the "Alta Loma" sand appears to be broken up by numerous clay lenses. The water from wells tapping the sands in this area ranges in chloride content from about 80 to about 200 ppm. The range in chloride content might be explained by inequalities in the flushing of the sands, due to the presence of the clay lenses or differences in permeability in different parts of the sand. Although the chloride content is variable in the water from different wells in this area, the lower part of the sand appears to yield water slightly higher in chloride content than the upper part.

The occurrence of a salt-water wedge in the deeper part of the "Alta Loma" sand first becomes apparent in the Alta Loma area, which is down dip from the Dickinson area. The earliest indication of the vertical gradient of chloride content in the sand is seen in analyses made in 1916 of water taken from the original city of Galveston wells, which were drilled in 1893 and 1894. The chloride content of water from 24 of 25 of these wells, all screened at about the same interval, ranged from 191 to 443 ppm. The remaining well, L-40, yielded water having a chloride content of 992 ppm. However, this well was screened much deeper than the others, and a study of the nearest electrical log shows that it was probably screened in the lowest part of the main sand body. This well was sampled again in 1899 and the analysis at that time showed a chloride content of 1,014 ppm. Thus, it appears that the salty water has always been present in the lower part of the sand, as there was very little pumping in the area before that date.

QUALITY OF WELL WATER (continued)

Beaumont Clay (Alta Loma Sand) (continued)

From 1914 to 1927, seven new wells were drilled to replace the old wells at Alta Loma (pl. 3). These wells were located generally to the southeast of the original field, and it should be emphasized that this direction is down the dip of the formation and toward the thicker sand section. The rate of pumping in the well field increased very slowly from 3.28 mgd in 1915 to 4.5 mgd in 1935, and likewise the chloride content of the water increased very little during that period. The record is not complete for the period from 1915 to about 1932 but it appears that, at least from 1932 to 1935, well 3 yielded water having the highest chloride content, 431 ppm. This was to be expected, as the pumping was centered near well 3 during the period 1932-35. Owing to the lower head in that vicinity, more of the deeper and saltier water was drawn into that well.

In 1935 well 8 was drilled still farther southeast. When this well went into operation the center of pumping was shifted toward the southeast, and the chloride content in the water in well 4 increased until it was the highest in the field. During this period, water from wells 1, 2, 6, and 7 showed increases in chloride content, but the content did not become as high as that in wells 3, 4, 5, and 8. Water from well 8 showed a rapid increase in chloride content, until in May, 1951, it contained about 800 ppm of chloride. Although the center of pumping is northwest of well 8, this well taps a thicker section of sand than the other wells and is of much higher capacity. Consequently, a higher percentage of the deeper, saltier water is drawn into it.

From 1940 to 1942 the city of Galveston was engaged in a test-drilling program, one of the objects of which was to determine the position and extent of the salt water in the "Alta Loma" sand in the Alta Loma area. (From the results of this program, it was found that in the area to the north of Alta Loma the main sand body is relatively thin and contains water lower in chloride, although even in this area a vertical chloride gradient within the sand body is apparent. Although wide variations in chloride content were found both laterally and vertically, it is believed that, generally speaking, the test-drilling program strengthens the "salt-water wedge" theory.

From the results of the test-drilling program, six new wells (Nos. 9-14), were drilled north of Alta Loma in 1942. These wells constitute what is known as the "new field" in contrast to the "old field", which consists of wells 1 to 8. The locations of all these wells are shown in figure 6. Wells 9 to 13 were put in operation in 1943 and have been operated more or less continuously since then. Well 14 has not yet been put in use. When the new field was put into operation, production from the old field was curtailed. Water from wells in the "new field" has shown slight increases in chloride content, but at a rate not nearly as great as that in the old field during its time of rapid chloride increase.

From a study of the chlorographs of wells 9 through 13 in the "new field", it can be seen that well 12 shows the greatest amount of salt-water encroachment of any of the "new wells". This may be explained by its unfavorable position on the down-dip side of the cone of depression. Most of the water at this location is coming from the southeast, where the saltier water is known to occur.

QUALITY OF WELL WATER (continued)

Beaumont Clay (Alta Loma Sand) (continued)

Except for a short, rapid rise in chloride content immediately after the well was put in operation, well 9 has shown an actual improvement in the quality of its water. This could be explained by its favorable position on the up-dip side of the cone of depression, where a larger proportion of water of better quality is being drawn into the cone.

Inasmuch as saline water is known to occur in the deeper parts of the "Alta Loma" sand at the Alta Loma well fields and still more saline water occurs a short distance down the dip from Alta Loma, and as a hydraulic gradient has been established toward Alta Loma, the encroachment of salt water may be expected to continue. However, if separate cones of depression are maintained at the "old field" and in the Texas City area, the resultant protective pumping may slow down the rate of encroachment in the "new field".

Prior to the test-drilling program by the city of Galveston between 1940 and 1942, it was generally believed that the "Alta Loma" sand was underlain by thick, persistent beds of clay. The test wells showed that the clay beds are present, but that they are not very thick or persistent and that they are underlain by or interbedded with sands that contain salty water. The extreme variation in thickness of the individual beds of clay suggest that they may be absent in some places. It seems possible, therefore, that some salt water could move upward from these lower sands into the main sand body of the "Alta Loma". Further evidence of interconnection lies in the fact that the artesian head in the underlying salt-water sands is, and has been, approximately the same as that in the main sand body. The relation is shown in the hydrographs of wells E-92, which is screened from 661 to 775 feet opposite the main sand body of the "Alta Loma" sand (fig. 31), and of well E-93, which is screened from 850 to 870 feet in the first underlying sand. There has been no significant pumping from these lower sands in Galveston County. In order for the large decline in the water level in well E-93 to have occurred, there must have been some connection with the main sand body. Between 1942 and 1945 the city of Galveston, withdrawing water from the "Alta Loma" sand, increased its pumping from 8.6 million gpd to 11.7 million gpd. Approximately the same decline in water levels that occurred throughout the area adjacent to the city's well fields in the "Alta Loma" sand was observed in well E-93.

As there is little doubt that there are interconnections between the main sand body for the "Alta Loma" sand and the underlying sand, there is probably some recharge of salty water to the main sand body from the underlying sand. However, because the vertical permeabilities are probably less than horizontal permeabilities and the interconnection in some places may be remote, it seems probable that only a small part of the encroachment that has taken place in the main sand body has been from below.

Texas Board of Water Engineers in cooperation with the U. S. Geological Survey and the city of Galveston   Bulletin 5302

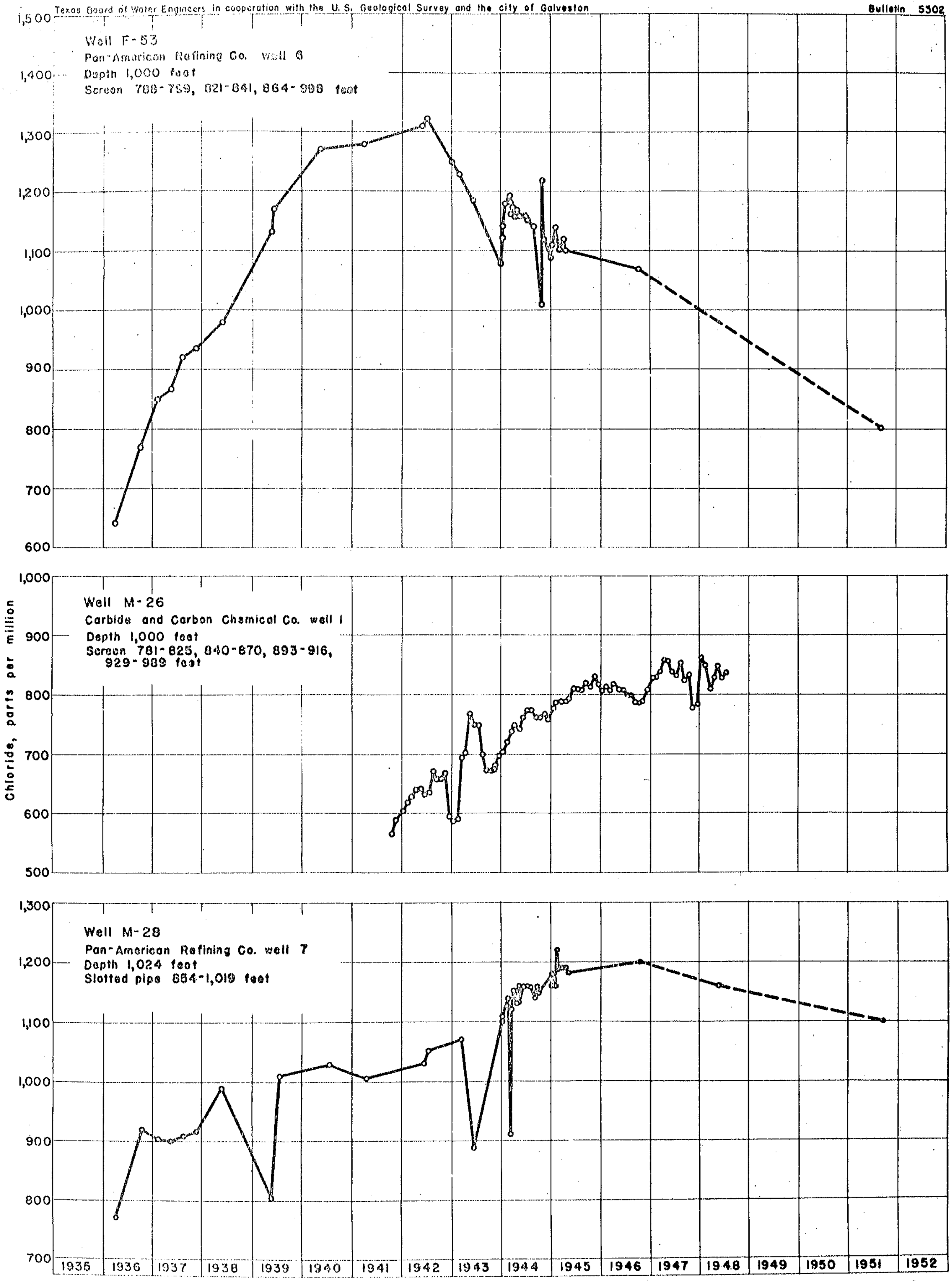

FIGURE 30.- Graphs showing fluctuation of chloride content of the water from wells in the "Alta Loma" sand in the Texas City area, Galveston County, Tex.

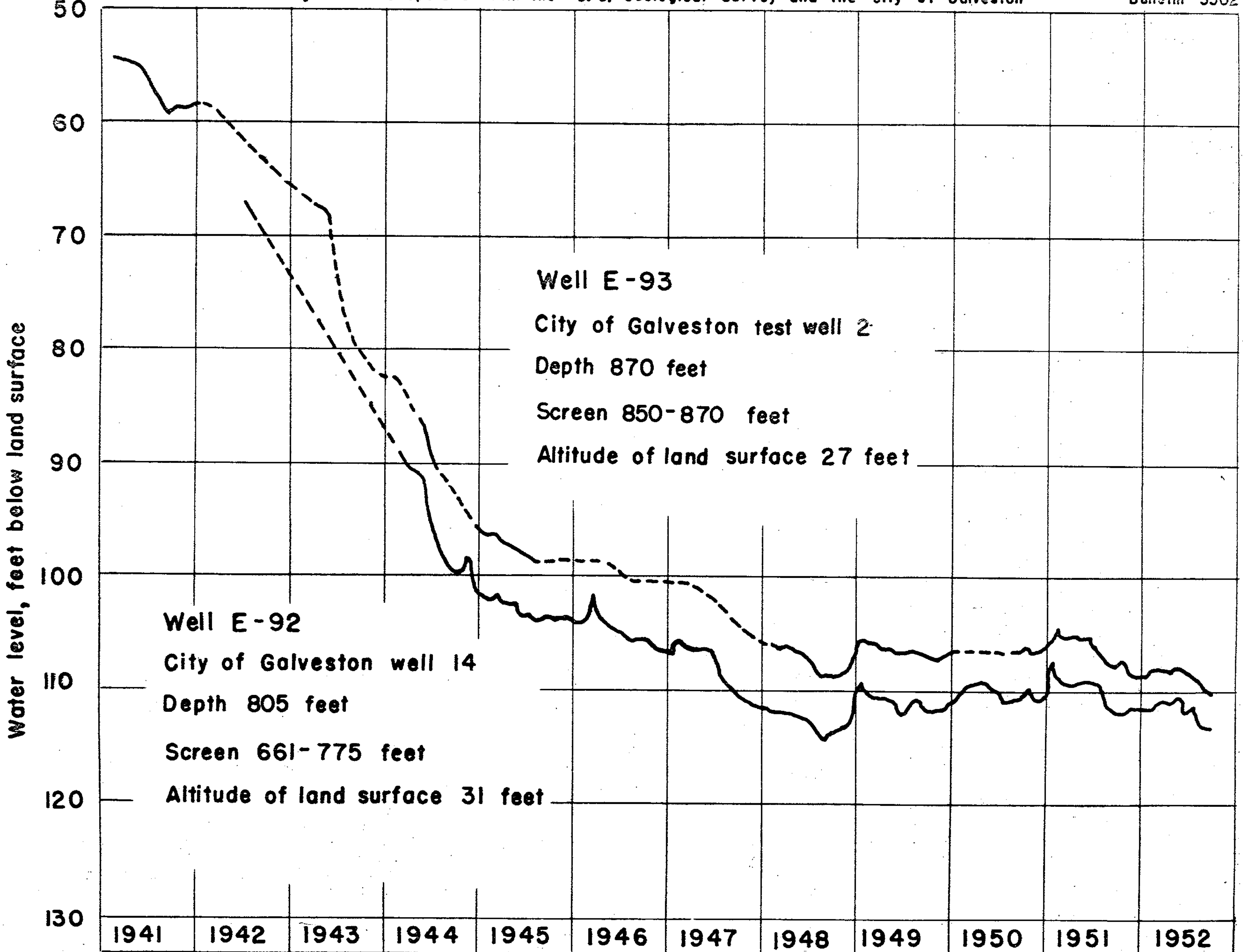

FIGURE 31 - Comparison of decline of artesion pressure in a well screened in the main sand body of the "Alta Loma" sand and a well screened in the underlying sand.

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QUALITY OF WELL WATER (continued)

Upper Part of Beaumont Clay

With the exception of beach sands near the coast on Galveston Island and Bolivar Peninsula, the upper part of the Beaumont clay is the youngest aquifer in Galveston County. It is believed that the unit was laid down as a deltaic and flood-plain deposit except along the coast, where it was deposited in lagoons or in the open Gulf. The deltaic and flood-plain facies probably contained fresh water at the time of deposition. Under the force of gravity, this water gradually moved down dip, replacing the saline water in the lagoonal or marine facies. Simultaneously, precipitation entered the sandy zones at the outcrop, thus providing a driving force to accelerate the flushing action.

The sands of the upper part of the Beaumont are very lenticular and limited in areal extent. Accordingly, the quality of the water from these sands varies somewhat from place to place in the county. In general, the quality of water in the upper part of the Beaumont is superior to that of water in the "Alta Loma" sand in the southern part of Galveston County; whereas, the water from the "Alta Loma" is superior in northern Galveston County and in Harris County. In the Texas City area, sands of the upper part of the Beaumont clay are the only aquifers from which water may be withdrawn containing less than 1,000 ppm of dissolved solids.

The water from the upper part of the Beaumont clay is relatively soft; the hardness is of the carbonate or "temporary" type. Bicarbonate and chloride are the predominant acidic constituents. Sulfate and nitrate are present in only small amounts. The predominant basic constituents are sodium and calcium.

The quality of water from wells screened opposite sands in the upper part of the Beaumont clay varies according to the depth and location of the wells. The dissolved-solids content of the water as a general rule increases down dip, although the range in concentration is far less than that in the "Alta Loma" sand.

A large number of samples of water from wells that withdraw water from the upper part of the Beaumont have been analyzed by the Geological Survey at Austin. Other samples have been analyzed by other analysts as noted in the tables. Analyses of representative waters from the upper part of the Beaumont clay are shown graphically in figure 33. The heights of the several sections of the diagrams correspond to the quantities of the constituents reported in the table of analyses.

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Texas Board of Water Engineers in cooperation with the U. S. Geological Survey and the city of Galveston

Bulletin 5502

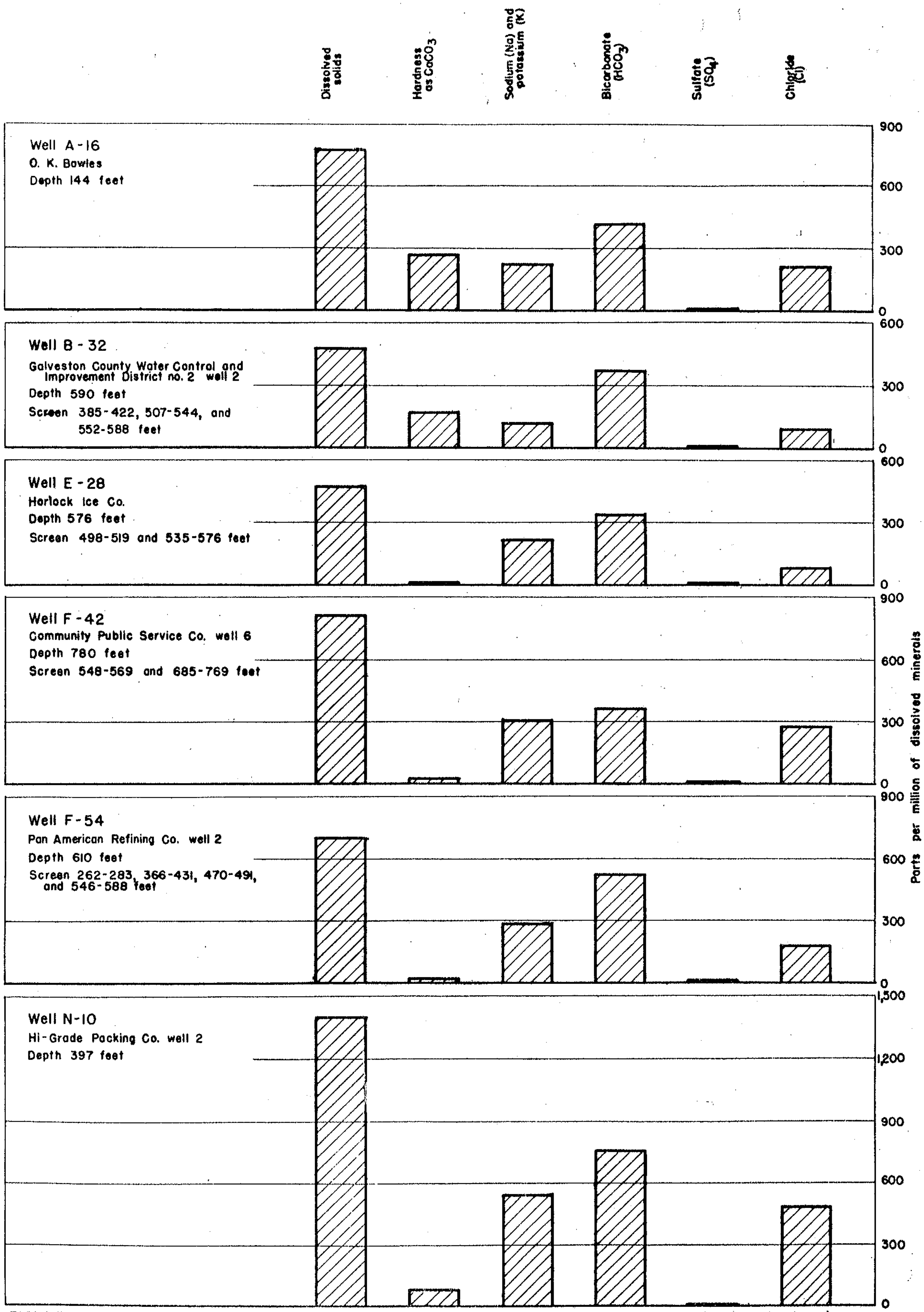
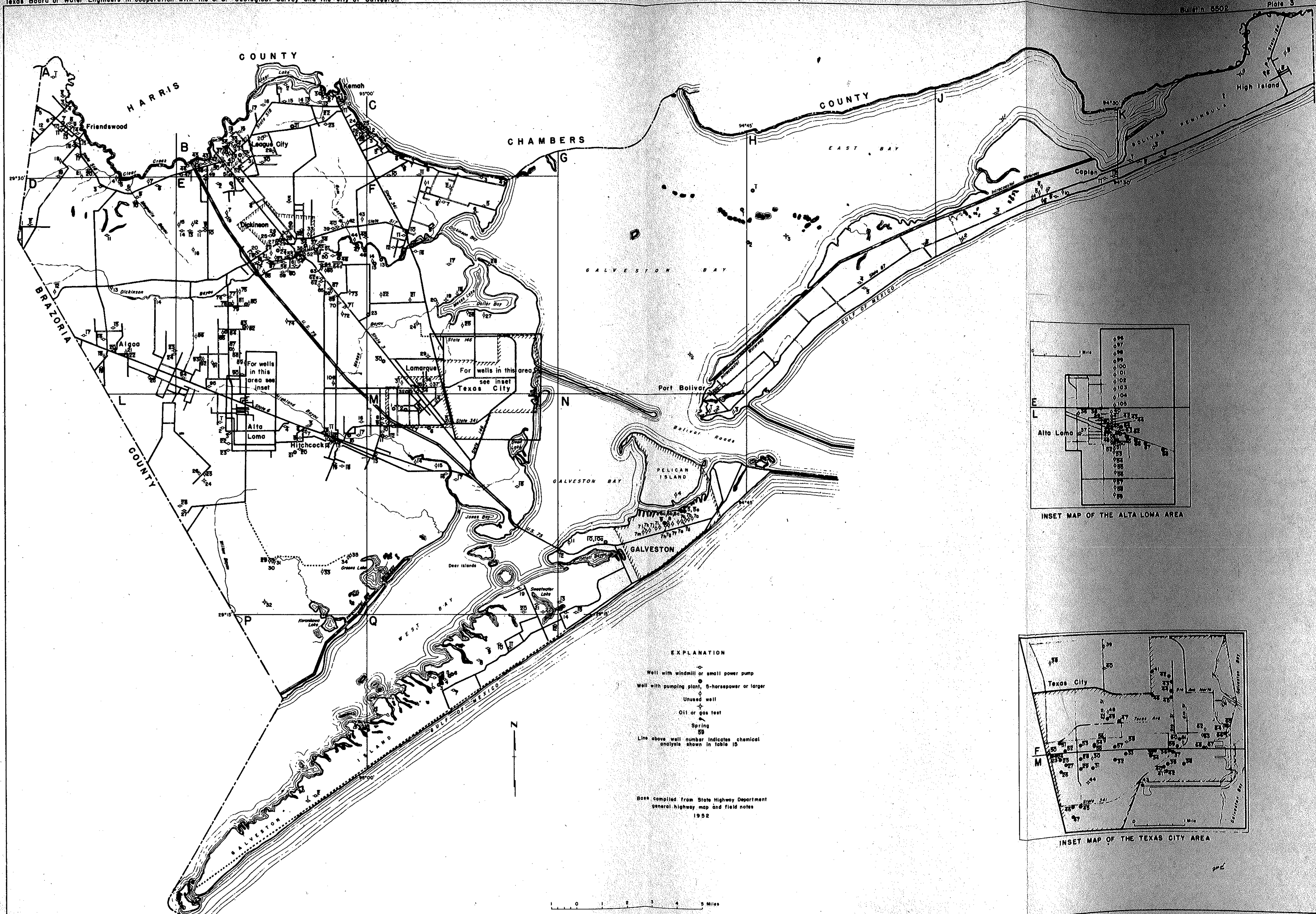


FIGURE 33.-Quality of water from typical wells in the sands of the upper part of the Beaumont clay in Galveston County, Tex.

Texas Board of Water Engineers in cooperation with the U.S. Geological Survey and the city of Galveston



MAP SHOWING LOCATION OF WELLS IN GALVESTON COUNTY, TEXAS

LITERATURE ABSTRACT B

LAND-SURFACE SUBSIDENCE AND ITS RELATION TO THE WITHDRAWAL OF GROUND WATER IN THE HOUSTON-GALVESTON REGION, TEXAS

PLANT ENGINEERING DEPARTMENT

LITERATURE ABSTRACT - B

LAND-SURFACE SUBSIDENCE AND ITS RELATION TO THE WITHDRAWAL OF GROUND WATER IN THE HOUSTON-GALVESTON REGION, TEXAS

BY: A. G. WINSLOW AND W. W. DOYEL

(REPRINT FROM ECONOMIC GEOLOGY, VOL. 49, NO. 4, JUNE-JULY, 1954)

The Houston-Galveston region, as discussed here, includes Harris and Galveston Counties and parts of Brazoria, Chambers, Fort Bend, Liberty, and Montgomery Counties, Texas. The region lies on the Gulf Coastal Plain of Texas and consists of a nearly flat plain rising from sea level at the Gulf of Mexico to a maximum altitude of 318 feet in northwestern Harris County. The slope of the land surface, however, is not uniform, the area between the Gulf Coast and Houston being much flatter than the inland part.

The region contains the most heavily industrialized areas of the Texas Gulf Coast, and in 1950 it contained about 13 percent of the total population of the State of Texas, although containing only 1.5 percent of the land area. Most of the industry and population and much of the rice irrigation in the region is dependent on ground water for its water supply, and during 1952 a total of about 330 million gallons of water a day was pumped from wells.

The geology of the Houston-Galveston region as it applies to the occurrence of ground water has been described by a number of authors. The description by Lang and Winslow is summarized here in order that the relationship between subsidence and the withdrawal of ground water may be shown.

The Houston-Galveston region is on the Gulf Coastal Plain of Texas and is underlain by a thick series of Tertiary and Quaternary deposits. The sediments consist mostly of unconsolidated sands and clays dipping gently toward the coast. The dip of the beds is greater than the slope of the land surface and successively older formations crop out toward the interior. The presence of this typical coastal-plain type of structure, together with the occurrence of relatively impermeable layers of clay interbedded with and overlying the sands, result in conditions favorable for the occurrence of artesian water.

The geologic formations that supply most of the water to wells in the region are the Willis sand of Pliocene age and the Lissie formation, Alta Loma sand, and Beaumont clay of Pleistocene age. The Lissie and Willis formation have not been separated in the sub-surface and are considered a single aquifer. Figure 1 is a cross section across Harris County and part of Galveston County based on electrical logs of oil tests and water wells.

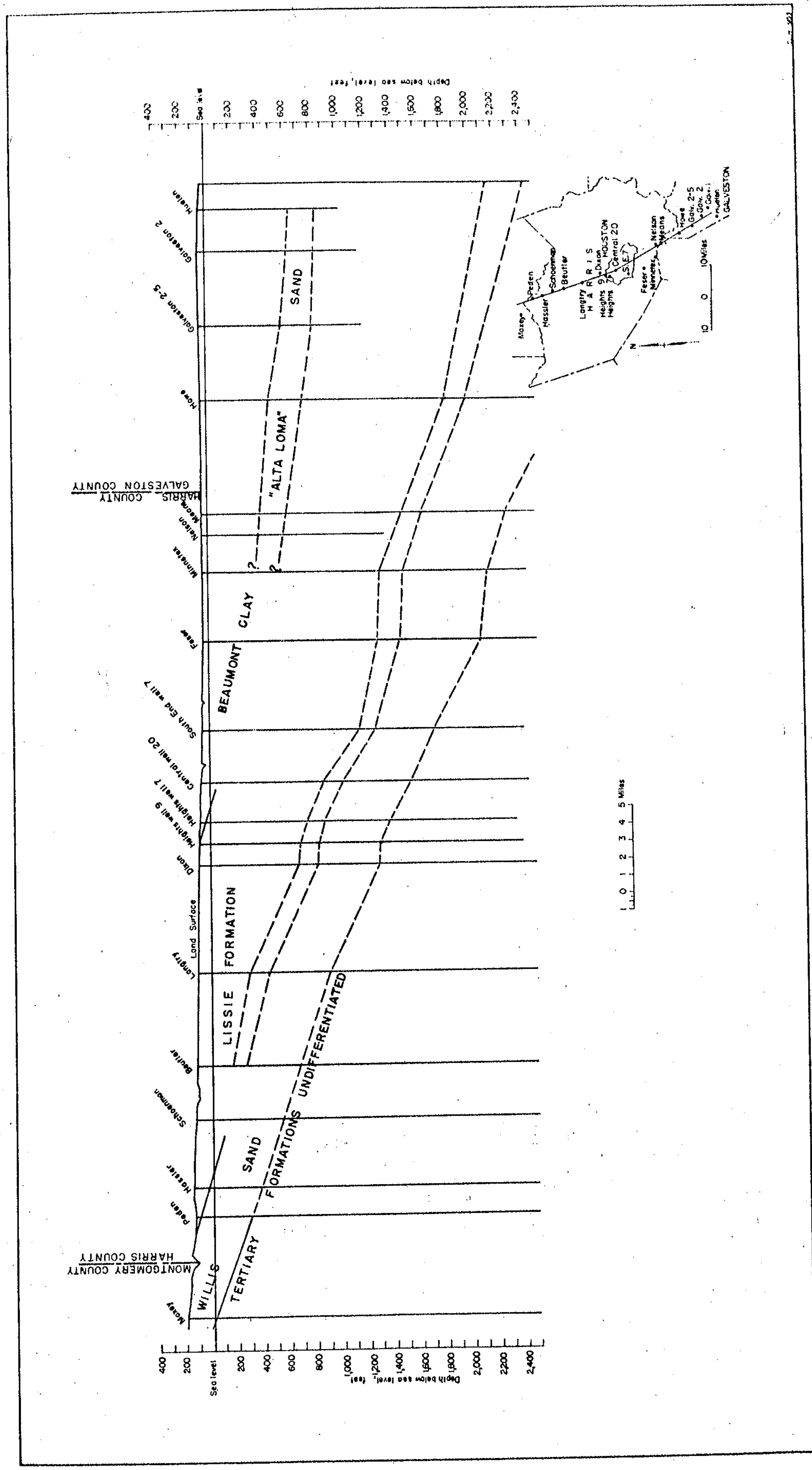


FIGURE 1. Cross section from southern Montgomery County to the vicinity of Alta Loma, Galveston County, Texas

FIG. 1.

The Lissie and Willis formation, which have a maximum combined thickness of about 2,200 feet in the region, are composed of unconsolidated sands and clays in which the sands predominate, especially in the lower part. The sands are lenticular and fine to coarse grained. The clay beds are more continuous and may be traced greater distances. The Lissie and Willis are the principal source of water supply in the Houston area but contain salt water in Galveston County. The sands of the Lissie and Willis are the most heavily pumped in the region and the largest declines in artesian pressure have taken place in them.

The Alta Loma sand overlies the Lissie formation in the southern part of the region and consists of 100 to 300 feet of very permeable sand interbedded with a few thin layers of clay. The so-called Alta Loma sand is the principal aquifer in eastern Harris County and in Galveston County and, at Alta Loma, 20 miles northwest of Galveston, is the source of the water supply for the City of Galveston. The percentage of sand is much greater in the Alta Loma than in the Lissie and Willis formation.

The Beaumont clay, which overlies the so-called Alta Loma sand, has a maximum thickness of about 1,200 feet in southern Galveston County, and consists largely of calcareous clay containing a few beds of fine sand. Although the sands have relatively low permeabilities, they comprise the principal aquifer in the Texas City area. The percentage of sand is much less in the Beaumont than in either the Lissie and Willis formations or the Alta Loma sand.

"The United States Coast and Geodetic Survey has established extensive nets of first and second-order level lines covering most of the region. The first leveling in the region was the first-order line from Smithville to Galveston, which was run in 1905 and 1906. The next was in 1918 when a first-order line was run from Sinton, Texas, to New Orleans, La. During the period between 1932 and 1936 several other first- and second-order lines were run and the two original lines were releveled.

In 1942 and 1943 a large number of second-order lines were established in the region and most of the old lines were releveled. At this time subsidence in the Houston area was noted from the results of leveling, although the actual amount of subsidence was not determined because of changes in datum."

In 1951 most of the first-order lines were releveled to the datum used in 1943, and the true nature of the subsidence became apparent. Profile A-A' (fig. 2), extending from a point in southern Montgomery County southward to Houston and thence southeastward to Galveston, shows that the subsidence has occurred on a regional scale, though it is greatest in the Texas City area. The greatest subsidence discovered by the U. S. Coast and Geodetic Survey in the Houston area was 1.345 feet at South Houston, and the greatest amount found in the Texas City area was 2.641 feet at La Marque. (USC&GS B.M. A-639). However, leveling by engineers at industrial plants about 2 miles east of La Marque indicates that even greater subsidence has taken place there. Profile B-B' (fig. 3) shows the subsidence along a line from Katy eastward to Houston, thence northeastward to a point near Dayton. The regional nature of the subsidence is shown by this profile also. The dashed lines shown on both profiles represent the decline in artesian pressure head between 1943 and 1951 in wells along the lines of the profiles.

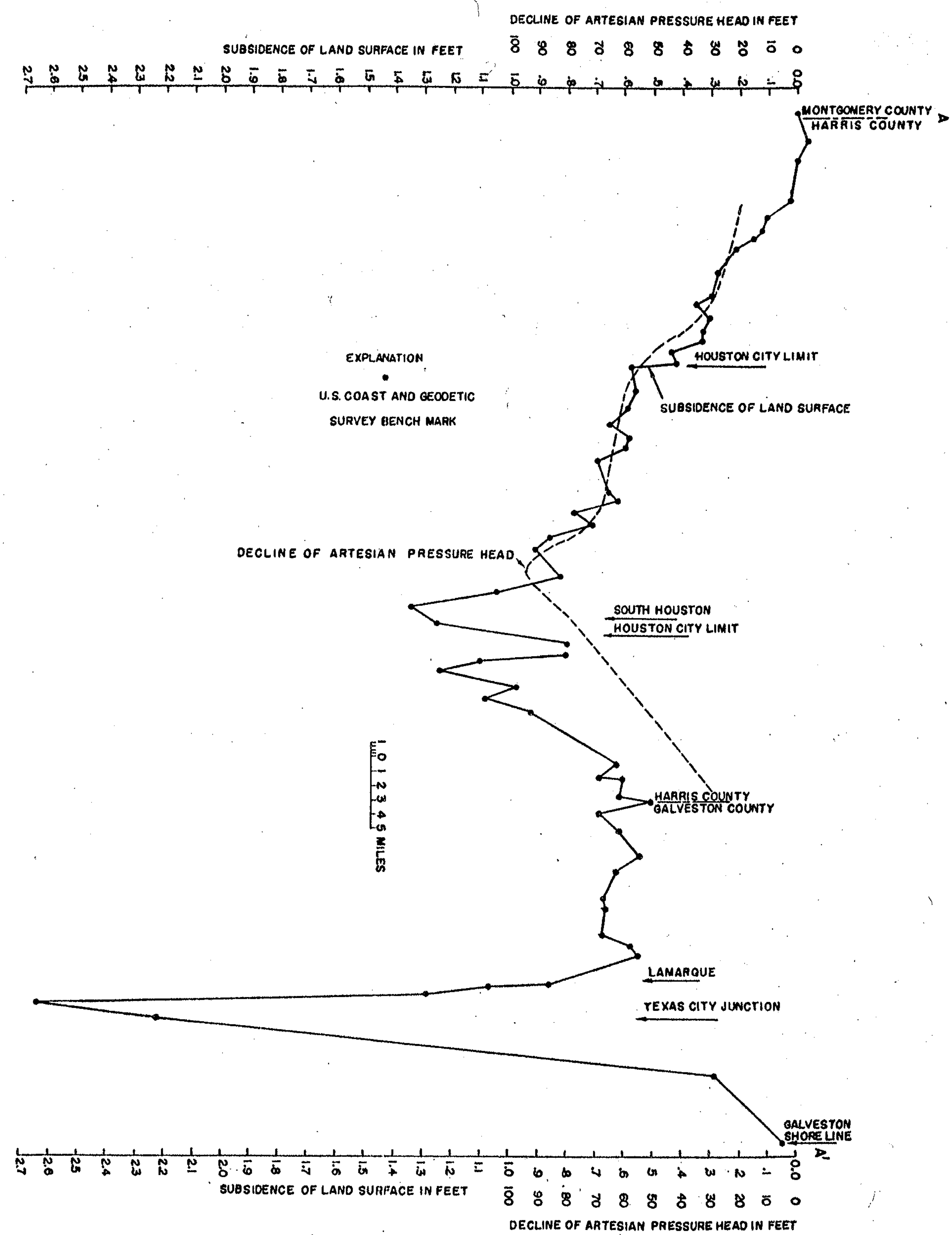


FIGURE 2. Profile A-A' showing subsidence and decline of artesian pressure head from a point in southern Montgomery County to Galveston

FIG. 2.

Although probably more subsidence has occurred in the Houston area than was shown by the releveling, the local differences in the rate of settlement have been small. Consequently, few problems resulting from differential settlement, such as clogging of sewer lines or breaking of water mains, have been reported in the Houston area. In the Texas City area, however, the differential settlement is greater and such difficulties have been experienced.

Subsidence of the land surface due to withdrawal of underground fluids has been noted in many places, and the processes of compaction involved in the subsidence have been discussed. Meinzer has shown that part of the weight of the overburden is supported by the hydraulic pressure, and that a reduction in hydraulic pressure increases the load on the skeleton of the aquifer. He stated also that the compression probably occurs largely in the finer-grained materials. As water is withdrawn, the hydrostatic pressure in the sands is reduced and a pressure difference is established between the clays and the sands, causing water to move from the clays into the sands. The weight of the overlying material causes compaction of the aquifer in proportion to the reduction in pressure head, most of the compaction taking place in the clays.

Tolman and Poland in describing the land-surface subsidence in the Santa Clara Valley in California attribute the subsidence to the compaction of the clays following the removal of ground water. In a discussion of the subsidence of the Terminal Island area near Long Beach, California, Harris and Harlow also gave the removal of ground water as one of the factors contributing to the subsidence, although the removal of oil and gas has probably caused most of the subsidence.

In the Houston-Galveston region the withdrawal of large quantities of ground water probably caused the compaction of the clays and, to a much smaller degree, of the sands and, consequently, the land-surface subsidence. As the artesian pressure in the sands is lowered by pumping, a hydraulic gradient is established between the sands and adjacent clay beds. As a result, the water is drained from the clays and the artesian pressure which helps to support the weight of the overlying material is decreased, causing the clays, which are less competent than the sands, to be compacted. It may be assumed that the more deeply buried sediments are already partially compacted and that with the increasing depth less compaction is possible.

The relation between the decline in artesian pressure and the land-surface subsidence in the Houston-Galveston region is shown on the profiles (fig. 2 and 3). In the northern part of the region, where the fresh-water bearing formations are predominantly sand, the ratio between the subsidence of the land surface and the decline of artesian pressure head is about one foot of subsidence to 100 feet of decline. In the southern part of the region, where the fresh-water-bearing formations contain a larger percentage of clay, the ratio is greater, indicating that subsidence may be ascribed principally to the compaction of the clays. The ratio of subsidence to the decline of artesian pressure head as shown by the profiles may not be the true ratio because of the presence of a time lag between a decline in artesian pressure and the corresponding surface subsidence. The time lag is introduced because of the slow rate at which water drains from the clays in response to a change in pressure.

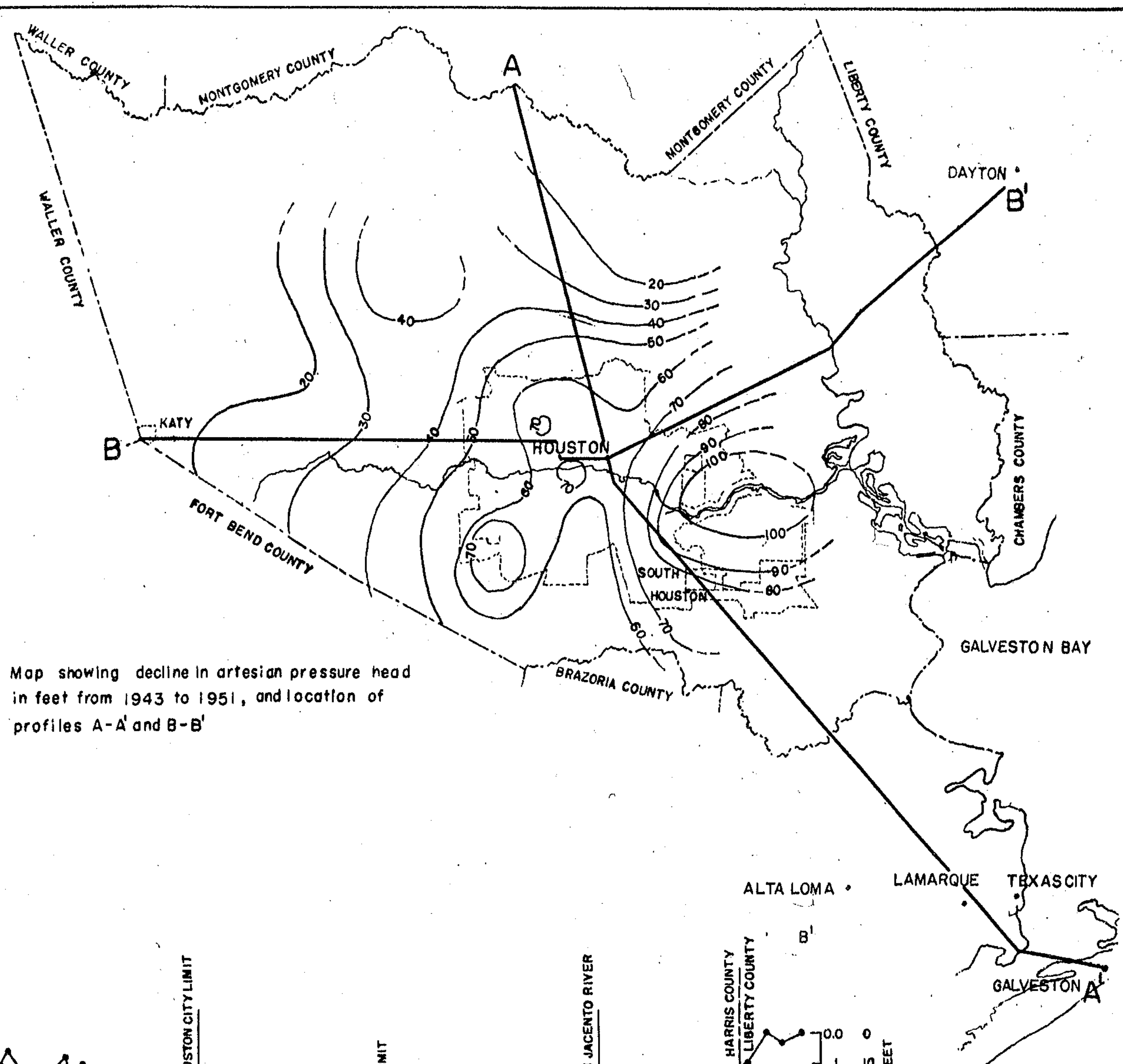


FIGURE 4. Map showing decline in artesian pressure head in feet from 1943 to 1951, and location of profiles A-A' and B-B'

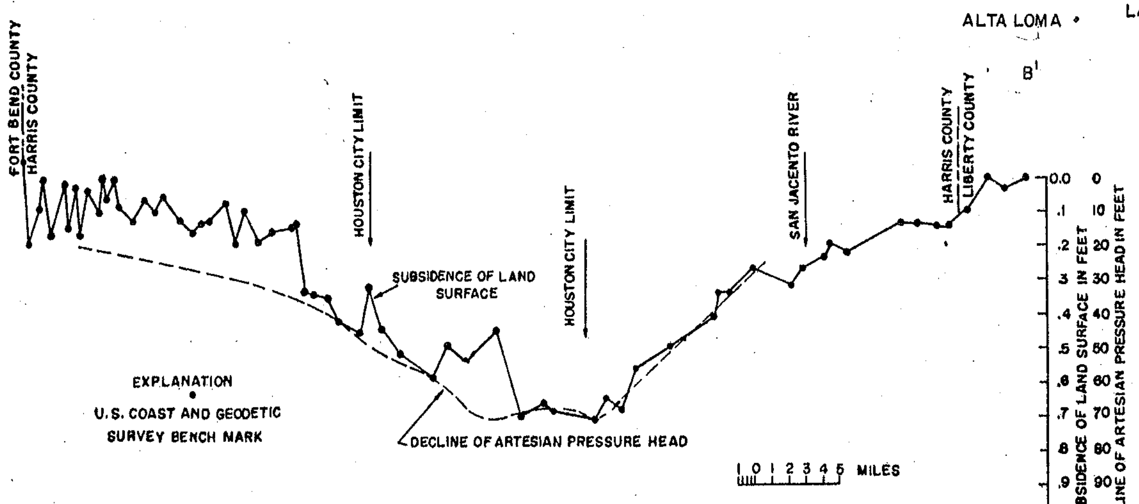


FIGURE 3.- Profile B-B', showing subsidence and decline of artesian pressure head from Katy through Houston to a point near Dayton

FIGS. 3 AND 4

The relation between subsidence and the withdrawal of ground water in the Houston-Galveston region is further complicated by the presence of many oil fields. The reduction of bottom-hole pressures following the removal of oil and gas and associated water probably causes compaction and subsidence in a manner similar to that caused by the withdrawal of fresh water. The depth from which the oil and gas is produced, however, would have an effect on the amount of subsidence possible, because the deeper the clays are, the more they are already compacted due to load and the less they can compact following a reduction in liquid or gas pressure. Pratt and Johnson have described a land-surface subsidence of several feet in the Goose Creek field in eastern Harris County following withdrawals of large quantities of oil and gas from shallow depths. They also state that Gaillard Peninsula, an area of considerable extent which had been used for grazing for many years, sank below the level of Galveston Bay after the development of the Goose Creek field. Although Pratt and Johnson ascribe the subsidence principally to the withdrawal of oil and gas, there was a considerable increase in the development of ground water in the area from 1917 to 1926. It seems reasonable to attribute part of the subsidence to the withdrawal of ground water.

The possible effect of oil fields on the subsidence is shown in the profile A-A' (fig. 2) at South Houston. It is at this point that the greatest amount of subsidence in the Houston area is recorded. This is probably associated with the withdrawal of oil and gas in the South Houston field, as well as the withdrawal of ground water in the region as a whole. From 1943 through 1951 approximately 22,000,000 barrels of oil and water, as well as an unknown amount of gas, were produced from the South Houston field. According to records of the Stanolind Oil and Gas Company the average bottom-hole pressure in the field dropped about 356 pounds per square inch during the same period. This is equivalent to a drop in head of about 820 feet of water. Thus, at South Houston a relatively small amount of fluid has been produced, but the large pressure decline accompanying the production has probably caused a substantial part of the subsidence.

The volume of water released by compaction of water-bearing materials in artesian aquifers is not always accounted for in ground-water studies. Tolman in discussing ground water in the Livermore Valley, California, states "This study indicates that where water levels have been similarly lowered by overpumping, water may be furnished by compaction of alluvial material in sufficient amounts to revise all prior estimates of specific yield and capacity of ground-water reservoirs and introduces a new factor in the ground-water inventory."

As the volume of subsidence is a measure of the amount of water released due to the compaction, it is apparent that the quantity released in the Houston-Galveston region is of considerable importance. It is not possible to contour the subsidence in the region and thereby compute the volume accurately because the level lines in the vicinity of the Houston Ship Channel were not releveled during the 1951 leveling program. Figure 4, which shows the decline in artesian pressure head in the Houston and Pasadena areas from 1943 to 1951 indicates that the greatest decline in head took place in the vicinity of the Houston Ship Channel, and it is probable that the greatest amount of subsidence likewise took place in that area.

Although a precise determination of the volume of subsidence cannot be made, an approximation is possible. It is estimated that the volume was in the order of magnitude of 200,000 acre-feet, and that during the same period about 1,150,000 acre-feet of water was pumped. Inasmuch as the volume of water furnished by compaction must equal the volume of subsidence, it appears that approximately one-sixth of the water pumped during the period of 1943 to 1951 has been supplied from storage, the remaining five-sixths having come from recharge in the outcrop areas. Short-term pumping tests indicate storage coefficients of 0.001 or less for the sands, indicating that 0.1 percent or less of the water pumped was taken from storage in the sands. The remainder of the approximately 17 percent must have been supplied from storage in the clays. It should be emphasized that the values given above are only approximations. It should be pointed out also that neither the effect of time lag between withdrawal of ground water and compaction nor the effect of the withdrawal of oil and gas has been included in these estimates.

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LITERATURE ABSTRACT C

SALT WATER AND ITS RELATION TO FRESH GROUND WATER IN HARRIS COUNTY, TEXAS

PLANT ENGINEERING DEPARTMENT

LITERATURE ABSTRACT - C

SALT WATER AND ITS RELATION TO FRESH GROUND WATER IN HARRIS COUNTY, TEXAS

BY: ALLEN G. WINSLOW AND WILLIAM W. DOYEL, GEOLOGISTS

UNITED STATES GEOLOGICAL SURVEY

(TEXAS BOARD OF WATER ENGINEERS - BULLETIN 5409 - JUNE 1954)

Harris County, in the west Gulf Coastal Plain in southeastern Texas, contains one of the most heavily concentrated areas of ground-water withdrawal in the United States. Large quantities of water are pumped to meet the requirements of the rapidly growing population, for industry and for rice irrigation. The water is pumped from artesian wells which tap a thick series of sands ranging in age from Miocene to Pleistocene.

The water-bearing sands, many of which contained slightly saline water, were deposited with interbedded clays. Subsequent artesian circulation has flushed the sands, probably to the limits of the Ghyben-Herzberg principle. The base of the fresh-water sands ranges in depth from about 100 feet over the salt dome near Hockley to more than 3,000 feet in the northeastern part of the county.

Before large scale ground-water withdrawals were begun, the hydraulic gradient sloped gently toward the coast. However, as large quantities of water were withdrawn a large cone of depression was established; the hydraulic gradient was reversed; and salt water began to move slowly toward the centers of pumpage.

The rate of movement of the salt water is very slow and the closest salt water is probably five miles from centers of pumpage in the deeper sands. However, the threat of salt-water intrusion is present and the rate of advance of the salt-water should be watched by means of strategically placed observation wells (fig. 12).

Other less probable sources of salt-water contamination which are discussed include upward movement of salt-water from below, vertical movement around salt domes or along faults, downward seepage from surface sources, and contamination through leaking wells (fig. 14).

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January 17, 1958

Prepared cooperatively by the United States Geological Survey and the Texas Board of Water Engineers

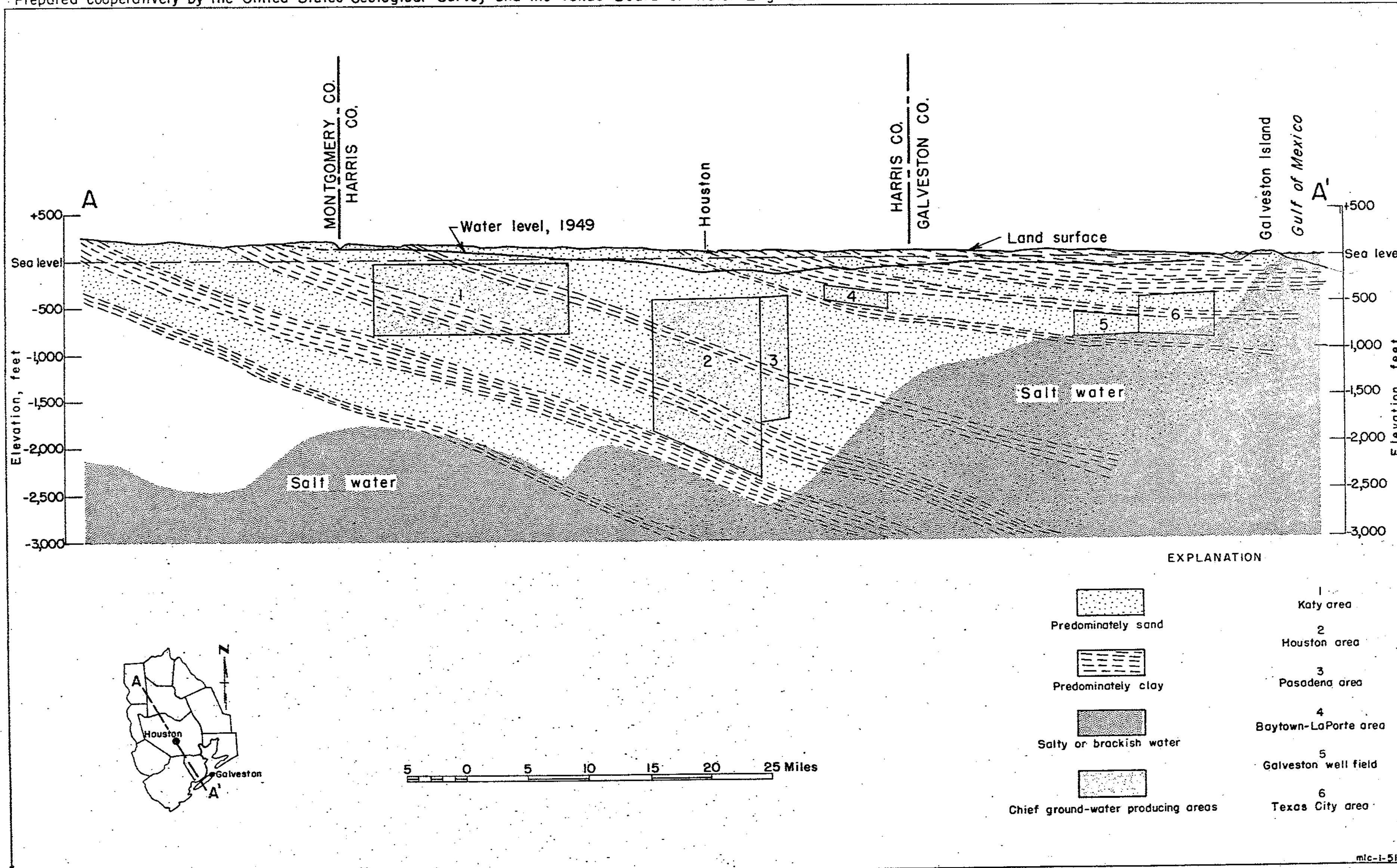

FIGURE 12.-Generalized cross section showing chief ground water-bearing formations in the Houston Gulf Coast region.

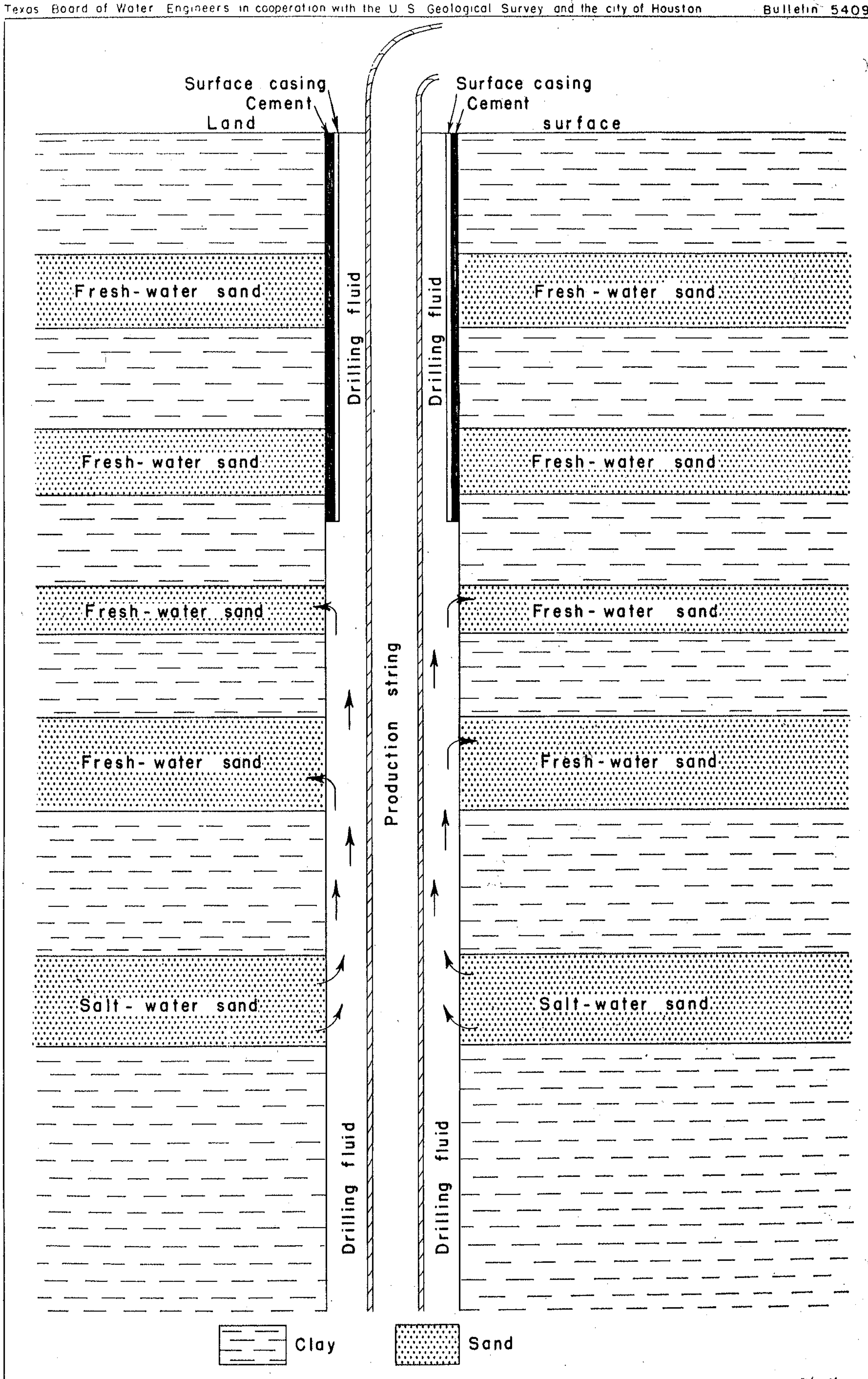

FIGURE 14.- Diagram of oil well showing possibility of circulation between sands in uncased portion of hole.

LITERATURE ABSTRACT D

GROUND SUBSIDENCE AT LONG BEACH, CALIFORNIA

PLANT ENGINEERING DEPARTMENT

LITERATURE ABSTRACT - D

GROUND SUBSIDENCE AT LONG BEACH, CALIFORNIA

BY: D. H. STORMONT

(THE OIL AND GAS JOURNAL - NOVEMBER 28, 1955)

Previous articles have indicated the ground subsidence which occurred at Long Beach, California, following the extended heavy oil pumpage will eventually total 27 feet. The area of settlement is a bowl shaped cavity approximately 20 square miles in size and includes the entire Long Beach harbor and industrial district.

The author states that a gigantic water flood using ocean water may be launched to save Long Beach from further sinking.

It would take the world's biggest flood--injection of a million barrels per day--to halt the destructive subsidence. Even that remedy would be 3 years in restoring reservoir pressures in Wilmington field and stabilizing the land surface.

For the land has already dropped several feet, and it's still sinking in the harbor area because of oil and gas withdrawals from Wilmington. The city has invested millions just to repair the damage. Dikes have been built to ward off an invasion of the Pacific Ocean. Producing facilities have been raised with earth fills.

Other areas of Long Beach, away from the center of oil production, are threatened unless corrective measures are taken. Engineers predict an ultimate subsidence of 4 feet in the downtown area. It will sink that much if producing activities in Wilmington aren't expanded beyond presently developed limits. And if the undeveloped southeastern part of the field is drilled, drained zones will be crushed by overlying rock and a drop of some 8 or 10 feet is expected.

Up to now the city has been engaged in a running battle to keep the Pacific from flooding harbor installations at high tide. Now engineers propose to use that sea water to prop up depleted reservoir rocks and hold the beach above tide level.

The Cause

They found that subsidence is definitely related to production of oil from the Tar, Ranger, and Terminal zones of Wilmington field. Empirical mathematical relationships between the depth of the depressed land area and the production of fluids from the field checked remarkably well for the past 9 years.

Production of one billion barrels of fluids from these zones has resulted in a cavity 22 feet deep at its center. The engineers said the epicenter can be expected to drop an additional 13 feet.

That is considerably more than was indicated by earlier studies, which concluded the center would sink only some 27 feet.

The latest study listed these possible causes of sinking:

1. Earth movements.
2. Surface loading and vibrations.
3. Reactions in shallow-water sands.
4. Fluid withdrawal from oil reservoirs and associated strata.

The first three possibilities were considered but for one reason or another they were believed to be of little or no importance.

On the other hand, they found that center of maximum subsidence tends to remain vertically above the geometric center of fluid withdrawals. The center of fluid withdrawal could not be determined accurately. But the approximate center has shifted to the southeast as production was extended in that direction.

Using material-balance principles, authors of the study report arrived at a cause-and-effect relationship between the depth of the depressed land area and the production of fluids. These revealed that "since 1947 the depth of subsidence has been a logarithmic function of the cumulative withdrawal of oil, the net vacated space in the oil reservoir rock, and the reservoir replacement volume (net vacated space plus volume of water influx)."

This relationship was found to hold true not only for the epicenter but also for 32 benchmarks in the sinking area.

What to Do About It

To halt the serious land drop, three steps were mentioned:

1. Stop oil production. California would lose the field which led the state in oil production last year.

2. Inject gas to restore pressure in the underground reservoirs.

3. Inject salt water into the partially depleted reservoirs.

Salt-water injection was recommended because sea water is readily available and sufficient volumes of gas are not. Its feasibility is being checked in a pilot flood which has been operating for some time.

A full-scale, coordinated water-injection program should result in a substantial increase in the ultimate recovery of oil, in addition to retarding and eventually stopping subsidence.

Since the process of compaction resulting from reservoir pressure decline is essentially irreversible, the restoration of pressure in depressured portions of the field would not raise the land surface any significant degree. Restoration of pressure, however, would arrest further settlement of the land and would cause the oil to have characteristics that are more desirable. Thus, the problem involves an important element of timeliness.

The epicenter of the sunken bowl is near the Southern California Edison Co. power plant on Terminal Island. And the current rate of subsidence there was shown to be about 1.5 feet annually.

If injection of 1,000,000 bbl. of sea water daily were started immediately, it would require 3 years to fill voids created by gas and fluids already withdrawn from the Tar, Ranger, and Terminal zones. And by then, the area would have sunk an additional 3 or 4 feet.

Action taken in the past to cope with subsidence has been to remedy the effects rather than eliminate the cause. Although foundations have been raised, earthen dikes constructed, land filled in, and relatively small-scale gas injection and water flood operations have been implemented, no major action of the magnitude necessary has been taken to prevent the subsidence directly. These facts and the impracticability of abandoning the field, or of injecting large volumes of gas, plus the cause-and-effect implication of the fluid withdrawal-subsidence correlation, lead to water flooding as the apparent solution of the problem.

Another interesting article on this subject by Messrs. Frank G. Miller and W. H. Somerton, titled Water Injection Measures to Halt Wilmington Sinking appeared in the December 19, 1955, issue of the Oil and Gas Journal.

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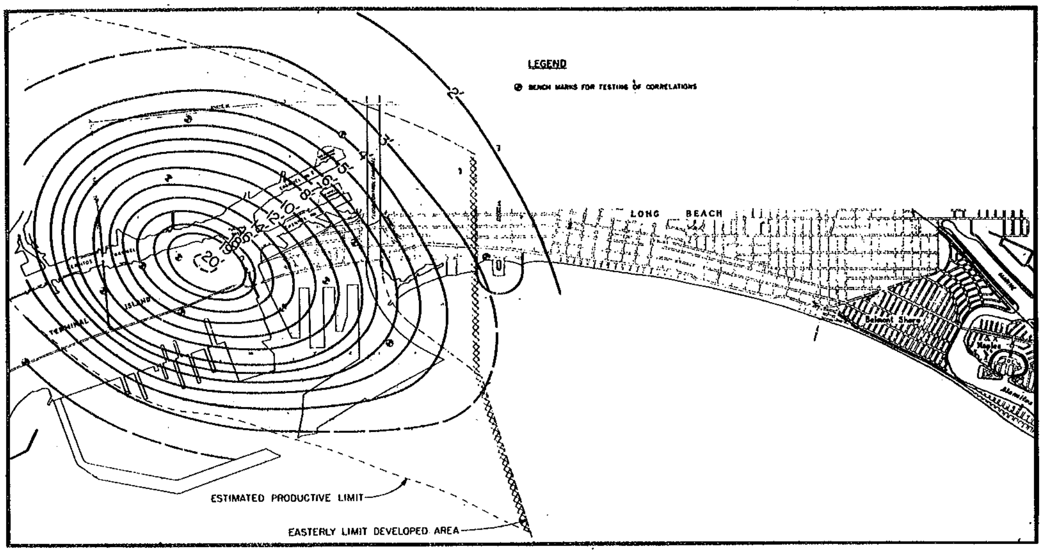
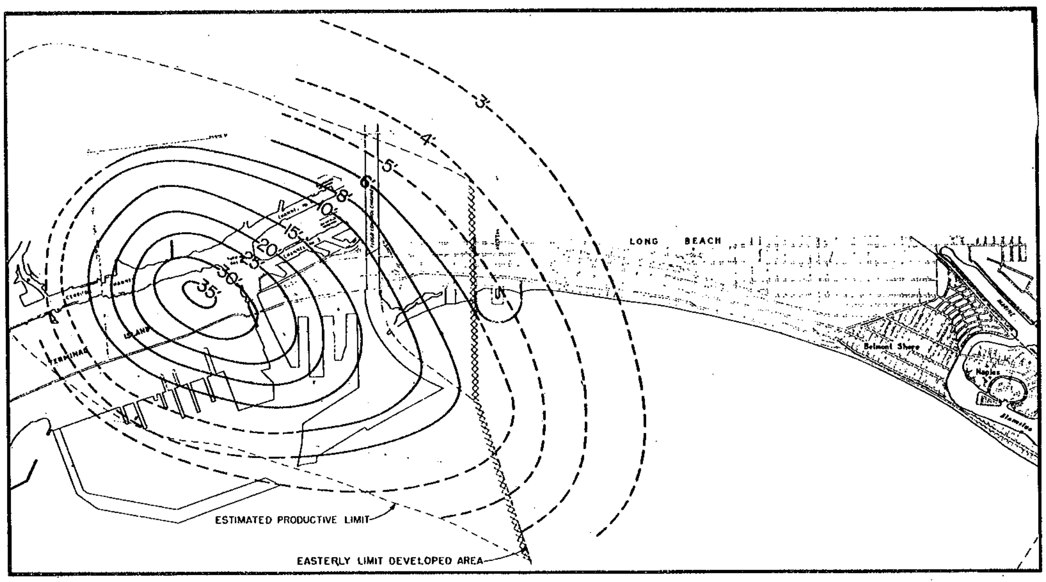
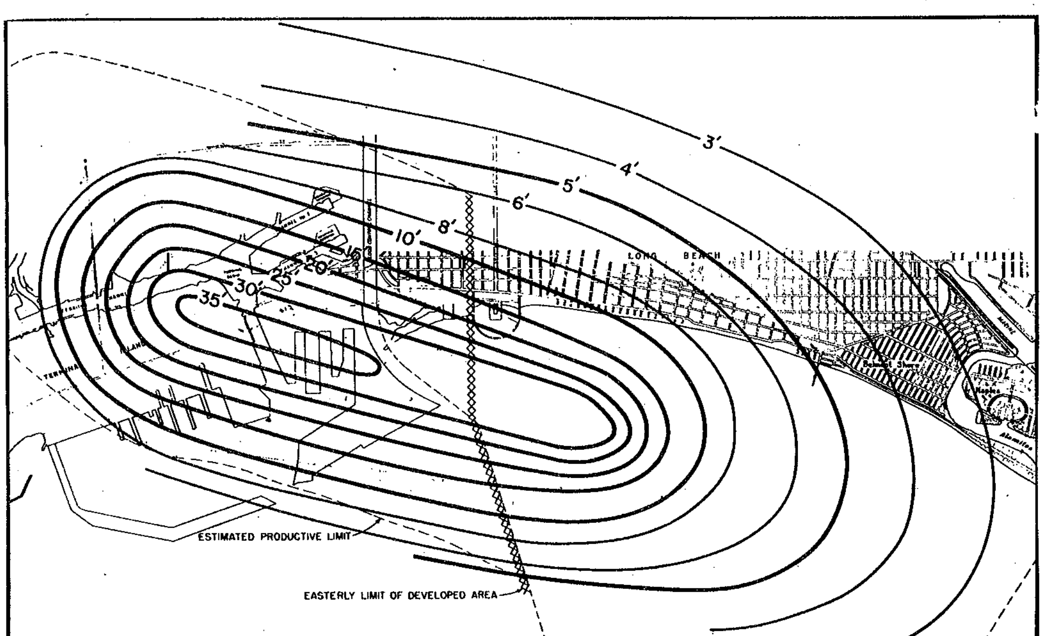
SUBSIDENCE CONTOURS - LONG BEACH, CALIFORNIA



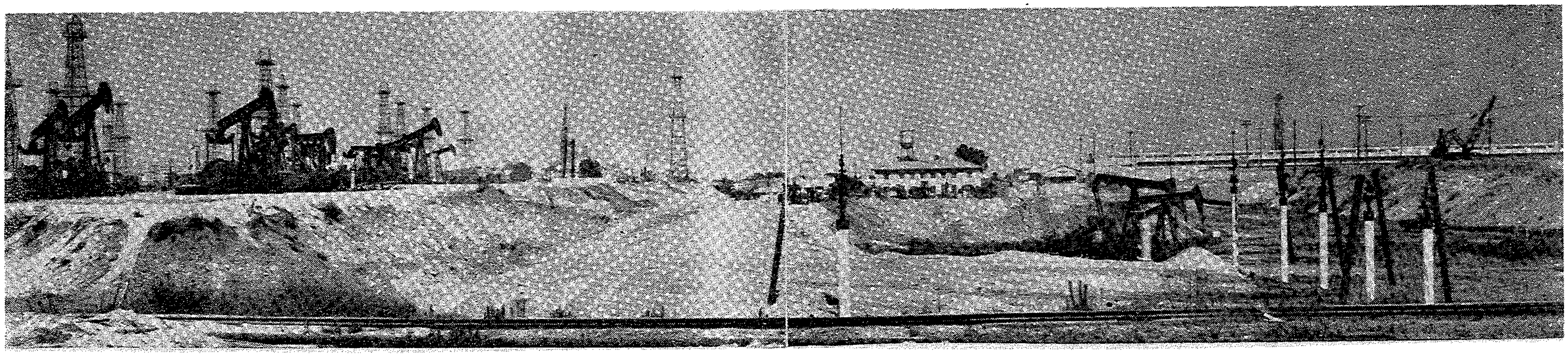
SUBSIDENCE contours in Wilmington oil field as of August 1, 1954. (Long Beach Harbor Department). Fig. 5.



SUBSIDENCE contours showing size and shape of ultimate subsidence bowl, predicted on basis of all further oil production from presently developed area of field. Fig. 6.



SUBSIDENCE contours showing size and shape of ultimate subsidence bowl, predicted on basis of future oil production from the presently developed southeastern area of the field. Fig. 7.



EFFECT OF SUBSIDENCE ON OIL WELL PUMPING OPERATIONS IN WILMINGTON OIL FIELD. GROUND LEVEL OF THE PUMPING WELLS ON THE LEFT HAS BEEN RAISED FROM THE LEVEL SHOWN IN THE PICTURE AT THE RIGHT. EXTENSIONS OF THE OIL WELL CASING APPEARING AS WHITE VERTICAL POSTS WILL BE UNDERGROUND WHEN THE LAND IS FILLED IN.

LITERATURE ABSTRACT E

MEXICO CITY IS SINKING

PLANT ENGINEERING DEPARTMENT

LITERATURE ABSTRACT - E

MEXICO CITY IS SINKING

(LIFE MAGAZINE, NOVEMBER 17, 1952)

(SCIENCE NEWS LETTER, MAY 23, 1953)

Mexico City is sinking and as its streets sag and buildings buckle, ancient flood troubles return to plague the capital. Ever since the century began, one of the major cities of the Western hemisphere, Mexico City, has been sinking. The ground level has dropped as much as 16 feet and is now sinking at a rate of 20 inches a year. Streets have sagged, buildings buckled and the city's old floor troubles have returned.

A commission went back in its investigation to the conquistadores. Mexico City was originally built on an island in Lake Texcoco, and to overcome floods the Spaniards built great drainage sewers and drained the lake. Then, to get water, wells were drilled into the subsoil. Sucked dry by 9,000 wells, the subsoil started to collapse and the ground to fall. In the rainy season, water from the drainage and sewage systems, which should run off, now backs up above ground level to flood the sinking city.

Several excellent photographs accompanying the article illustrate the effect of subsidence on the Cathedral of Mexico (down 11 feet); Bronze Horse monument (down 16 feet); a multi-story office building where a 3 foot wide wedge shaped opening now separates it from the adjacent structure; tilting of a church tower in the downtown area; and many examples of damaged apartment houses in the tenement section.

In the Science News Letter article on this same subject considerable data is listed covering the use of rehydration water wells to abate the ground subsidence.

The sinking that has lowered certain sections of the city 20 feet since 1900 is due to the fact that the clay subsoil of the Valley of Mexico is highly compressible, in certain zones being composed of 85% water and 15% solid material. Comparatively, for example, the subsoil of Boston is composed of 40% to 50% water and 60% to 50% of solid material.

Mexican hydraulic engineers call this situation "depression", or a lack of pressure. They plan to restore the equilibrium by means of newly-installed rehydration wells, pumping the overflow rain water during the rainy season, from June to September, down into the subsoil.

This will have the further effect of solving one of the city's major problems, flooding of the lowest areas during heavy rainfalls. Last year, after prolonged rainfall, many downtown streets were like canals and were negotiable only by small boats. The water overflowed onto the sidewalks and into stores, causing hundreds of thousands of pesos of damage in ruined merchandise, to say nothing of complete disruption of transportation in those areas.

Sometimes the modern inhabitants feel that the Aztecs might have picked a better location for their capital city than situating it in the middle of a lake. Indian engineers struggled with the problem before the Spaniards' arrival, and constructed dikes and canals to keep the waters under control. Their histories record at least three major inundations before Cortes conquered their empire. In the period from 1517 to 1900, 13 major floodings are recorded, some so great that inhabitants moved out and up into higher levels and waited for the waters to subside.

One of the most striking aspects of the sinking problem in the past has been the difficulties in construction of large buildings in the Mexican capital. With expert help from engineers from all over the world, modern Mexican buildings are now erected on "floating foundations" that allow the buildings to adapt themselves to the fall of the ground level, and in the last ten years, for the first time, the sky line is being marked with buildings over 15 stories high.

Of course, the "sinking city" has its romantic note. As the rest of the city sinks in varying degrees, the Monument to Independence - a golden angel atop a high marble column - has been rising. And no one asks or wants to know the "scientific" explanation for this comforting phenomenon.

JBW:ag
January 17, 1958

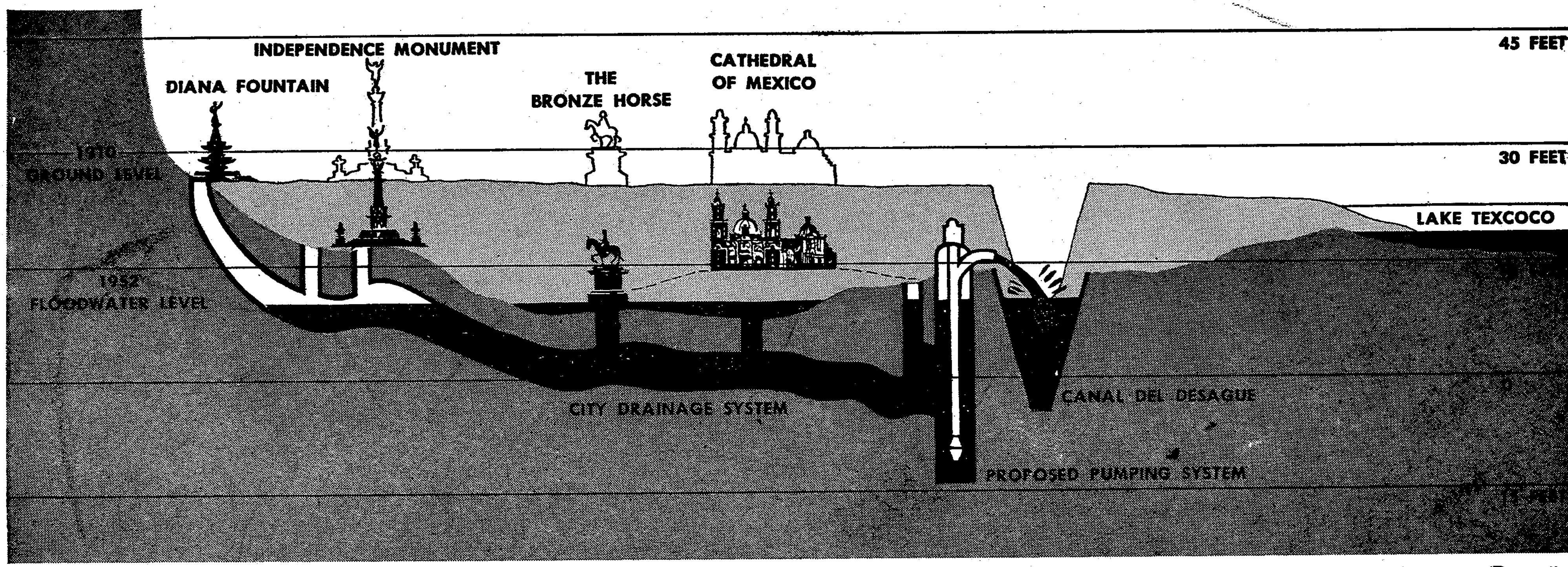


CHART OF DESCENT shows effects on city landmarks. Diana Fountain, on firm ground at foot of hill, has kept its level while Bronze Horse, erected on soft subsoil of drained lake bed, has sunk 16 feet to flood level. Cathedral, on higher ground at a distance (*dotted line*), has sunk 11 feet. Main drainage (Desagüe) canal, having sunk less, is now too high to receive sewer system discharge. Work has begun on pumping system to lift flood waters (shown in blue) into canal.