TEXAS WATER DEVELOPMENT BOARD

REPORT 188

LAND-SURFACE SUBSIDENCE IN THE HOUSTON-GALVESTON REGION, TEXAS

By

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U.S. Geological Survey

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ABSTRACT

The pumping of large amounts of ground water in the Houston-Galveston region, Texas, has resulted in water-level declines of as much as 200 feet (61 meters) in wells completed in the Chicot aquifer and as much as 325 feet (99 meters) in wells completed in the Evangeline aquifer during 1943-73. The maximum average annual rates of decline for 1943-73 were 6.7 feet (2.0 meters) in the Chicot aquifer and 10.8 feet (3.3 meters) in the Evangeline aquifer. During 1964-73, the maximum rates were 10 feet (3.0 meters) in the Chicot and 17.8 feet (5.4 meters) in the Evangeline. The declines in artesian pressures have resulted in pronounced regional subsidence of the land surface.

The center of subsidence is at Pasadena, where as much as 7.5 feet (2.3 meters) of subsidence occurred between 1943 and 1973. More than 1.0 foot (0.3 meter) of subsidence occurred at Pasadena between 1906 and 1943. The maximum amount of subsidence during 1964-73 was about 3.5 feet (1.1 meters).

In the southern part of Harris County, about 55 percent of the subsidence is a result of compaction in the Chicot aquifer. The area in which subsidence is 1 foot (0.3 meter) or more has increased from about 350 square miles (906 square kilometers) in 1954 to about 2,500 square miles (6,475 square kilometers) in 1973.

Estimates of subsidence are based on the amout of water level decline, the thickness of the clay, and the compressibility of the clay. At Seabrook, it is estimated that for each 1 foot (0.3 meter) of average water-level decline, 1 foot (0.3meter) of clay would compact 0.000031 foot (0.00094 centimeter). At Seabrook, for 1 foot (0.3 meter) of water-level decline, 0.0248 foot (0.756 centimeter) of subsidence would occur.

Planned use of surface water instead of ground water will probably result in some recovery of artesian pressures. If pressure recovery occurs the rate of subsidence should decrease substantially in the more critical areas.

LAND-SURFACE SUBSIDENCE IN THE HOUSTON-GALVESTON REGION, TEXAS

INTRODUCTION

Land-surface subsidence has become critical in parts of the Houston-Galveston region of Texas. Some low-lying areas along Galveston Bay are subject to inundation by normal tides, and an even larger part of the region may be subject to catastrophic flooding by hurricane tides. The Houston-Galveston region, as described in this report, includes all of Harris and Galveston Counties and parts of Brazoria, Fort Bend, Waller, Montgomery, Liberty, and Chambers Counties. Figure 1 shows the principal areas of ground-water withdrawals in the region and the average rate of pumping in 1972.

Several reports have described land-surface subsidence as a result of compaction of fine-grained material in the subsurface (Winslow and Doyel, 1954; Winslow and Wood, 1959; and Gabrysch, 1969). The compaction is caused by loading due to pressure declines associated with the removal of subsurface fluids, principally water, oil, and gas. These reports and other reports listed in the references describe the geologic and hydrologic conditions resulting in land-surface subsidence. A generalized cross section of the hydrologic system is shown on Figure 2. The Chicot and Evangeline aquifers furnish all of the ground water pumped in the Houston-Galveston region.

For those readers interested in using the metric system, metric equivalents of English units of measurements are given in parentheses. The English units used in this report may be converted to metric units by the following conversion factors:

From		Multiply By	To Obtain	
Unit	Abbreviation		Unit	Abbreviation
acre	—	0.004047	square kilometer	km^2
foot	ft	0.3048 30.48	meter centimeter	m cm
million gallons per day	mgd	0.04381	cubic meter per second	m^3/s
square mile	mi^2	2.590	square kilometer	km^2

DEVELOPMENT OF GROUND WATER IN THE HOUSTON-GALVESTON REGION

Houston Area

In 1887, when the city of Houston purchased a private water-supply company, the demand for water for municipal supply was 1 to 2 mgd (0.04 to 0.09 m^3/s). The demand grew steadily, and in 1972, the Houston Water Department used 164 mgd (7.2 m^3/s) of ground water and about 58 mgd (2.5 m^3/s) of treated surface water.

In 1973, the water department increased the use of surface water to 63 mgd (2.8 m^3/s) and decreased the use of ground water to 156 mgd (6.8 m^3/s). Prior to 1954, at which time the ground-water supply was supplemented by surface water from Lake Houston, the total public supply was obtained from the ground-water reservoirs. Public supply is the largest use of ground water in the Houston area; in 1972, only 11 mgd (0.5 m^3/s) of a total of 195 mgd (8.5 m^3/s) pumped in the Houston area was used for purposes other than public supply.

Pasadena Area

Pumping of ground water for industrial use in the Pasadena area began near the end of World War I and grew steadily until 1936, when annual pumpage was about 15 mgd (0.5 m^3/s). In 1937, the construction of a paper mill increased the pumping rate to 30 mgd (1.3 m^3/s). Production increased rapidly during and following World War II.

Surface water from Lake Sheldon and the San Jacinto River was brought into the area in 1942, but the amount of surface water used was less than 20 mgd (0.9 m^3/s) until Lake Houston was completed in 1954. In 1953, 87 mgd (3.8 m^3/s) of ground water was used in the area. In 1972, 120 mgd (5.3 m^3/s) of ground water and 82 mgd (3.6 m^3/s) of surface water was used. In

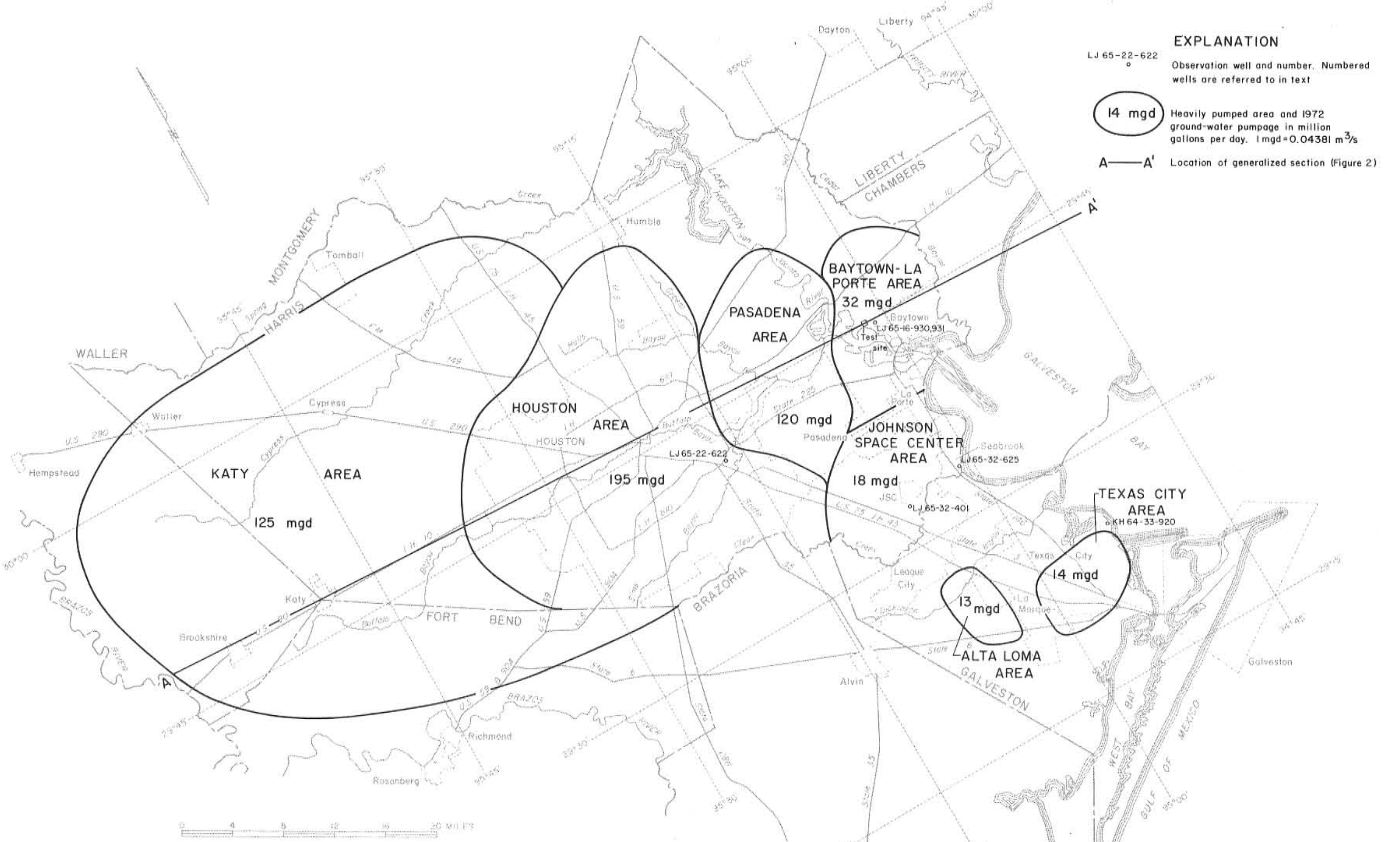

Figure 1

Locations of Principal Areas of Ground-Water Withdrawals and Average Rates of Pumping in 1972

Base from Texas Highway Department county highway maps

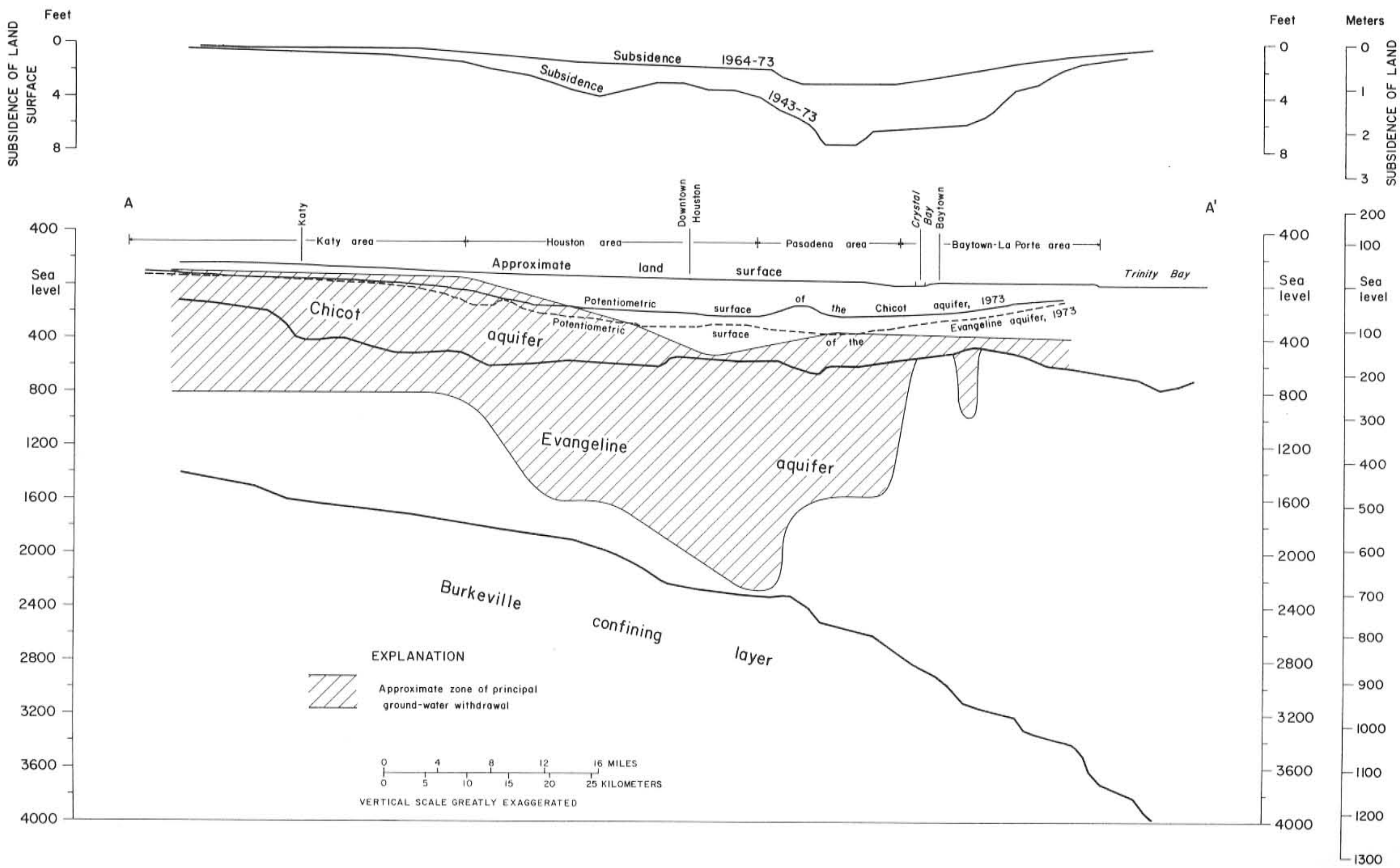

Figure 2

Generalized Hydrologic Section in the Houston-Galveston Region

1972, about 104 mgd (4.6 m^3/s) of ground water was pumped for industrial use.

Katy Area

. All water used in the Katy area is ground water, and more than 88 percent of the water pumped is used for rice irrigation. Rice irrigation in the Katy area began in the 1890's, increased gradually until about 1935, then increased rapidly until 1954 when 64,600 acres (216 square kilometers) were irrigated. Acreage limitations caused a decline in the acreage of rice planted in 1955 and 1956, but the acreage increased again as a result of additional allotments and allotment transfers from other coastal areas. In 1956, 40,700 acres (165 square kilometers) of rice were planted, and in 1972, 48,800 acres (197 square kilometers) were planted.

The total amount of water used for rice irrigation is related not only to the acreage planted, but also to precipitation, seepage, evaporation and other losses, and individual farm practices.

Ground-water pumping increased from about 1 mgd (0.04 m^3/s) in 1893 to about 60 mgd (2.6 m^3/s) in 1946, and then rapidly increased to about 160 mgd (7.0 m^3/s) in 1954. In 1972, pumping in the area was 125 mgd (5.5 m^3/s), of which 110 mgd (4.8 m^3/s) was for rice irrigation.

Baytown-LaPorte Area

Ground-water pumping from large-capacity industrial wells in the Baytown-LaPorte area began about 1918. The pumping rate increased from about 5 mgd (0.2 m^3/s) in 1919 to about 9 mgd (0.4 m^3/s) in 1927, averaged about 15 mgd (0.7 m^3/s) from 1928 to 1946, then gradually increased to about 32 mgd (1.4 m^3/s) in 1972. In 1972, 24 mgd (1.1 m^3/s) of the ground water pumped was for industrial purposes.

Alta Loma Area

The city of Galveston began pumping from a well field in the Alta Loma area in 1894. Withdrawals gradually increased from about 2 mgd (0.09 m^3/s) in 1896 to nearly 5 mgd (0.2 m^3/s) in 1937. Between 1937 and 1944, the withdrawals increased to about 12 mgd (0.5 m^3/s) and remained at about that rate until 1972. In 1972, ground-water pumping increased to 13 mgd (0.6 m^3/s). In August 1973, the use of surface water from Lake Houston began at a rate of 6 mgd (0.3 m^3/s).

Texas City Area

Ground-water pumping in the Texas City area increased from less than 2 mgd (0.09 m^3/s) in 1930 to about 12 mgd (0.5 m^3/s) in 1940, then increased to about 24 mgd (1.1 m^3/s) in 1944 and 1945. Withdrawals decreased slightly at the end of World War II, then decreased rapidly after 1948 when surface water from the Brazos River was brought into the area. Ground-water withdrawals averaged about 10 mgd (0.4 m^3/s) from 1950 to 1960, then gradually increased to 14 mgd (0.6 m^3/s) in 1972. About 53 percent of the water pumped in 1972 was for industrial use.

DECLINES IN WATER LEVELS

As a result of large amounts of water having been pumped from the ground, the pressure in the artesian aquifers has declined. This decline in pressure, reflected by lower water levels in wells, is the principal cause of regional land-surface subsidence. Figures 3 and 4 show the declines in water levels for 1964-73 and 1943-73 in wells tapping the Chicot aquifer, and Figures 5 and 6 show the declines in water levels for the same periods in wells tapping the Evangeline aquifer. These periods correspond to periods of releveling of lines of bench marks by the National Geodetic Survey.

In the Pasadena and Baytown-LaPorte areas, where ground-water withdrawals are heavily concentrated, the decline of water levels in wells completed in the Chicot aquifer was about 200 feet (61 meters) during 1943-73. The maximum average rate of decline during 1943-73 was about 6.7 feet (2.0 meters) per year. During 1964-73, the center of the area of maximum decline shifted eastward into the Baytown-LaPorte area, where as much as 90 feet (27 meters) of water-level decline occurred. The maximum average rate of decline for the Chicot aquifer during 1964-73 was 10 feet (3.0 meters) per year.

Water levels in wells completed in the Evangeline aquifer declined as much as 160 feet (48.8 meters) between 1964 and 1973, and as much as 325 feet (99 meters) between 1943 and 1973. The maximum average rate of decline during 1964-73 was about 17.8 feet (5.4 meters) per year; the maximum average rare during 1943-73 was about 10.8 feet (3.3 meters) per year.

The maps showing water-level declines in the Evangeline aquifer were constructed from water-level measurements in multiscreened wells. The maps showing water-level declines in the Chicot aquifer are based on measurements in multiscreened wells in the northwest

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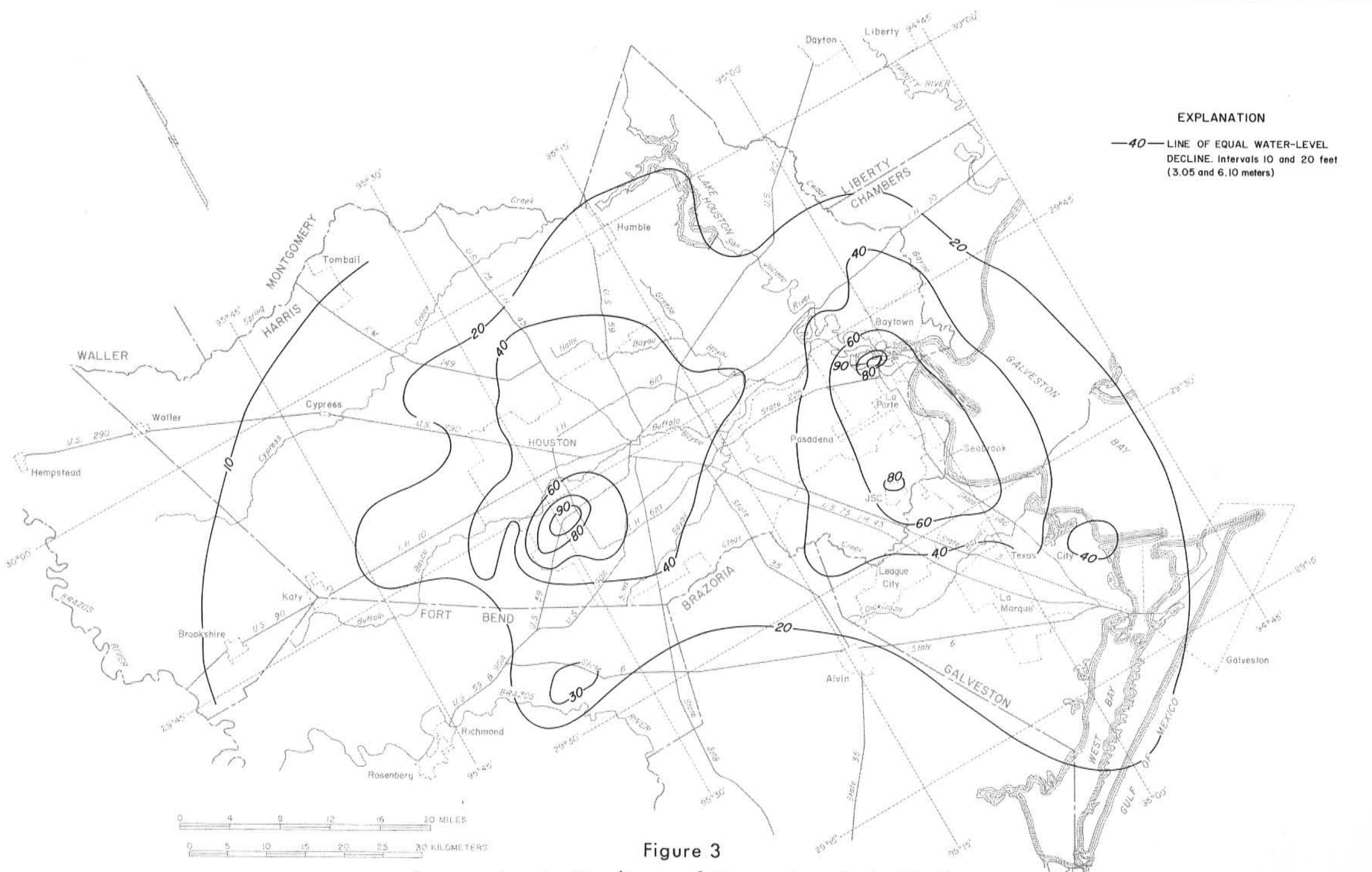

Figure 3

Approximate Declines of Water Levels in Wells Completed in the Chicot Aquifer, 1964-1973

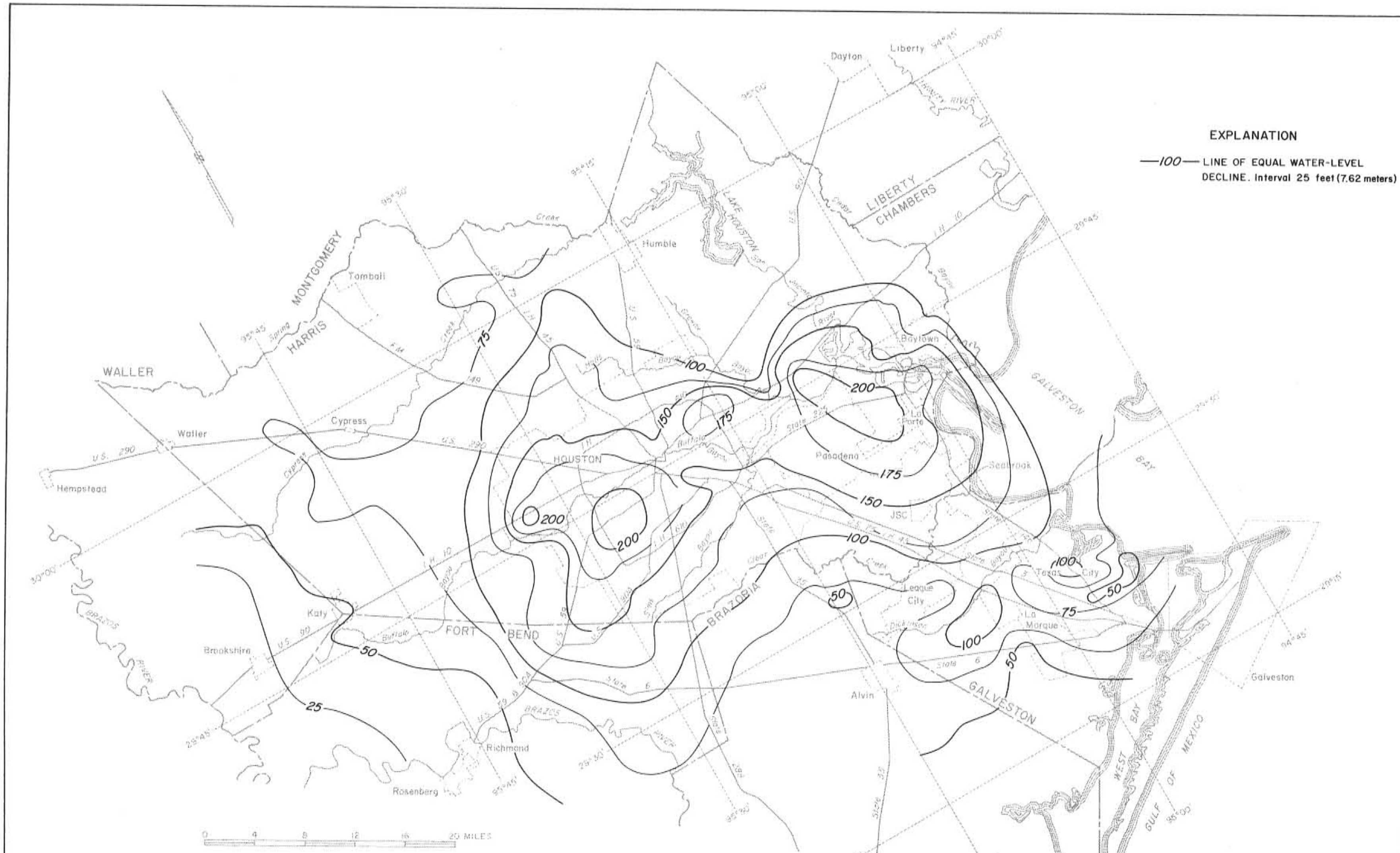

Figure 4
Approximate Declines of Water Levels in Wells Completed in the Chicot Aquifer, 1943-1973

Base from Texas Highway Department county highway maps

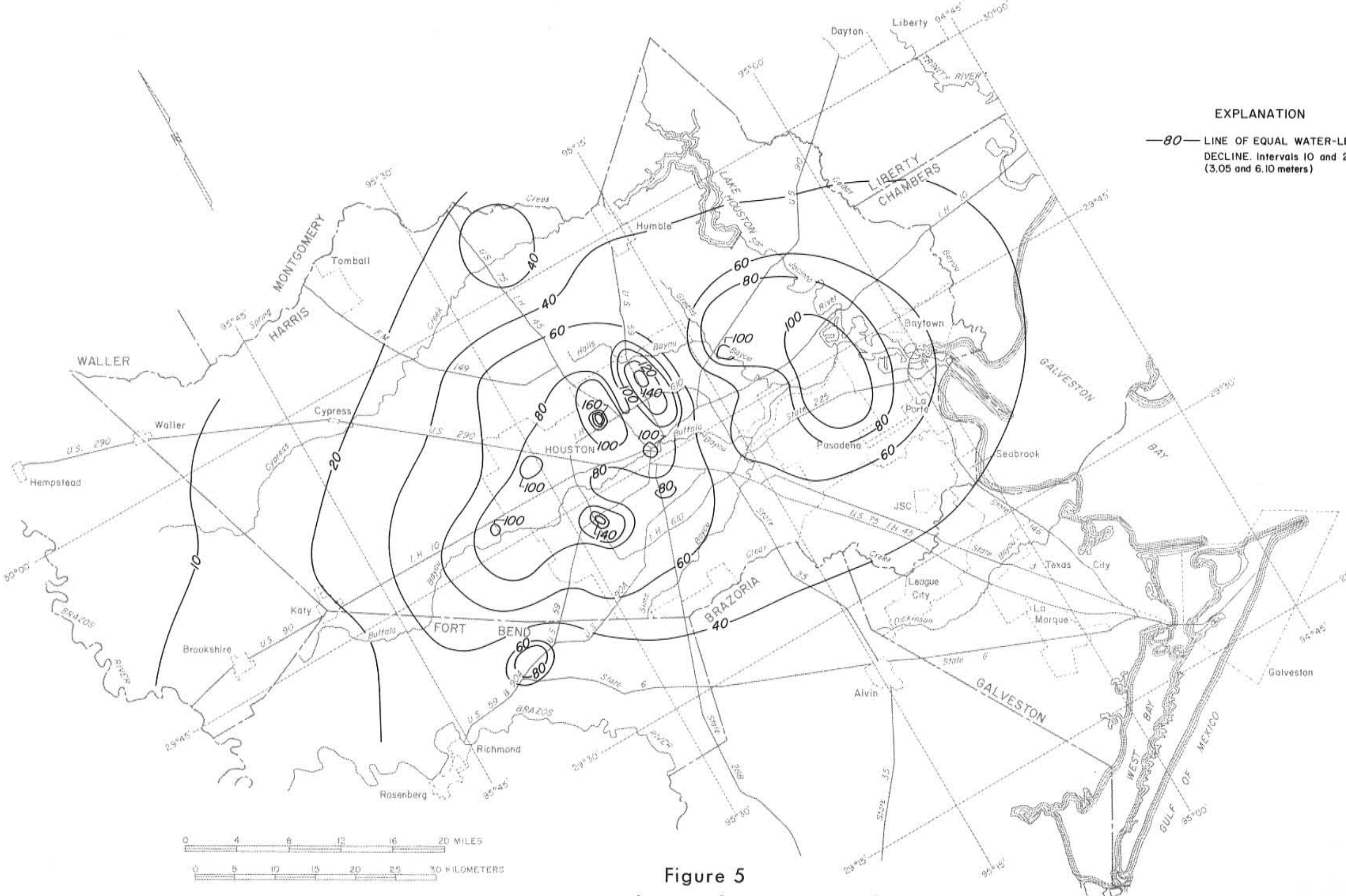

Figure 5

Approximate Declines of Water Levels in Wells Completed in the Evangeline Aquifer, 1964-1973

Base from Texas Highway Department county highway maps

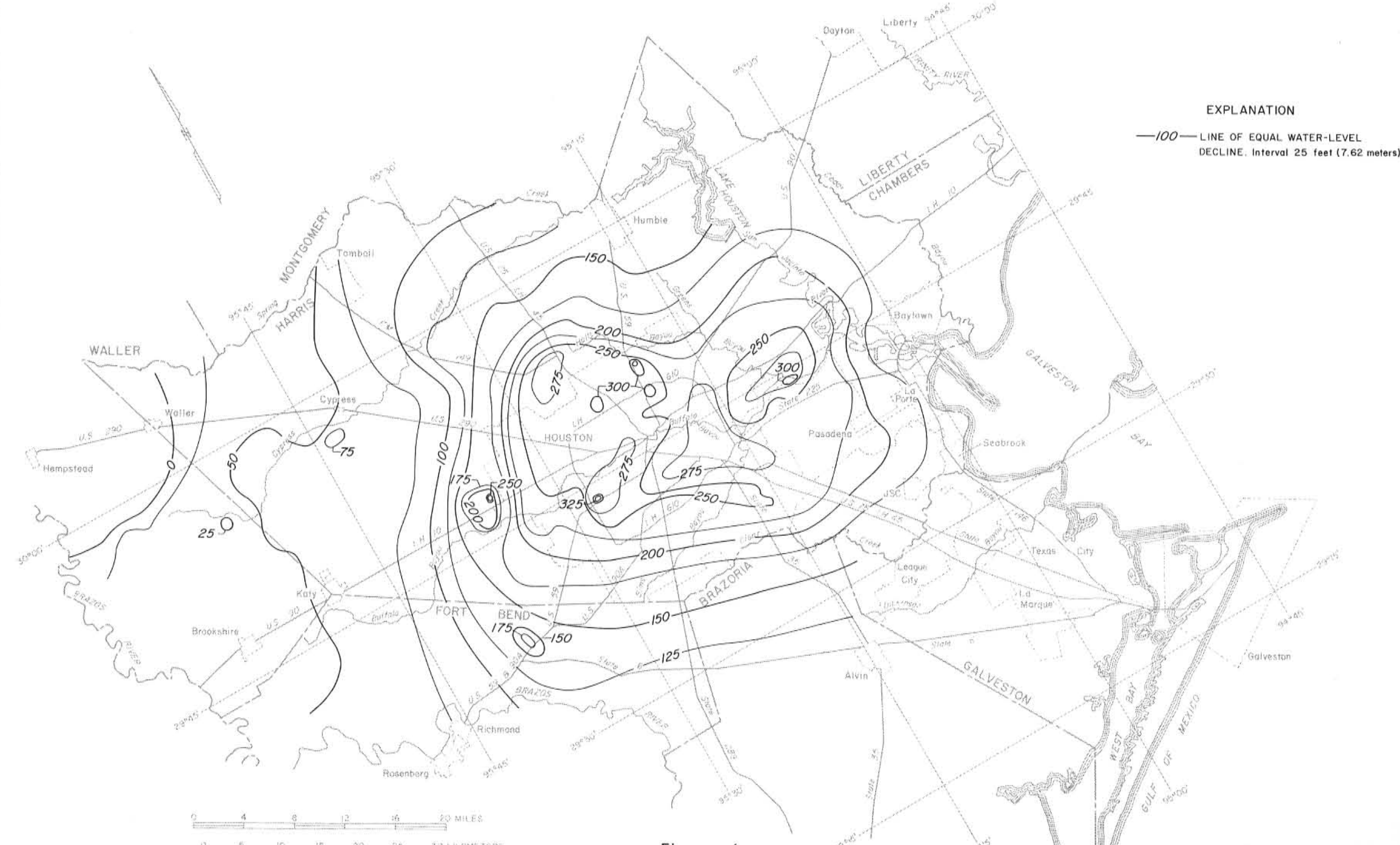

Figure 6
Approximate Declines of Water Levels in Wells Completed in the Evangeline Aquifer, 1943-1973

Base from Texas Highway Department county highway maps

half of the region and on measurements in wells completed in the basal sand of the Chicot aquifer in the southeast half of the region.

The water-level declines shown on the map are composite average declines in artesian pressure. Not every sand at a particular location exhibits the same amount of pressure decline; therefore, not every clay layer has the same amount of loading. Figure 7 shows the potentiometric profile and depth to water in wells completed at different depths at Baytown. The water level for the depth interval 390-500 feet (119-152 meters) was used in determination of the declines shown on Figures 3 and 4.

COMPACTION AND LAND-SURFACE SUBSIDENCE

The withdrawal of water from an artesian aquifer results in an immediate decrease in hydraulic pressure. With a reduction in pressure, an additional load, equal to the reduction in pressure, is transferred to the skeleton of the aquifer. The pressure difference between the sands and clays causes water to move from the clays to the sands, and this in turn results in compaction of the clays. Because the clays are mostly inelastic, most of the compaction is permanent. Less than 10 percent rebound can be expected from a total recovery of artesian pressure.

Figures 8 and 9 show the amount of subsidence in Houston-Galveston region for 1964-73 and 1943-73. These maps were constructed from data obtained from the National Geodetic Survey leveling program, supplemented by data from local industries. Some subsidence occurred before 1943, but the amount is difficult to determine. Winslow and Doyel (1954, p. 18)stated:

"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, Louisiana. During that 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."

An approximation of the amount and extent of the subsidence that occurred between 1906 and 1943 is shown on Figure 10. The maximum amount of subsidence shown on Figure 10 occurred in the Goose Creek oil field. Pratt and Johnson (1926) concluded that the withdrawal of oil and gas from the Goose Creek field had caused 3.25 feet (1.0 meter) of subsidence between 1918 and 1925. Data to determine subsidence since 1925 are not available. Pratt and Johnson observed that subsidence was restricted to the area of production.

Land-surface subsidence resulting from the pumping of ground water first occurred in the Texas City area, where minor discrepancies in altitude data were noticed between 1938 and 1940 (American Oil Company, 1958). Before subsidence was definitely known, the search for an outside source of water was begun. After recognition of the subsidence problem, efforts were made to obtain water for industrial use from outside the area, and the delivery of surface water from the Brazos River began in 1948. Ground-water pumping for all uses decreased from about 24 mgd (1.1 m^3/s) in 1948 to about 10 mgd (0.4m^3/s) in 1952.

The decrease in ground-water withdrawals resulted in partial recovery of artesian pressures in the aquifers and in a greatly decreased rate of subsidence. Only about 0.2 foot (6.1 centimeters) of subsidence occurred at Texas City in each of the two 5-year periods 1954-59 and 1959-64. The indicated rate of subsidence during those two periods was about 0.04 foot (1.2 centimeters) per year compared to a reported rate of as much as 0.366 foot (11.2 centimeters) per year between 1940 and 1952.

Since 1964, a gradual increase in ground-water pumping in the Texas City area and the effects of pumping outside the area have caused water levels to decline to below their 1948 levels. An accelerated rate of land-surface subsidence is now occurring. Figure 8 shows that about 1.0 foot (0.3 meter) of subsidence occurred between 1964 and 1973, which is a rate of about 0.11 foot (3.4 centimeters) per year.

The center of the largest subsidence "bowl" in the region is in the vicinity of the Houston Ship Channel at Pasadena. As much as 7.5 feet (2.3 meters) of subsidence occurred between 1943 and 1973 (Figure 9). The water level declines due to pumping before 1937 and between 1937 and 1943 caused subsidence in excess of 1.0 foot (0.3 meter) between 1906 and 1943. The maximum amount of subsidence between 1964 and 1973 was about 3.5 feet (1.1 meters); the average maximum rate of subsidence was about 0.4 foot (12.2 centimeters) per year.

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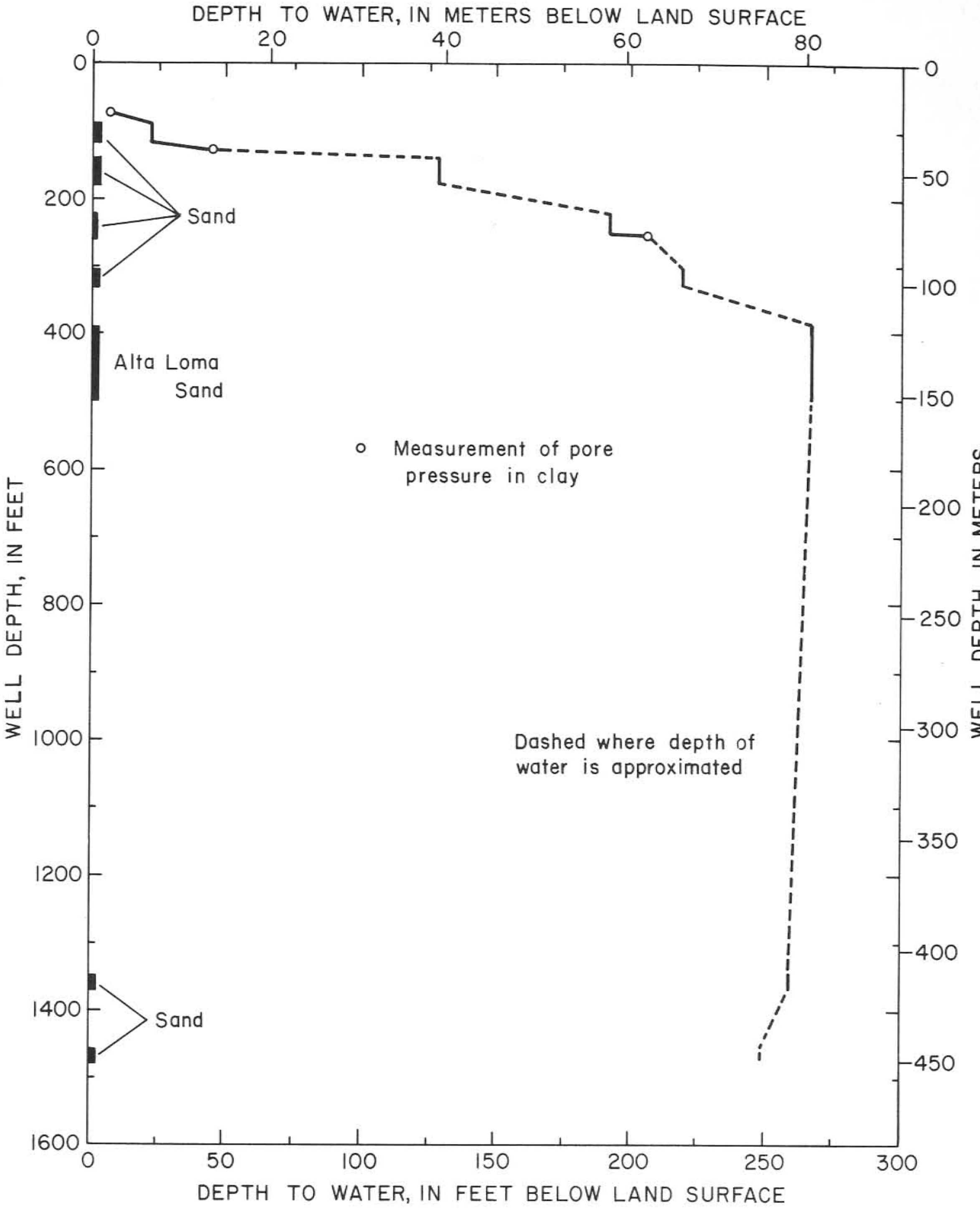

Figure 7
Depth to Water in Wells Versus Depth of Well Completion at Baytown, March 1974

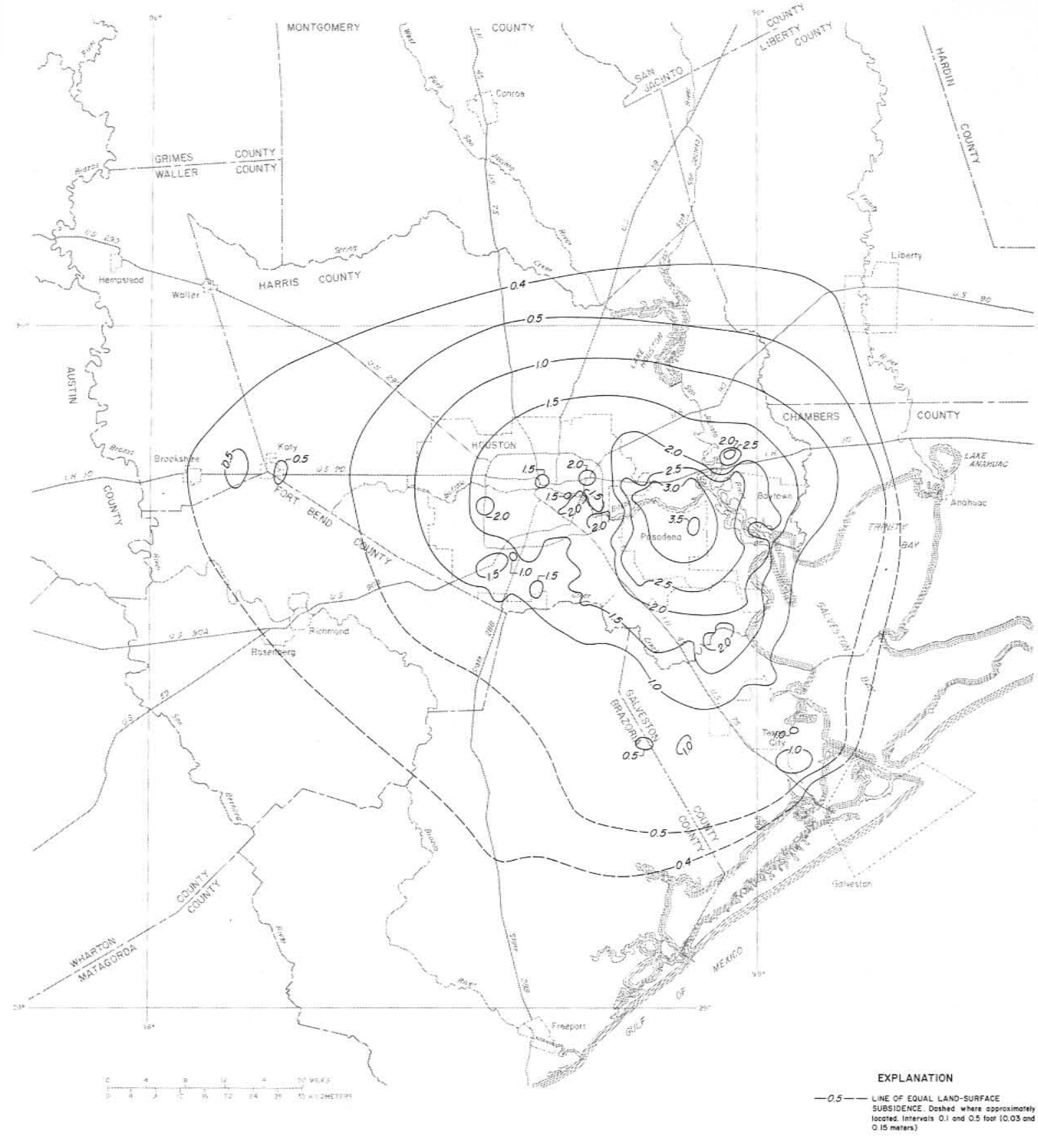

Figure 8
Subsidence of the Land Surface, 1964-1973

Base from Texas Highway Department county highway maps

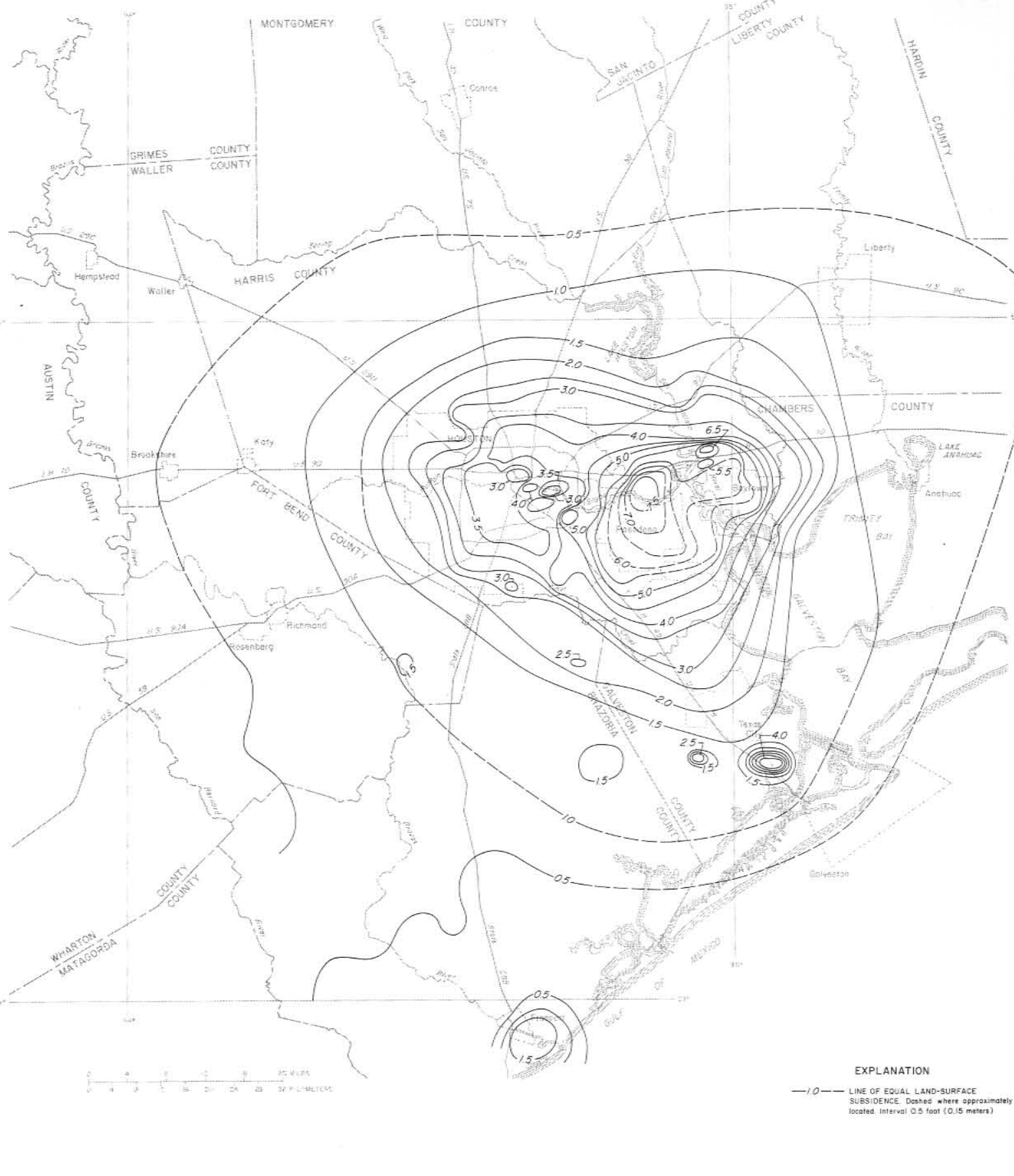

Figure 9
Subsidence of the Land Surface, 1943-1973

Base from Texas Highway Department county highway maps

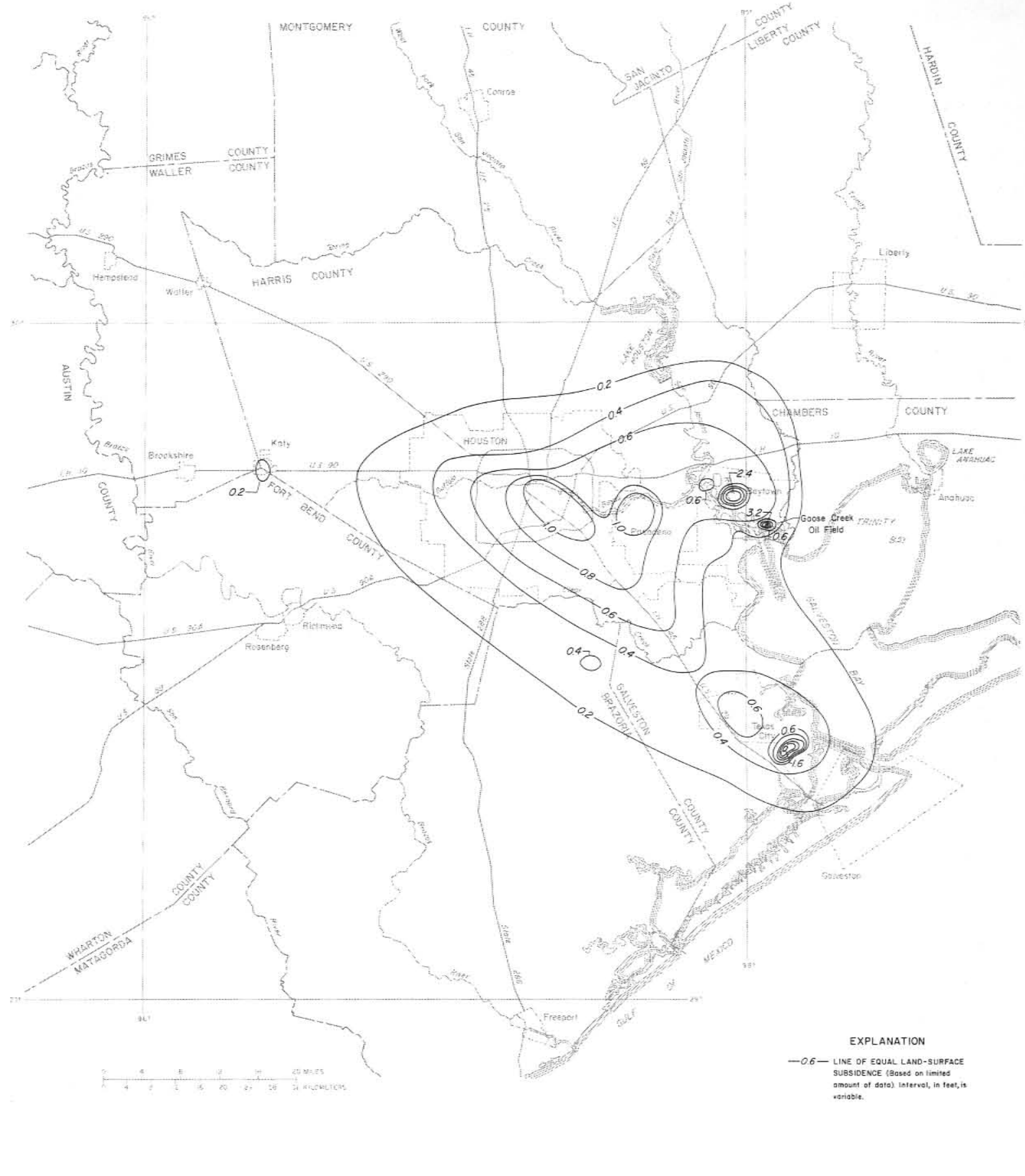

Figure 10
Approximate Subsidence of the Land Surface, 1906-1943

Base from Texas Highway Department county highway maps

The area of active subsidence is expanding. Between 1943 and 1954, about 350 square miles (906 square kilometers) had subsided 1 foot (0.3 meter) or more; by 1964, 1,3550 square miles (3,497 square kilometers) had subsided 1 foot (0.3 meter) or more. By 1973, 2,500 square miles (6,476 square kilometers) had subsided 1 foot (0.3 meter) or more. About 4,700 square miles (12,173 square kilometers) subsided 0.5 foot (0.15 meter) or more between 1943 and 1973.

Except at low altitudes near the waterfront, subsidence is not generally recognized because it is regional in nature. The changes in altitudes are not abrupt, and subsidence has not caused widespread structural damage.

Under the several ground-water investigation programs in the Houston-Galveston region, borehole extensometers (compaction recorders) have been installed to monitor compaction. To date (1974), seven such monitors have been installed at five sites, and two additional monitors at two other sites are planned. The first monitor was installed on the east side of Houston in 1958 in an abandoned well. The well failed in 1962 and the monitor was destroyed. The second monitor was installed in 1962 at the Johnson Space Center and has been maintained since then. The compaction monitored at this site and the subsidence are shown in Figure 11. Five monitors were installed in 1973 at four sites: east of Houston; west of Baytown; at Seabrook; and at Texas City. The compaction recorded at these sites is shown on Figure 12.

At the Johnson Space Center in southern Harris County, the land surface subsided about 2.12 feet (0.65 meter) between 1964 and 1973 (Figure 11). Compaction of the material between the land surface and a depth of 750 feet (229 meters) was measured as 1.17 feet (0.357 meter) during the same period. Therefore, 55 percent of the subsidence resulted from compaction of the upper 7500 feet (229 meter) of material. The monitor at this site is recording all compaction in the Chicot aquifer.

Figure 12b shows the amount of compaction measured at two depth intervals at Baytown. The upper curve shows that 0.038 foot (1.16 centimeters) of compaction, from land surface to a depth of 431 feet (131 meters), occurred from July 24, 1973, until April 5, 1974. The lower curve shows that 0.088 foot (2.68 centimeters) of compaction, from land surface to a depth of 1,475 feet (450 meters), occurred during the same period. The estimated rate of subsidence at the site during 1964-73 was 0.19 foot (5.79 centimeters) per year.

On the basis of this short period of record (8-1/2 months) at Baytown, about 28 percent of the subsidence is due to compaction between the land surface and a depth of 431 feet (131 meters), 37 percent is due to compaction from 431 to 1,475 feet (131 to 450 meters), and 35 percent is due to compaction below 1,475 feet (450 meters).

Detailed analysis of subsidence, artesian-pressure declines, total clay-bed thickness, individual clay-bed thickness, clay properties, and pressure profiles at sites at Baytown, Texas City, and Seabrook indicates the following:

1. The change in pressure in both sand and clay layers varies from one depth to another; measurement of a single well does not necessarily define the changes in pressure in the entire aquifer.

2. The average clay-bed thickness is about 15 feet (4.6 meters). The hydraulic conductivity (permeability) of the material is such that 90 percent of the hydrodynamic compaction of the clay due to a decline in artesian pressure will occur in about 5 years. If secondary effects, such as a change in the clay structure, are neglected, 90 percent of the subsidence due to a particular pressure decline would occur within about 5 years after the pressure had declined. On the basis of data and calculations, 80 to 85 percent of the expected subsidence due to hydrodynamic compaction caused by pressure decline to date has already occurred. Although secondary or nonhydrodynamic effects are probably sizeable in some parts of the world, there is no evidence that such effects would contribute more than a few percent of the total amount of subsidence in the Houston-Galveston region.

3. The specific-unit compaction value, which is the compaction of deposits per unit of thickness per unit of increase in applied stress during a specified time period, is a useful tool in predicting subsidence for small changes in applied stress. If the amount of subsidence for a particular change in artesian pressure is known, and the amount of fine-grained material can be determined, a fair estimate can be made of expected subsidence for a predicted change in artesian pressure.

In the Houston-Galveston region, the amounts of subsidence for several periods of time are known, observation wells have yielded a fair history of artesian-pressure decline, and electrical logs can be used to determine clay thickness. At Seabrook the average specific-unit compaction value is estimated to be 3.1×10^{-5} foot^{-1}. That is, for every foot (0.3 meter) of

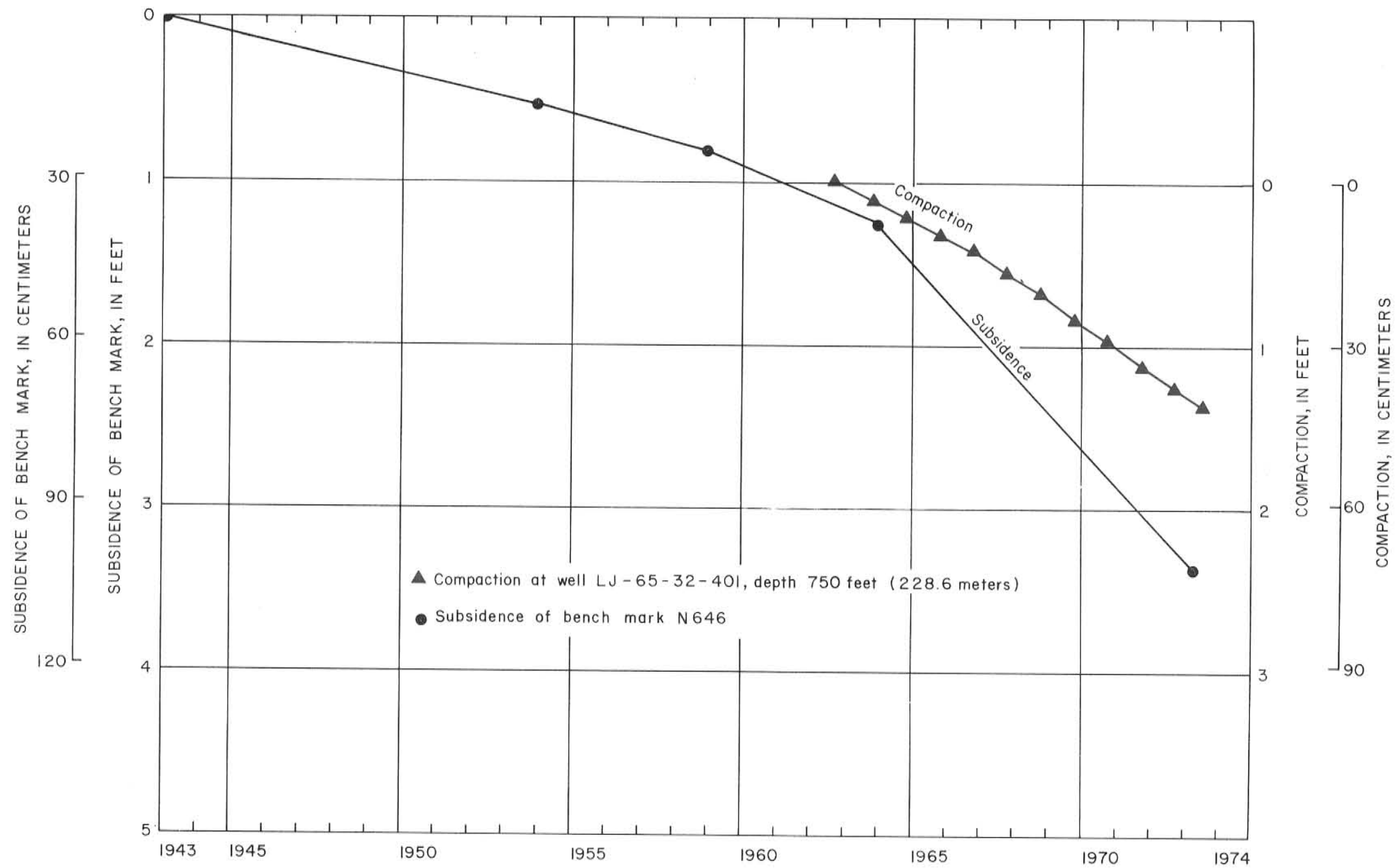

Figure 11

Measured Compaction and Subsidence at the Johnson Space Center

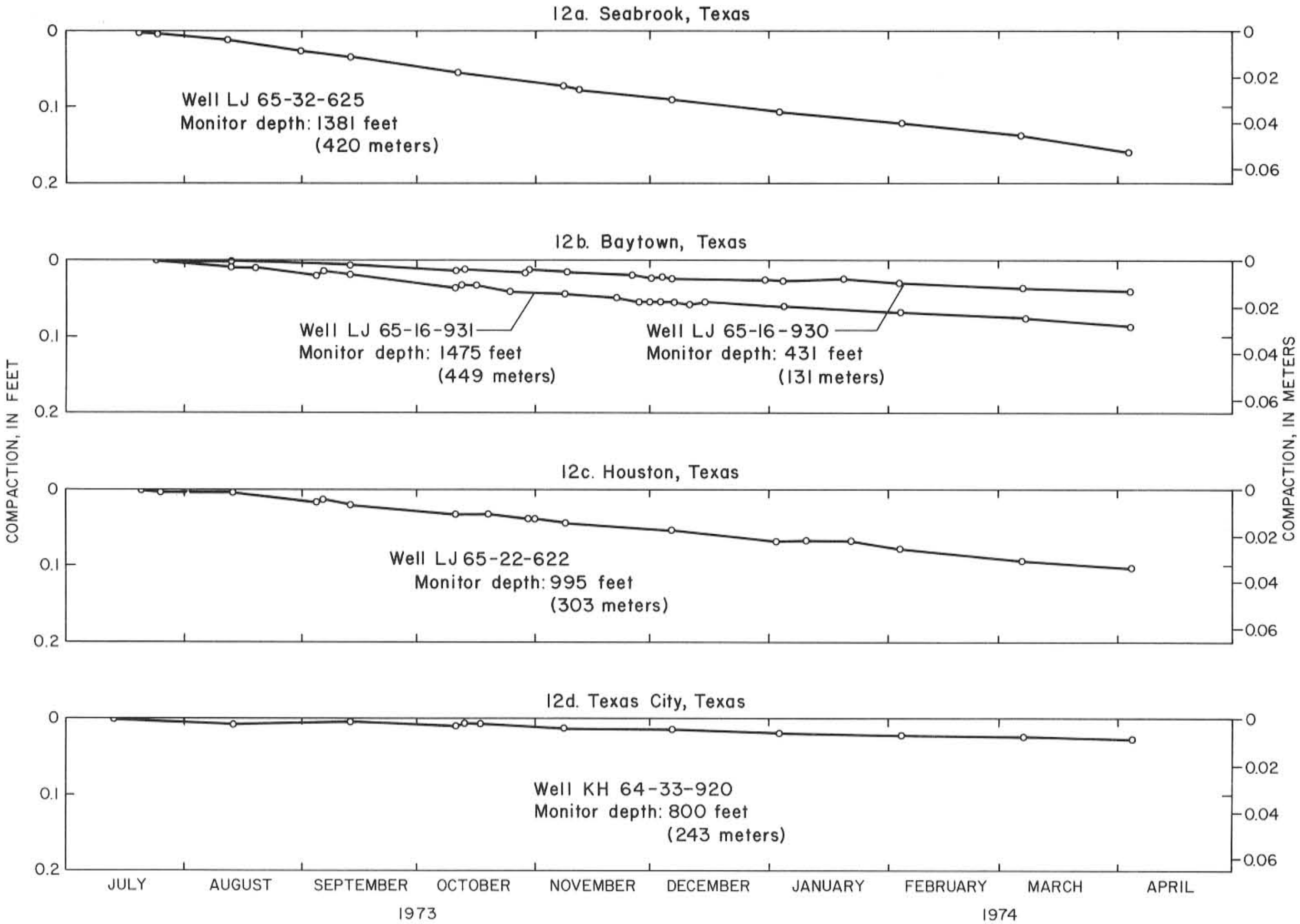

Figure 12
Measured Compaction in the Houston-Galveston Region

water-level decline, each foot of clay will compact 0.000031 foot (0.000944 centimeter). At this site, it is estimated that 800 feet (244 meters) of fine-grained compactible material is present, and that for each foot of water-level decline, 0.0248 foot (0.7559 centimeter) of subsidence will occur.

PLANNED DEVELOPMENT AND SUBSIDENCE

Pumping of ground water in the Houston-Galveston region has continued to increase, and the rates of artesian-pressure decline and subsidence have accelerated. Subsidence will continue at a rate dependent on the decline in pressure resulting from ground-water pumping. Commitments for about 166 mgd (7.3 m^3/s) of surface water from Lake Livingston have been received from 24 major ground-water users in the southern part of Harris County. The increased use of surface water will decrease the use of ground water and will probably result in some recovery of artesian pressure. Surface water probably will not be available until early 1976.

The city of Galveston began using surface water in August 1973 and has decreased ground-water withdrawals by about 6 mgd (0.3 m^3/s). A rise in water levels in some wells in the Alta Loma area has been noted. Decreases in ground-water pumping are also planned in the Baytown area, and several other communities in Harris and Galveston Counties are studying the possibility of obtaining surface water. With recovery of artesian pressures, the rate of subsidence should decrease substantially in the more critical areas.

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