GROUND-WATER WITHDRAWALS AND LAND-SURFACE SUBSIDENCE IN THE HOUSTON-GALVESTON REGION, TEXAS, 1906-80

By R. K. Gabrysch

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METRIC CONVERSIONS

Factors for converting inch-pound units to metric equivalents are give in the following table:

From	Multiply by	To obtain
acre	0.004047	square kilometer (km^2)
foot	0.3048 304.8	meter (m) millimeter (mm)
foot per year (ft/yr)	304.8	millimeter per year (mm/yr)
Foot $^{-1}$	3.2808	meter $^{-1}$ (m^{-1})
mile	1.609	kilometer (km)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
pound per square inch (lb/in^2)	0.07031	kilogram per square centimeter (kg/cm^2)
pound-force per square inch (lbf/in^2)	6.895	kilopascal (kPa)
square mile	2.590	square kilometer (km^2)

National Geodetic Vertical Datum of 1929 (NGVD of 1929): A geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called "mean sea level."

GROUND-WATER WITHDRAWALS AND

LAND-SURFACE SUBSIDENCE IN THE

HOUSTON-GALVESTON REGION, TEXAS, 1906-80

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ABSTRACT

The withdrawal of large amounts of ground water in the Houston-Galveston region, Texas, has resulted in water-level declines of as much as 250 feet (76 meters) in wells completed in the Chicot aquifer and as much as 300 feet (91 meters) in wells completed in the Evangeline aquifer during 1943-77. Since late 1976, changes in pumping distribution resulting from efforts to control subsidence and the introduction of surface water from Lake Livingston have altered the pattern of water-level changes. In the Johnson Space Center and Baytown-La Porte areas (Chicot aquifer), and in the Pasadena area (Evangeline aquifer), water levels rose about 20 feet (6.1 meters) during 1973-77. However, in the western Houston area (Evangeline aquifer), water levels have continued to decline at an increasing rate through 1977.

The declines in water levels have caused pronounced regional subsidence of the land surface. The center of regional subsidence is the Pasadena area, where more than 9 feet (2.7 meters) and possibly as much as 10 feet (3.0 meters) of subsidence occurred between 1906 and 1978. Almost 9 feet (2.7 meters) of subsidence occurred between 1943 and 1978. Localized centers of subsidence exist throughout the region, especially in the Baytown-La Porte and Texas City areas.

Evaluation of tide records from five gages in Galveston Bay and the tidal reaches of Buffalo Bayou indicates that changes in elevations of significantly less than 0.5 foot (150 millimeters) and possibly as little as 0.1 foot (30 millimeters) can be detected.

The unit measure of compressibility, specific-unit compaction, ranged from 1.0×10^{-5} to 4.0×10^{-5} feet^{-1} (3.28×10^{-5} to 1.31×10^{-4} m^{-1}) of compaction per foot of clay thickness per foot of average water-level change for 1906-78. The greatest compressibility was at the Clear Lake site and the least compressibility was at the Lake Houston site. The data indicate that the compressibility is related to the age of the sediments and the depth of burial of the sediments.

INTRODUCTION

The U.S. Geological Survey has cooperated for many years with the Texas Department of Water Resources (and its predecessor agencies), the Cities of Houston and Galveston, and more recently (1975), the Harris-Galveston Coastal Subsidence District to collect and analyze data to evaluate the water resources of the Houston-Galveston region. 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 (fig. 1). The principal areas of ground-water withdrawals and the average rate of pumping during 1978 are shown in figure 1.

Because the principal constraint to development of the ground-water resources is land-surface subsidence, considerable effort since the mid-1950's has been devoted to collecting and analyzing data to define the cause and magnitude of subsidence. The purposes of this report are: (1) To present data on ground-water withdrawals, changes in water levels, and land-surface subsidence; (2) to describe subsidence monitoring; (3) to relate stress changes to compaction at individual sites; and (4) to describe a technique and parameters that could be used to predict subsidence.

AQUIFERS

Numerous reports on the ground-water hydrology of the Houston region have described the aquifers by using an interpretation of the subsurface geology. The reports have consistently stated that the structure and stratigraphy is very complex, and that delineation of the aquifers is extremely difficult. The first attempt to model the ground-water system during the early 1960's was partly successful, but probably the greatest benefit obtained from the first model was the development of a different approach to the analysis of the aquifers. Much more emphasis was placed on ground-water hydraulics, and as a result, the subsurface was divided into two major aquifers, the Chicot and Evangeline, and a confining layer, the Burkeville. The Chicot and Evangeline aquifers are composed of layers of sand and clay. The Burkeville confining layer underlies the Chicot and Evangeline; it is composed mostly of clay with some layers of sand. The Chicot aquifer, which overlies the Evangeline, contains not only the more permeable sand layers, but also the more compressible clay layers. The Burkeville greatly restricts the vertical flow of water in most of the region except in the northern part where it contains several permeable sand layers and thus is not as restrictive. Gabrysch (1980), drawing on previous interpretations, presented the most recent maps showing the altitude of the bases of the Chicot and Evangeline.

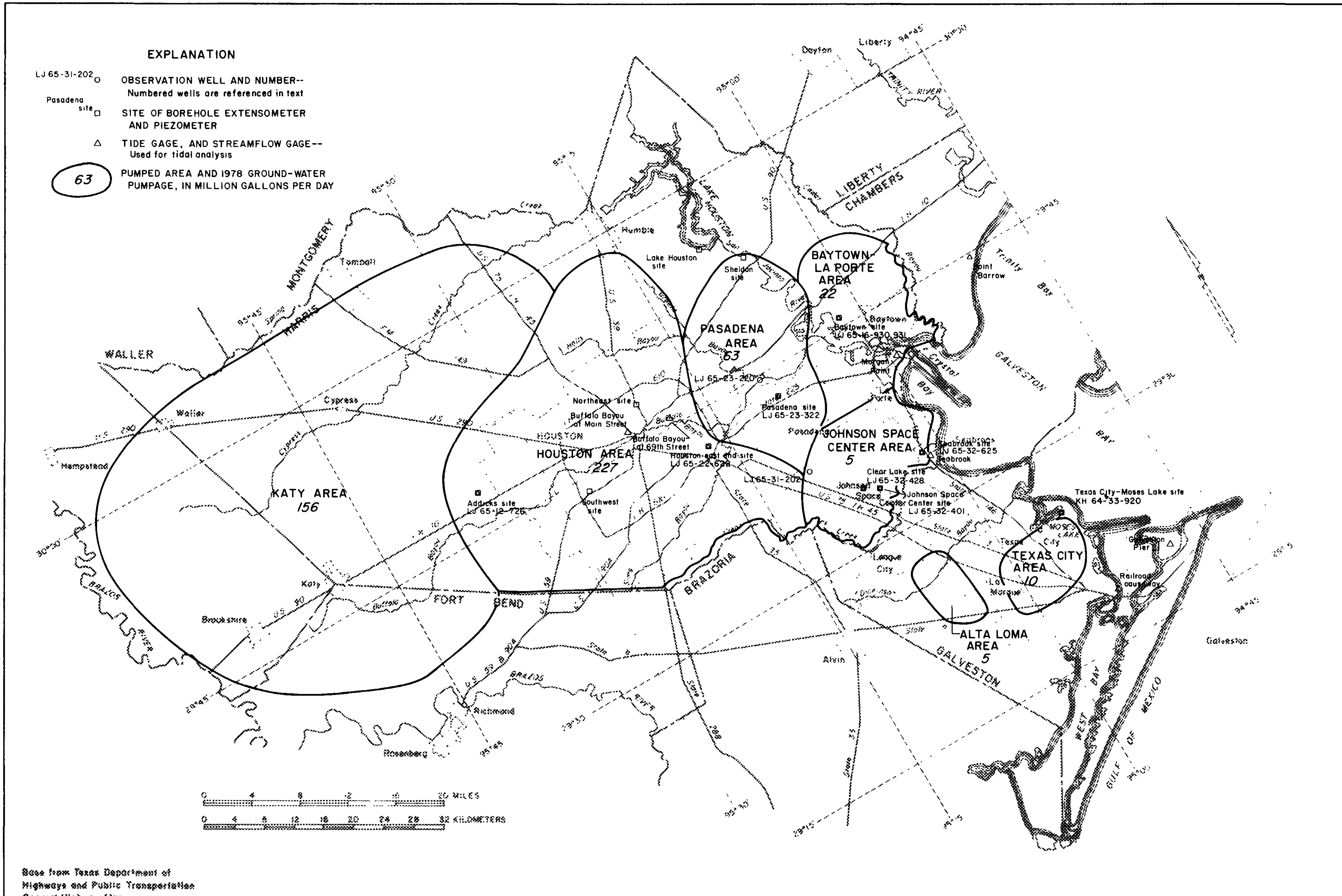


Figure 1.-Location of principal areas of ground-water withdrawals and average rates of pumping for 1978

GROUND-WATER WITHDRAWALS IN THE HOUSTON-GALVESTON REGION

Records of ground-water pumping for 1960-78 are presented in figures 2-7. A graph of pumping for the entire region (fig. 2) shows that pumping increased from about 311 Mgal/d (13.6 m^3/s) during 1960 to 532 Mgal/d (23.3 m^3/s) during 1974. Because of the use of surface water from Lake Livingston on the Trinity River, increased use of water from Lake Houston, and conservation measures, ground-water pumping decreased to about 502 Mgal/d (22.0 m^3/s) during 1978.

Houston Area

Withdrawals of ground water in the Houston area increased about 132 percent from 98 Mgal/d (4.3 m^3/s) during 1960 to 227 Mgal/d (9.9 m^3/s) during 1978. About 83 percent of the water being pumped in the area was used by the city of Houston. The increase in ground-water use has been fairly uniform except for 1972-76 (fig. 3). The city increased the use of surface water each year from 1971 through 1978 leading to a decrease in the use of ground water during 1972-75. By 1976, even though the city had periodically increased the use of surface water, the rapidly increasing population required an increase in the pumping of ground water. During 1978, water use by the city was 333 Mgal/d (14.6 m^3/s), of which 189 Mgal/d (8.3 m^3/s) was ground water and 144 Mgal/d (6.3 m^3/s) was surface water from Lake Houston.

Katy Area

Ground water used in the Katy area is principally for the irrigation of rice. The amount of ground water pumped during 1960-78 is shown in figure 4. Of the 156 Mgal/d (6.8 m^3/s) pumped during 1978, 112 Mgal/d (4.9 m^3/s) was for irrigation. It is apparent from figure 4 that pumping fluctuates widely due to irrigation needs. The average rate of pumping for 1960-78 was 134 Mgal/d (5.9 m^3/s).

Pasadena Area

Ground water pumped in the Pasadena area is used mostly for industrial purposes. During 1968, the year of maximum pumping, 113 Mgal/d (5.0 m^3/s) or 90 percent of the total of 126 Mgal/d (5.5 m^3/s) was used by industries in the area. Pumping increased until 1968 and then decreased slowly until 1976, probably because of water-conservation measures and slight increases in the use of surface water from Lake Houston (fig. 5). Ground-water withdrawals during 1976 were about 106 Mgal/d (4.6 m^3/s). Pumping decreased rapidly during 1977 and 1978 because industries in southern Harris County began using additional surface water from Lake Livingston on the Trinity River, which became available during late 1976. Use of ground water for public supply in the Pasadena area increased about 15 percent during 1969-78. Ground-water pumping by the city of Pasadena decreased from 8.0 Mgal/d (0.35 m^3/s) during 1969 to 3.9 Mgal/d (0.17 m^3/s) during 1978 because of the use of surface water from Lake Houston. Ground-water withdrawal for all uses during 1978 was about 63 Mgal/d (2.8 m^3/s).

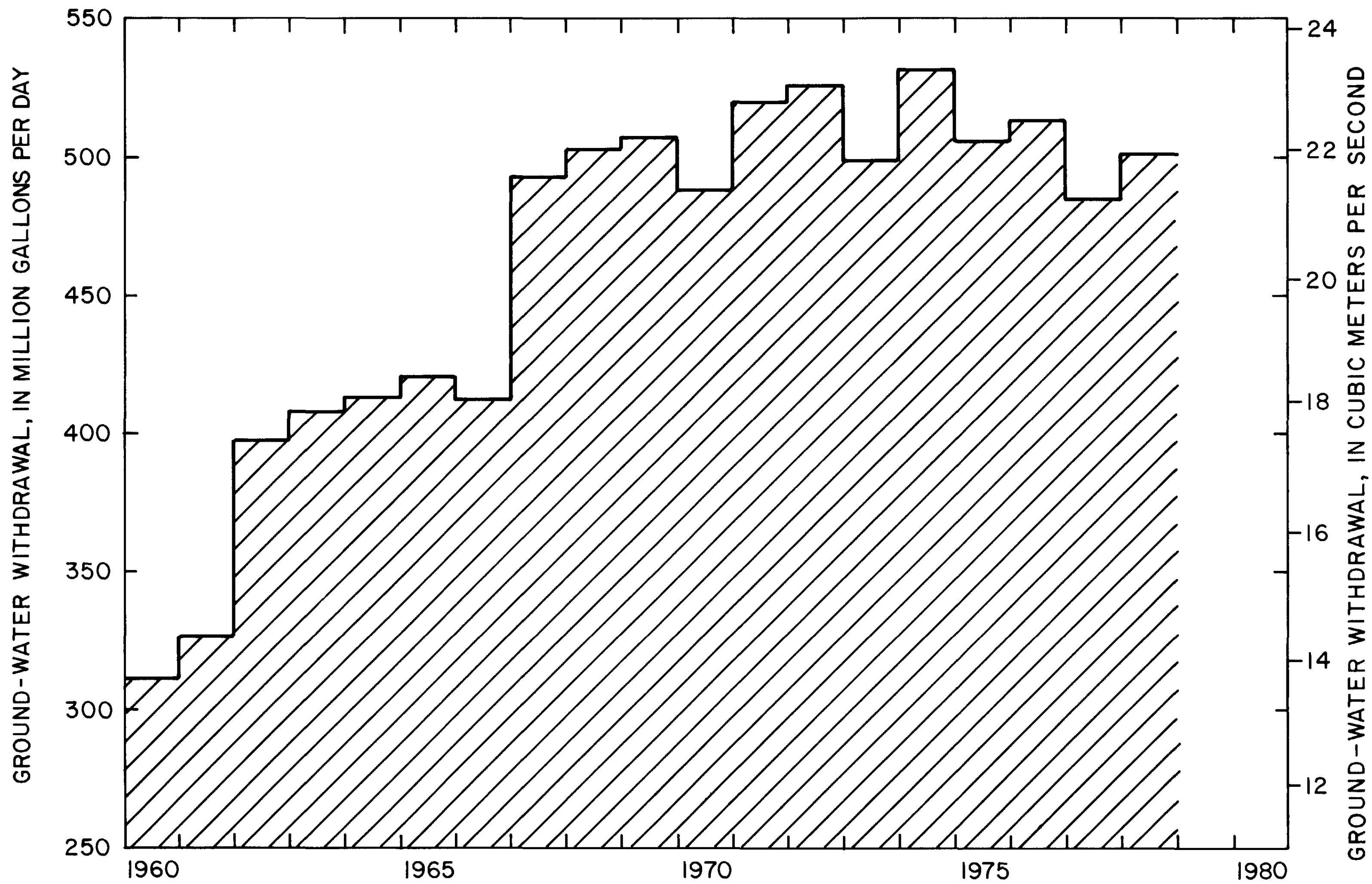


Figure 2.-Withdrawals of ground water in the Houston-Galveston region, 1960-78

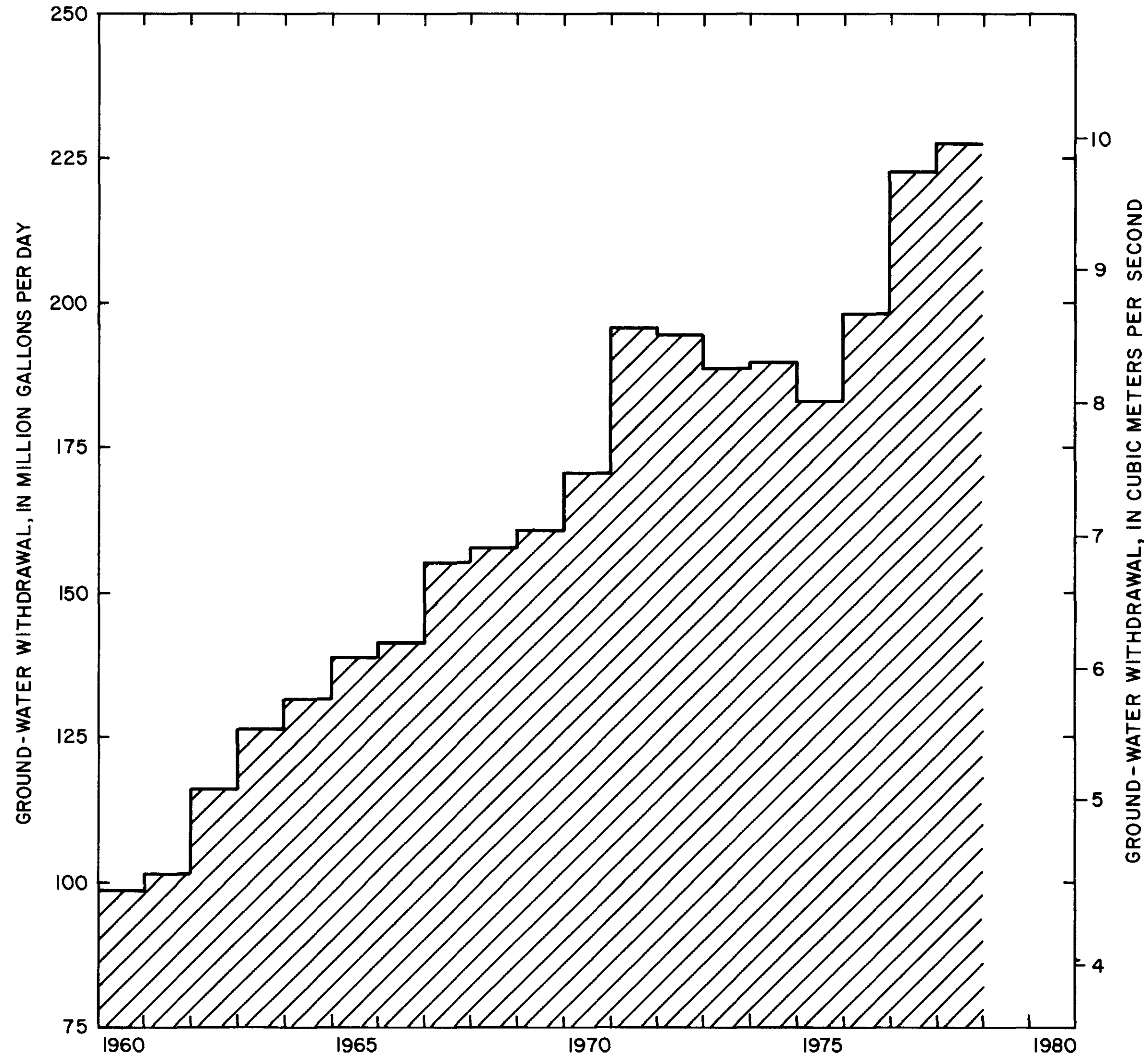


Figure 3.- Withdrawals of ground water in the Houston area, 1960-78

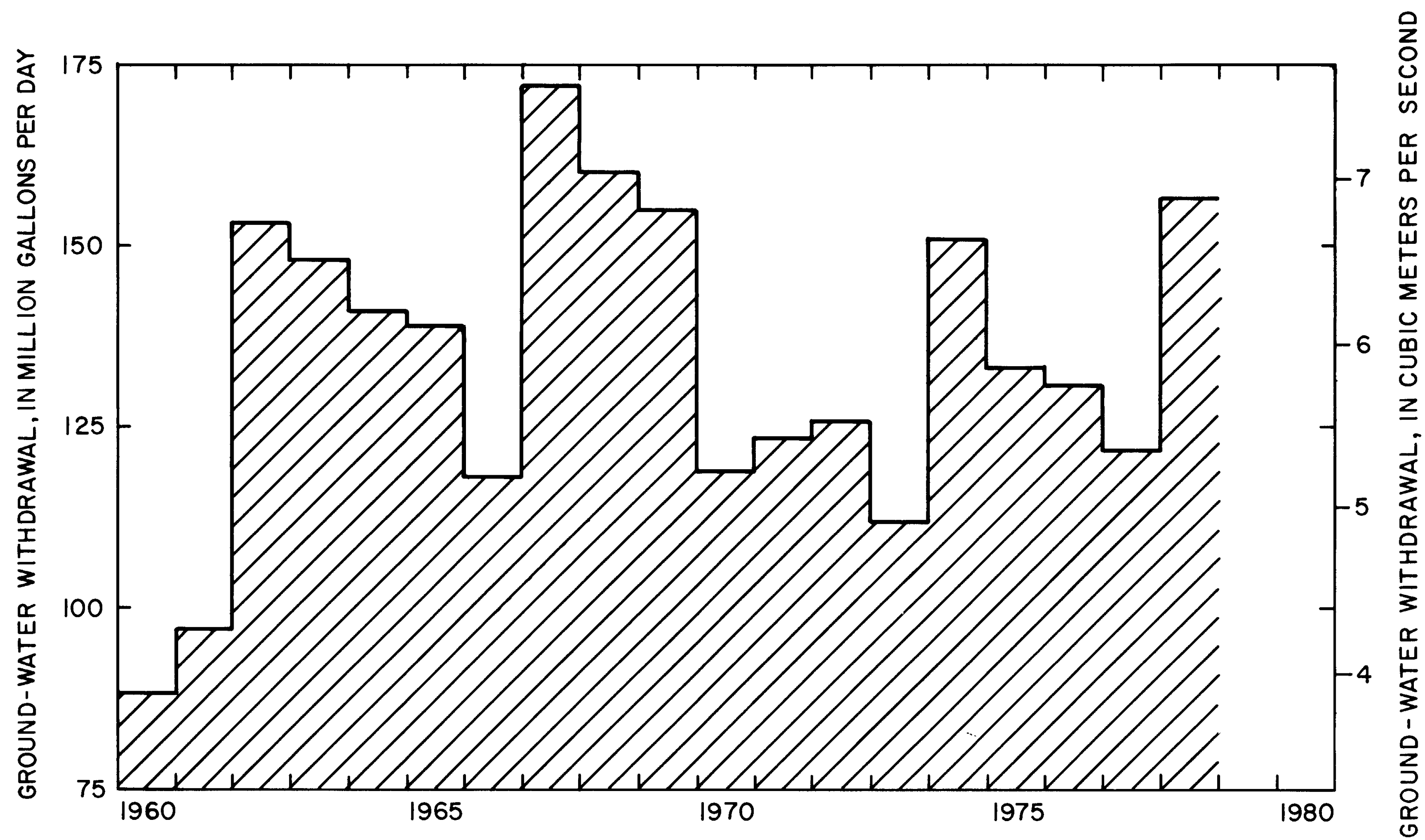


Figure 4.-Withdrawals of ground water in the Katy area, 1960-78

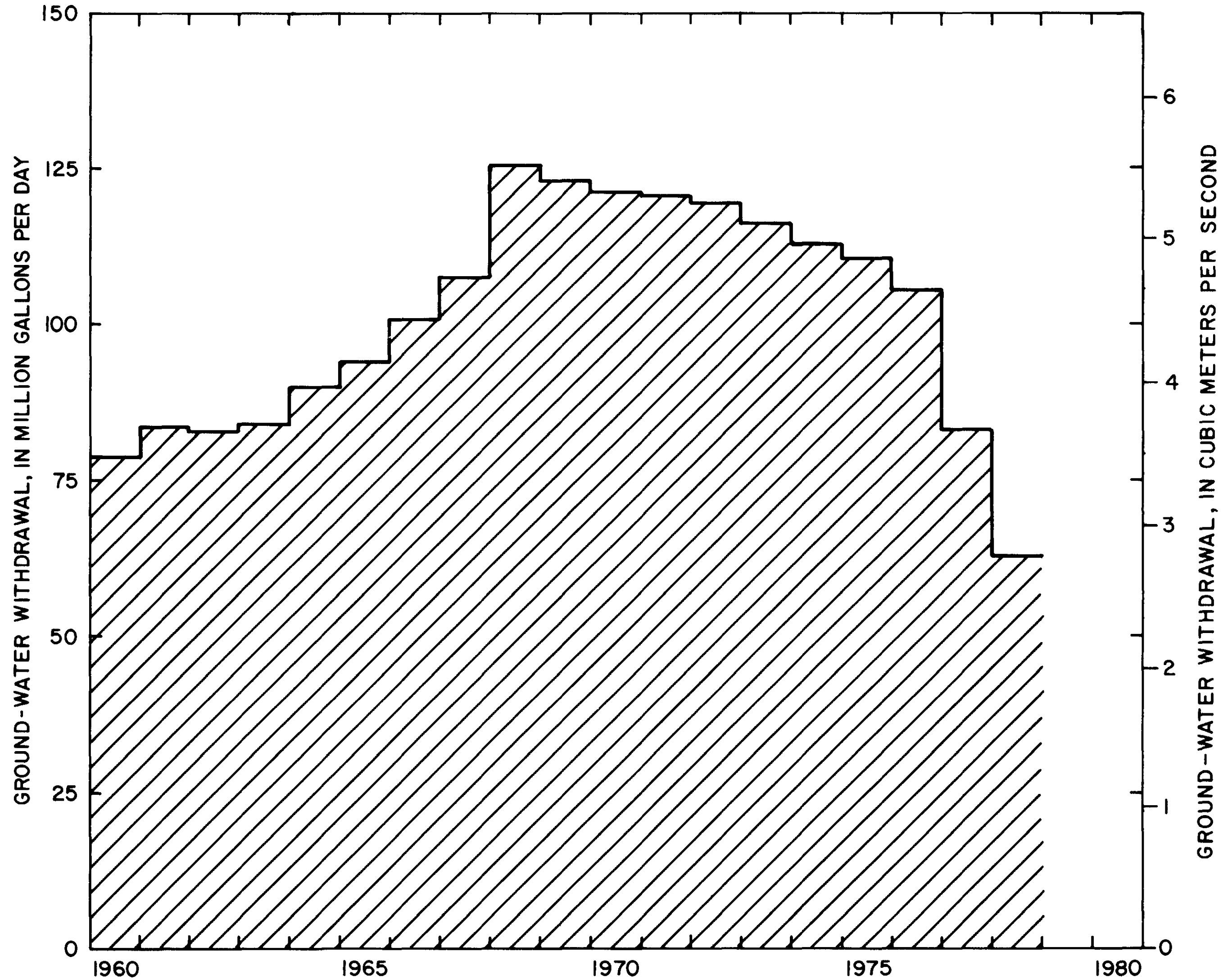


Figure 5.-Withdrawals of ground water in the Pasadena area , 1960-78

Baytown-La Porte Area

Use of ground water in the Baytown-La Porte area is about equally divided between public supply and industry. Ground-water pumping in the area slowly increased until 1973. During 1972, about 32 Mgal/d (1.4 m^3/s) was pumped (fig. 6). The decrease in ground water pumped since 1972 reflects increased use of surface water by industry. A total of 21.6 Mgal/d (0.95 m^3/s) of ground water was pumped in the area during 1978.

Texas City Area

Pumping in the Texas City, Alta Loma, and Johnson Space Center areas is shown in figure 7. Ground-water pumping in the Texas City area increased slowly from 9.8 Mgal/d (0.43 m^3/s) during 1960 to 15.5 Mgal/d (0.68 m^3/s) during 1971, decreased slightly to 14 Mgal/d (0.61 m^3/s) during 1976, and decreased to 9.7 Mgal/d (0.42 m^3/s) during 1978. The decrease in the use of ground water in the recent years probably was due to conservation measures and the increased use of surface water by industry. During 1978, of the 9.7 Mgal/d (0.42 m^3/s) pumped, 7.3 Mgal/d (0.32 m^3/s) was for municipal supply and 2.4 Mgal/d (0.11 m^3/s) was for industrial use.

Alta Loma Area

All ground water pumped in the Alta Loma area is for municipal supply. Until late 1973, the city of Galveston was entirely dependent on wells in the area for its supply. At that time, the city was using about 13 Mgal/d (0.57 m^3/s) of ground water. The rate of ground-water pumping in the Alta Loma area began decreasing during late 1973 (fig. 7) because of introduction of surface water from Lake Houston. The city of Galveston purchased 6 Mgal/d (0.26 m^3/s) of surface water during 1973, with increased purchases during later years. By 1978, ground-water pumpage in the area was only 2.7 Mgal/d (0.12 m^3/s).

Johnson Space Center Area

Pumping of ground water in the Johnson Space Center area (formerly the NASA area) was 1.2 Mgal/d (0.05 m^3/s) during 1960. Pumping increased gradually until 1976, when 20.6 Mgal/d (0.90 m^3/s) was pumped for municipal supply and industrial use (fig. 7). During 1976, the Johnson Space Center, Clear Lake City, and Nassau Bay began using some surface water from Lake Houston. During 1978, total ground-water pumping decreased to 5.1 Mgal/d (0.22 m^3/s), of which 4.0 Mgal/d (0.18 m^3/s) was for municipal use.

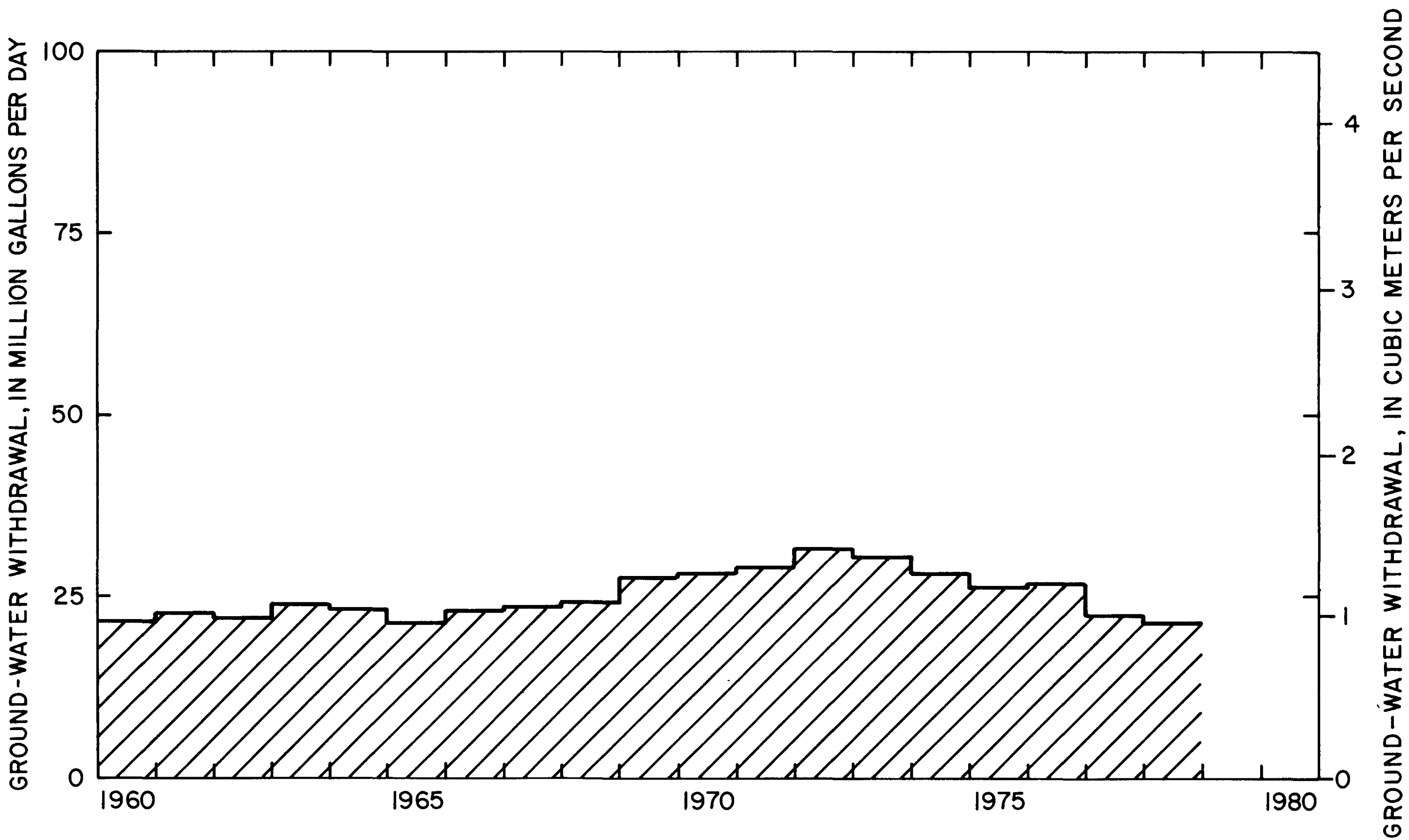


Figure 6.-Withdrawals of ground water in the Baytown- La Porte area, 1960-78

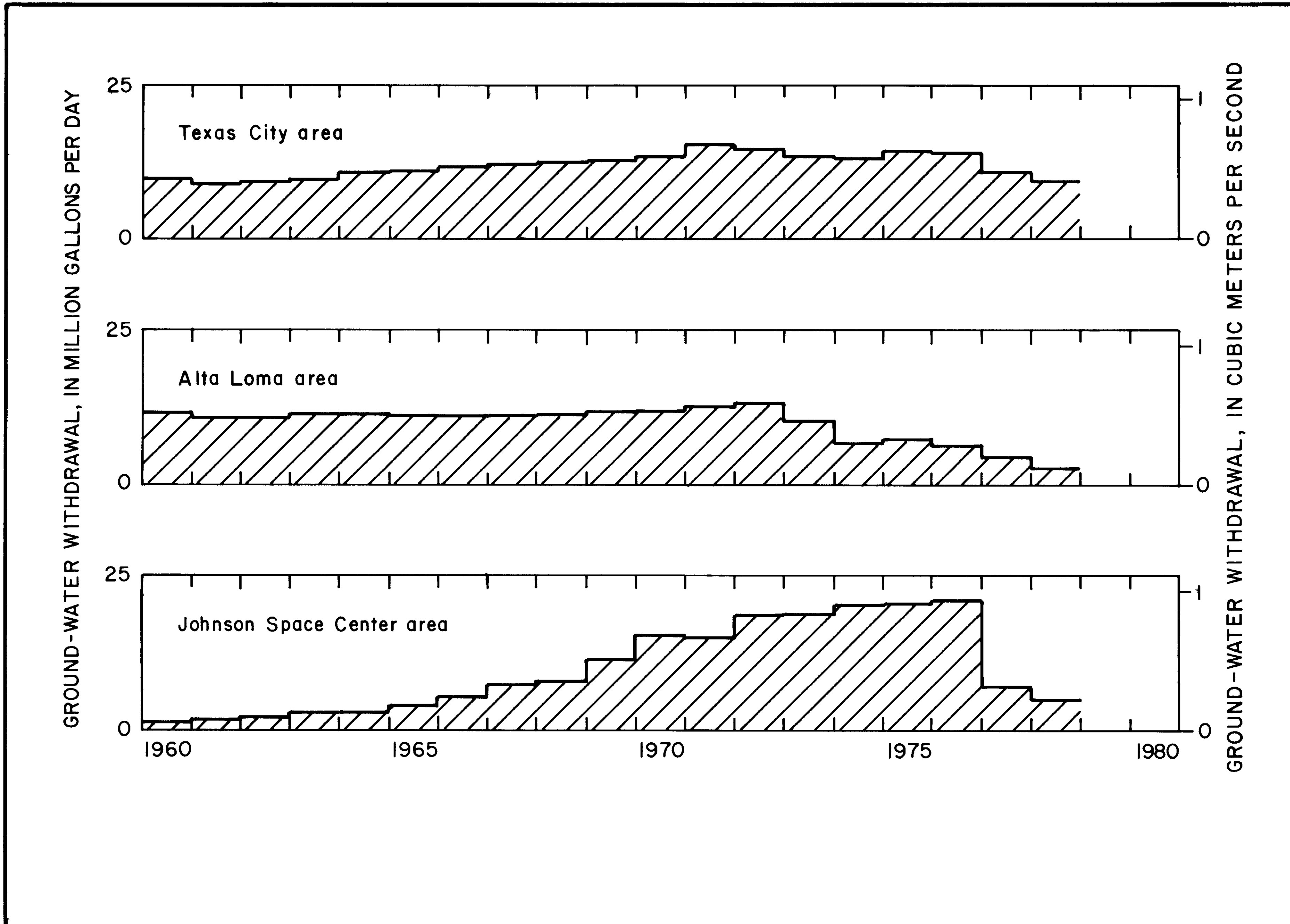


Figure 7.-Withdrawals of ground water in the Texas City, Alta Loma, and Johnson Space Center areas, 1960-78

CHANGES IN WATER LEVELS

Water levels generally declined in the region from the beginning of development until 1977. Some rises in water levels occurred in a small part of the region during the mid-1950's because of decreases in ground-water pumping associated with use of water from Lake Houston. Also, because the rate of ground-water pumping after 1966 remained relatively constant (fig. 2), the rates of water-level decline decreased in much of the region. A hydrograph of a well in the Pasadena area (fig. 8) shows an example of the change in the rate of decline beginning about 1968.

The hydrograph in figure 8 also shows the effect of the decrease in ground-water pumping in the Pasadena area following the introduction of water from Lake Livingston late in 1976. The water level in well LJ-65-23-220 rose about 65 feet (20 m) from December 1976 to December 1979.

During 1977 and 1978, water levels rose in Galveston and southern Harris counties but accelerated declines in water levels occurred in western and northern Harris County. Water-level change maps to 1977 were prepared because they are more representative of maximum water-level declines (maximum increase in stress) that have occurred in the region. The changes in water levels for 1943-77 and 1973-77 in wells completed in the Chicot aquifer are shown in figures 9 and 10, and changes in water levels for the same periods in wells completed in the Evangeline aquifer are shown in figures 11 and 12.

Water levels declined more than 50 feet (15 m) between 1943 and 1977 in wells completed in the Chicot aquifer in most of the Houston-Galveston region. The maximum decline of water levels in wells completed in the Chicot aquifer, which occurred in the Johnson Space Center area (fig. 9), was about 250 feet (76 m). Much of the decline was a result of ground-water development after 1970. The development was located between cones of depression centered in the Alta Loma area, the Pasadena area, and the Baytown-La Porte area. Water levels declined as much as 225 feet (69 m) in the southwestern part of the Houston area. Some of the decline resulted from leakage to the deeper, more extensively pumped Evangeline aquifer. During 1973-77, water levels rose as much as 20 feet (6.1 m) in wells in the Baytown-La Porte and Johnson Space Center areas (fig. 10). In the southwestern part of the Houston area, water levels declined as much as 20 feet (6.1 m). The changes reflect decreased pumping in the Baytown-La Porte and Johnson Space Center areas and increased pumping in the southwestern part of Houston area. Water levels rose as much as 5 feet (1.5 m) in the Alta Loma area, reflecting the continual decrease of pumping since 1973.

Figure 8.-Hydrograph showing changes in water levels in a well completed in the Chicot aquifer in the Pasadena area

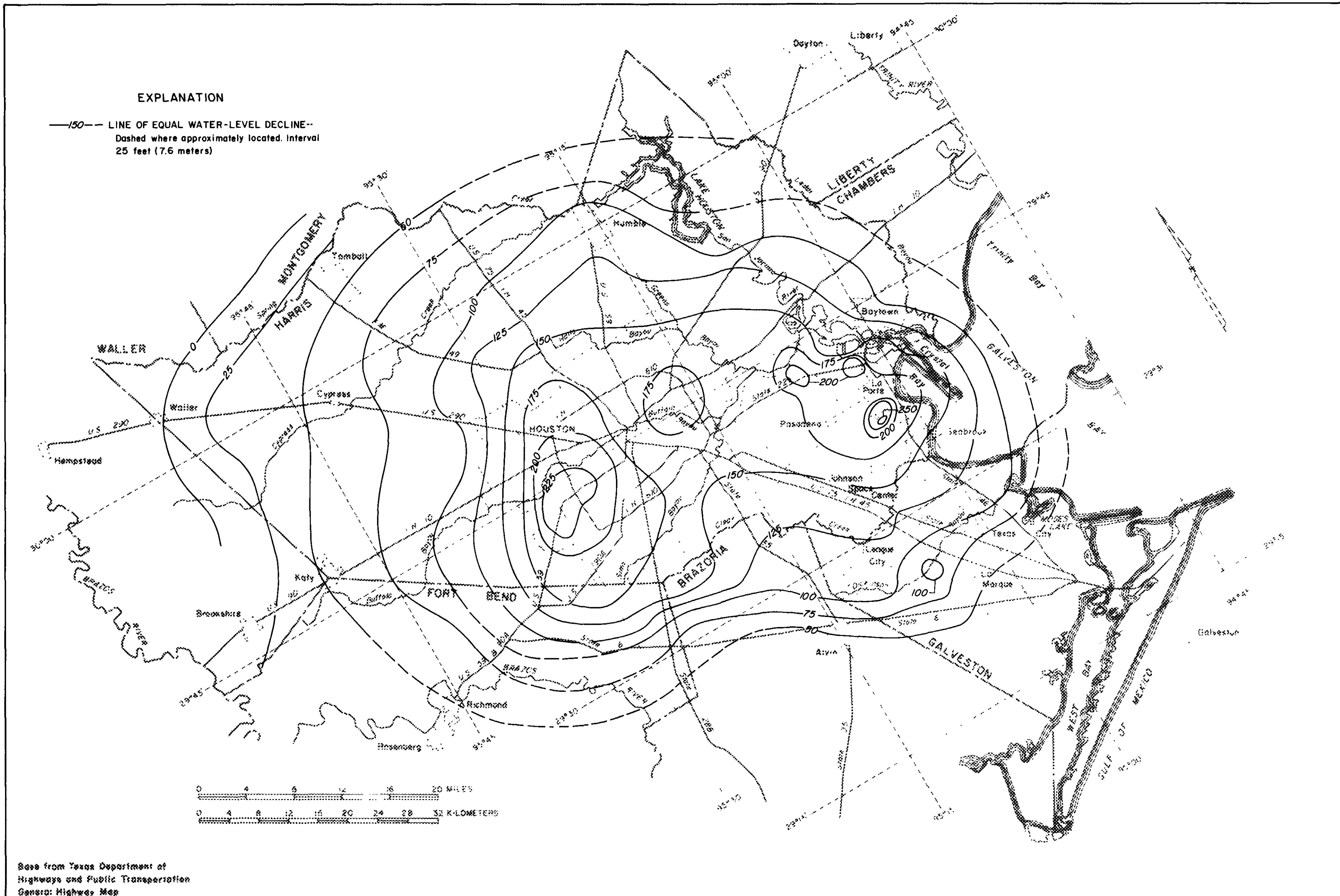


Figure 9.-Approximate declines of water levels in wells completed in the Chicot aquifer, 1943-77

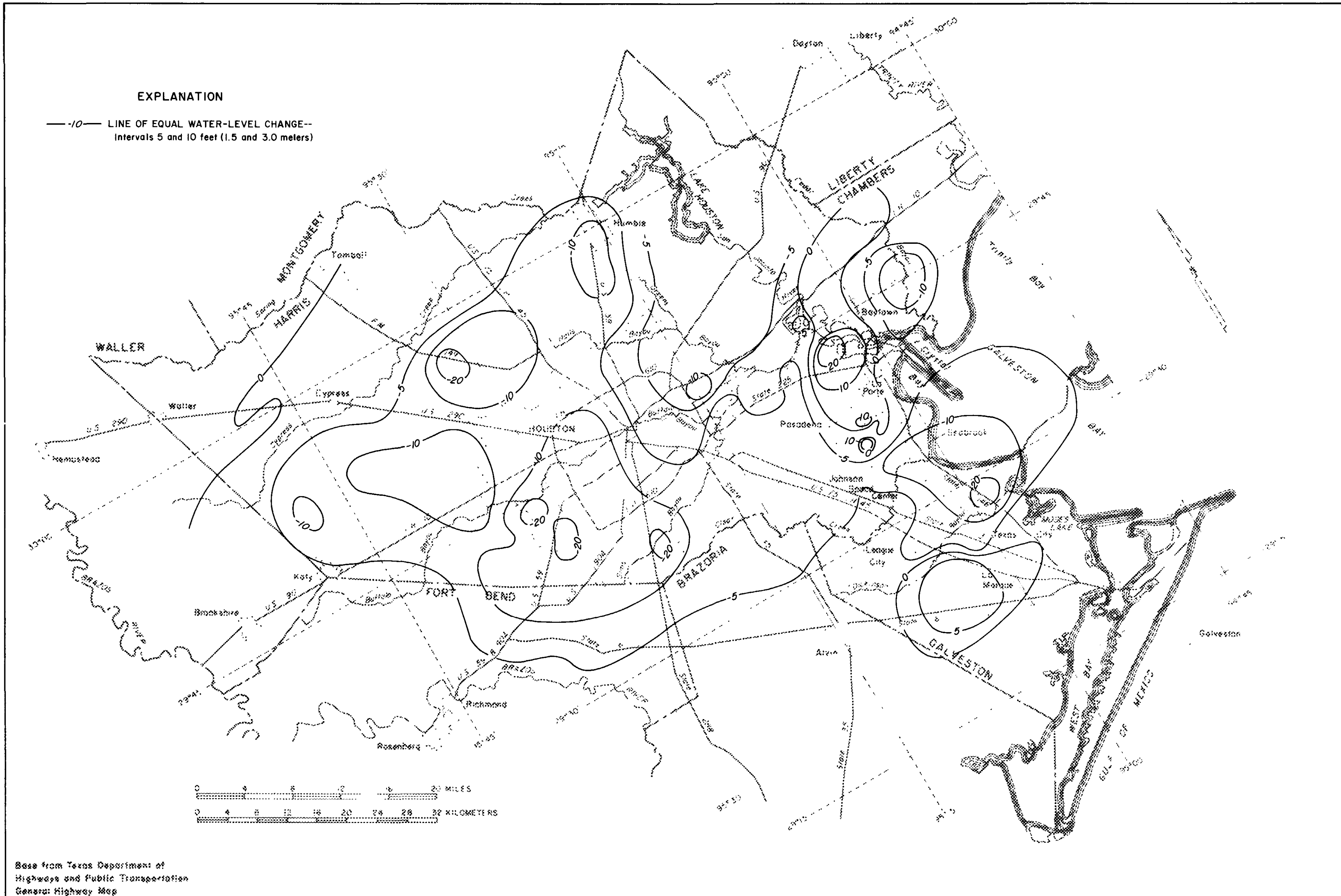
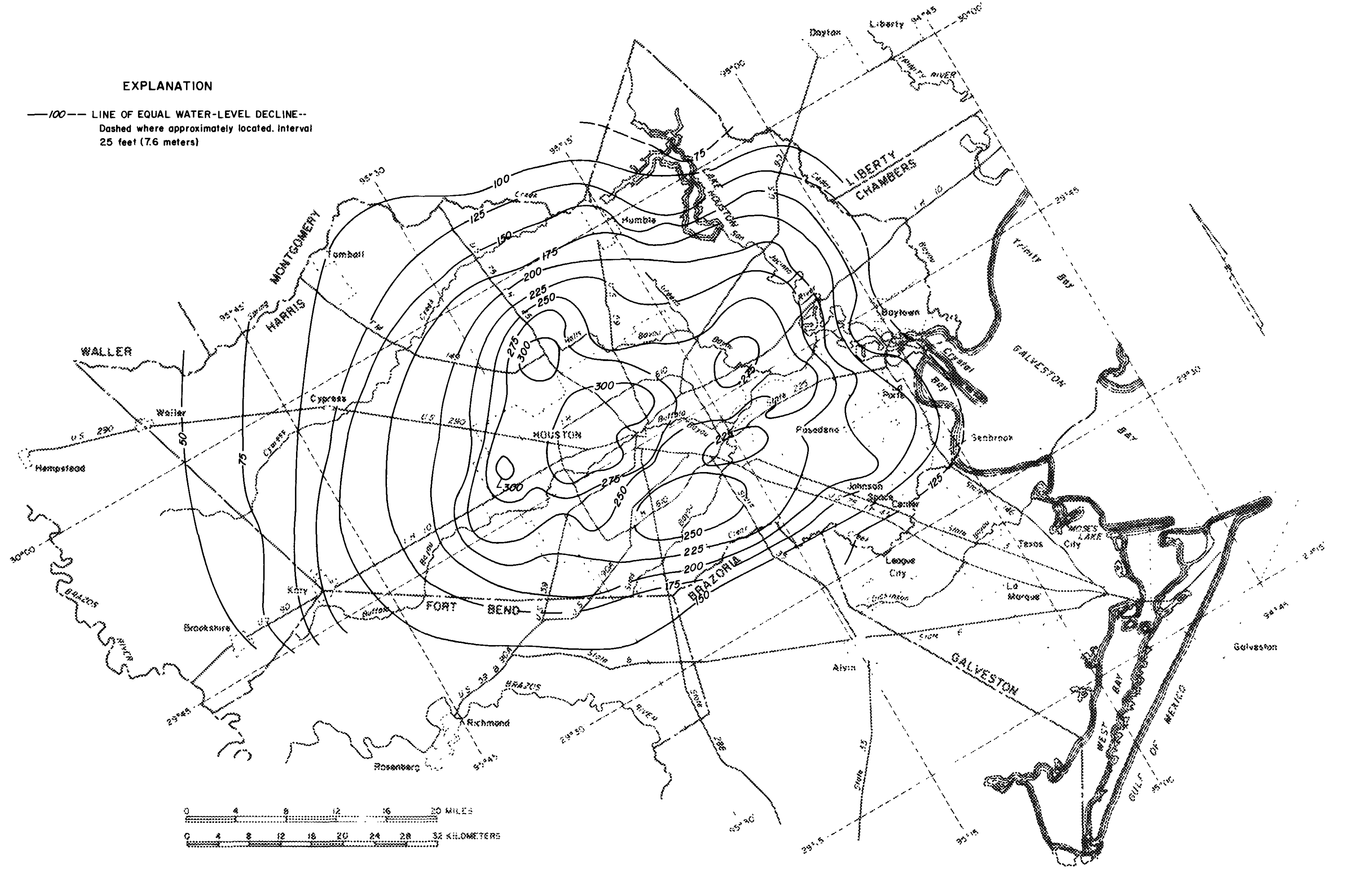


Figure 10.-Approximate changes in water levels in wells completed in the Chicot aquifer, 1973-77

EXPLANATION

—100— — LINE OF EQUAL WATER-LEVEL DECLINE--
Dashed where approximately located. Interval 25 feet (7.6 meters)

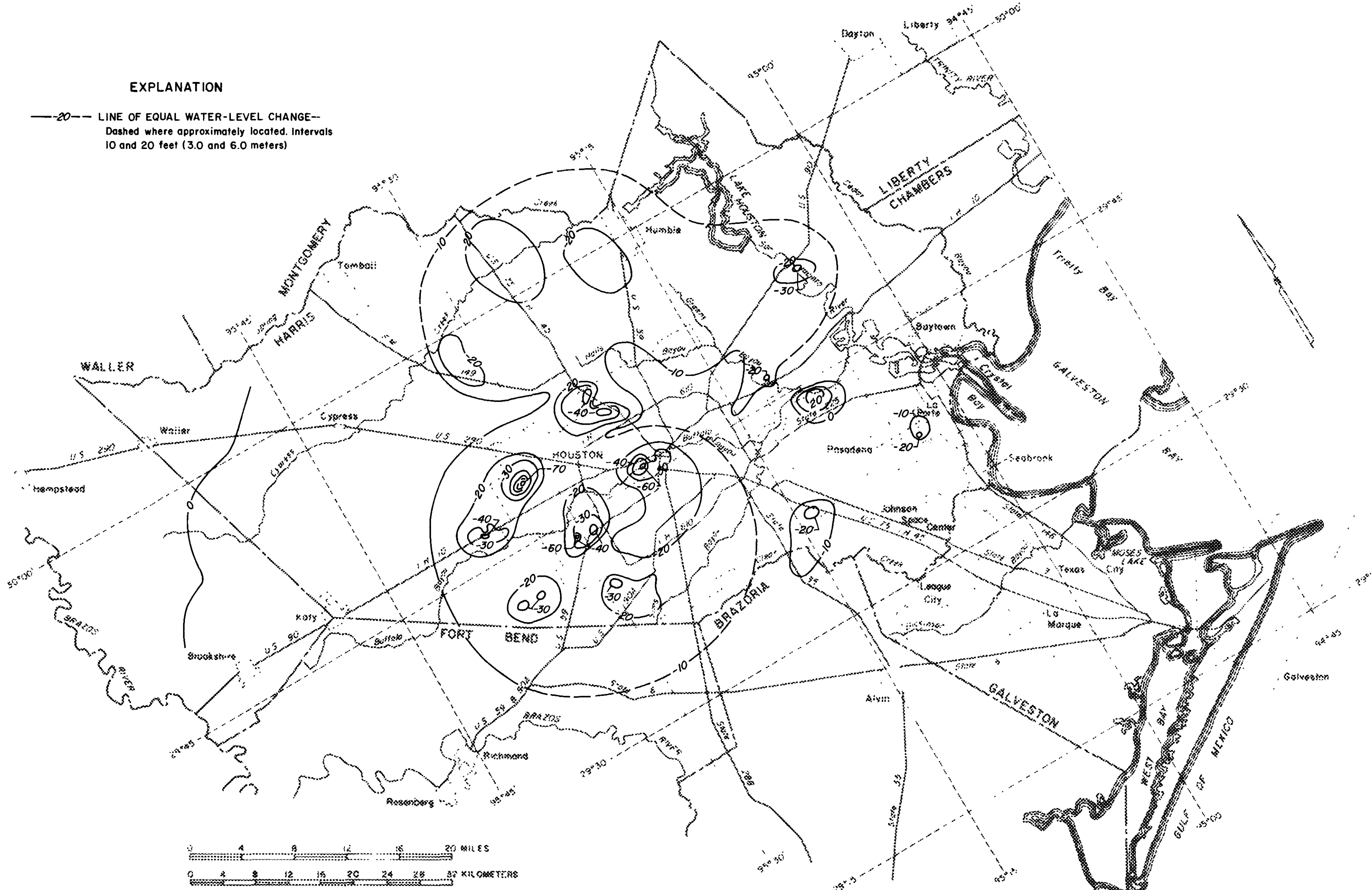


Base from Texas Department of Highways and Public Transportation General Highway Map

Figure 11.-Approximate declines of water levels in wells completed in the Evangeline aquifer, 1943-77

EXPLANATION

——-20—— LINE OF EQUAL WATER-LEVEL CHANGE--
Dashed where approximately located. Intervals 10 and 20 feet (3.0 and 6.0 meters)



Base from Texas Department of Highways and Public Transportation General Highway Map

Figure 12.-Approximate changes in water levels in wells completed in the Evangeline aquifer, 1973-77

Water levels in wells completed in the Evangeline aquifer declined as much as 300 feet (91 m) between 1943 and 1977 (fig. 11). The maximum decline occurred in the Houston area where most pumping is from the Evangeline aquifer. As much as 275 feet (84 m) of decline occurred in the western part of the Pasadena area. Water levels declined at least 100 feet (30 m) in most of the Houston-Galveston region. Between 1973 and 1977 the effect of the change in the distribution pattern of pumping is reflected in the amount of decline (fig. 12). In the Pasadena area, as much as 20 feet (6.1 m) of water-level rise was measured, while in the Houston area, as much as 70 feet (21 m) of decline was measured. The maximum average rate of decline in the Houston area for 1943-77 was about 9 feet (2.7 m) per year as compared to about 17.5 feet (5.3 m) per year for 1973-77.

LAND-SURFACE SUBSIDENCE

The principal method used to measure land-surface subsidence has been to compare elevations of bench marks at specific locations determined at different times. These elevations were obtained by conventional, but very precise, leveling methods. Most of the determinations were made by the National Geodetic Survey and their predecessor agency, the U.S. Coast and Geodetic Survey. Elevations determined by private and public entities other than the National Geodetic Survey (City of Houston; Texas Department of Highways and Public Transportation; U.S. Army Corps of Engineers; and others) also have been used.

If it is necessary to determine small changes in elevation at a specific location, the use of borehole extensometers (compaction monitors) probably is the best method. Compaction monitors have the disadvantages of large initial cost and small areal application, but they have the advantages of a continuous record, preciseness, and a determination of the interval of compaction causing subsidence.

Another potential method of subsidence measurement for short periods of time (although much less precise) in coastal areas is by changes in tide elevations. The difference in mean tides at two stations is approximately the change in elevation between the two stations. Care needs to be exercised in determining the tide stage to eliminate effects such as wind and storm runoff.

Subsidence from Repeated Surveys

The relation between changes in water levels and compaction of subsurface material leading to land-surface subsidence has been described in previous reports. Subsidence based on the 1973 releveling was reported by Gabrysch and Bonnet (1975). During 1978, the National Geodetic Survey, in cooperation with the Harris-Galveston Coastal Subsidence District and others, redetermined the elevations of bench marks in the region. First-order elevations also were determined for marks along some new lines. Differences in elevations from the numerous surveys since 1906 were used to prepare subsidence maps shown in this report. The amounts of subsidence in the Houston-Galveston region for 1906-78, 1943-78, and 1973-78 are shown in figures 13-15.

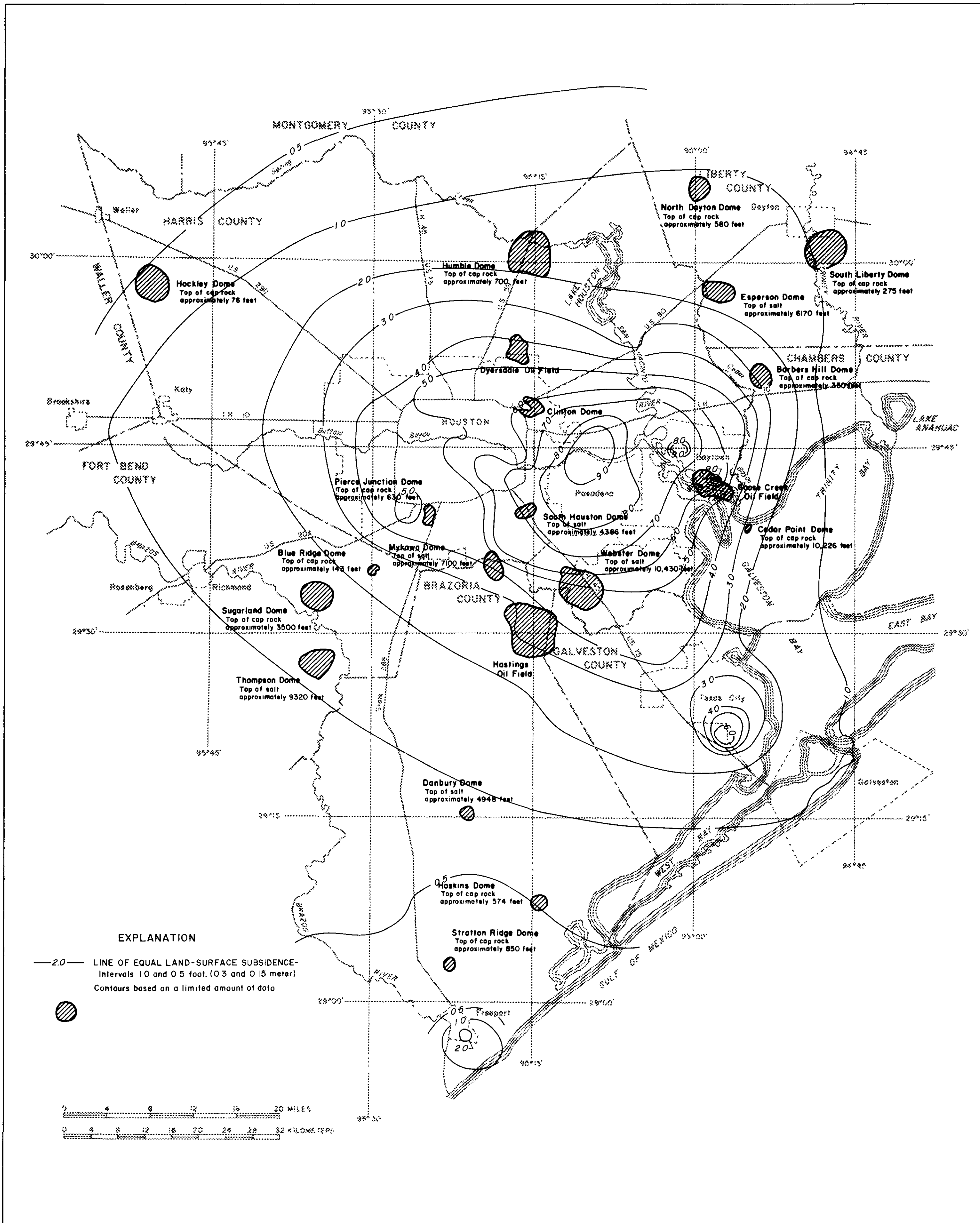


Figure 13.-Approximate land-surface subsidence, 1906-78

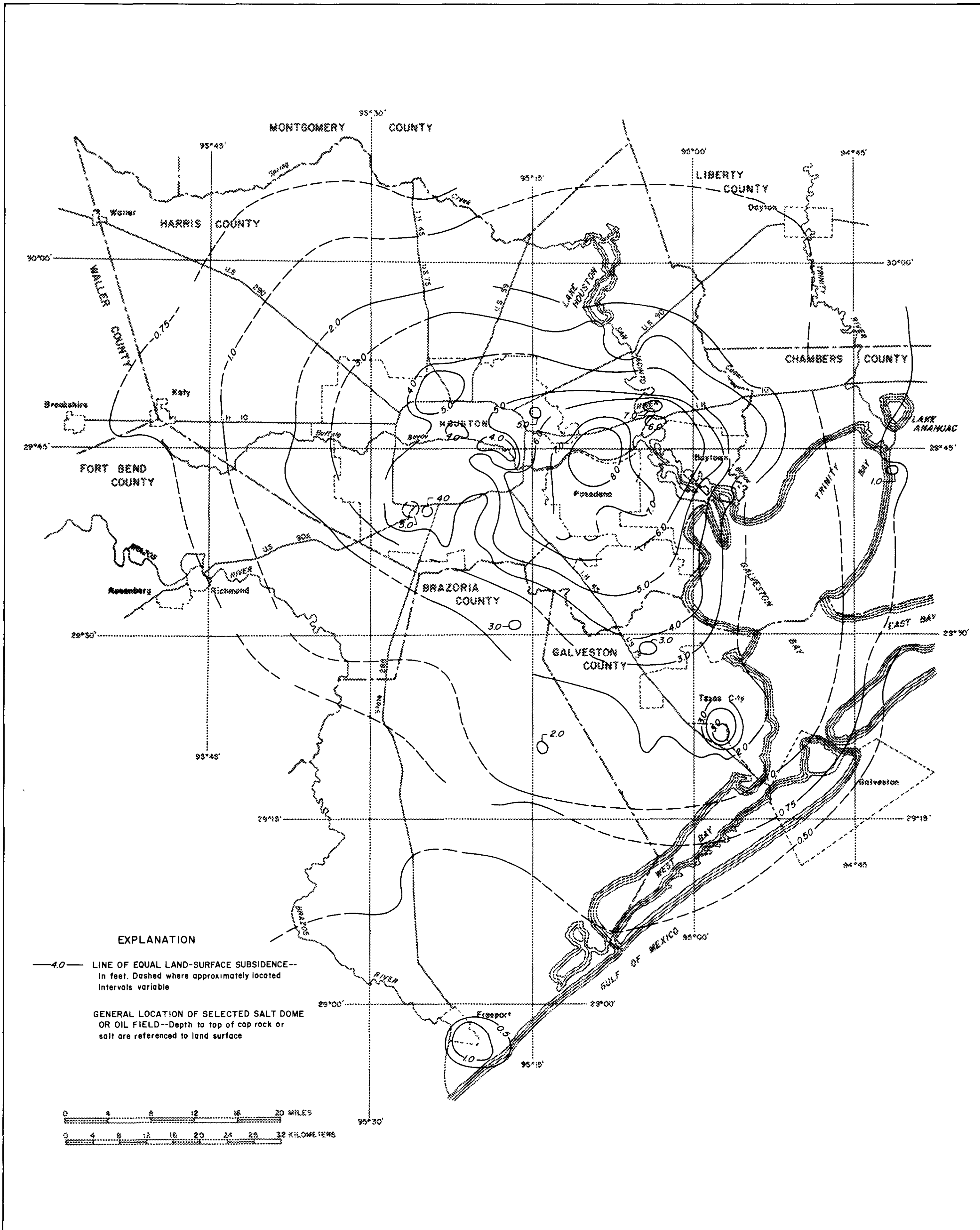


Figure 14.-Approximate land-surface subsidence, 1943-78

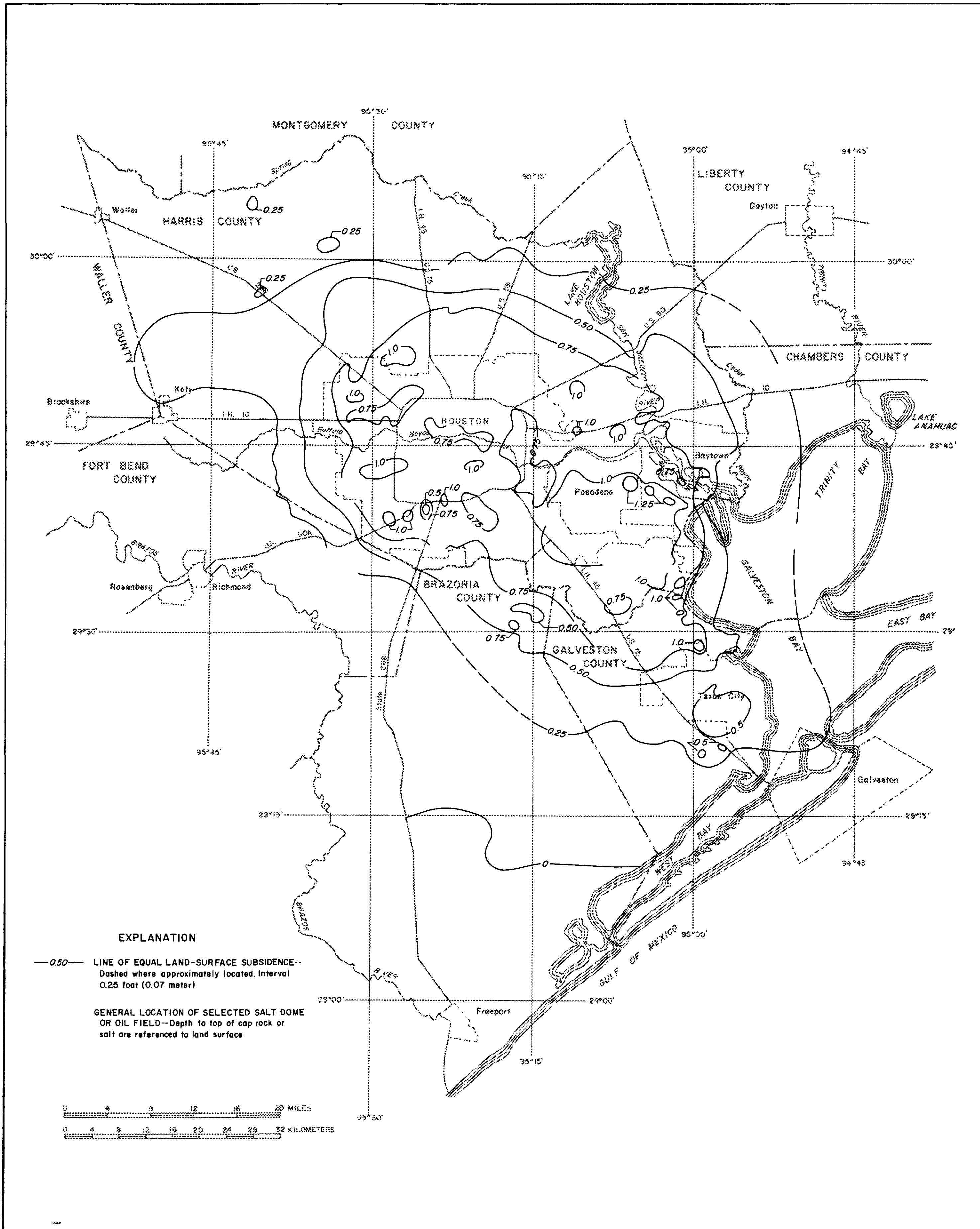


Figure 15.-Approximate land-surface subsidence, 1973-78

Data on subsidence for 1906-43 is sparse. Few bench marks along the single line established during 1906 still remain and none of the marks established before 1943 exist in the area of maximum subsidence. The 1906-78 subsidence map was obtained principally by addition of maps showing the subsidence during 1906-43 and 1943-78. Subsidence during 1906-78 exceeded 9.0 feet (2.7 m), and may have been as much as 10 feet (3.0 m) in the Pasadena area (fig. 13). A smaller center of subsidence on the western side of Baytown, where a bench mark subsided 9.1 feet (2.8 m) during 1915-78, is a result of ground-water pumping. Another deep, localized center of subsidence is in the Goose Creek oil field on the southeastern side of Baytown. There, at least 9 feet (2.7 m) of subsidence has resulted from the local withdrawal of oil, gas, associated saltwater, and fresh ground water. Another center of subsidence is in the Texas City area where localized withdrawals of ground water have caused as much as 6 feet (1.8 m) of subsidence.

The center of subsidence at Freeport in the extreme southern part of the region is due to the pumping of ground water from wells less than 500 feet (152 m) deep. By 1978, the land had subsided slightly more than 2 feet (0.6 m) locally as compared to about 0.5 foot (0.15 m) regionally. Subsidence in the Freeport area probably was several tenths of a foot (several tens of millimeters) more than indicated by leveling data. Differences between elevations determined in 1973 and 1978 show a rise in the land surface of as much as 0.2 foot (60 mm). Because water levels have continued to decline, it is reasonable to assume subsidence has continued, and that the apparent rise in the land surface computed from leveling data results from network-adjustment differences.

The maximum subsidence of the land surface during 1943-78 (fig. 14) exceeded 8.0 feet (2.4 m). Two bench marks in the Pasadena area subsided 8.87 and 8.97 feet (2.70 and 2.73 m). Localized centers of subsidence occur in several places, most notably at Texas City where more than 5 feet (1.5 m) of subsidence occurred with less than 3 feet (0.9 m) due to regional effects.

Less subsidence is evident over some salt domes than away from the domes. An example is at the Pierce Junction Dome in the western part of the Houston area. Less than 4 feet (1.2 m) of subsidence occurred locally, while between 4 and 5 feet (1.2 and 1.5 m) occurred regionally. Other irregularities are related to localized declines in water levels and differences in the thickness and compressibility of the sediments.

The maximum subsidence for 1973-78 (fig. 15) was more than 1.25 feet (0.38 m). The maximum change in elevation was in the Pasadena area, where a bench mark subsided 1.4 feet (0.43 m). Changes in pumping distribution in the latter part of the period (decreases in pumping in the southern part of the region and increases in the western part) have caused large changes in water levels (loading and unloading). The effects on subsidence rates have been local because of the short time involved, but will become regional as the changes in water levels become regional.

Compaction and Subsidence from Borehole-Extensometer Records

The borehole extensometers (compaction monitors) in use in the Houston-Galveston region are holes, drilled and cased to selected depths, into which smaller diameter standpipes have been installed. Compaction of the interval between the land surface and the bottom of the standpipe is continuously monitored by a clock-driven recorder. The boreholes used for the extensometers at the Clear Lake, Pasadena, and Addicks sites were drilled to the base of the Evangeline aquifer, the deepest aquifer being pumped in most of the region. Because little or no water-level decline has occurred below the aquifer, these extensometers measure total man-caused compaction. Except for a small amount of natural subsidence of the base of the aquifer, the top of the inner pipe remains at a constant elevation. During 1979, there were 10 extensometers in operation at 8 sites in Harris and Galveston Counties. At each site, piezometers were constructed for analyses of stress-causing compaction.

Johnson Space Center and Clear Lake Sites

The Johnson Space Center and Clear Lake sites are in southern Harris County (fig. 1). The Johnson Space Center site was established during 1962 by the U.S. Geological Survey as part of the subsidence research effort. A casing was installed in a borehole drilled for evaluation of subsidence potential prior to construction of the Johnson Space Center. A weight attached to a cable was lowered to the bottom of the 770-foot (235-m) hole. The cable was counterweighted at the surface, and a recorder was installed to monitor compaction of the depth interval from the land surface to 770 feet (235 m). The elasticity of the cable and friction in the system prompted a replacement of the cable-weight assembly by a standpipe in the cased hole in 1974. The extensometer at the space center was the second extensometer installed and is the oldest in existence in the Houston-Galveston region.

Additional information about compaction and subsidence was needed, and during 1976 the Harris-Galveston Coastal Subsidence District funded the installation of two extensometers and three separate piezometers at the Clear Lake site. The Clear Lake site was selected so that the information obtained could be coupled with information from the Johnson Space Center site. The two extensometers at the Clear Lake site were designed to measure total man-caused subsidence and to obtain additional information on the relation of compaction to depth.

The deepest extensometer was completed at 3,072 feet (936 m) in the Burkeville confining layer at the base of the Evangeline aquifer. Because pumping in the Houston-Galveston region is restricted to the Chicot and Evangeline aquifers, it was assumed that no pressure decreases occurred below the Evangeline aquifer. During 1976, the National Geodetic Survey determined the elevations of the inner pipes at the Clear Lake, Pasadena, and Addicks sites so that by comparison with future determinations, the degree of stability of the inner pipes could be determined. The elevations were determined again during 1978, and the measurements indicated a loss in elevation of the inner pipe of 0.003 foot (0.9 mm) at the Clear Lake site. The second extensometer, completed to a depth of 1,740 feet (530 m), was designed to measure compaction from the land surface to about the middle of the Evangeline aquifer. Compaction measured by the shallow extensometer at the Clear Lake site has consistently been about equal to that measured by the deep extensometer indicating all the compaction is occurring above 1,740 feet (530 m).

The compaction and difference in compaction at the Johnson Space Center and Clear Lake sites are shown in figure 16. The extensometer at the Johnson Space Center site is designed to measure compaction in the Chicot aquifer; the extensometer at the Clear Lake site is designed to measure compaction in both the Evangeline and Chicot aquifers. The graphs (fig. 16) show that during late 1978 and early 1979, the subsurface material expanded. Analysis further indicates that more expansion occurred in the Evangeline and Chicot aquifers than in the Chicot alone and that further compaction occurred in the Chicot aquifer by late 1979. The graph of the difference in compaction (fig. 16) indicates that all compaction during the last 6 months of 1979 occurred in the Chicot aquifer. Thus by 1979, recoveries of artesian pressure in the Evangeline aquifer were sufficient to stop compaction in that aquifer; recoveries of pressure in the Chicot had not yet been sufficient to stop compaction.

Of the 0.15 foot (45 mm) of subsidence that occurred from December 1976 to October 1978, 0.05 foot (15 mm) was the result of compaction in the Evangeline aquifer and 0.1 foot (30 mm), 67 percent, was a result of compaction in the Chicot aquifer. This compares with a long-term estimate of 55 percent of subsidence being a result of compaction in the Chicot aquifer. The graph of compaction in the Chicot aquifer shows a decreased rate beginning during late 1976. The decreased rate probably is the result of decreased rates of regional artesian-pressure declines and the decrease in ground-water pumping by Johnson Sapce Center, Nassau Bay, and Clear Lake City in mid-1976. Graphs of water-level measurements in piezometers at the Johnson Space Center and Clear Lake sites are shown in figure 17. The measurements for the graphs were selected to correspond to the time at which elastic rebound began (October 1978) and when compression in the Chicot aquifer resumed (February 1979). The graphs (fig. 17) also show measurements for October 1979, at which time cumulative compaction in the Chicot began to exceed the previously measured compaction.

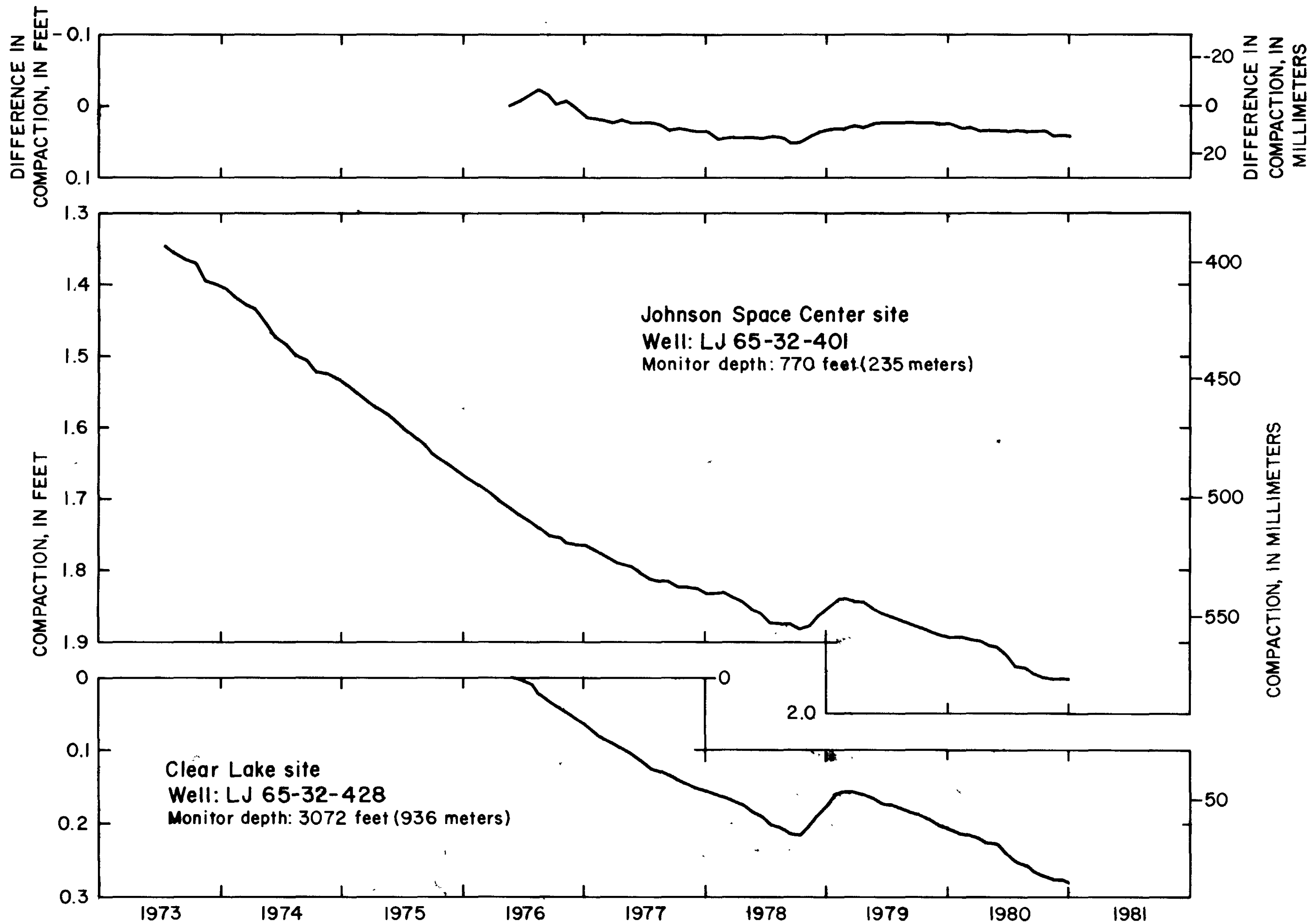


Figure 16.-Measured compaction and cumulative difference at the Johnson Space Center and Clear Lake sites

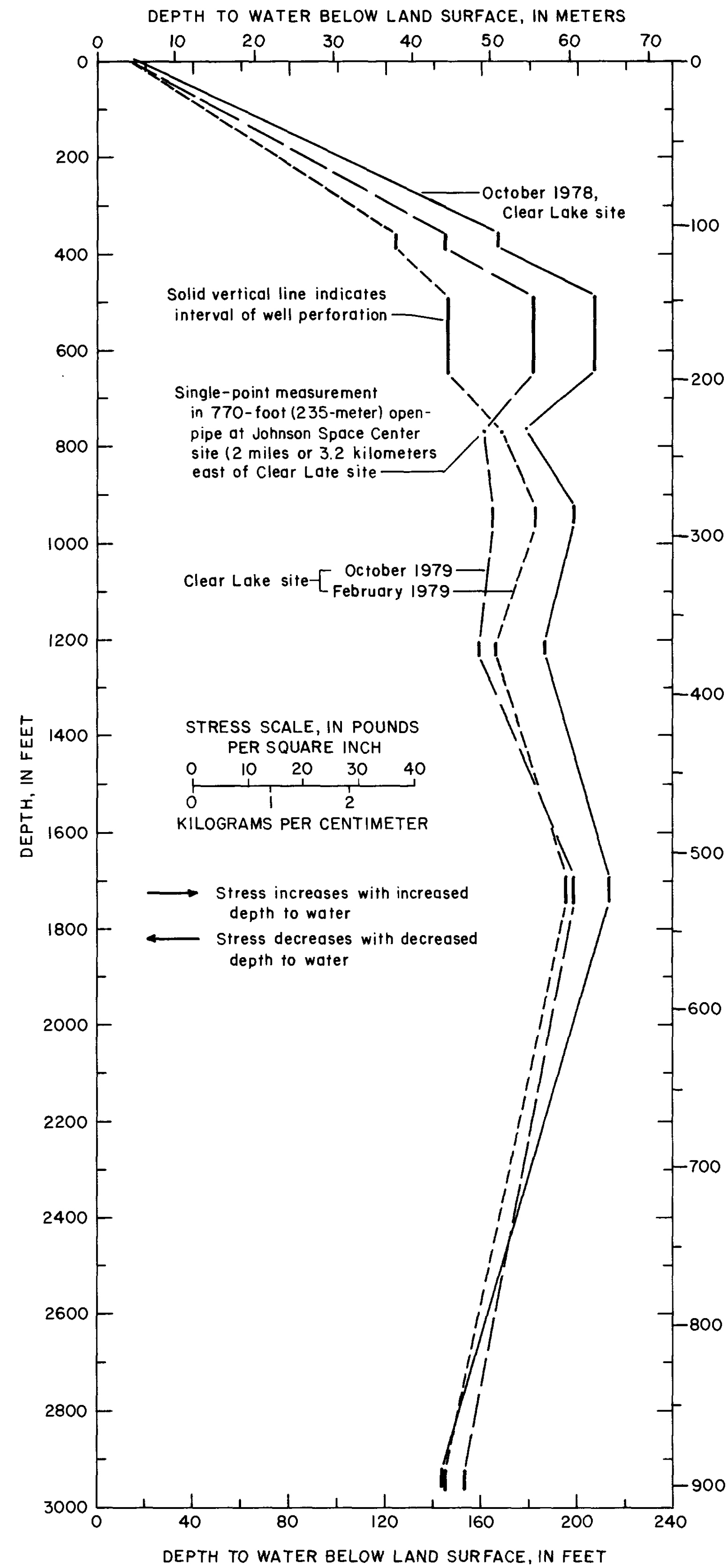


Figure 17.-Potentiometric profiles and changes in effective stress at the Johnson Space Center and Clear Lake sites

Most of the rise in water levels in the shallow piezometers from October 1978 to February 1979 was probably the result of increased pressure due to an escape of gas from a ruptured gas well in the vicinity of Ellington Air Force Base. Hydrographs show a rapid rise in water levels in the Chicot aquifer beginning in late 1978. The rise in water levels cannot be accounted for by decreased ground-water pumping, but coincide with the reported casing rupture during November 1978. The estimated depth to water near the gas well before the leak was 200 feet (61 m) below land surface. The shut-in pressure of a water well near the gas well was reported to be 92 lb/in^2 (634 kPa) or 212 feet (65 m) of water during November 1978. Rises in water levels in wells began quickly. In the most distant well, 13 miles (21 km) from the reported leak, a slight rise was noted during December 1978.

A typical hydrograph of the water level in a well in the Chicot aquifer is shown in figure 18. The very sharp rise in water levels from late 1978 to early 1979 followed by a rapid decline, along with practically no change in pumping patterns, indicated that most of the rise was the effect of the pressure of the gas. The approximate amount and extent of the effect is shown in figure 19.

The potentiometric profile for October 1979 shows a decline in water levels in the shallow piezometers from February 1979 (fig. 17). The decline is interpreted as a dissipation of the gas pressure. Water levels in the deep piezometers have continued to decline as a result of updip (inland) pumping. It is noteworthy that even though the water level in the deepest piezometer has continued to decline (thus increasing loading of the deeper section), compaction of the deeper fine-grained material probably is negligible.

Records from the two extensometers at the Clear Lake site indicate that subsidence at that location is a result of compaction of material above a depth of 1,740 feet (530 m). For the period of record (May 26, 1976, to Dec. 9, 1980), the compaction measured by the 3,072-foot (936-m) extensometer was 0.278 foot (84.7 mm), and the compaction measured by the 1,740-foot (530-m) extensometer was 0.276 foot (84.1 mm), a difference of 0.002 foot (0.6 mm) in about 4.5 years. The measurements by the National Geodetic Survey indicated a loss in elevation of the inner pipe in the 1,740-foot (530-m) extensometer of 0.007 foot (2 mm) during 1976-78.

A graph of subsidence measured by the extensometers at the Pasadena, Clear Lake, and Addicks sites (fig. 20) shows subsidence at the Clear Lake site decreased from about 0.090 foot (27.4 mm) during 1977 to 0.013 foot (4.0 mm) during 1978 then increased to about 0.075 foot (22.9 mm) during 1980.

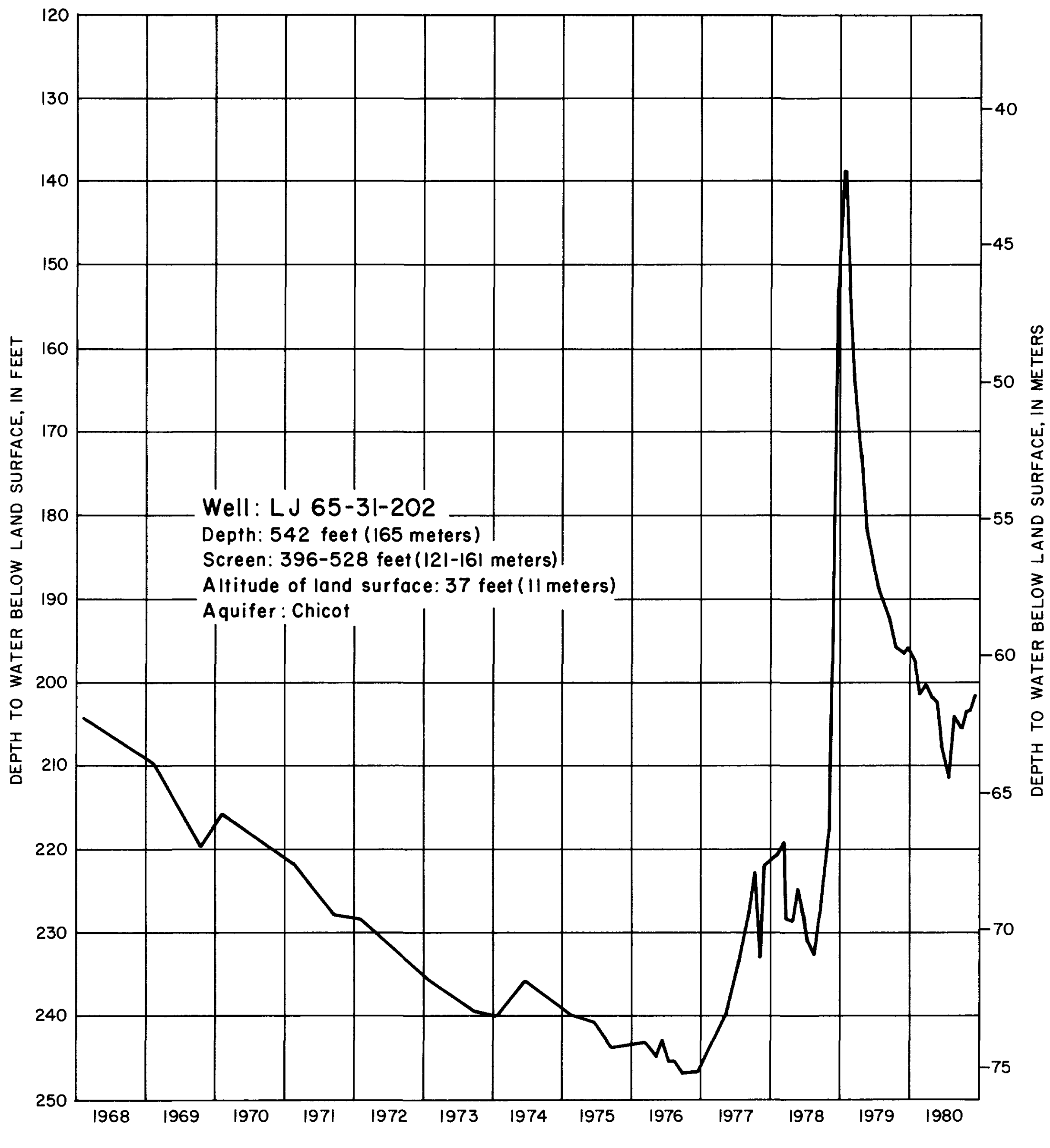


Figure 18.-Hydrograph of a well in southeastern Harris County showing water-level rise caused by gas pressure

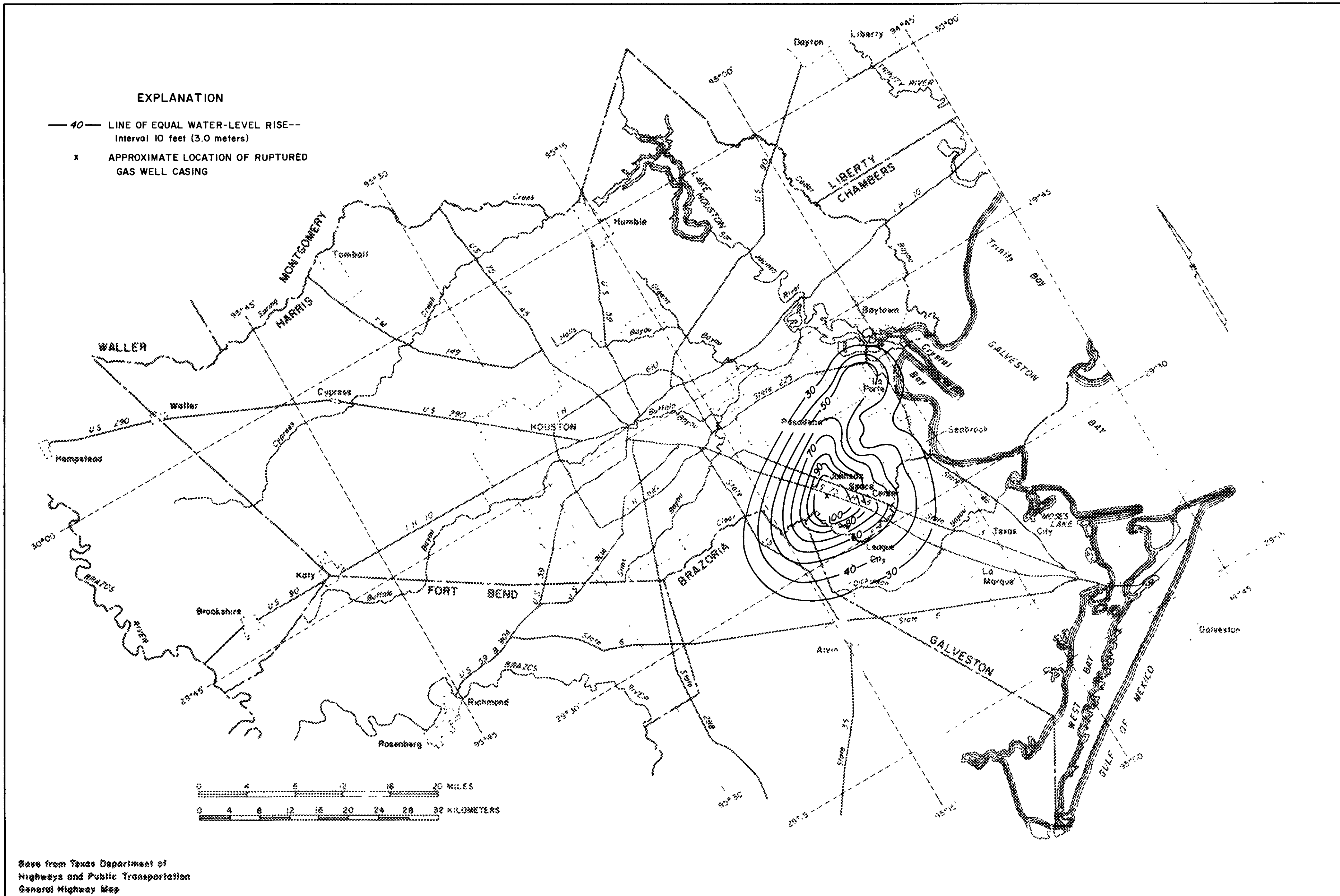


Figure 19.-Rise in water levels in wells in the Chicot aquifer due to a ruptured gas well

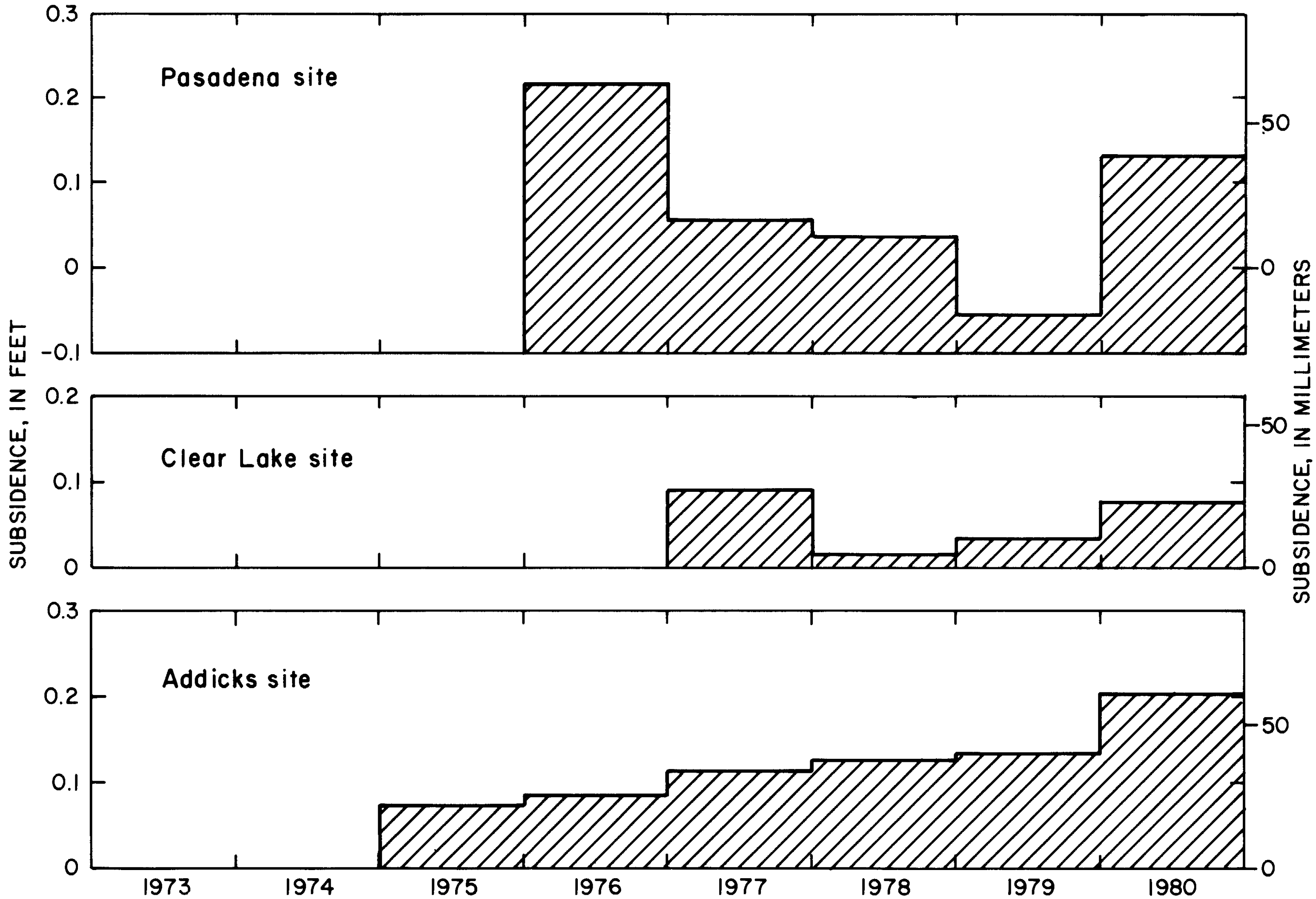


Figure 20.-Annual subsidence measured by extensometers at the Pasadena, Clear Lake, and Addicks sites

Seabrook Site

The Seabrook site (fig. 1) was established during 1973 to evaluate subsidence at Seabrook and Kemah. The report of findings (Gabrysch and Bonnet, 1976a) was used by the funding agency, the U.S. Army Corps of Engineers, in their consideration of protective measures in the Seabrook-Kemah area. The extensometer was installed to a depth of 1,381 feet (421 m) and is used to measure compaction from the land surface to that depth. A graph of the extensometer record at Seabrook (fig. 21) reflects a change in the rate of compaction during late 1976. The interpretation of the record for this site is the same as for the Johnson Space Center site; that is, regional decreases in rates of water-level decline and decreases in pumping both contributed to the decreased rate of compaction.

The erratic pattern of compaction between late 1977 and late 1978 probably was due to effects of nearby pumping during a transition from ground-water to surface-water use. The rebound that occurred between November 1978 and February 1979 is related to regional recoveries in water levels due to decreased ground-water pumping and water-level rises due to gas pressure. By October 1979, compaction exceeded that recorded during November 1978; therefore, at the Seabrook site, recoveries in pressures in the sands were insufficient to overcome residual excess pore pressure, and additional subsidence is occurring.

Water levels are measured in piezometers at eight depths to define the change in stress associated with the change in compaction. The water levels in piezometers at the Seabrook site for November 1978, April 1979, and October 1979 are shown in figure 22. At these times, elastic rebound began, reached its maximum, and compaction exceeded the 1978 maximum. The measurements by the National Geodetic Survey indicated about 1.06 feet (0.32 m) subsidence at the site as compared to about 0.90 foot (0.27 m) as determined from the extensometer record.

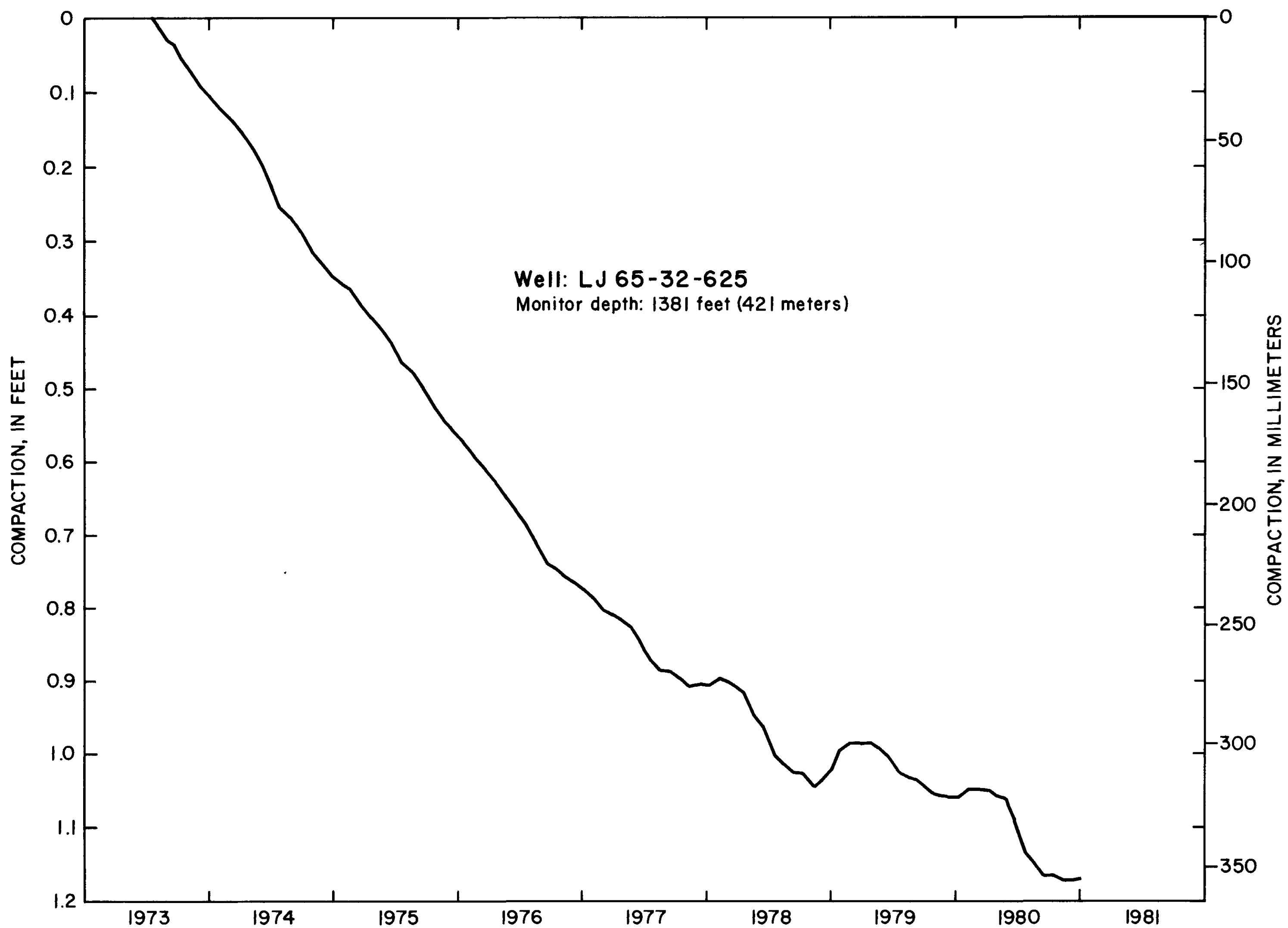


Figure 21.-Cumulative compaction at the Seabrook site

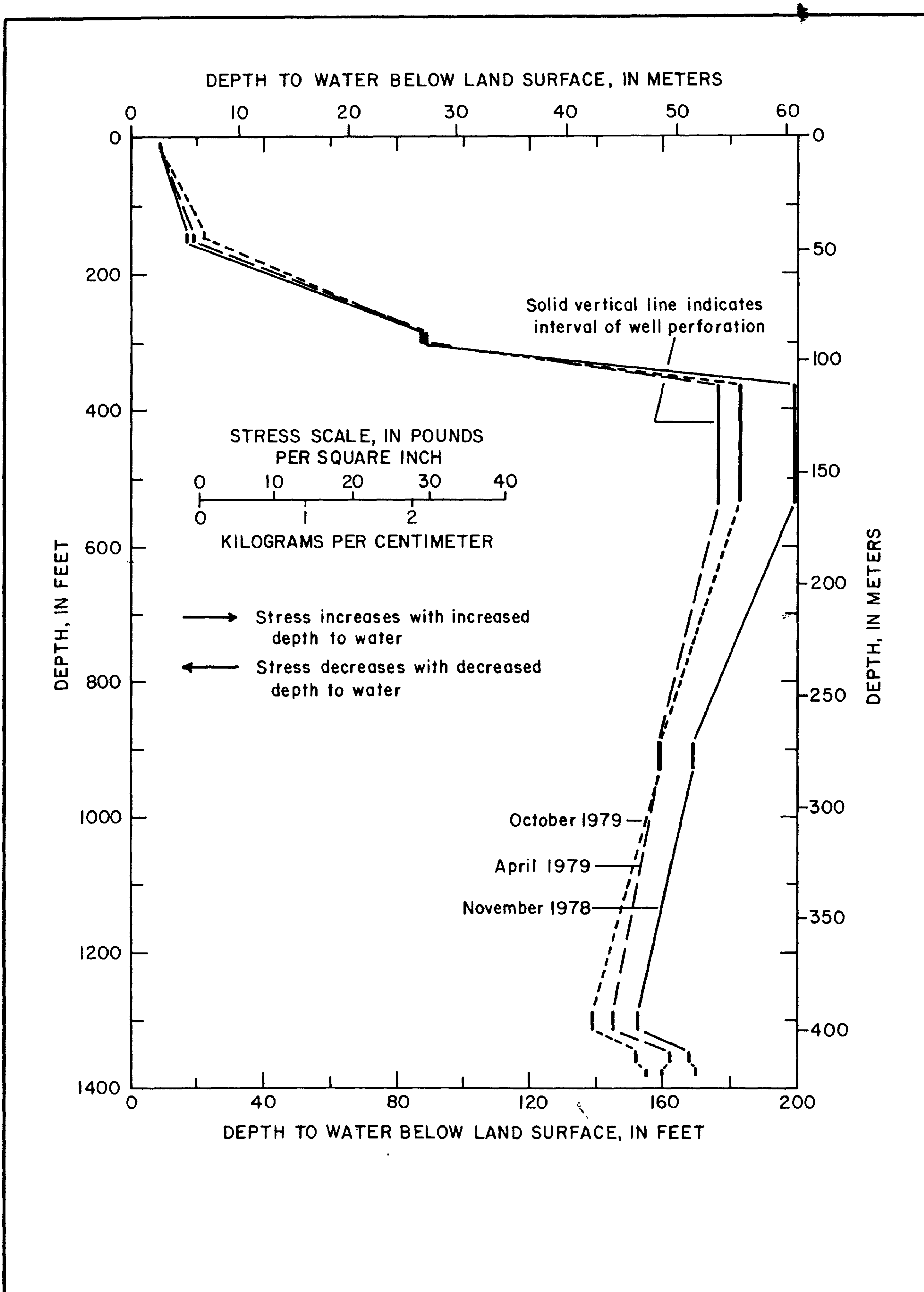


Figure 22.-Potentiometric profiles and changes in effective stress at the Seabrook site

Pasadena Site

Construction of facilities for subsidence studies at the Pasadena site (fig. 1) began during 1975 with the installation of an extensometer for the Texas Department of Highways and Public Transportation. Data from the extensometer is being used in the design of a bridge across the Houston Ship Channel. The extensometer was designed to measure total man-caused subsidence. The hole was drilled to a depth of 2,870 feet (875 m), about 15 feet (4.6 m) into the Burkeville confining layer. Casing with slip joints (to allow compressive strain without casing failure) at depths of 247, 507, and 995 feet (75, 155, and 303 m) below land surface was set to 2,826 feet (861 m). A well screen was placed in a sand at 2,707 to 2,717 feet (825 to 828 m) to allow measurement of water levels corresponding to changes in pressure near the base of the Evangeline aquifer. The inner pipe extends from the top of the cement plug at a depth of 2,830 feet (863 m) to land surface. During 1975, piezometers were installed to depths of 100 and 390 feet (30 and 119 m) in cooperation with the City of Houston. These two piezometers and a 34-foot (10-m) deep piezometer drilled during 1974 were used to study encroachment of saline water (Jorgensen, 1976). During 1976, four additional piezometers were drilled to depths of 730, 936, 1,328, and 1,817 feet (223, 285, 405, and 554 m) for the Harris-Galveston Coastal Subsidence District to complete the installation.

A graph of compaction (subsidence) at the Pasadena site (fig. 23) shows a marked decrease in the rate of subsidence beginning in September 1976. This change probably was due to the regional decrease in the rate of water-level declines associated with the stabilization of pumping. The apparent increase in subsidence during 1978 may have been due to shrinkage of near-surface material (soil) above the water table as a result of decreased soil moisture as well as continued subsidence caused by pressure declines.

The rebound from November 1978 to April 1979 indicated elastic response of the system to rises in artesian pressure and swelling of the soil. The lack of compaction from April 1979 to May 1980, following rebound from November 1978 to April 1979, indicated that net recoveries of artesian pressure at the site exceeded residual excess pore pressure and subsidence had stopped. However, compaction resumed during May 1980, and by December 1980 subsidence exceeded the maximum of September 1978 by about 0.03 foot (9 mm). Subsidence at the Pasadena site decreased from 0.216 foot (65.8 mm) during 1976 to -0.055 foot (-16.8 mm) during 1979 and then increased to 0.136 foot (41.5 mm) during 1980 (fig. 20).

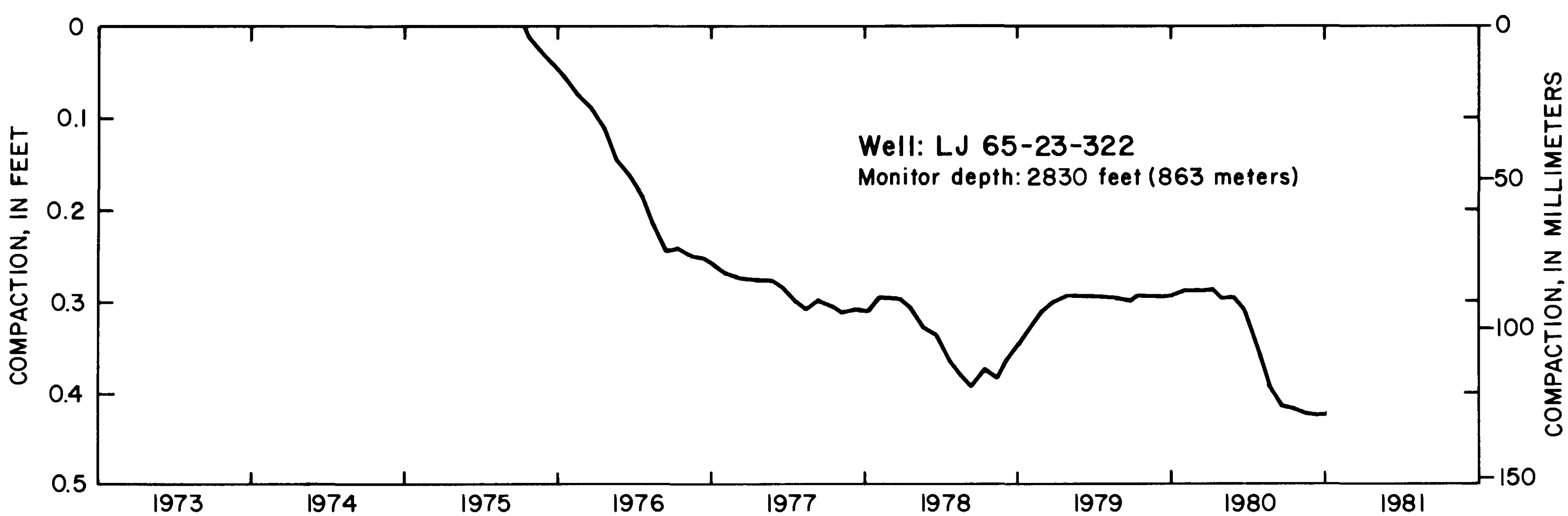


Figure 23.-Cumulative compaction at the Pasadena site

An evaluation of the water-level data shows that stresses below a depth of about 350 feet (107 m) continue to decrease, although at a slower rate, while stresses above 350 feet (107 m) increased through 1979 and remained almost constant during 1980. Analysis of the extensometer records from Pasadena and Clear Lake indicates subsidence during 1980 resulted from compaction of shallow material. The rebound that occurred during 1978-79, followed by the rapid compaction during 1980 and the marked decrease in the rate of compaction during late 1980, indicates an elastic response of the ground-water system.

The water levels measured in piezometers during March and November 1978 and during April and December 1979, times for which definite changes in the subsidence pattern were observed, are shown in figure 24. The measurements by the National Geodetic Survey indicated a rise of 0.033 foot (10 mm) in elevation of the inner pipe during 1976-78.

Addicks Site

Construction at the Addicks site (fig. 1) was begun during 1974 with installation of an extensometer to the top of the Burkeville confining layer at a depth of 1,802 feet (549 m). A piezometer also was installed to a depth of 49 feet (15 m) during 1974. During 1977, two additional piezometers were drilled to depths of 153 and 237 feet (47 and 72 m). Measurements in the extensometer, the three piezometers, a City of Houston water well located at the site, and a nearby abandoned 360-foot (110-m) deep water well are used to analyze stress changes causing subsidence.

A graph of compaction (subsidence) shows that subsidence at the Addicks site is seasonal (fig. 25). The rate of subsidence during the winter is less than during the summer. The rate of subsidence at the site has increased since the record began as indicated by the increasing slope of the graph. During 1975, the first full year of record, the land surface subsided about 0.074 foot (22.6 mm); during 1980, the land surface subsided about 0.206 foot (62.8 mm) as shown in figure 20.

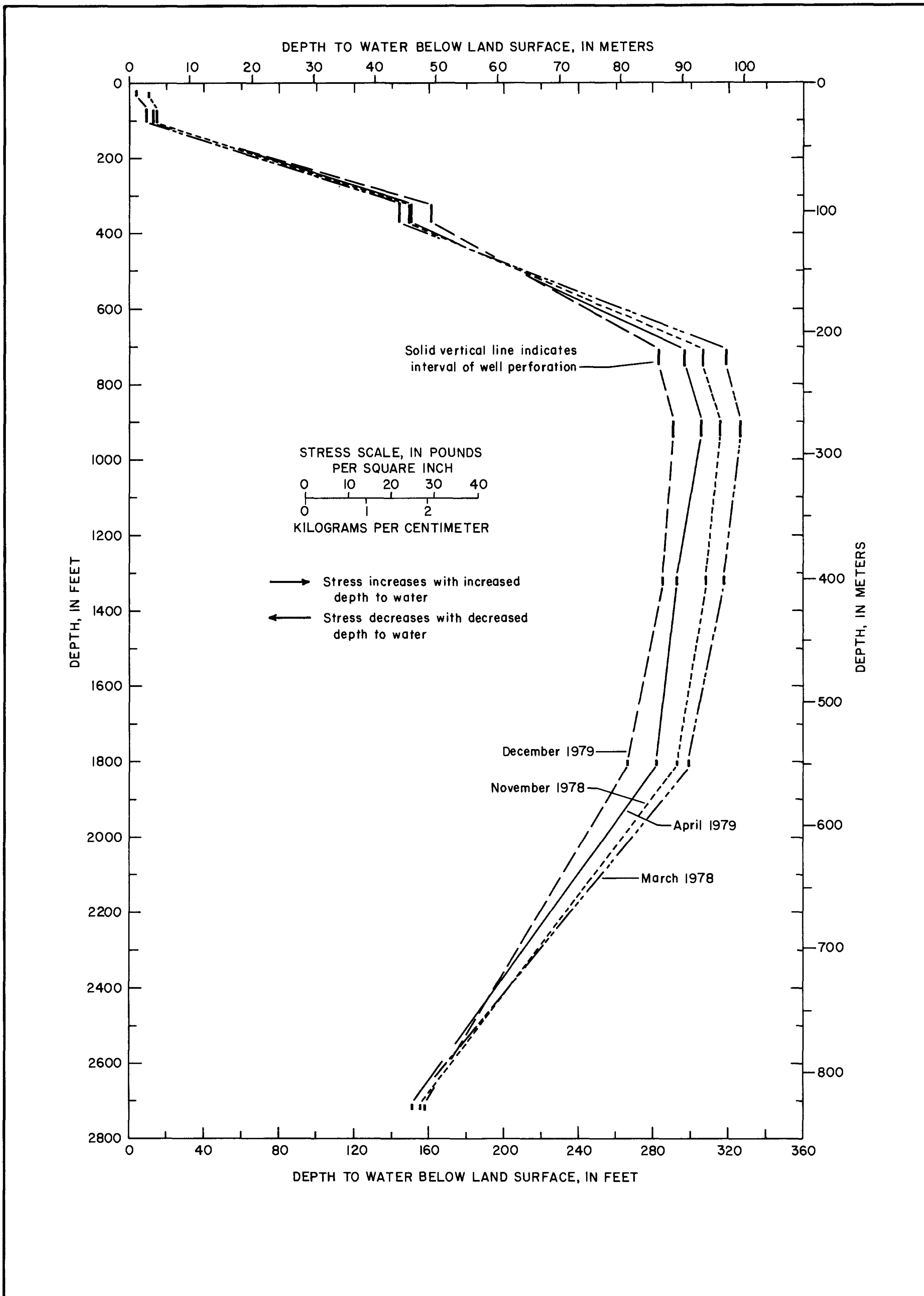


Figure 24.-Potentiometric profiles and changes in effective stress at the Pasadena site

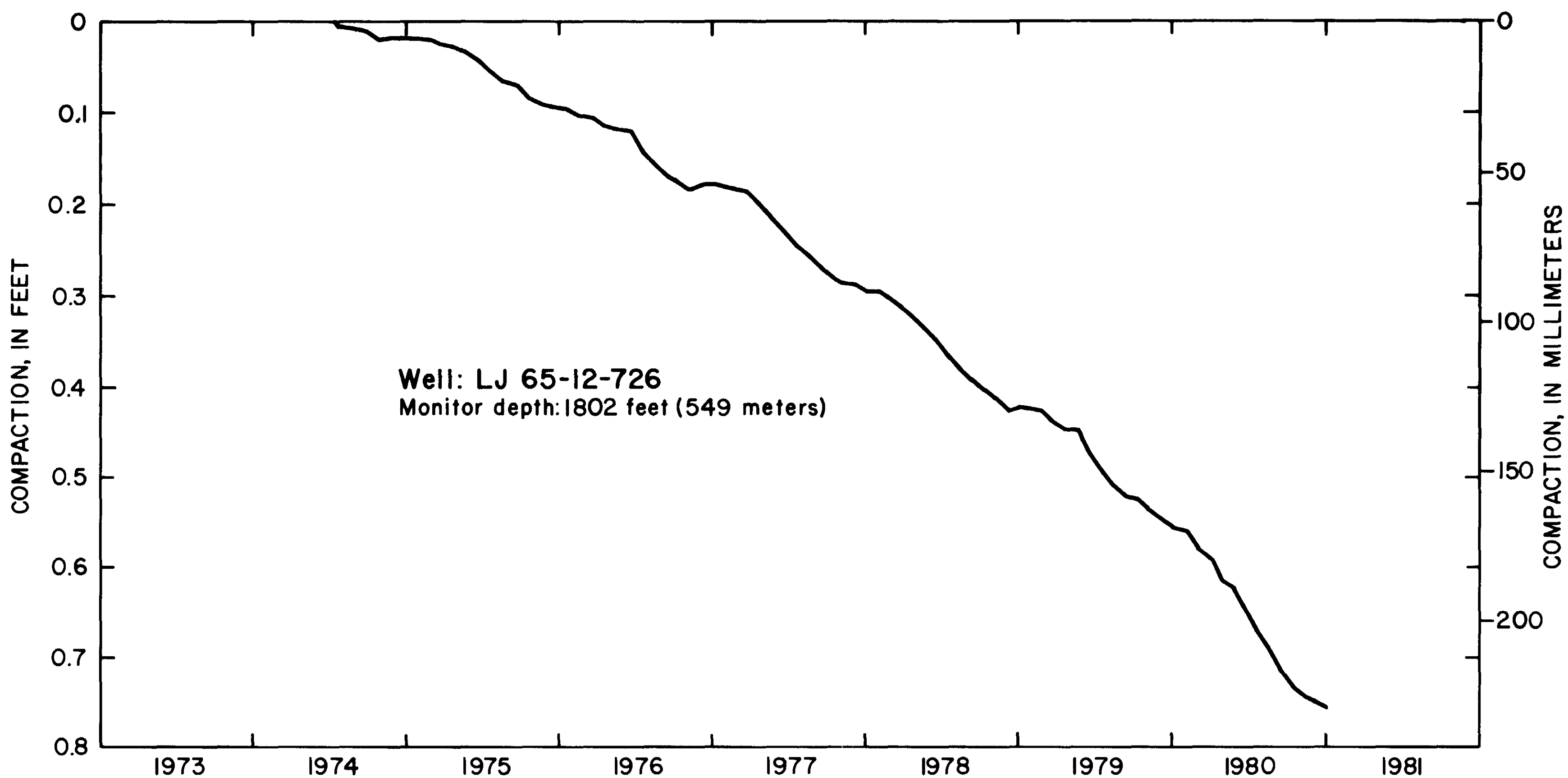


Figure 25.-Cumulative compaction at the Addicks site

Subsidence at the site from about mid-1976 to about mid-1978 as determined from leveling, was 0.22 foot (67 mm) as compared to subsidence of 0.24 foot (73 mm) as determined from the extensometer record for July 1976 to July 1978. The apparent difference is small; larger discrepancies are likely because elevations are not determined instantaneously. The measurements by the National Geodetic Survey indicated a rise in elevation of the inner pipe of the extensometer of 0.013 foot (4.0 mm). It is not likely that the pipe rose but rather that adjustment errors exist. The land surface is subject to less subsidence per unit water-level decline at Addicks than in areas closer to the Gulf of Mexico. However, the Addicks area has been subjected to accelerated water-level declines. The City of Houston, for at least the past 15 years, has been shifting ground-water production to the western part of the region to minimize the effect of subsidence in areas of low elevation. The water levels in piezometers measured during January or February of 1976, 1977, 1978, and 1979 are shown in figure 26. The profiles generally show an increase in depth to water each year.

Houston East End Site

The first extensometer in the Houston region was installed by the Geological Survey at the Houston East End site. It was installed in an abandoned City of Houston well in 1958 but failed during the early 1960's because the well casing collapsed. A new extensometer-piezometer, set to a depth of 995 feet (303 m), was constructed by the Geological Survey in 1973 as a part of its research effort. In 1974, a 64-foot (20-m) deep piezometer was installed in cooperation with the City of Houston for a study of encroachment of saline water in shallow sands. The two piezometers and the extensometer provide valuable but limited information at this site.

A graph of compaction at the site (fig. 27) shows that the contribution to subsidence by compaction of materials to a depth of 995 feet (303 m) was at a constant rate of 0.15 foot (46 mm) per year from 1973 to mid-1976. A slight decrease in the rate of compaction from mid-1976 to sometime during 1977 probably was due to a decreased rate of regional water-level declines. The further decrease in the rate of compaction during 1978 and 1979 was due to a rise in water levels at the site as a result of decreased ground-water pumping, mainly east of the site.

Subsidence at the site, based on elevations determined by the National Geodetic Survey during the spring of 1973 and mid-1978, was 0.8 foot (244 mm) as compared to a measured compaction of 0.67 foot (204 mm) from July 1973 to July 1978. On the basis of these measurements, about 84 percent of the subsidence was due to compaction of the material to a depth of 995 feet (303 m).

A graph of measurements made in the piezometers (fig. 28) shows a slight increase (3 feet or 0.9 m) in the depth to water from May 1976 to August 1977 and a sizable (42 feet or 12.8 m) rise in water levels between August 1977 and December 1979 in the deepest piezometer. The measurements coincide with the changes in slopes (changes in rates of compaction) shown in figure 27.

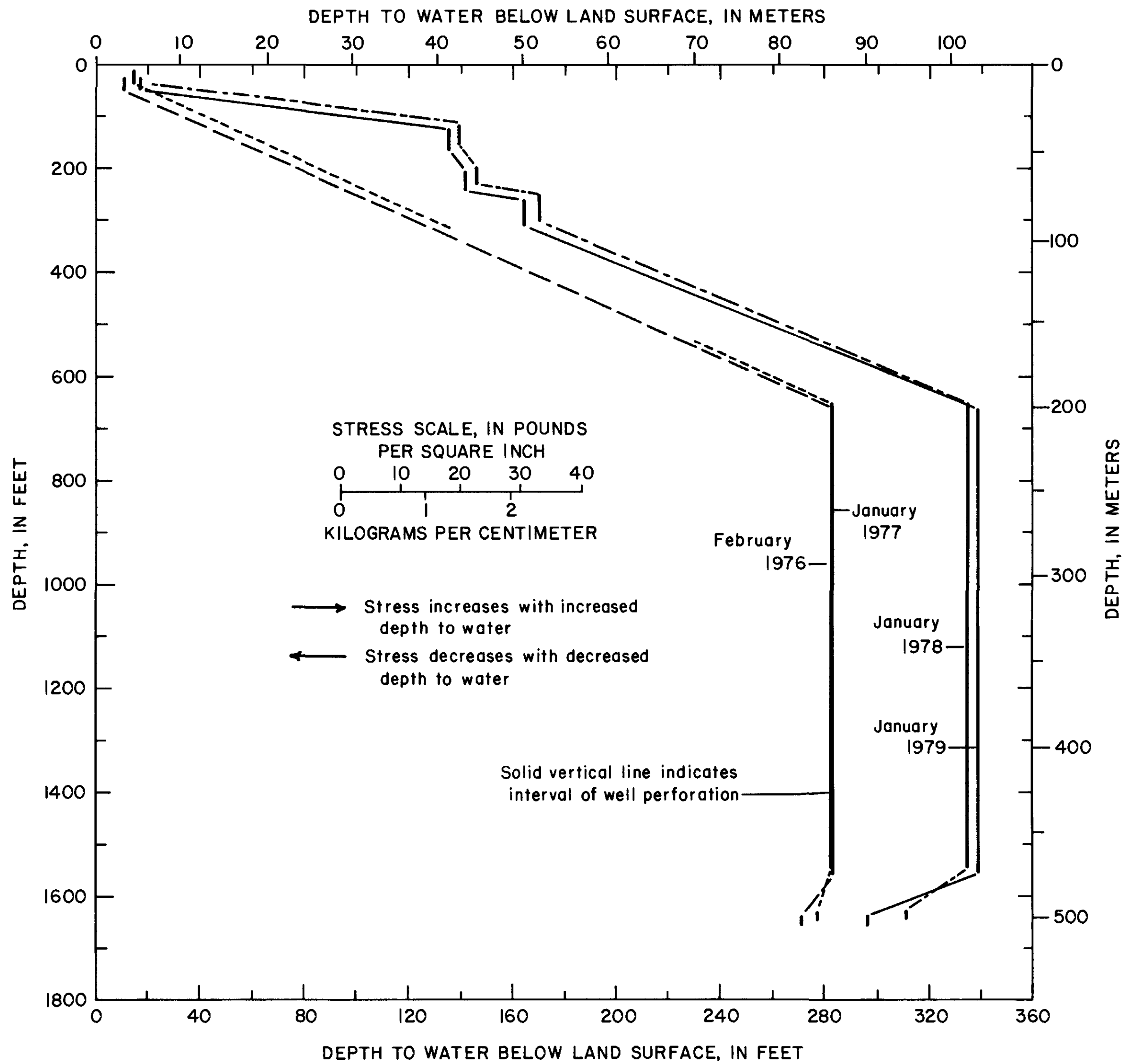


Figure 26.- Potentiometric profiles and changes in effective stress at the Addicks site

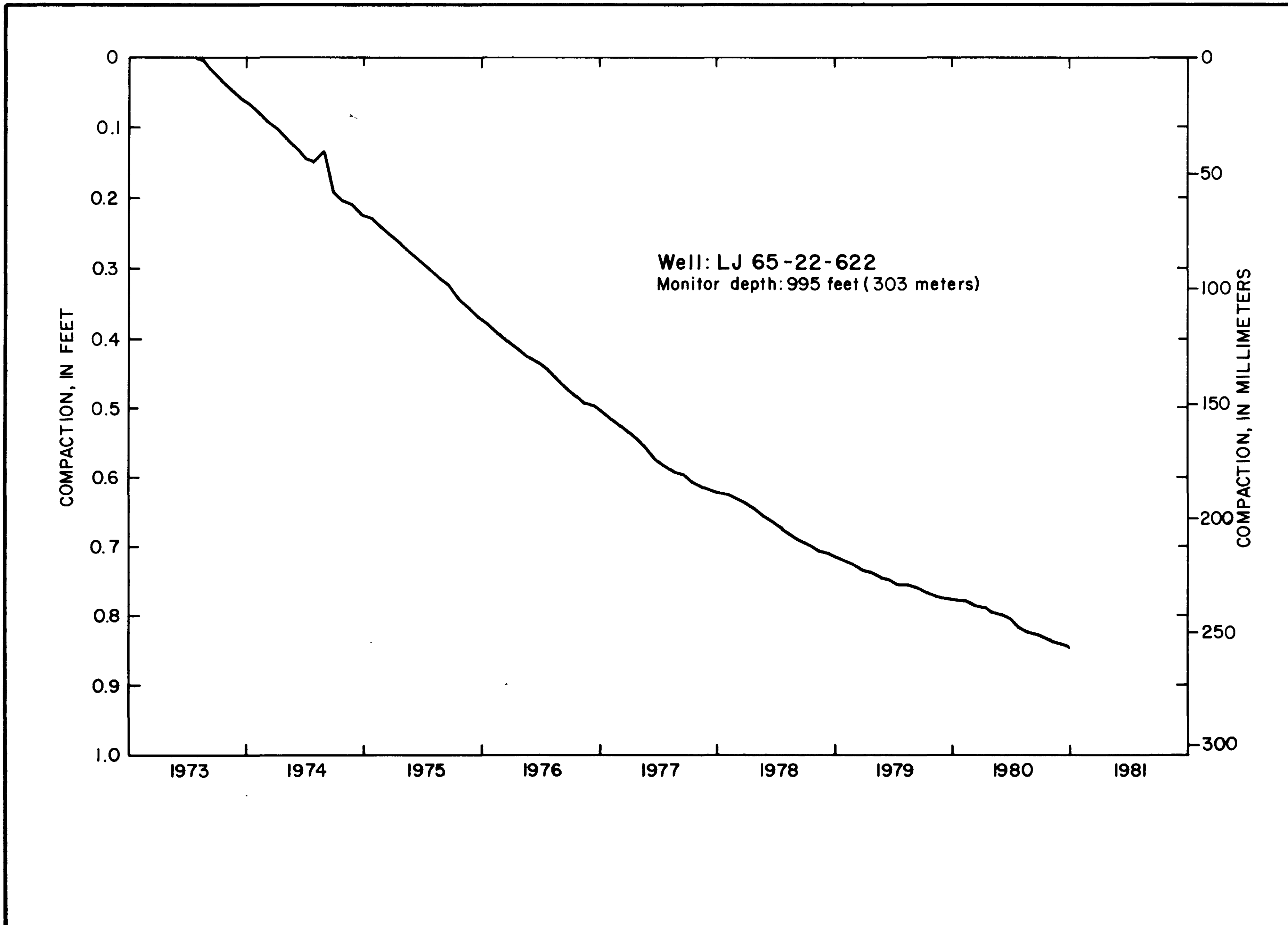


Figure 27.-Cumulative compaction at the Houston East End site

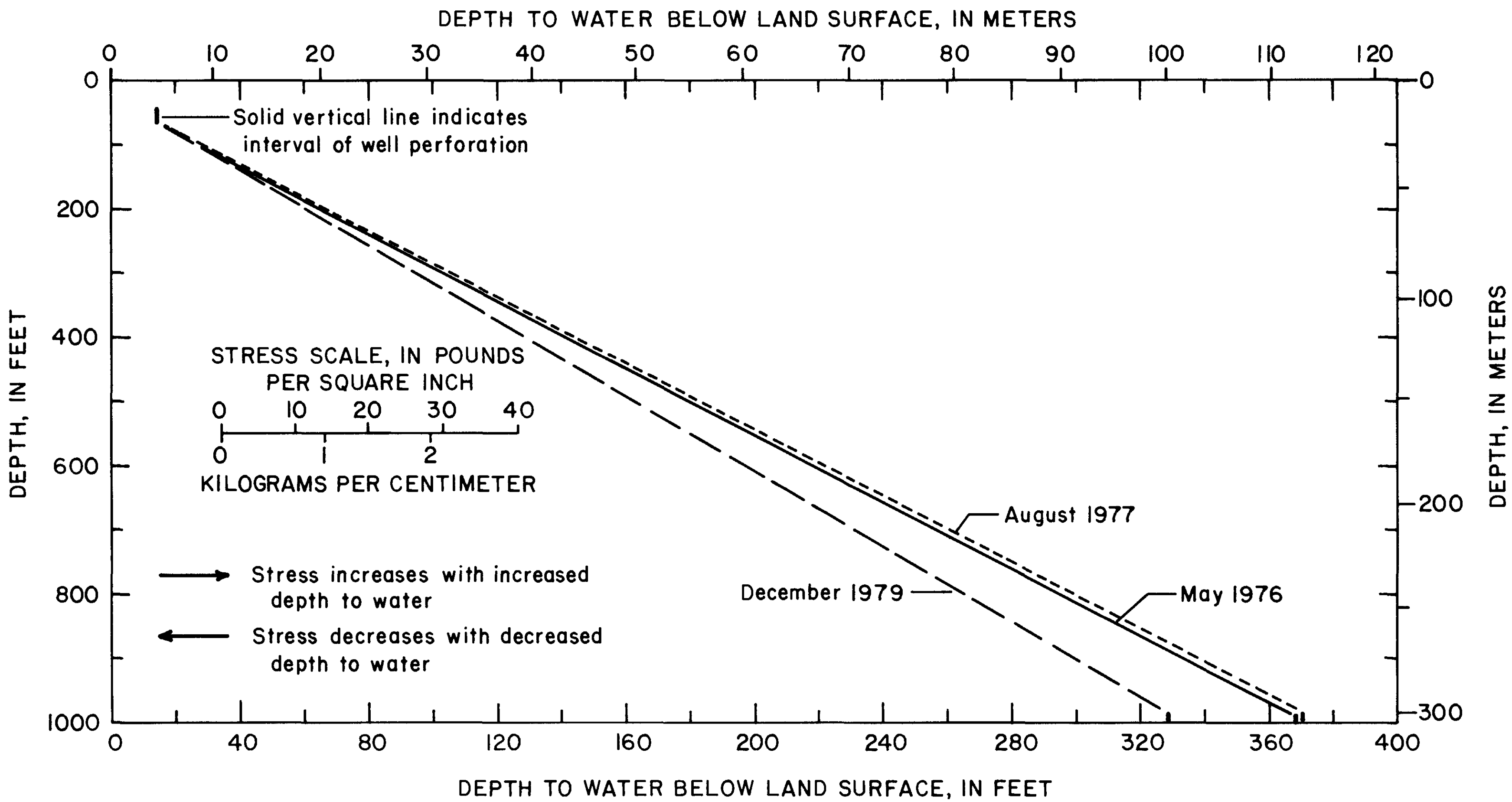


Figure 28.-Potentiometric profiles and changes in effective stress at the Houston East End site

Baytown Site

The Baytown site (fig. 1) was established during 1972 to evaluate subsidence in the Burnet, Scott, and Crystal Bays area of Baytown, Texas. The report of findings (Gabrysch and Bonnet, 1974) was used by the funding agency, the U.S. Army Corps of Engineers, to suggest protective measures for the Brownwood subdivision. Two extensometers were installed to depths of 431 and 1,475 feet (131 and 450 m) to measure compaction in two depth intervals. Bench marks were established at the site during 1973 by the National Geodetic Survey to periodically determine total subsidence. In addition to the two extensometers, piezometers were installed to depths of 60, 110, 170, 234, 324, 430, 1,365, and 1,475 feet (18, 34, 52, 71, 99, 131, 416, and 450 m). Pressure transducers were installed in clay layers at depths of 71, 126, 259, and 344 feet (22, 38, 79, and 105 m) to measure clay-pore pressure to determine the excess pore pressure that would cause compaction. The transducers failed after approximately 1 year. Measurements indicated that excess pore pressures were equivalent to 0, 8, 42, and 135 feet (0, 2.4, 13, and 41 m) of artesian head. To arrest compaction, artesian-pressure heads must be raised in the sands adjacent to those clay layers by the same values.

A graph of extensometer measurements of compaction that occurred in the depth intervals 0-431 feet (0-131 m) and 0-1,475 feet (0-450 m) is shown in figure 29. The cumulative difference between extensometer measurements, representing the compaction that has occurred in the depth interval 431-1,475 feet (131-450 m), also is shown in figure 29.

The irregularities (abrupt changes in compaction) are a result of shrinking and swelling of the top few feet of soil associated with soil-moisture changes. Both extensometers are affected about equally by the shrinking and swelling. Analysis of the measurements for a short term can be misleading because the shrink-swell effect is significant and cannot be eliminated from the past record. The individual extensometer record (fig. 29) indicates that the compaction rate of the depth interval 0-1,475 feet (0-450 m) had slowed beginning about July 1978 to almost zero by the end of 1979. Subsidence at the site, based on elevations determined by the National Geodetic Survey, was about 0.6 foot (183 mm) between spring 1973 and mid-1978. Measurements from the extensometers show compaction of about 0.33 foot (101 mm) between the land surface and 431 feet (131 m) and about 0.37 foot (113 mm) between 431 and 1,475 feet (131 and 450 m). Monitored compaction at the site was about 0.7 foot (214 mm) which exceeded the 0.6 foot (183 mm) of subsidence determined by National Geodetic Survey elevations.

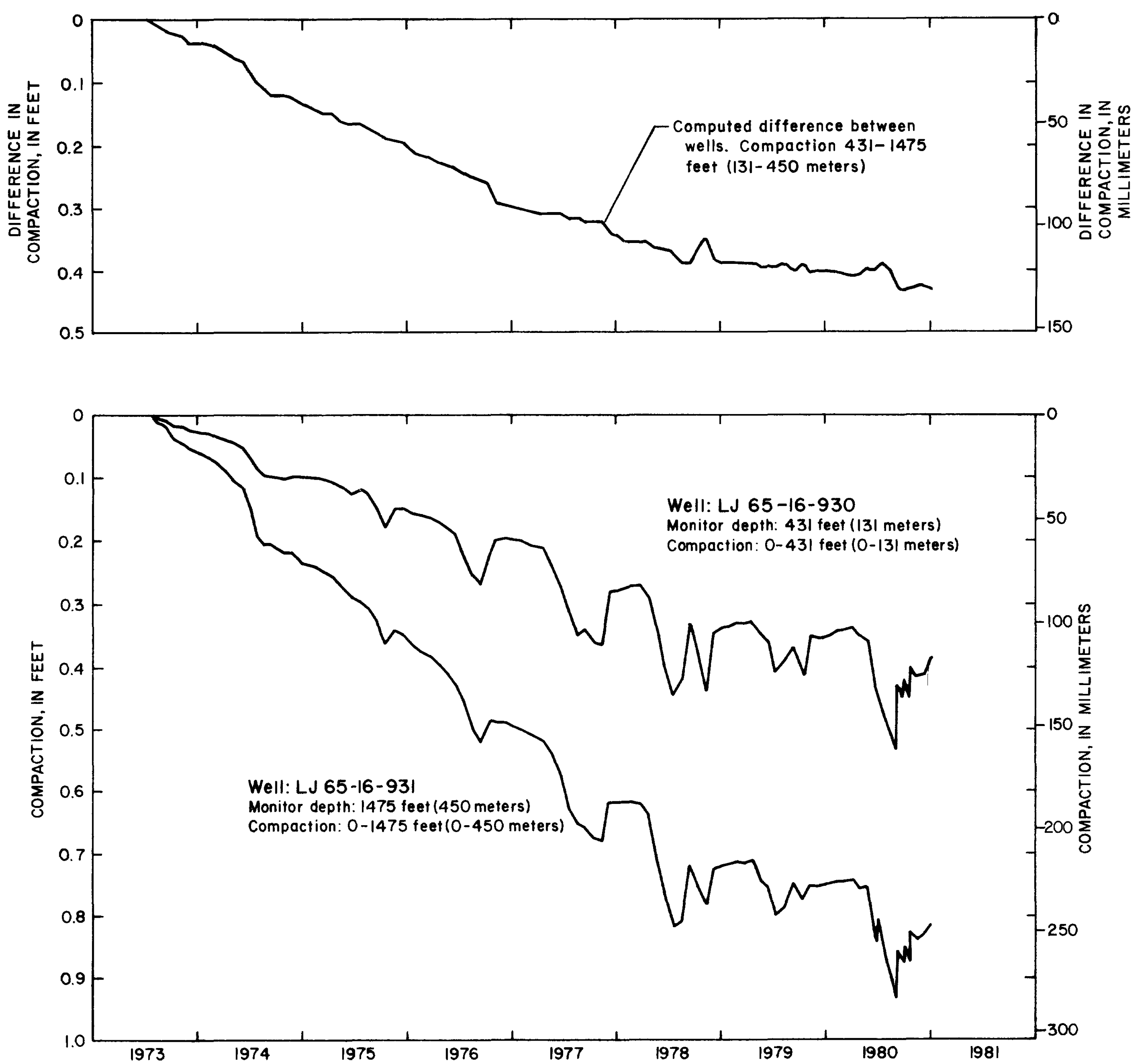


Figure 29.-Cumulative compaction at the Baytown site

Compaction measured by the extensometers probably does not reflect total subsidence because some compaction leading to subsidence may occur below a depth of 1,475 feet (450 m). The discrepancy between compaction and subsidence may be the result of: (1) Inability to compare records from the extensometers to those obtained from leveling because the elevations determined by leveling are not instantaneous; (2) instability of bench marks used in the leveling; and (3) inability to determine compaction associated with pumping of ground water from the extensometer record at a particular time because of the shrink-swell phenomenon. The design of extensometers for new installations now incorporates concrete piers beneath the slab supporting the recorder to eliminate shrink and swell from the monitor record.

Plots of water-level measurements in wells versus depth of well completion at the Baytown site for August and November 1978 and April and December 1979 are shown in figure 30. The measurements were selected for times of changes in compaction rate that appeared to be related to artesian-pressure changes rather than to soil-moisture changes. The plots show that stress on the material to a depth of 1,475 feet (450 m) decreased from August 1978 to December 1979 because of rising water levels.

Texas City-Moses Lake Site

The Texas City-Moses Lake site (fig. 1) was established for the Corps of Engineers by the Geological Survey during 1973 to evaluate subsidence in the vicinity of the mouth of Moses Lake. A report of findings was presented by Gabrysch and Bonnet (1976b). For the evaluation, an extensometer was installed to a depth of 800 feet (244 m). In addition, piezometers were constructed to depths of 24, 210, 302, 400, 535, 790, and 1,060 feet (7.3, 64, 92, 122, 163, 241, and 323 m). Bench marks were established at the site during 1973 by the National Geodetic Survey to periodically determine elevations.

A graph of the measured compaction for the period of record is shown in figure 31. The graph indicates that compaction of material in the depth interval 0-800 feet (0-244 m) was at an almost constant rate of about 0.04 ft/yr (12 mm/yr) from July 1973 to July 1977. Between July 1977 and November 1978, the rate of compaction decreased to about 0.02 ft/yr (6.0 mm/yr). Between November 1978 and December 1980, there was about 0.015 foot (4.6 mm) compaction in the depth interval. After May 1980, the recorded compaction may be due to shrinkage of near-surface material during a period of less than normal rainfall. On the basis of the geology of the area, and the artesian-pressure decline, most of the subsidence should result from compaction of the material from land surface to a depth of 800 feet (244 m). However, subsidence at the site as determined from National Geodetic Survey data was 0.33 foot (101 mm) and measured compaction was 0.17 foot (52 mm) indicating that about 50 percent of the subsidence was due to compaction of material below a depth of 800 feet (244 m).

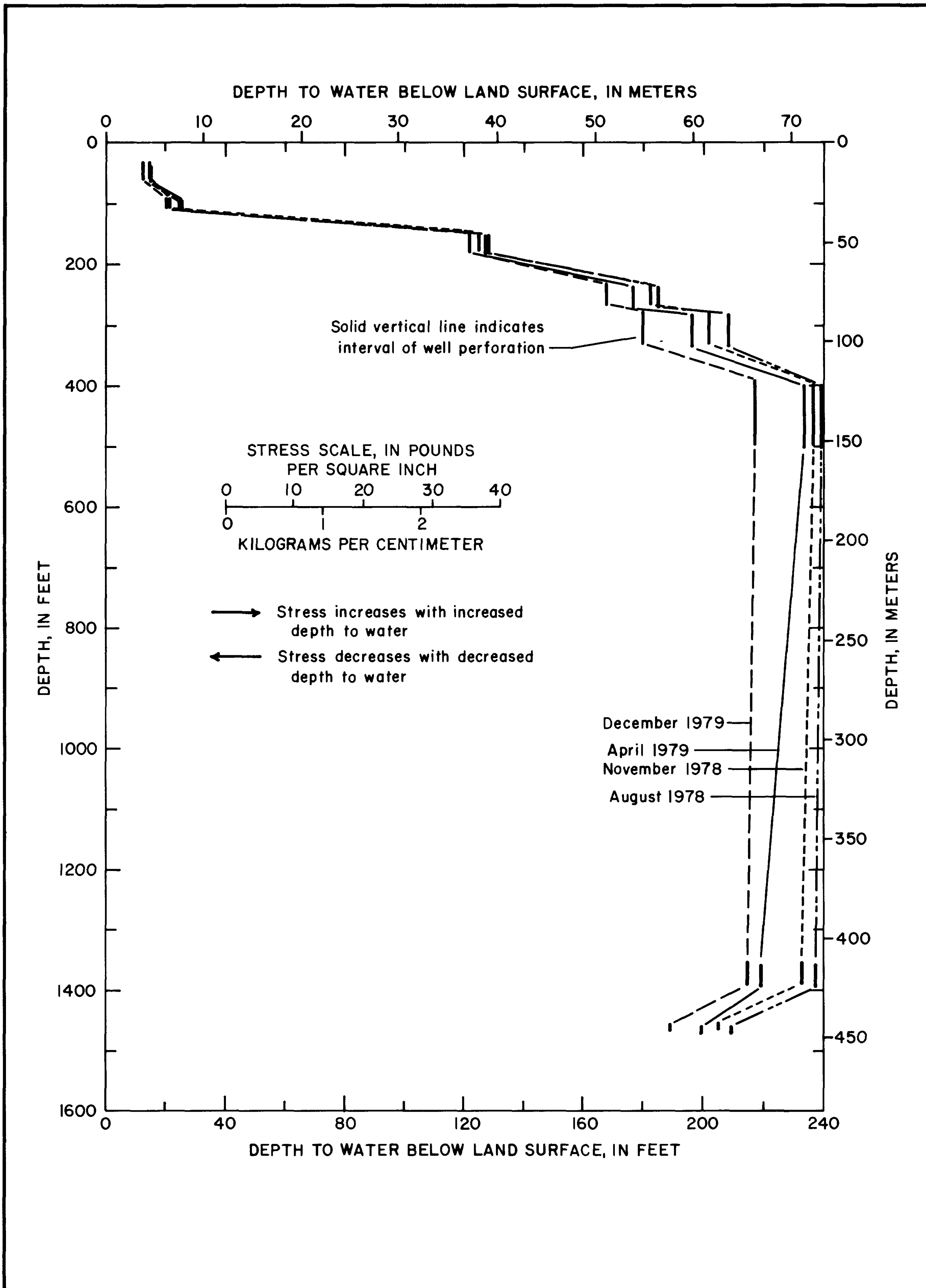


Figure 30.-Potentiometric profiles and changes in effective stress at the Baytown site

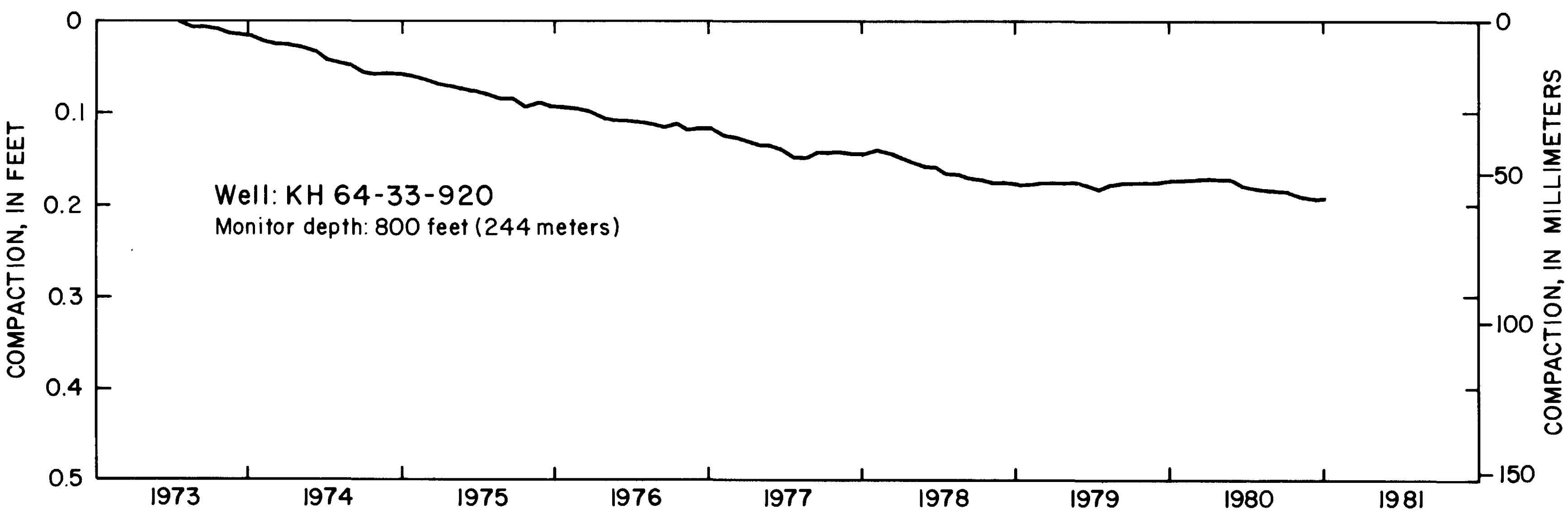


Figure 31.-Cumulative compaction at the Texas City-Moses Lake site

Plots of water-level measurements in wells versus depth of well completion at the Texas City-Moses Lake site for November 1978 and December 1979 are shown in figure 32. The profile of water levels shown by the graph for November 1978 defines a stress coincident with the cessation of compaction (fig. 31). The December 1979 profile shows a decrease in depths to water from November 1978, representing a further unloading of the material to a depth of 1,060 foot (323 m).

Subsidence from Tide Records

The accepted datum for vertical measurements is called National Geodetic Vertical Datum. The National Geodetic Vertical Datum of 1929 (NGVD of 1929), currently in use, is based on records from 21 tide stations in the United States and 5 in Canada. According to Swanson (1974), "The NGVD of 1929 is fixed and does not take into account the changing stands of sea level. Because of the many variables affecting sea level, the relationship between NGVD and local mean sea level is not consistent from one location to another in either time or space." For this reason, mean sea level should not be confused with the National Geodetic Vertical Datum. However, the change in the difference in mean gage height (mean water level) with time between stations a few miles apart can be a measure of changes in elevation between the stations.

An evaluation was made of tide-gage records from five sites in the Galveston Bay complex and records from two stream-gaging sites in the tidal reach of Buffalo Bayou to determine their use in estimating differential subsidence. The locations of the gaging sites are shown in figure 1. Monthly mean gage height determined from the records of gages at Galveston Pier 21, Seabrook, Morgan Point, Point Barrow in the Galveston Bay complex, Galveston railroad causeway, and Buffalo Bayou at 69th and Main Streets are shown in figure 33.

Comparison of the difference in monthly mean stage obtained at Seabrook, Morgan Point, Buffalo Bayou at 69th and Main Streets, and Point Barrow gages to the Galveston railroad causeway gage is presented in figure 34. The differences shown by figure 34 were adjusted to zero in January 1964.

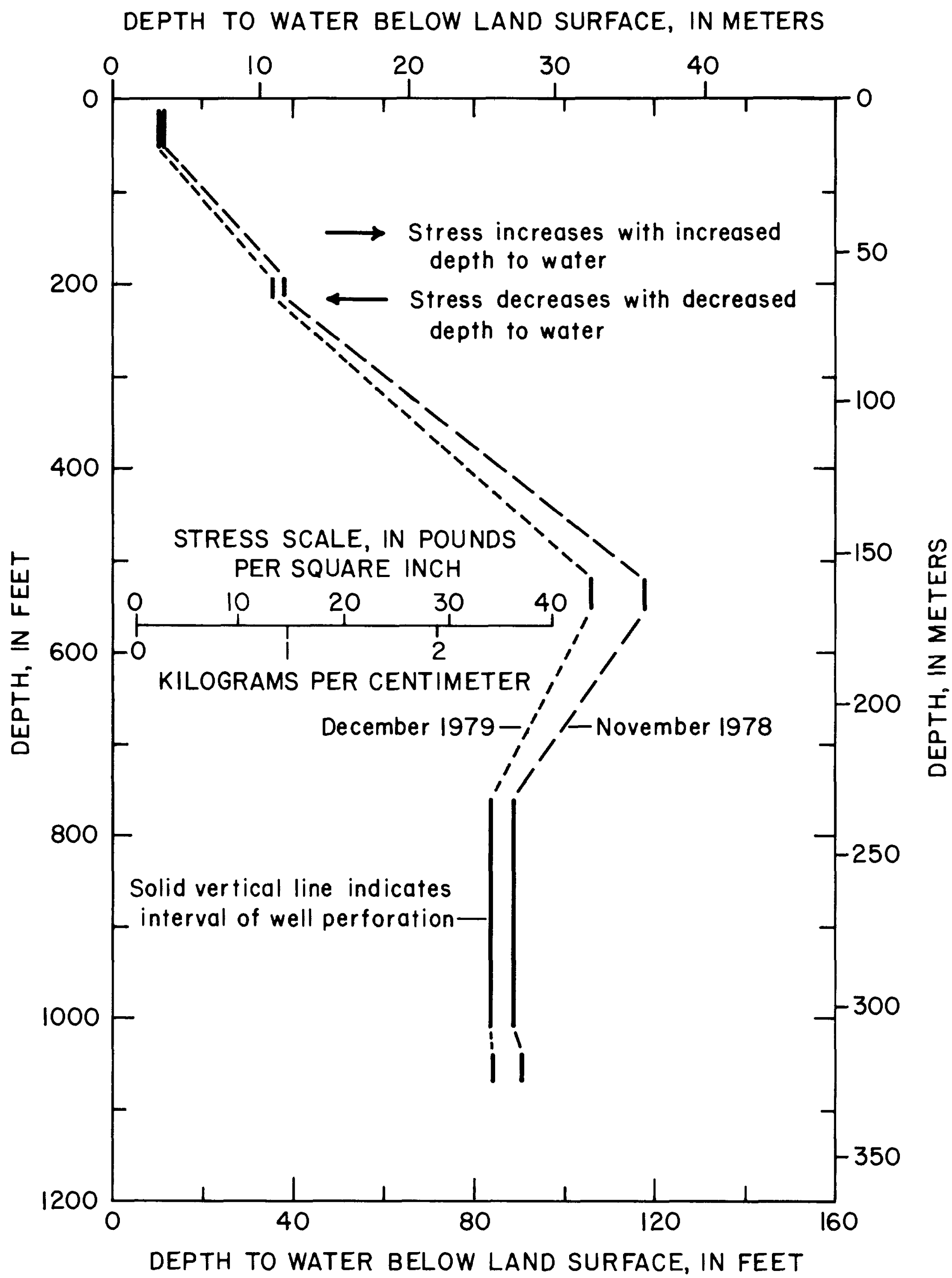


Figure 32.-Potentiometric profiles and changes in effective stress at the Texas City-Moses Lake site

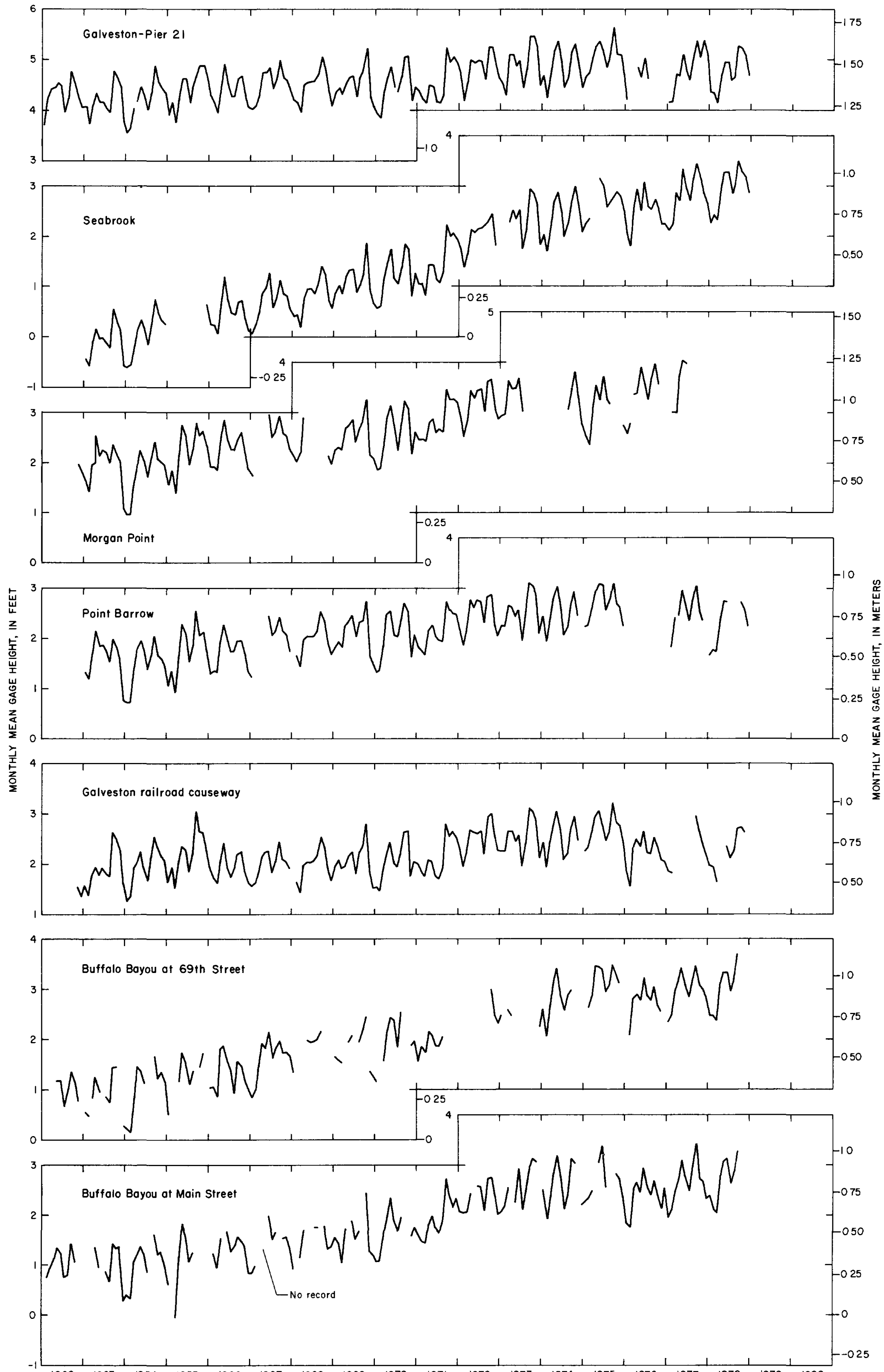


Figure 33.-Monthly mean gage heights in the Houston-Galveston region

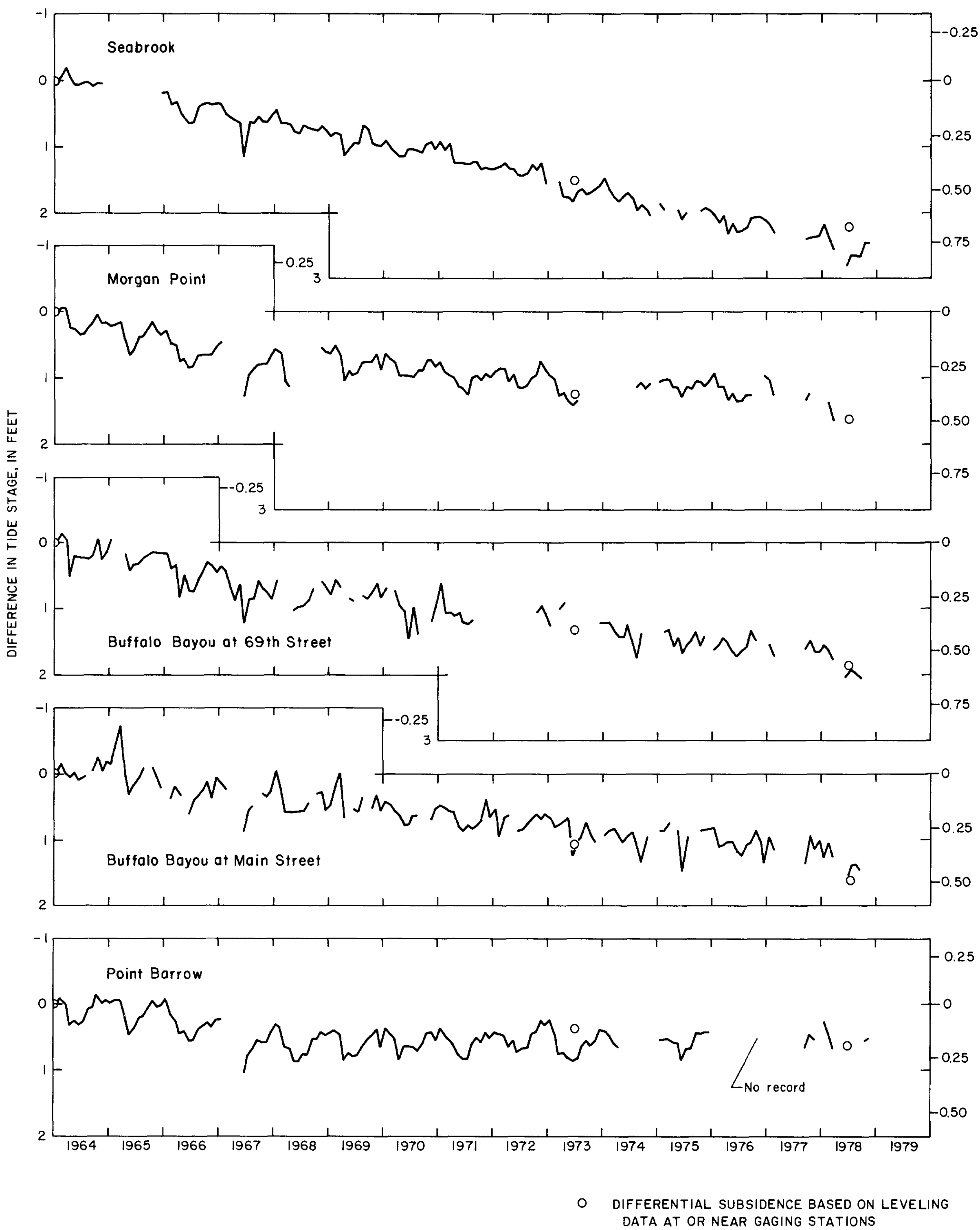


Figure 34.-Difference in the mean monthly tide stage relative to the gage record at the Galveston railroad causeway

The railroad-causeway gage was selected as a base station because it probably is more representative of short-term changes in the bay complex than the Pier 21 gage. However, using the Pier 21 gage as a base did not yield appreciable differences in results. The gaging stations, the operators, and the dates records began are listed in the following table:

Station	Operator 1/	Beginning of record
Galveston Pier 21	NOAA	April 1908
Seabrook	USACE	January 1963 2/
Morgan Point	do.	October 1962 2/
Point Barrow	do.	October 1962
Galveston railroad causeway	do.	October 1962
Buffalo Bayou at 69th Street	USGS	April 1961
Buffalo Bayou at Main Street	do.	January 1962

1/ NOAA - National Oceanic and Atmospheric Administration.
USACE - U.S. Army Corps of Engineers.
USGS - U.S. Geological Survey.
2/ Gage relocated in 1973.

The graphs of figure 34 show that the differences in mean monthly stage range considerably. Analysis of the records indicate seasonal effects, wind, and freshwater inflow probably contribute to the fluctuations. The trends of the graphs, however, agree with the direction of movement of the land surface. Use of a moving average of the differences smoothes the short-term effects and shows the trend more clearly.

Graphs of 12-month moving averages of the differences in mean monthly gage heights for the Seabrook, Morgan Point, Buffalo Bayou at 69th Street and at Main Street, and Point Barrow gages, using the Galveston railroad causeway as a base are shown in figure 35. The average shown for any month is the average of the monthly difference for that month and the preceding 11 months. Elevations of bench marks were determined during 1963-64 by the National Geodetic Survey. To facilitate the comparison of the average change in relative tide stage, it was assumed the elevations were correct, and the graphs in figure 35 were adjusted to zero difference for that date.

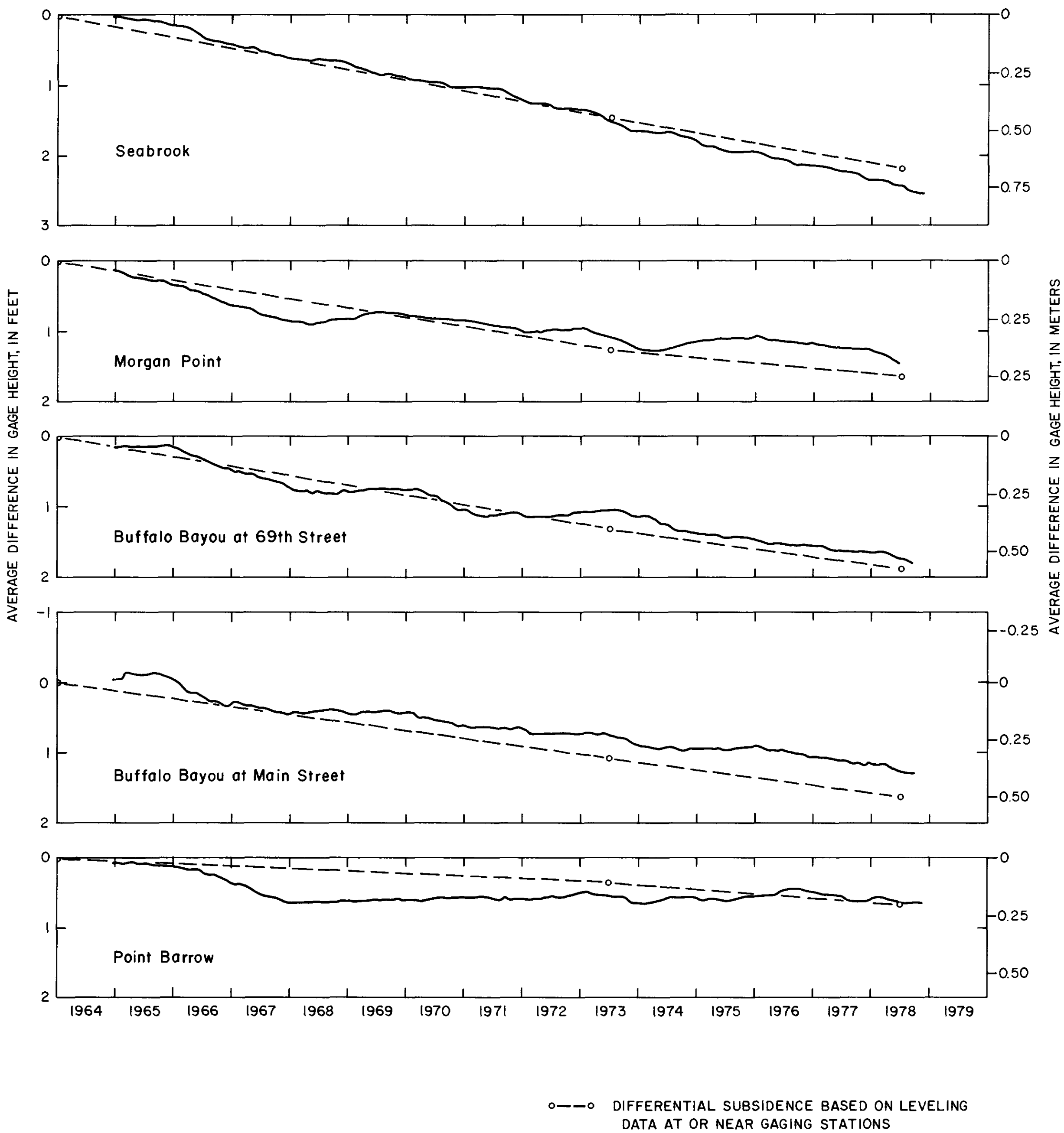


Figure 35.-Twelve-month average of difference in the mean monthly gage heights relative to the gage record at the Galveston railroad causeway

The change in elevation of each station was determined from measurements made by the National Geodetic Survey during 1963-64, 1973, and 1978, the times during which regional releveling programs were accomplished. The relative change in elevation between each gage and the gage at the causeway was determined and is shown on graphs in figures 34 and 35.

The differential subsidence between the listed stations and the Galveston railroad causeway gage for 1964-78 is shown in the following table:

Gaging station	Bench mark	Differential subsidence, in feet, based on: Tide data	Level data
Seabrook	C170	2.45	2.20
Morgan Point	E1007	1.45	1.62
Point Barrow	S660	.62	.63
Buffalo Bayou at 69th Street	R174	1.72	1.88
Buffalo Bayou at Main Street	J8	1.28	1.62

The differential subsidence between gages, shown on the graphs for 1964-78, was assumed to be the average difference in either July or August 1978. The differential subsidence from level data was determined from elevations of bench marks at or near the gaging stations.

At all but the Seabrook gage, the differential subsidence from the level data exceeded that from the tide records. The maximum difference between the two methods of obtaining differential subsidence was 0.34 foot (100 mm) at the Buffalo Bayou at Main Street gage. The gage at Main Street is more affected by freshwater inflow than the other gages. Also, bench mark J8 at the gage is the tie mark used for the main level lines in the network and the point at which errors in levels are adjusted. Even with first-order standards of leveling, adjustments of several tenths of a foot are allowable. It appears from evaluation of the data that changes in elevation of significantly less than 0.5 foot (150 mm), and possibly as little as 0.1 foot (30 mm), can be detected from tide records of the Galveston Bay area.

PREDICTING SUBSIDENCE

Planning development of ground water in the Texas coastal area needs to include consideration of the impact of land-surface subsidence. Reasonable estimates of the magnitude of subsidence in areas subject to flooding either by tidal inundation or alteration of surface drainage need to be made prior to development. If movement along faults (activation or acceleration) leads to structural damage, and if the movement is related to man-caused subsidence, estimates of the magnitude of subsidence also need to be made.

The information necessary for estimating probable subsidence is: (1) Amount of compressible material; (2) stress on the system (water-level change); and (3) degree of compressibility of the subsurface material. The information needed is not available in sufficient detail for most of the Texas coastal area. The most readily available of the necessary data is the amount of compressible material in the subsurface. Such data may be obtained from evaluation of the thousands of electrical logs of oil and water-well test holes. In the Houston-Galveston region, data on water-level changes in different sands is being collected. From this data, estimates of pressure change (stress change) at various depths for various time intervals may be made.

Data on the degree of compressibility of the subsurface material are less readily available than either of the other factors in predicting subsidence. Laboratory values of compressibility determined from tests of cores have been used with limited success. The expense of obtaining undisturbed cores and the difficulty in obtaining representative cores precludes their use for regional appraisal. Where subsidence has been well documented, such as in the Houston-Galveston region, subsidence data may be coupled with historic stress changes and the amount of compressible material to determine compressibility.

Models for subsidence evaluation at specific sites have been developed, as have hydrologic models to predict changes in water levels as a result of pumping. In the Houston-Galveston region, a three-dimensional digital model that incorporates subsidence has been developed by Meyer and Carr (1979). In construction of the model, the multitude of sand and clay layers of the Chicot and Evangeline aquifers were grouped into four layers. Two layers represented the sand and two layers represented the clay. The loading of the two-aquifer system was equated to the water-level changes in the large multiscreened wells, and the model was calibrated against historical changes in water levels. The volume of subsidence has been compared to the volume of ground water pumped for several periods of time to determine the amount of water yielded by compaction of the fine-grained material. Because about 20 percent of the water pumped from the Chicot and Evangeline aquifers in the Houston-Galveston region results from compaction, subsidence estimates are essential. However, the estimates of changes in water levels as related to water yielded by compaction are subject to much less error than estimates of subsidence as related to water-level declines. Therefore, the model needs to be used cautiously for subsidence prediction.

Compressibility

Records of compaction at different depth intervals obtained from extensometers, subsidence based on elevation data, and laboratory testing show that most of the subsidence is due to compaction of shallow material. It is suspected that compressibility of the material is related both to the age of sediment and the depth of burial. Limited data indicate that the base of the compacting interval is at or above the base of the Evangeline aquifer. For much of the Houston-Galveston region, the base of the compacting interval probably is the base of the Evangeline aquifer. The decline in artesian head in aquifers below the Evangeline has been small; and, therefore, loading of material below the Evangeline has been small. Data from the Clear Lake site, where no appreciable compaction of the lower part of the Evangeline aquifer was occurring even though artesian-head declines were occurring, indicate that compaction of the deeper clay layers needs to be excluded in estimating large-scale subsidence.

Clay Thickness

The base of the compacting interval within the Evangeline aquifer is not known. Measurements of water levels are sufficient to conclude that the entire thickness of the aquifer has been affected by loading. Therefore, the total clay thickness of the Evangeline was determined from electrical logs and is shown in figure 36.

The increase in clay thickness from about 500 feet (152 m) in the northern part of the region to about 2,500 feet (760 m) along the Gulf of Mexico reflects both an increase in thickness of the aquifer and an increased percentage of clay in the system. Only a very small amount of the clay in the southern part of the region is compacting. Most of the subsidence is due to compaction of clay in the Chicot aquifer.

A map of clay thickness for the Chicot aquifer is shown in figure 37. The Chicot aquifer does not thicken toward the coast as rapidly as the Evangeline. Regionally, the clay thickness increases from less than 100 feet (30 m) in the northwest part of the region to about 600 feet (183 m) in the southern part. Locally in the southern part, however, the clay thickness may be as much as 700 feet (213 m).

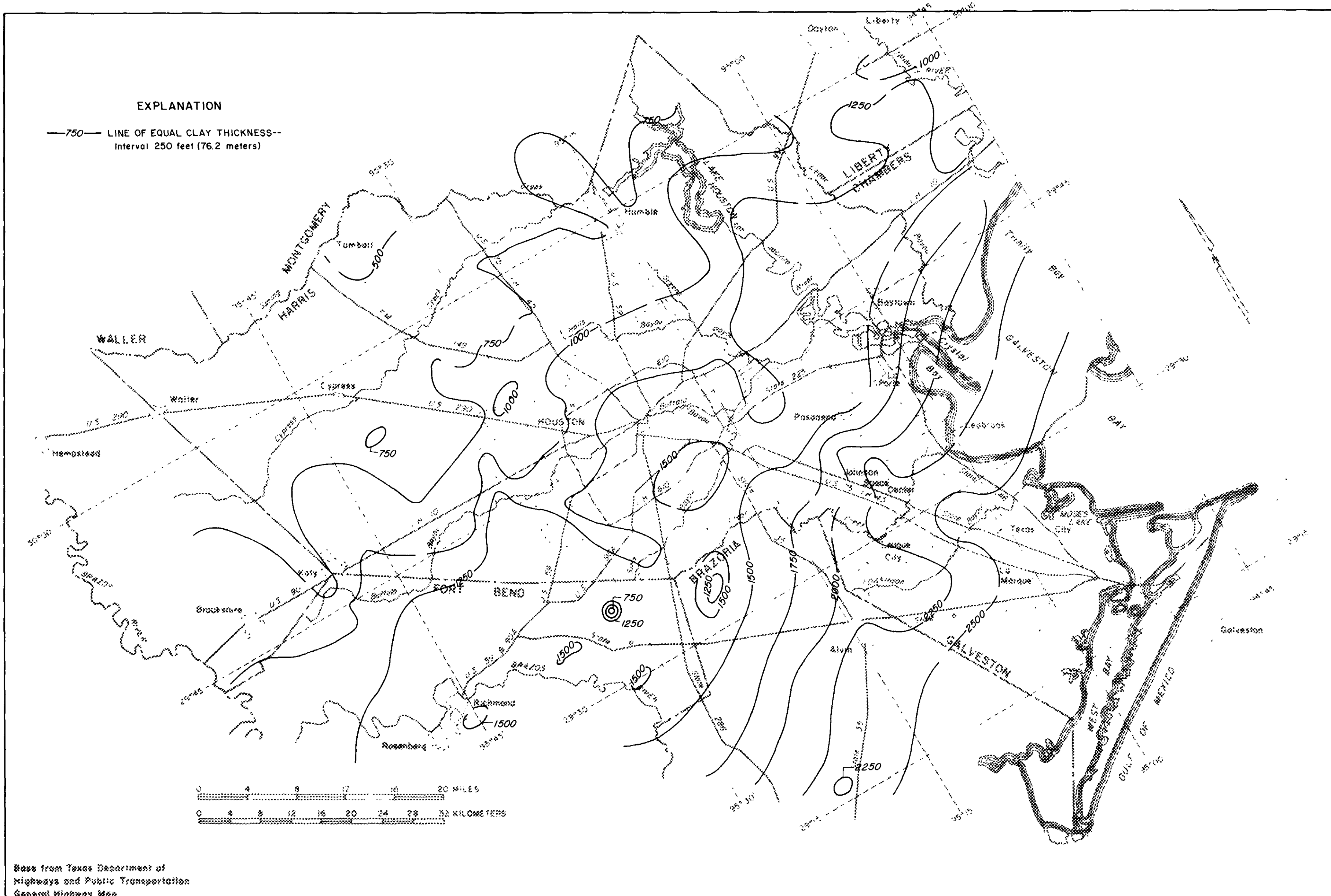


Figure 36.- Approximate thickness of clay in the Evangeline aquifer

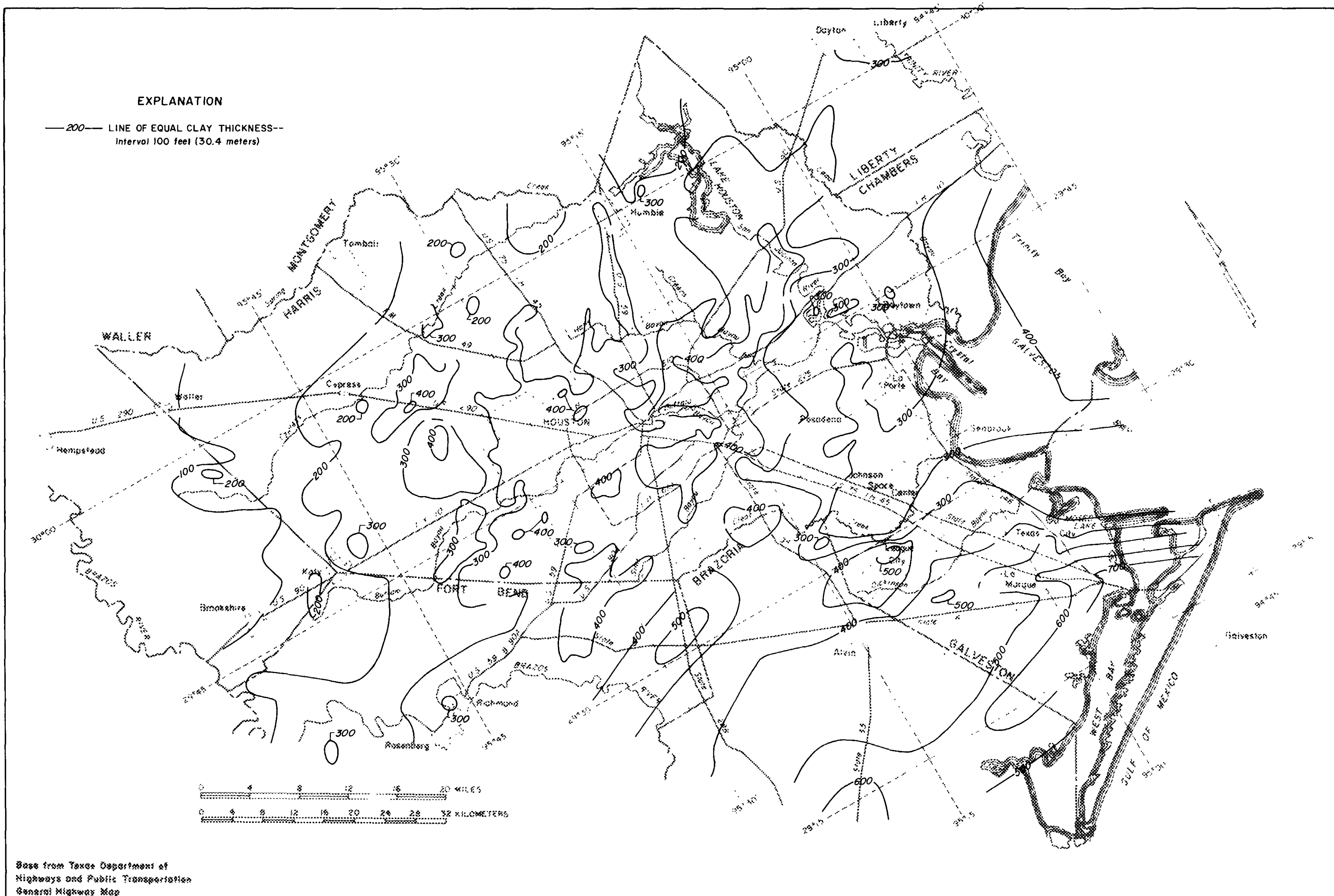


Figure 37.-Approximate thickness of clay in the Chicot aquifer

Stress

The change in stress applied to the fine-grained material in the Houston-Galveston region that leads to compaction and subsidence is caused by ground-water withdrawal. Changes in stress (water-level changes, artesian-head changes) in the Houston-Galveston region have been described in this report as well as in previous reports of ground-water development and subsidence. The relation of subsidence to water-level decline was presented in graphical form by Winslow and Doyel (1954) and later by Winslow and Wood (1959). Gabrysch (1969) showed that the ratio of subsidence to artesian-head declines was not constant for the region and related changes in the ratio to clay thickness (in terms of percentage). The range in the ratio was from 0.6 foot (180 mm) of subsidence per 100 feet (30 m) of water-level decline in the western part of the region, where 40 percent of the system is clay, to about 2.1 feet (640 mm) of subsidence per 100 feet (30 m) of water-level decline in the eastern part of the region, where 70 percent of the system is clay.

Because of the many alternating sand layers that yield water and the clay layers that retard vertical movement of water between sand layers, the change in stress or artesian-head decline varies vertically, laterally, and with time. At any particular time, the change in stress at a particular depth is the decrease in artesian head from the original conditions to current conditions at that depth.

Examples of the variations of change in stress in the Houston-Galveston region are apparent from analysis of figures 17, 22, 24, 26, 28, 30, and 32. During 1980, piezometers and extensometers were installed at the Southwest, Northwest, and Lake Houston sites (fig. 31). Potentiometric profiles at those sites are shown in figures 38-40. Because under original conditions the water level was at or above land surface, the depths to water below land surface shown by the profiles represent minimum change in stress in feet of water.

Potentiometric-surface (water-level) maps based on measurements were presented in the numerous reports of ground-water availability in the Gulf Coast area. Because the measurements generally were in multiscreened production wells, historic declines in water levels represent maximum long-term change in stress on part of the ground-water system. Those parts of the system, above and below the screened interval, generally have had less decline and less change in stress. Correlations of subsidence to decline in water levels based on those measurements, although useful in gross approximations of anticipated subsidence, likely would lead to an error in approximation if withdrawals of water were from deeper or shallower parts of the ground-water system. The predicted subsidence would be underestimated if the withdrawals were from the shallow, more compressible material.

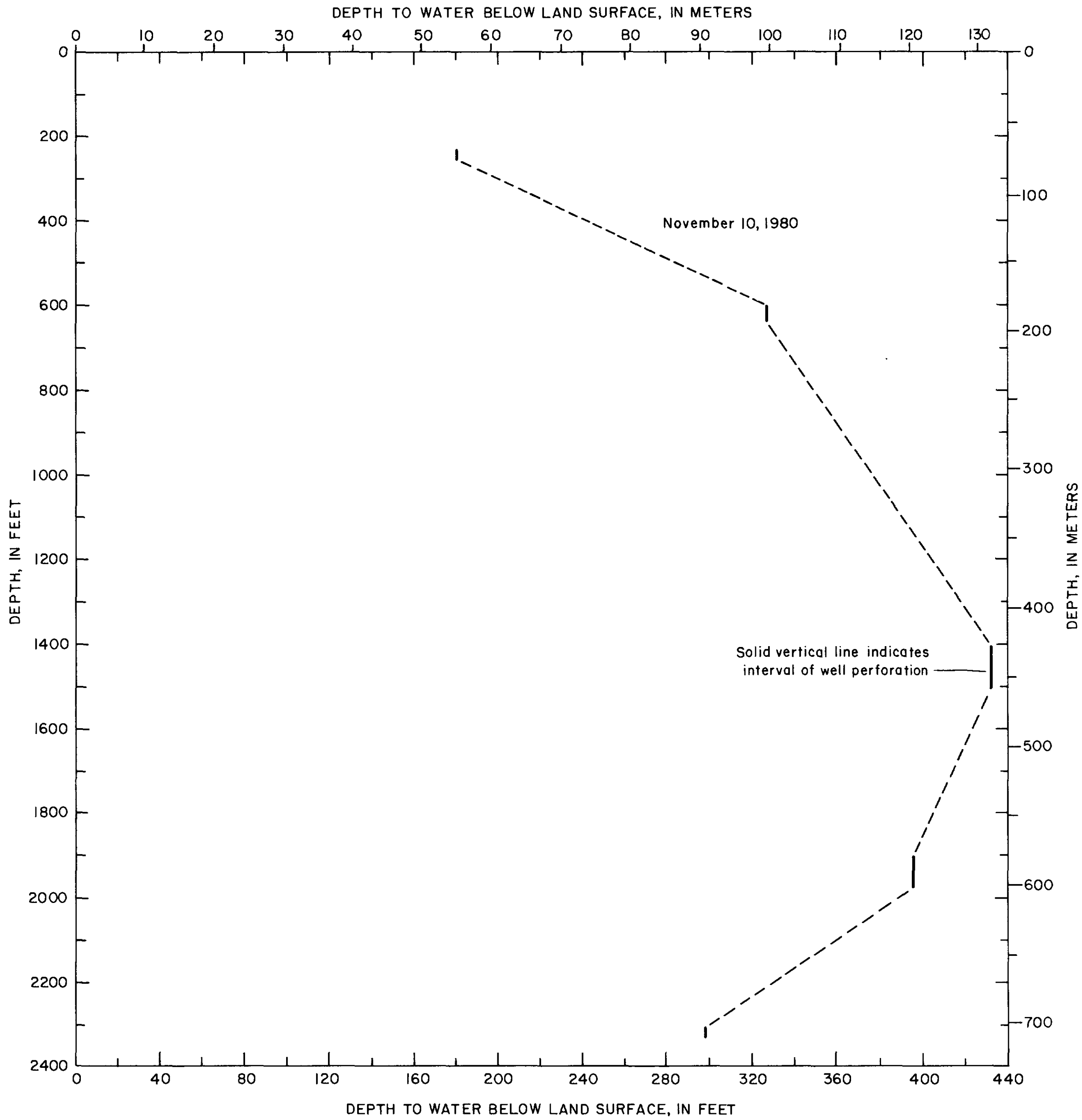


Figure 38.-Potentiometric profiles at the Southwest site

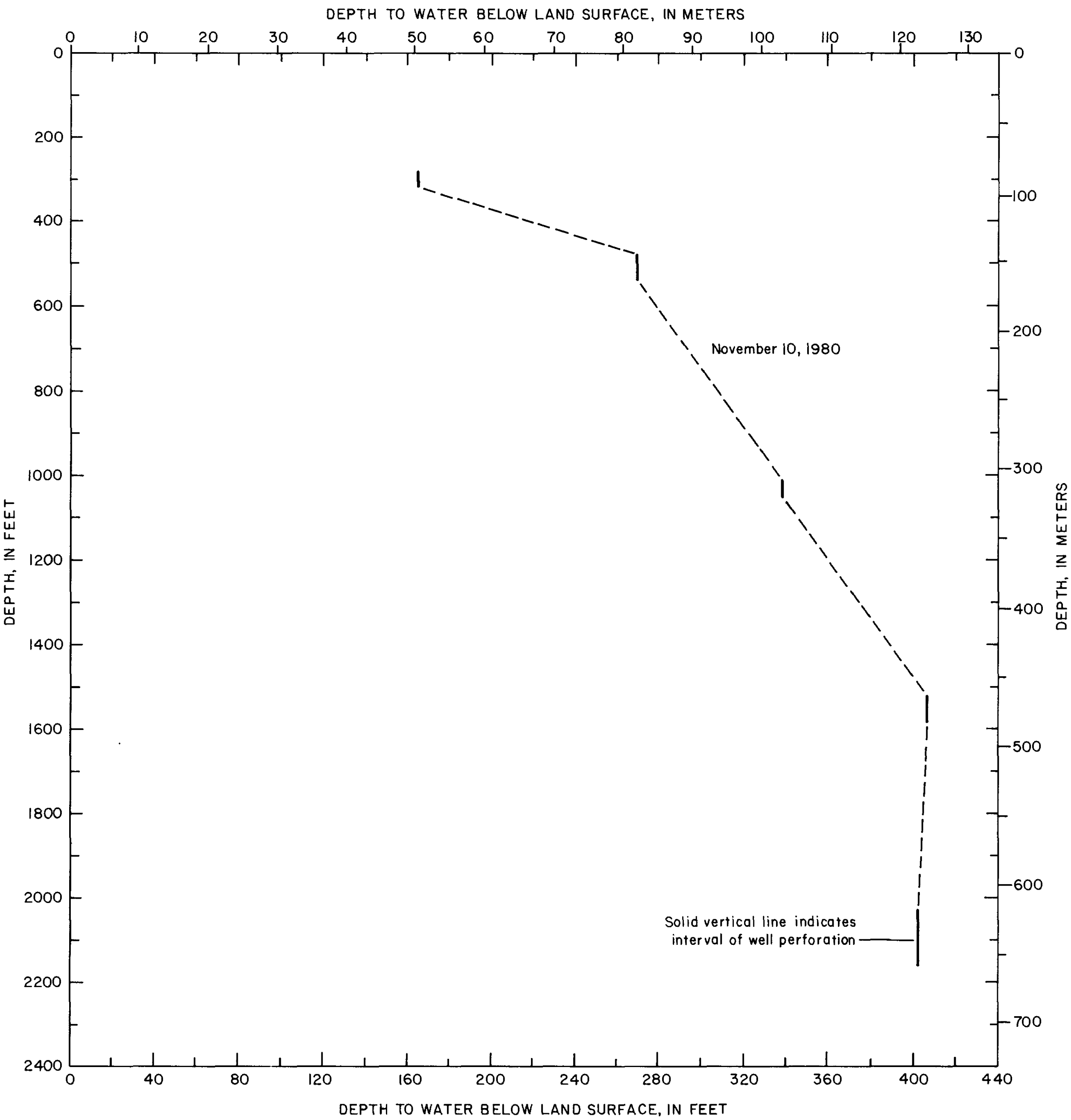


Figure 39.-Potentiometric profiles at the Northeast site

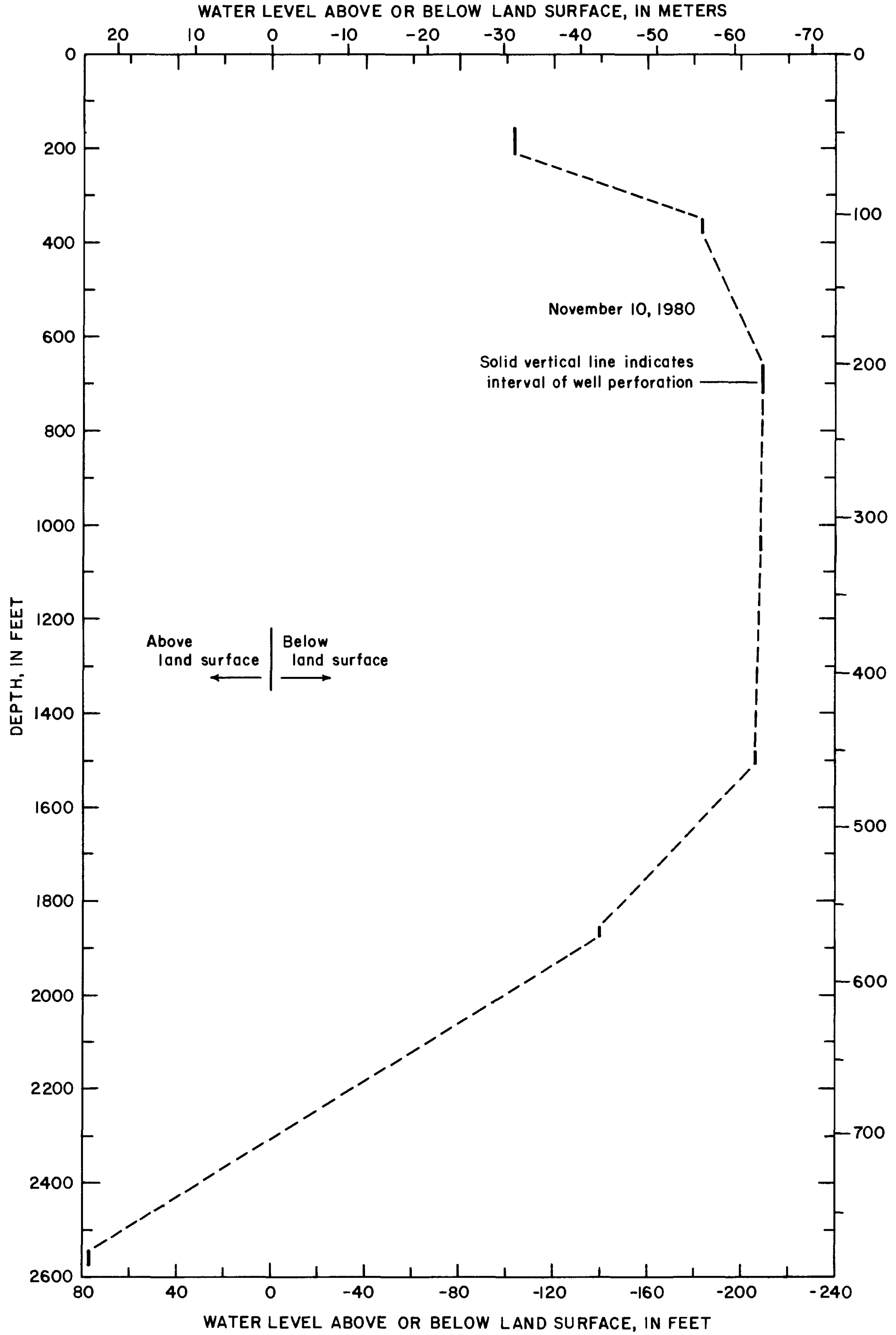


Figure 40.-Potentiometric profiles at the Lake Houston site

Specific-Unit Compaction

Specific-unit compaction is defined as the compaction of deposits, per unit of thickness per unit of increase in applied stress, during a specified time period. Ultimate specific-unit compaction is attained when pore pressure in beds of fine-grained material have reached hydraulic equilibrium with pore pressures in contiguous aquifers; at that time, specific-unit compaction equals gross compressibility of the system.

Specific-unit compaction was calculated for 10 sites (fig. 31) in Harris and Galveston Counties. The results of the calculations are presented in table 1. The calculations show that for each site where estimates of specific-unit compaction were made for 1906-43, the values were significantly less than for later periods. The smaller value is an indicator that the system was loaded and compacted by natural processes before ground-water withdrawal began, and that recompression (and subsidence) will be less than initial compression for the same stress. Estimates of specific-unit compaction need to be based on later periods for predicting rates of subsidence.

Because the specific-unit compaction is computed for periods of time during compaction, it is not a measure of ultimate compaction. Residual compaction at three sites in the Houston-Galveston region was estimated at 15-20 percent. For the ultimate subsidence, the estimated ultimate specific-unit compaction at Seabrook was 1.0 x 10^{-4} foot^{-1} (3.28 x 10^{-4} m^{-1}) and at Moses Lake near Texas City was 1.4 x 10^{-4} feet^{-1} (4.59 x 10^{-4} m^{-1}) (Gabrysch and Bonnet, 1976a,b).

Water levels and water-level changes based on measurements in the numerous wells in the region, especially those presented in maps such as figures 9-12, are representative of the parts of the aquifers where stress is greatest. Therefore, application of those measurements to clay thickness and specific-unit compaction (table 1) will exaggerate expected subsidence. The ratios of maximum change in stress to average change in stress (used in calculations of specific-unit compaction) also are shown in table 1. These ratios applied to the measurements in production wells will contribute to better estimates of subsidence.

Table 1.--Average specific-unit compaction in the Houston-Galveston region

Site	Period	Maximum stress change (feet of water)	Average stress change (feet of water)	Ratio of maximum to average stress	Average annual stress change (feet per year)	Clay thickness (feet)	Specific-unit compaction (feet^{-1})
Addicks	1906-43		68		1.8		6.1×10^{-6}
	1943-64		76		3.6		1.4×10^{-5}
	1943-73		214		7.1		1.2×10^{-5}
	1943-78		248		7.1		1.3×10^{-5}
	1964-73		138		15.3		1.0×10^{-5}
	1973-78		34		6.8		2.0×10^{-5}
	1906-78	414	316	1.31	4.4	730	1.1×10^{-5}
Baytown	1906-43		166		4.5		1.2×10^{-5}
	1943-64		64		3.0		5.8×10^{-5}
	1943-73		114		3.8		5.4×10^{-5}
	1943-78		107		3.1		6.4×10^{-5}
	1964-73		50		5.6		5.0×10^{-5}
	1973-78		-7		-1.4		-
	1906-78	310	273	1.14	3.8	1,000	3.2×10^{-5}
Clear Lake 1/	1906-43		84		2.3		8.1×10^{-6}
	1943-64		105		5.0		3.2×10^{-5}
	1943-73		122		4.1		5.6×10^{-5}
	1943-78		137		3.9		6.0×10^{-5}
	1964-73		17		1.9		2.0×10^{-4}
	1973-78		15		3.0		9.0×10^{-5}
	1906-78	286	221	1.29	3.1	590	4.0×10^{-5}
Houston-Northeast	1906-78	522	358	1.46	5.0	1,020	1.5×10^{-5}
Houston-Southwest	1906-78	532	366	1.45	5.1	915	1.2×10^{-5}
Lake Houston	1906-78	270	216	1.25	3.0	1,300	1.0×10^{-5}
Moses Lake 2/	1906-43		73		2.0		1.1×10^{-5}
	1943-64		21		1.0		7.8×10^{-5}
	1943-73		38		1.3		7.4×10^{-5}
	1943-78		38		1.1		9.0×10^{-5}
	1964-73		19		2.1		6.5×10^{-5}
	1973-78		0		0		-
	1906-78	118	110	1.07	1.5	500	3.8×10^{-5}
Pasadena	1906-43		177		4.8		4.0×10^{-6}
	1943-64		93		4.4		3.8×10^{-5}
	1943-73		160		5.3		4.0×10^{-5}
	1943-78		166		3.7		4.3×10^{-5}
	1964-73		67		7.4		4.3×10^{-5}
	1973-78		5		1.0		1.6×10^{-4}
	1906-78	382	342	1.12	4.8	1,140	2.3×10^{-5}
Seabrook 3/	1906-43		71		1.9		5.3×10^{-6}
	1943-64		68		3.2		3.3×10^{-5}
	1943-73		127		4.2		3.0×10^{-5}
	1943-78		127		3.6		4.0×10^{-5}
	1964-73		59		6.6		2.5×10^{-5}
	1973-78		-0.1		-		-
	1906-78	221	198	1.12	2.8	800	2.4×10^{-5}
Sheldon	1906-43		75		2.0		5.2×10^{-6}
	1943-64		111		5.3		8.4×10^{-6}
	1906-64	399	186	2.14	3.2	1,270	7.2×10^{-6}

1/ Base of compacting interval assumed to be 1,800 feet below land surface.
2/ Base of compacting interval assumed to be 1,660 feet below land surface.
3/ Base of compacting interval assumed to be 2,000 feet below land surface.

Baker and Follett (1973, fig. 17) related average annual subsidence to clay thickness and average annual water-level decline in Jackson County, Texas, about 90 miles (145 km) southwest of Houston. For the analysis of water-level change, six wells ranging in depth from 68 to 345 feet (21 to 105 m) were used. The extensively pumped zone, from 250 to 600 feet (76 to 183 m) thick, is between 100 and 350 feet (30 and 107 m) below land surface in some areas and between 200 and 800 feet (61 and 244 m) below land surface in other areas. Clay-bed thickness assumed affected by water-level change ranged from 350 to 750 feet (107 to 229 m). Equal water-level change through the depth interval of the zone was assumed. Thus, the water-level change (stress change) for the entire thickness was assumed equal to the maximum water-level change. The slope of the curve of figure 17 of Baker and Follett (1973) is equal to specific-unit compaction and is computed to be 1.27×10^{-5} feet^{-1} (4.17×10^{-5} m^{-1}). However, this value is based on maximum stress and is not directly comparable to values given in table 1. If Baker and Follet's zone represented the compacting interval, their value of specific-unit compaction probably is comparable to the specific-unit compaction (table 1) multiplied by the ratio of maximum to average stress given in table 1.

On the basis of comparisons of specific-unit compaction for 1906-78 presented in table 1, the susceptibility to clay compaction of each site in decreasing order is Clear Lake, Moses Lake, Baytown, Seabrook, Pasadena, Houston-Northeast, Houston-Southwest, Addicks, and Lake Houston. Least susceptible were the clay beds at the sites most inland from the coast. With the exception of the Clear Lake and Seabrook sites, specific-unit compaction at points equidistant from the coast generally are comparable. Selection of the base of the compacting interval, different patterns of loading through the vertical section, and different ratios of young, more compressible clay beds to old, less compressible clay beds cause error in estimates of compressibility. The specific-unit compaction at the Clear Lake site is about 1.7 times that at the Seabrook site but about 4.0 times that at the Lake Houston site.

SUMMARY AND CONCLUSIONS

Withdrawals of ground water in the Houston-Galveston region increased from about 311 Mgal/d (13.6 m^3/s) during 1960 to about 493 Mgal/d (21.6 m^3/s) during 1967. The withdrawals fluctuated from 1967, with an increase to about 532 Mgal/d (23.3 m^3/s) during 1974. Because of conservation measures and increased use of surface water, withdrawals of ground water decreased to about 502 Mgal/d (22.0 m^3/s) during 1978. Following the introduction of surface water from Lake Livingston on the Trinity River during late 1976, ground-water withdrawals decreased rapidly in southern Harris County, particularly in the Pasadena area. Pumping of ground water increased in the western and northern parts of Harris County from 1960-78 principally because of the increased withdrawal by the City of Houston. In the Houston area, where the City of Houston uses about 83 percent of the ground water being pumped, the withdrawal increased from about 98 Mgal/d (4.3 m^3/s) during 1960 to 227 Mgal/d (9.9 m^3/s) during 1978.

Water levels in wells generally declined in the region from the beginning of development until 1977. The rates of decline were less after 1966 than before because the rates of ground-water withdrawal during 1966-76 remained relatively constant. Water levels declined as much as 250 feet (76 m) in wells completed in the Chicot aquifer and as much as 300 feet (91 m) in wells completed in the Evangeline aquifer during 1943-77. Since late 1976, changes in pumping distribution resulting from efforts to control subsidence and the introduction of surface water from Lake Livingston have altered the pattern of water-level changes. In the Johnson Space Center and Baytown-La Porte areas (Chicot aquifer) and in the Pasadena area (Evangeline aquifer), water levels rose about 20 feet (6.1 m) during 1973-77. However, in the western Houston area (Evangeline aquifer), water levels have continued to decline at an increasing rate through 1977.

Subsidence of the land surface resulting from the withdrawal of large amounts of ground water may have been as much as 10 feet (3.0 m) in the Pasadena area during 1906-78. Of this maximum amount, almost 9.0 feet (2.7 m) occurred during 1943-78. The maximum amount of subsidence during 1973-78 was 1.4 feet (0.43 m), also in the Pasadena area. Based on records obtained from the extensometers at the Pasadena, Johnson Space Center, Seabrook, and Houston East End sites, the rate of subsidence in part of the region began to decrease during September 1976. The decreased rate probably was due to the regional decrease in the rate of water-level declines associated with the stabilization of pumping. Further decreases in the rates of compaction and subsidence during late 1978 resulted from rises in the water levels which began during late 1976.

Conventional leveling, extensometers, and tide gages may all be used for measuring subsidence. The principal method has been to compare elevations of bench marks at specific locations determined at different times by conventional, but very precise, leveling. Borehole extensometers may be used to determine small changes in elevations at specific locations. They have the disadvantages of large initial cost and small areal application, but they have the advantages of continuous record, preciseness, and determination of the interval of compaction causing subsidence. Tide gages may be used to determine changes in tide elevation between the two stations. This method can be used only in tidal reaches, is less precise than the other two methods, and has small areal application. The evaluation of tide records from five gages in Galveston Bay and the tidal reaches of Buffalo Bayou indicate that changes in elevations of less than 0.5 foot (150 mm) and possible as little as 0.1 foot (30 mm) can be detected from tide records of the Galveston Bay area. The procedure for estimating differential subsidence from tide records was kept as simple as possible and consisted of: (1) Determining monthly mean stage for each station; (2) determining the difference in monthly mean stage between each gage and the base gage at the railroad causeway at Galveston (adjusting the differences to zero in 1964); and (3) computing the average 12-month moving difference for each month based on 11 previous months. Because the stage is affected by short-term factors such as wind and freshwater inflow, estimates of differential subsidence need to use at least a 1-year record. Records of more tide stations in areas of known or suspected subsidence along the Gulf Coast need to be evaluated.

The use of historic data on water-level changes and subsidence in the Houston area offers promise as a simple method of predicting land-surface subsidence in the Gulf Coast region where subsidence has been minimal or where additional ground-water pumping is planned. Although existing data are inadequate to describe compressibility of fine-grained material in relation to the age of sediments or depth of burial, the existing data could be used for preliminary predictions of subsidence.

The unit measure of compressibility, specific-unit compaction, ranged from 1.0×10^{-5} to 4.0×10^{-5} feet^{-1} (3.28×10^{-5} to 1.31×10^{-4} m^{-1}) of compaction per foot of clay thickness per foot of average water-level change during 1906-78. The greatest compressibility was at the Clear Lake site, and the least compressibility was at the Lake Houston site. The data indicate that the compressibilities of clays at points equidistant from the coast generally are comparable. Clay thickness determined from the many logs available in the Texas Gulf Coast region can be applied to calculated water-level decline and estimated specific-unit compaction to predict subsidence before large-scale ground-water development is begun.

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