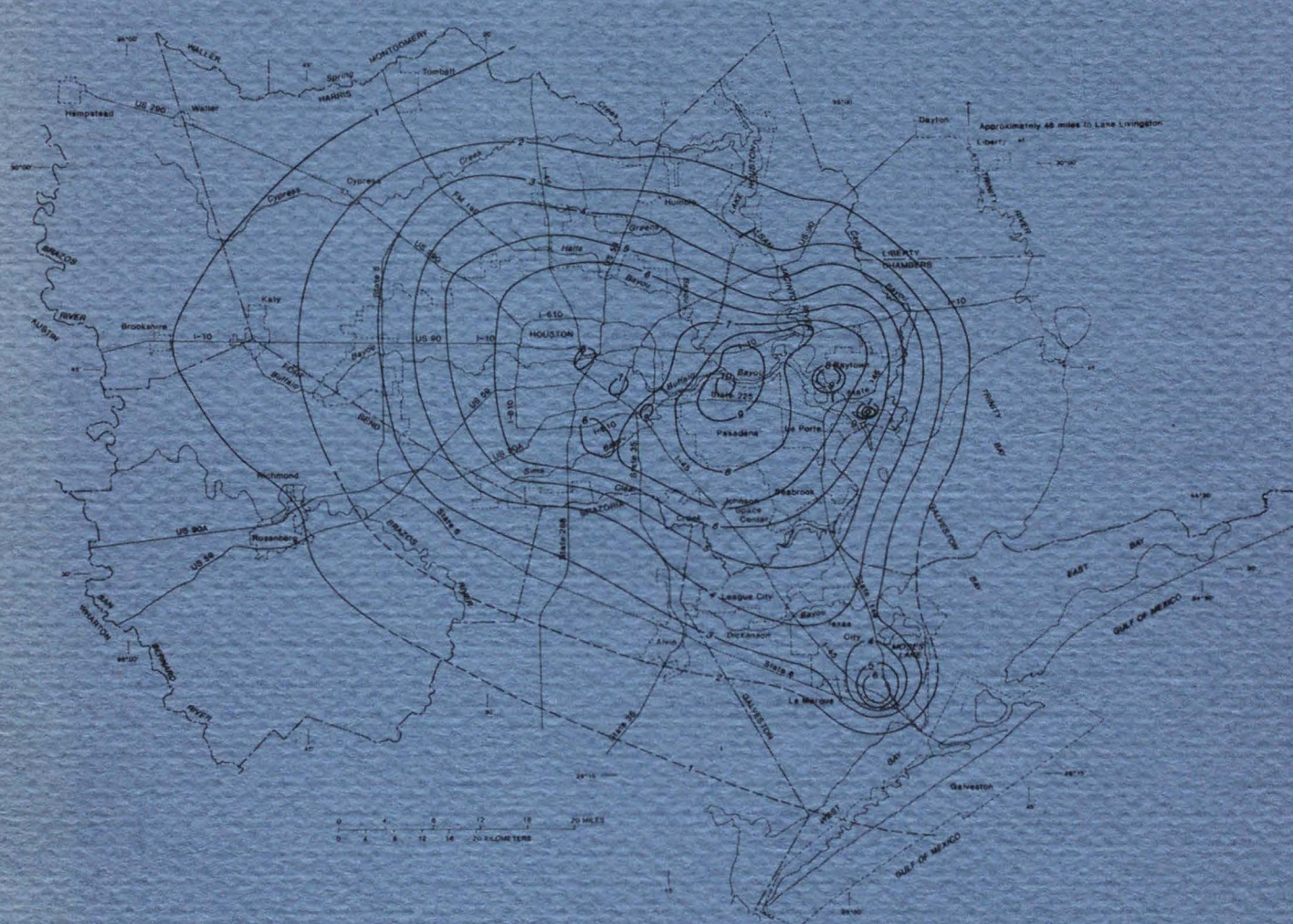


Land-Surface Subsidence Resulting From Ground-Water Withdrawals in the Houston- Galveston Region, Texas, Through 1987



Report of Investigations No. 90-01
Prepared by the U.S. Geological Survey in
cooperation with the Harris-Galveston Coastal
Subsidence District

(200)
G327L
1990

6200
G327l
1990

HARRIS-GALVESTON COASTAL SUBSIDENCE DISTRICT

1660 West Bay Area Boulevard

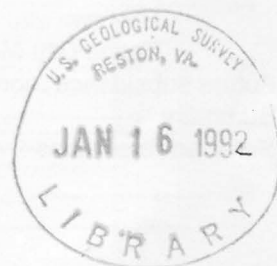
Friendswood, TX 77546

**LAND-SURFACE SUBSIDENCE RESULTING FROM GROUND-WATER
WITHDRAWALS IN THE HOUSTON-GALVESTON REGION, TEXAS,
THROUGH 1987**

By

R.K. Gabrysch and L.S. Coplin

U.S. Geological Survey



Prepared by the U.S. Geological Survey in cooperation
with the Harris-Galveston Coastal Subsidence District

1990

CONTENTS

	Page
Abstract	1
Introduction.....	2
Aquifers	2
Ground-water withdrawals.....	2
Houston Area.....	4
Katy Area.....	4
Pasadena Area.....	11
Baytown-La Porte Area	11
Texas City Area.....	11
Alta Loma Area.....	11
Johnson Space Center Area.....	12
Changes in water levels.....	12
Land-surface subsidence.....	12
Subsidence determined from repeated surveys	18
Compaction and subsidence determined from borehole-extensometer records	24
Southwest site	24
Northeast site	25
Lake Houston site	25
Johnson Space Center and Clear Lake sites	32
Seabrook site	32
Pasadena site	38
Addicks site	38
Houston East End site.....	38
Baytown site	44
Texas City-Moses Lake site.....	44
Future subsidence monitoring.....	51
Summary	51
Selected references.....	54

ILLUSTRATIONS

Figure 1. Map showing location of principal areas of ground-water withdrawals and average rates of pumping for 1987	3
2-7. Graphs showing ground-water withdrawals in the:	
2. Houston-Galveston region, 1970-87.....	5
3. Houston Area, 1970-87	6
4. Katy Area, 1970-87	7
5. Pasadena Area, 1970-87.....	8
6. Baytown-La Porte Area, 1970-87	9
7. Texas City, Alta Loma, and Johnson Space Center Areas, 1970-87	10
8. Hydrographs showing changes in water levels in wells in the Pasadena Area	13
9-17. Maps showing:	
9. Approximate changes in water levels in wells completed in the Chicot aquifer, 1943-87	14
10. Approximate changes in water levels in wells completed in the Evangeline aquifer, 1943-87	15
11. Approximate changes in water levels in wells completed in the Chicot aquifer, 1977-87	16

Figures 9-17. Maps showing--Continued

12.	Approximate changes in water levels in wells completed in the Evangeline aquifer, 1977-87-----	17
13.	Approximate land-surface subsidence, 1906-87 -----	19
14.	Approximate land-surface subsidence, 1943-87 -----	20
15.	Approximate land-surface subsidence, 1978-87 -----	21
16.	Approximate land-surface subsidence, 1978-83 -----	22
17.	Approximate land-surface subsidence, 1983-87 -----	23
18-27.	Graphs showing:	
18.	Cumulative compaction at the Southwest site -----	25
19.	Annual subsidence measured by extensometers at sites in the Houston-Galveston region-----	26
20.	Potentiometric profiles and changes in effective stress at the Southwest site -----	27
21.	Cumulative compaction at the Northeast site -----	28
22.	Potentiometric profiles and changes in effective stress at the Northeast site-----	30
23.	Cumulative compaction at the Lake Houston site-----	31
24.	Potentiometric profiles and changes in effective stress at the Lake Houston site -----	32
25.	Measured compaction and cumulative difference at the Johnson Space Center and Clear Lake sites-----	33
26.	Potentiometric profiles and changes in effective stress at the Johnson Space Center and Clear Lake sites-----	34
27.	Hydrograph of a well in southeastern Harris County showing water-level rise caused by gas pressure-----	36
28-39.	Graphs showing:	
28.	Cumulative compaction at the Seabrook site -----	37
29.	Potentiometric profiles and changes in effective stress at the Seabrook site-----	38
30.	Cumulative compaction at the Pasadena site-----	39
31.	Potentiometric profiles and changes in effective stress at the Pasadena site -----	40
32.	Cumulative compaction at the Addicks site-----	41
33.	Potentiometric profiles and changes in effective stress at the Addicks site -----	43
34.	Cumulative compaction at the Houston East End site-----	44
35.	Potentiometric profiles and changes in effective stress at the Houston East End site -----	45
36.	Measured compaction and cumulative difference at the Baytown site -----	46
37.	Potentiometric profiles and changes in effective stress at the Baytown site -----	47
38.	Cumulative compaction at the Texas City-Moses Lake site-----	48
39.	Potentiometric profiles and changes in effective stress at the Texas City-Moses Lake site -----	50
40.	Map showing locations of Global Positioning System benchmarks -----	51

METRIC CONVERSIONS

Factors for converting inch-pound units to metric (International System) units are given in the following table:

Multiply inch-pound unit	By	To obtain metric unit
acre	0.004047	square kilometer
foot	0.3048	meter
inch	25.4	millimeter
mile	1.609	kilometer
foot per year (ft/yr)	0.3048	meter per year
gallons per minute (gal/min)	0.06308	liter per second
million gallons per day (Mgal/d)	0.04381	cubic meter per second
square mile (mi ²)	2.590	square kilometer

Sea level: In this report "sea level" refers to the 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 "Sea Level Datum of 1929."

LAND-SURFACE SUBSIDENCE RESULTING FROM GROUND-WATER WITHDRAWALS IN THE HOUSTON-GALVESTON REGION, TEXAS, THROUGH 1987

By

R.K. Gabrysch and L.S. Coplin
U.S. Geological Survey

ABSTRACT

The ground-water system in the Houston-Galveston region, Texas is composed of layers of sand and compressible clay. The system has been divided into two major aquifers, the Chicot and Evangeline, and the underlying Burkeville confining unit. The Chicot aquifer overlies the Evangeline aquifer. The Chicot aquifer contains the most permeable sand layers and also the more compressible clay layers.

Large-scale ground-water withdrawals for public supply and rice irrigation began in the late 1800's and withdrawals for industrial use began after the opening of the Houston Ship Channel in 1915. Until 1954, when water from Lake Houston became available, Houston was the largest city in the United States using ground water exclusively for public supply. In 1954, the rate of ground-water pumpage in the entire region was 388 Mgal/d (million gallons per day). Ground-water pumpage increased with increased need to 507 Mgal/d in 1969. Pumpage during 1970-82 was relatively constant at about 500 Mgal/d but decreased to 416 Mgal/d by 1987. The rates of withdrawal in individual areas of the region changed significantly with the shifting of ground-water pumpage to the western part of the region, following importation of surface water to the eastern part from Lake Livingston on the Trinity River outside of the region.

Water levels in wells declined throughout the region prior to 1977 as a result of ground-water withdrawals. After 1976, when ground-water pumpage in the eastern part of the region was curtailed, water levels in wells began to rise. More than 140 feet of rise in water levels was measured in some wells in the Chicot aquifer by 1987 and more than 140 feet of rise in water levels was measured in some wells in the Evangeline aquifer. Meanwhile, water levels continued to decline in wells in the western part of the region. In the northwestern part of the region, the water level in a well in the Chicot aquifer declined as much as 60 feet; in the southwestern part of the region, the water levels in the Evangeline aquifer declined as much as 160 feet.

The declines in artesian pressure (declines in water levels) have resulted in land-surface subsidence of more than 1 foot in an area of about 3,640 square miles. The maximum subsidence has been about 10 feet in the Pasadena Area in the eastern part of the region between 1906 and 1987. However, in the Pasadena Area, the rate of subsidence of a benchmark has decreased from about 0.3 foot per year during 1973-78 to about 0.03 foot per year during 1978-87. The maximum rate of subsidence in the western part of the region increased from about 0.20 foot per year from 1973-78 to about 0.22 foot per year from 1978-87.

In 1987, a network of benchmarks was established throughout the region to facilitate the use of a satellite-based system, the Global Positioning System, for future use in subsidence determinations. Horizontal and vertical positions may be determined accurately, quickly, and inexpensively using the Global Positioning System.

INTRODUCTION

Land-surface subsidence, resulting from the lowering of water levels that commonly accompanies ground-water development, has occurred in many places in the world. One of the places where subsidence has been critical is in the Houston-Galveston region of Texas. Because of subsidence, the low-lying areas near Galveston Bay and the Gulf of Mexico have been further subjected to inundation by tidal waters; some land is submerged by normal tides and much more land is subjected to inundation during unusual tidal events caused by storms and hurricanes. Because of the ever increasing growth in industry, accompanied by growth in population, much more property and human life would be affected by inundation.

The U.S. Geological Survey has cooperated with the city of Houston since 1930, and with the Harris-Galveston Coastal Subsidence District since its inception in 1975, 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 1987 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 purpose of this report is to present data on ground-water withdrawals, changes in water levels, and land-surface subsidence; and to relate changes in pumpage to water-level decline and subsidence with emphasis on 1978-87.

AQUIFERS

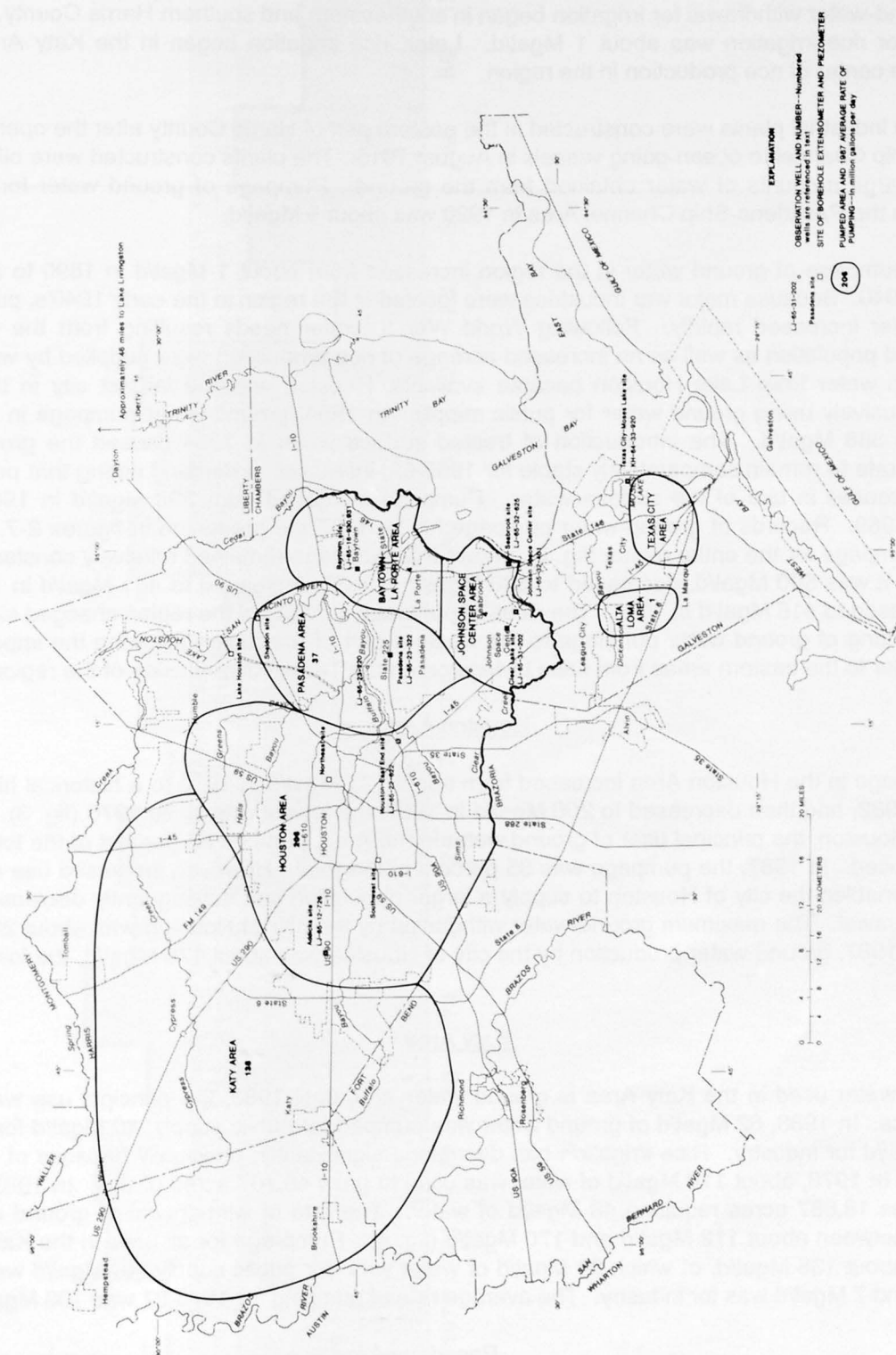
The ground-water system in the Houston-Galveston region is composed of lenticular deposits of sand and clay. The sand layers generally are interconnected laterally but the vertical connection is tortuous. The system is termed "leaky" and because it is under pressure greater than atmospheric, it is artesian.

The complex system has been divided into two major aquifers, the Chicot and the Evangeline, and a confining unit, the Burkeville. The Burkeville confining unit underlies the Chicot and Evangeline aquifers; it is composed mostly of clay with some layers of sand. The Chicot and Evangeline aquifers are composed of layers of sand and clay. The basis for separating the Chicot aquifer from the underlying Evangeline aquifer is primarily a difference in hydraulic conductivity, which in part causes the difference in the altitudes of the potentiometric surfaces of the two aquifers. The Chicot aquifer 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), using previous interpretations, presented the most recent maps showing the altitude of the bases of the Chicot and Evangeline aquifers.

The geology and hydrology of the Houston-Galveston region is discussed in detail in numerous reports. The most recent description was presented by Williams and Ranzau (1987).

GROUND-WATER WITHDRAWALS

Large-scale ground-water withdrawals for public supply and for rice irrigation in the Houston-Galveston region began in the late 1800's. The pumpage of ground water for Houston began in 1886. The Houston Water Works Company, an independent agency, had the first well drilled to a depth of 140 feet in 1886. The well was cased with a 15-inch pipe, and is reported to have had an initial flow of 1,000 gal/min. In 1906, the city of Houston purchased the system, which then included 45 flowing wells. The usage of water in 1906 was about 11 Mgal/d.



Ground-water withdrawal for irrigation began in southeastern and southern Harris County. In 1887, pumpage for rice irrigation was about 1 Mgal/d. Later, rice irrigation began in the Katy Area, which became the center of rice production in the region.

Large industrial plants were constructed in the eastern part of Harris County after the opening of the Houston Ship Channel to ocean-going vessels in August 1915. The plants constructed were oil refineries that used large amounts of water obtained from the ground. Pumpage of ground water for industrial purposes in the Pasadena-Ship Channel Area in 1920 was about 5 Mgal/d.

The pumpage of ground water in the region increased from about 1 Mgal/d in 1890 to about 154 Mgal/d in 1940. Because major war industries were located in the region in the early 1940's, pumpage of ground water increased rapidly. Following World War II, water needs resulting from the growth of industry and population as well as an increased acreage of rice production were supplied by wells. Until 1954, when water from Lake Houston became available, Houston was the largest city in the United States exclusively using ground water for public supply. In 1954, ground-water pumpage in the entire region was 388 Mgal/d. The introduction of treated surface water in 1954 caused the ground-water withdrawal rate to remain comparatively stable for 1955-62; increases in demand during that period were met by increases in use of the surface water. Pumpage increased from 398 Mgal/d in 1962 to 507 Mgal/d in 1969. Records of ground-water pumpage for 1970-87 are presented in figures 2-7. A graph showing pumpage for the entire region (fig. 2), shows that pumpage remained relatively constant through 1982 when it was 500 Mgal/d, decreased to 399 Mgal/d in 1983, increased to 451 Mgal/d in 1985, and then decreased to 416 Mgal/d in 1987. The rates of pumpage in areas of the region changed significantly with the shifting of ground-water pumpage to the western part of the region following the importation of surface water to the eastern areas from Lake Livingston on the Trinity River outside of the region.

Houston Area

Pumpage in the Houston Area increased from about 171 Mgal/d in 1970 to a historical high of 257 Mgal/d in 1982, and then decreased to 206 Mgal/d in 1987, the lowest rate since 1976 (fig. 3). In 1970, the city of Houston, the principal user of ground water in the Area, pumped 83 percent of the total ground water produced. In 1987, the pumpage was 85 percent of the total. However, increased use of surface water has enabled the city of Houston to supply a larger population and subsequently decrease ground-water withdrawal. The maximum ground-water withdrawal by the city of Houston was about 220 Mgal/d in 1980. In 1987, ground-water production by the city of Houston was about 176 Mgal/d, the lowest since 1975.

Katy Area

All water used in the Katy Area is ground water and, until 1983, the principal use was for irrigation of rice. In 1983, 62 Mgal/d of ground water was pumped for public supply, 40 Mgal/d for irrigation and 12 Mgal/d for industry. Rice irrigation has decreased significantly, principally because of economic conditions. In 1978, about 110 Mgal/d of water was used to grow 48,107 acres of rice. In 1987, the rice acreage was 18,887 acres requiring 48 Mgal/d of water. The rate of withdrawal of ground water has fluctuated between about 112 Mgal/d and 170 Mgal/d (fig. 4). Pumpage for all uses in the Katy Area in 1987 was about 138 Mgal/d, of which 84 Mgal/d of water was for public supply, 48 Mgal/d was for rice irrigation, and 7 Mgal/d was for industry. The average rate of pumping for 1970-87 was 138 Mgal/d.

Pasadena Area

The principal use of ground water in the Pasadena Area remains for industrial purposes. When production of ground water reached a peak in 1968, about 113 Mgal/d, or 90 percent of the 126 Mgal/d of water pumped, was used by industrial plants in the area. However, some surface water from Lake Houston became available in 1954. Use of the surface water and conservation measures allowed a

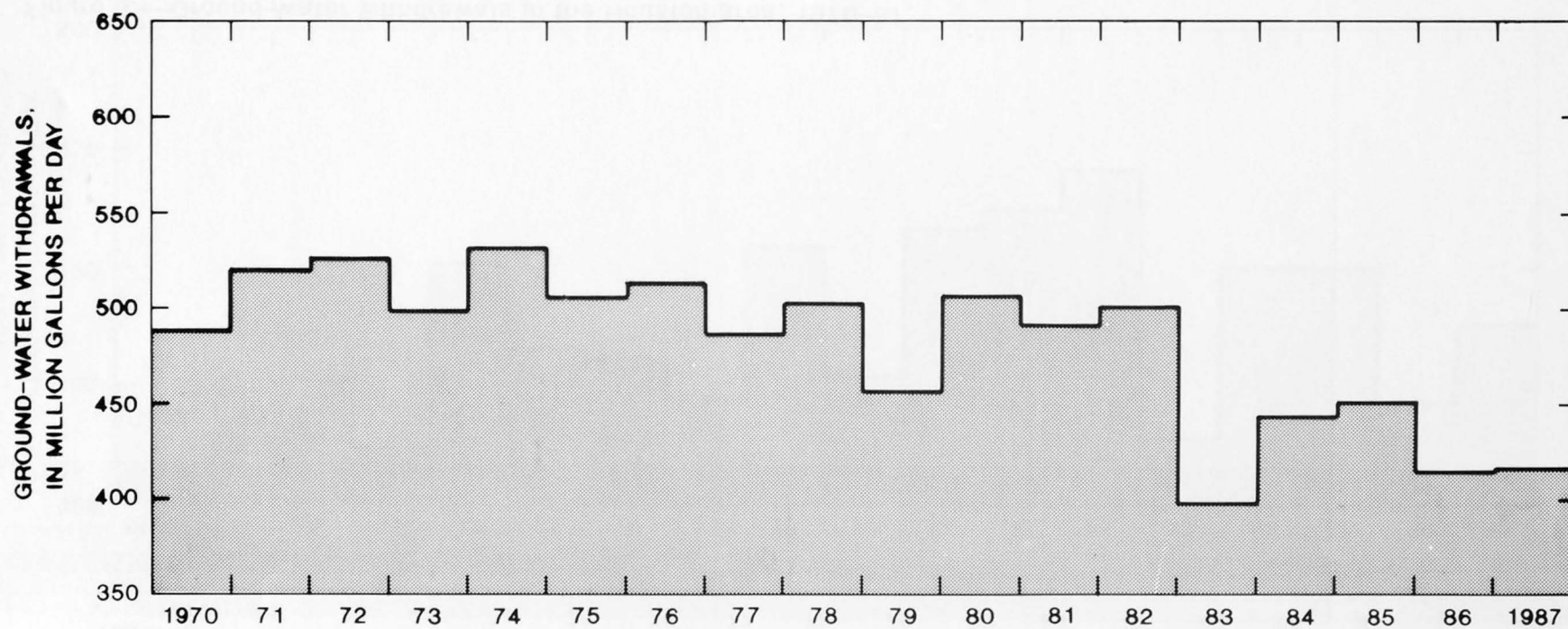


Figure 2.--Ground-water withdrawals in the Houston-Galveston region, 1970-87.

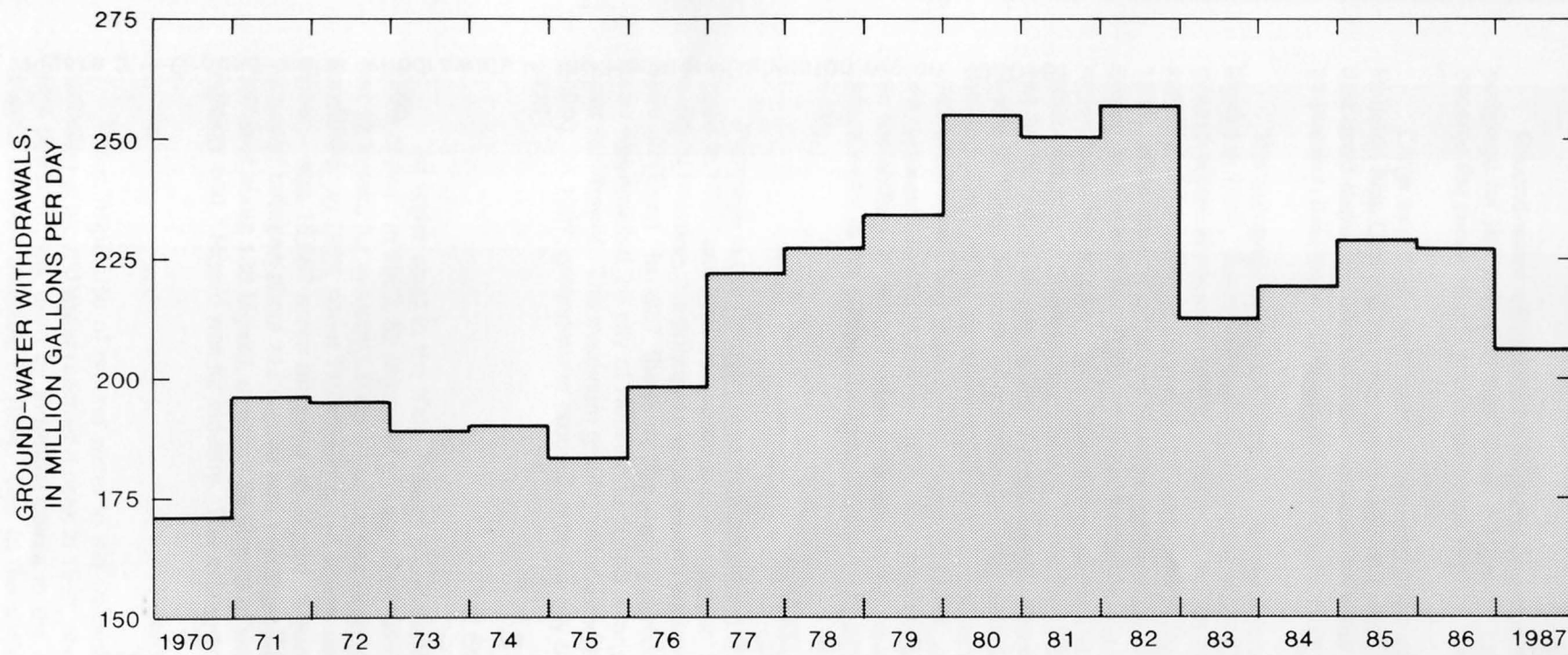


Figure 3.--Ground-water withdrawals in the Houston area, 1970-87.

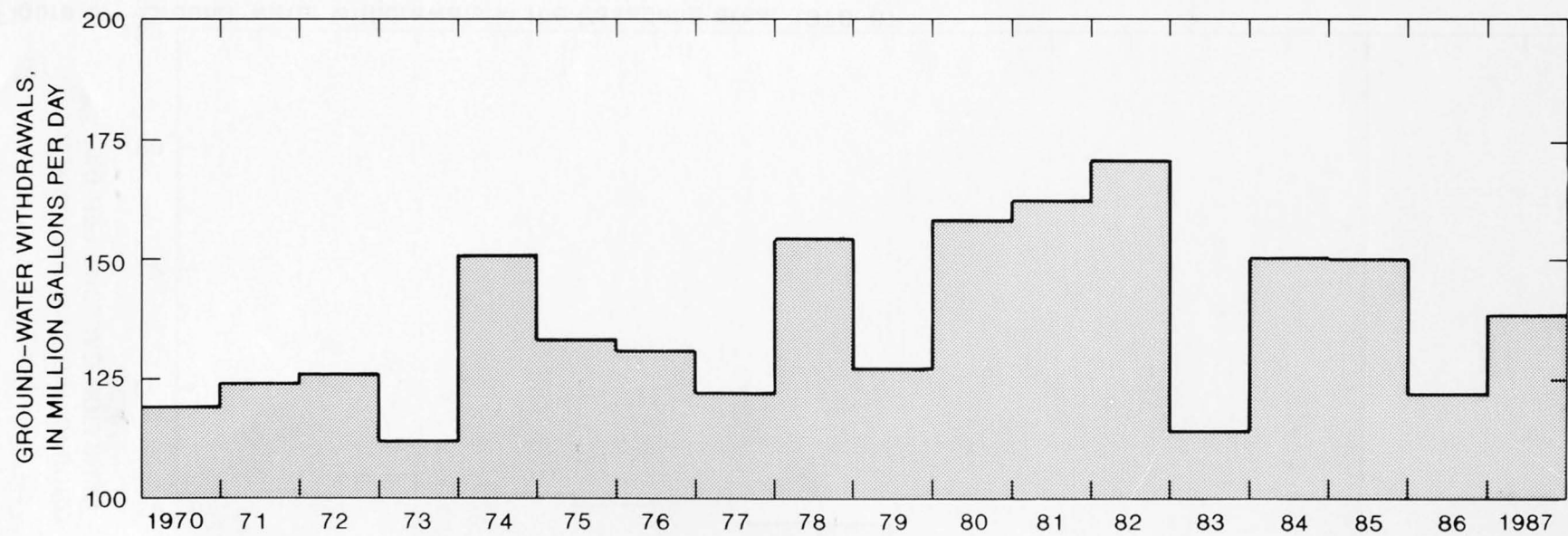


Figure 4.--Ground-water withdrawals in the Katy area, 1970-87.

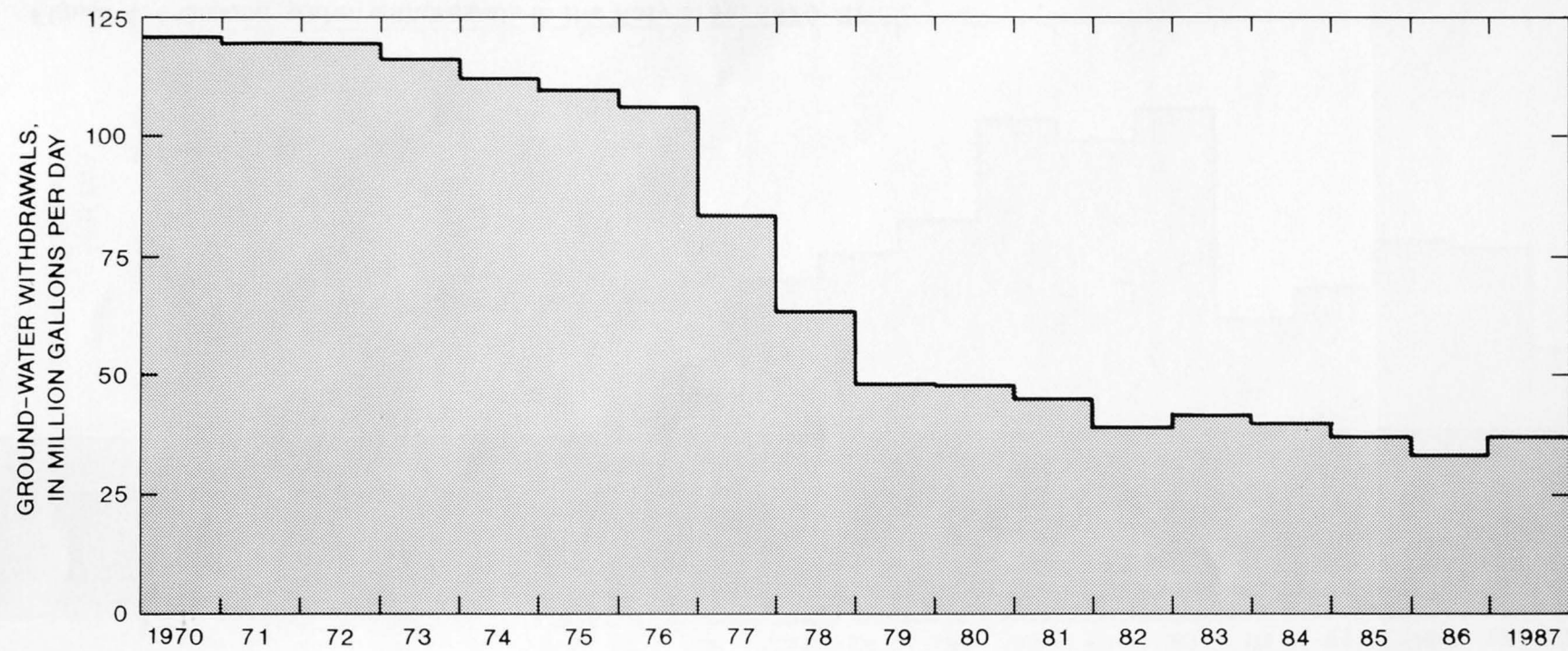


Figure 5.--Ground-water withdrawals in the Pasadena area, 1970-87.

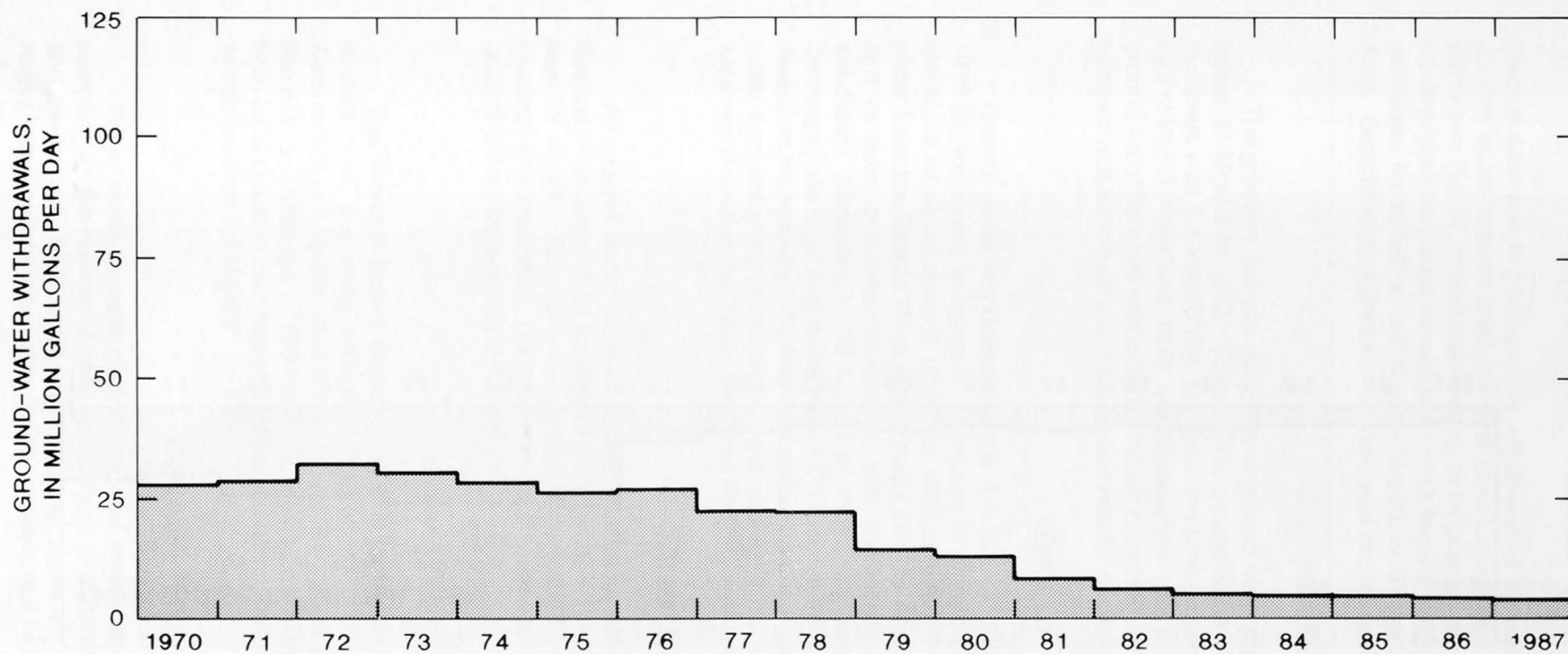


Figure 6.--Ground-water withdrawals in the Baytown-LaPorte area, 1970-87.

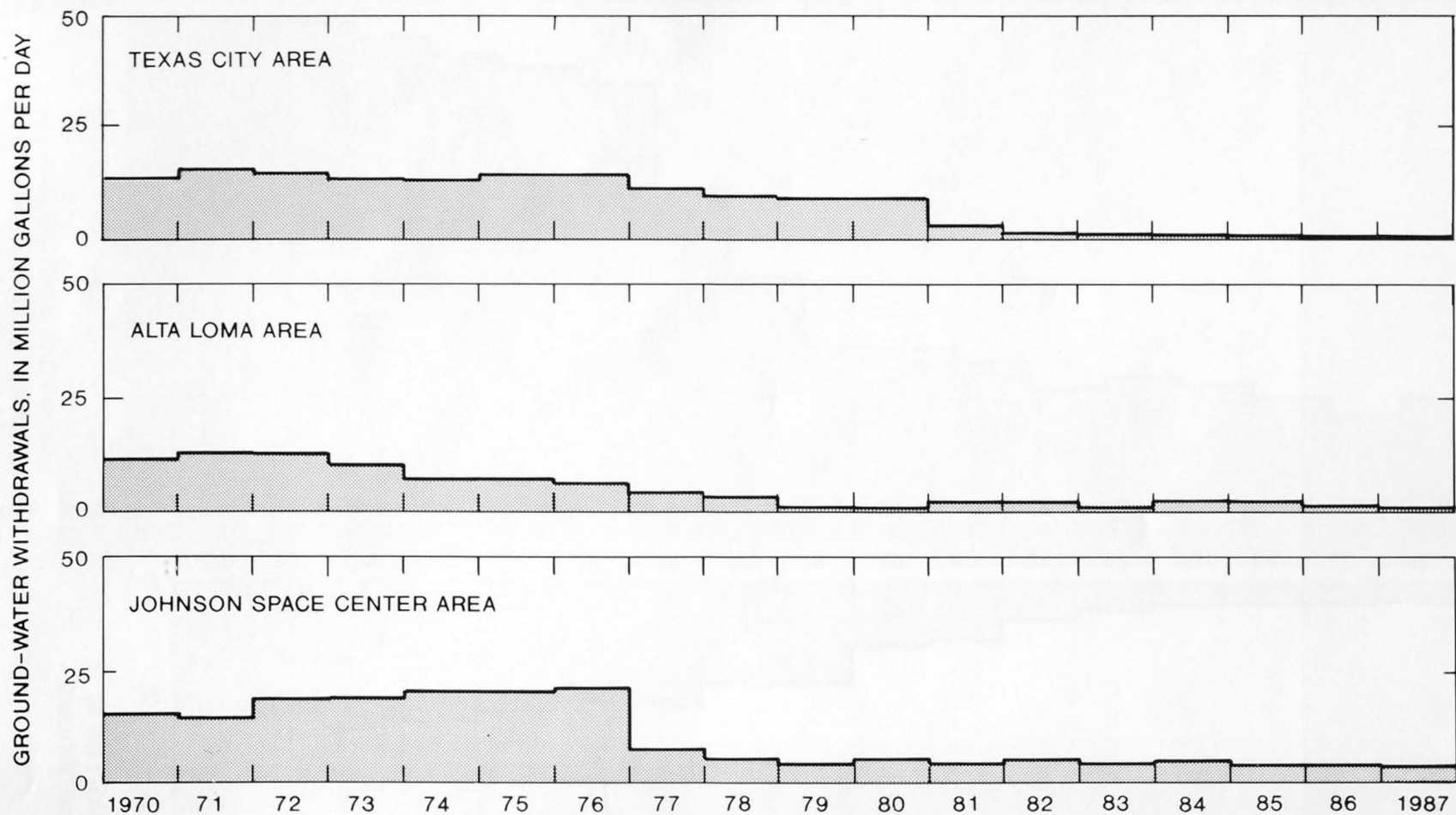


Figure 7.--Ground-water withdrawals in the Texas City, Alta Loma, and Johnson Space Center areas, 1970-87.

gradual decrease in ground-water withdrawal for industrial purposes until 1977, when a larger amount of surface water became available from Lake Livingston. In 1976, about 106 Mgal/d of ground water was withdrawn (fig. 5), of which 89 Mgal/d, or 84 percent, was for industrial purposes. Usage of ground water for municipal purposes increased from 13 Mgal/d in 1968 to 18 Mgal/d in 1987. In 1987, ground water withdrawn for industrial use was 19 Mgal/d, or 51 percent of the 37 Mgal/d produced in the Pasadena Area. Ground-water withdrawal in 1987 was about equal to that in 1942.

Baytown-La Porte Area

The greatest average daily rate of ground-water pumpage in the Baytown-La Porte Area (fig. 6) was about 32 Mgal/d in 1972. Since 1972, ground-water withdrawals decreased gradually until 1987 when pumpage was 4.4 Mgal/d (fig. 1). From the time ground-water withdrawals in the Area began, about the end of World War I until 1978, the principal use was industrial. In 1972, 24 Mgal/d or 75 percent of the ground water pumped was used by industry. In 1987, only 0.8 Mgal/d (or 18 percent) of the ground water pumped was for industry and 3.6 Mgal/d was for municipal supply.

Texas City Area

Ground-water withdrawals in the Texas City, Alta Loma, and Johnson Space Center Areas for 1970-87 are shown in figure 7. Pumpage of ground water in the Texas City Area began about 1893, increased slowly to about 2 Mgal/d in 1933, and then increased rapidly to 17 Mgal/d in 1944. In 1948, water from the Brazos River was brought into the Area to allow a reduction in ground-water production and to avert problems associated with subsidence and salt-water encroachment. Ground-water withdrawal decreased to 10 Mgal/d in 1951, and then increased slowly to 14 Mgal/d in 1976. The decreased use of ground water after 1976 resulted from increased use of surface water and conservation measures by industry. Further reduction in ground-water withdrawal in 1981 was caused by surface-water conversion by municipalities and additional use of surface water by industry. By 1987, ground-water withdrawal in the Texas City Area had been reduced to 0.7 Mgal/d.

Alta Loma Area

All ground water pumped in the Alta Loma Area has been for municipal supply. The city of Galveston obtained all its fresh water from wells in the Area until 1973. In 1972, ground-water pumpage was 13 Mgal/d. Ground-water pumpage decreased in the latter part of 1973 when water from Lake Houston was imported. The use of surface water was increased in stages since 1973 and as a result, ground-water use was only 0.7 Mgal/d in 1987.

Johnson Space Center Area

The Johnson Space Center Area was part of the Baytown-La Porte Area until 1962. Increased development, beginning with the construction of the Manned Spacecraft Center of the National Aeronautics and Space Administration, and associated ground-water withdrawal prompted separation into two Areas. Pumpage in 1960 was 1.2 Mgal/d, which increased to 20.6 Mgal/d in 1976. Surface water from Lake Houston then became available and ground-water usage was reduced. In 1987, ground-water withdrawal was 3.8 Mgal/d.

CHANGES IN WATER LEVELS

Water levels in wells declined in local cone-shaped depressions after the wells were drilled and pumped. As the number of wells and amount of withdrawal increased, the cones of depression expanded and intersected. As a result, major regional cones of depression formed in the Houston and Pasadena Areas, with smaller cones in the vicinity of major well fields.

Prior to 1977, water levels declined throughout the region except in a small area where ground-water pumpage was curtailed after water became available from Lake Houston in 1954. The decline of the water levels in the Pasadena Area is shown by the hydrograph in figure 8. Also shown is the effect of the decrease in ground-water withdrawal after water from Lake Livingston was introduced in late 1976. The water level in well LJ-65-23-220, completed in the Chicot aquifer, rose 107 feet from November 1976 to October 1987. The water level in well LJ-65-23-219, completed in the upper part of the Evangeline aquifer, rose 177 feet during the same period. The water level in a nearby well, more representative of the Evangeline aquifer, rose as much as 154 feet.

The magnitude and areal extent of water-level changes in wells in the Chicot and Evangeline aquifers for 1943-87 and 1977-87 are shown in figures 9, 10, 11, and 12. Water-level change maps were based on data from 1943 measurements. The measurements coincide with the establishment of a comprehensive network of benchmarks in 1943 upon which elevation changes (subsidence) are based. From 1943 to 1977, water levels generally declined. Decline maps to 1977 (Gabrysch, 1984, figs. 10, 11) are most representative of maximum water-level declines (maximum increase in stress) that have occurred in the region. Gabrysch (1984) discussed changes in water levels to 1977 and associated subsidence. Water-level change maps for 1943-87 represent the greatest decline in the western one-half of the region. More than 50 feet and as much as 300 feet of decline in water levels in wells in the Chicot aquifer occurred during 1943-87, as shown in figure 9. Also, water levels declined more than 50 feet and as much as 450 feet in wells in the Evangeline aquifer, as shown in figure 10.

The introduction of water from Lake Livingston to the eastern part of the region in 1976 allowed a large reduction in ground-water withdrawals, and consequently, large recoveries in artesian pressure. The recoveries are exemplified in figures 11 and 12, maps of changes in water levels in wells in the Chicot and Evangeline aquifers during 1977-87. Water levels rose more than 140 feet in wells in the Chicot aquifer (fig. 11) and more than 140 feet in wells in the Evangeline aquifer in the Pasadena Area (fig. 12). During 1977-87 this period, water levels continued to decline in the western part of the region. In the northwestern part of the region, the water level in a well in the Chicot aquifer declined about 60 feet; in the southwestern part of the region, the water levels in the Evangeline aquifer declined as much as 160 feet.

LAND-SURFACE SUBSIDENCE

The process of land-surface subsidence in the Houston-Galveston region has been described in previous reports listed in the references. Generally, subsidence is the consequence of a load being applied to a compressible material. The load, or stress, causing subsidence in the region is equal to the decline in artesian pressure (decline in water level times the unit weight of water) caused by ground-water withdrawal; the compressible material is the clay layers. The changes in water levels (both declines and rises) have been described in the preceding section. Rises in water levels are equivalent to an unloading of the clay beds, which leads to a decreased rate of subsidence.

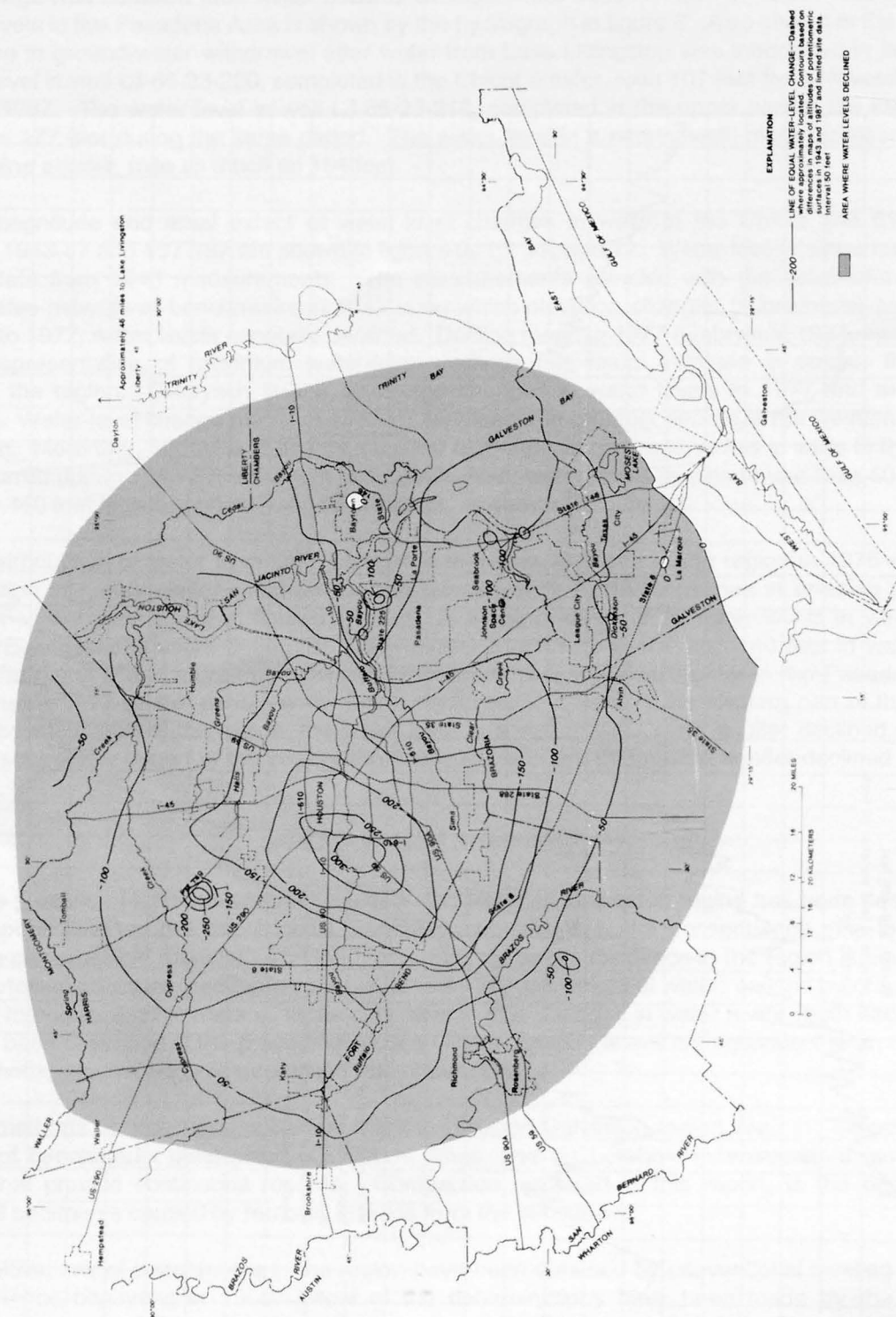
Two methods of measuring subsidence in the Houston-Galveston region are: (1) Comparison of elevations of benchmarks determined at different times, and (2) borehole extensometers (compaction monitors) that provide continuous records. Compaction, as used in this report, is the decrease in thickness of sediments caused by removal of fluids from the subsurface.

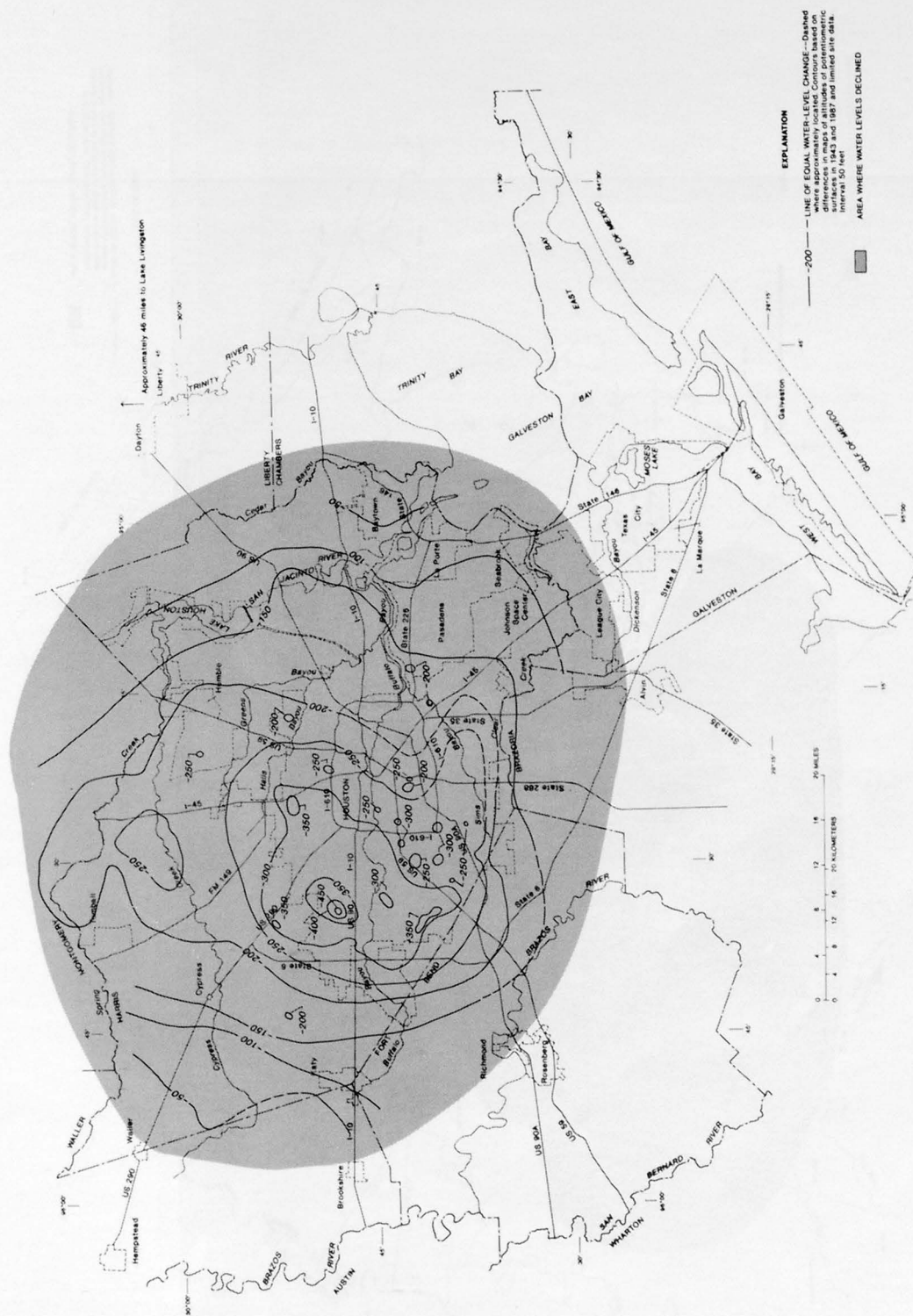
The elevations of benchmarks in the region have been obtained by conventional leveling methods at several times beginning in 1906. Most of the determinations have been made by the National Geodetic Survey and their predecessor agency, the U.S. Coast and Geodetic Survey. Elevations determined by other public agencies have been used to prepare maps of subsidence. Conventional leveling methods are appropriate in areal appraisals.

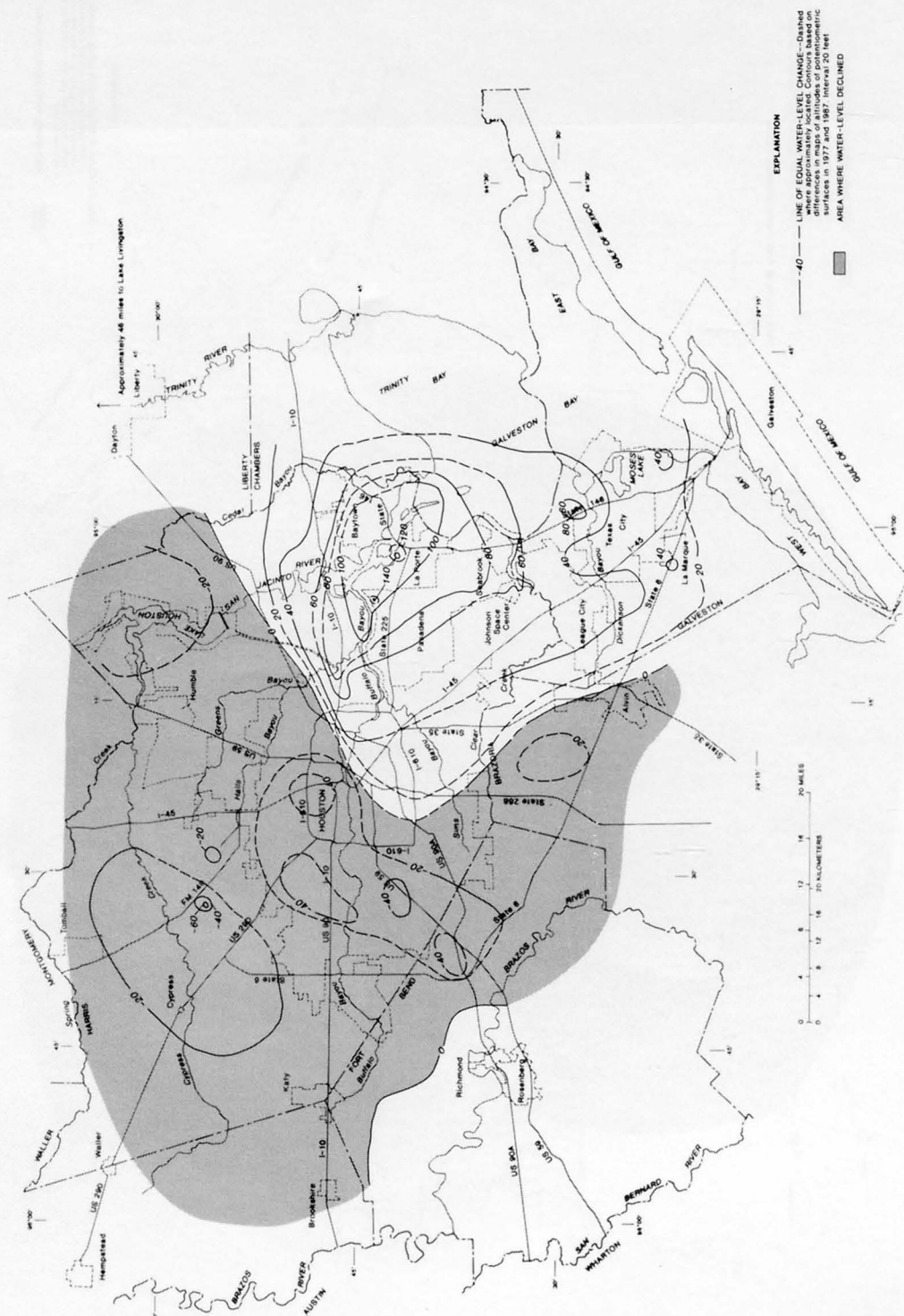
Data from borehole extensometers have been used to analyze subsidence in the region since 1958. The extensometers produce reliable continuous records and are precise. They also can be used to relate



Figure 8.--Hydrographs showing changes in water levels in wells in the Pasadena area.







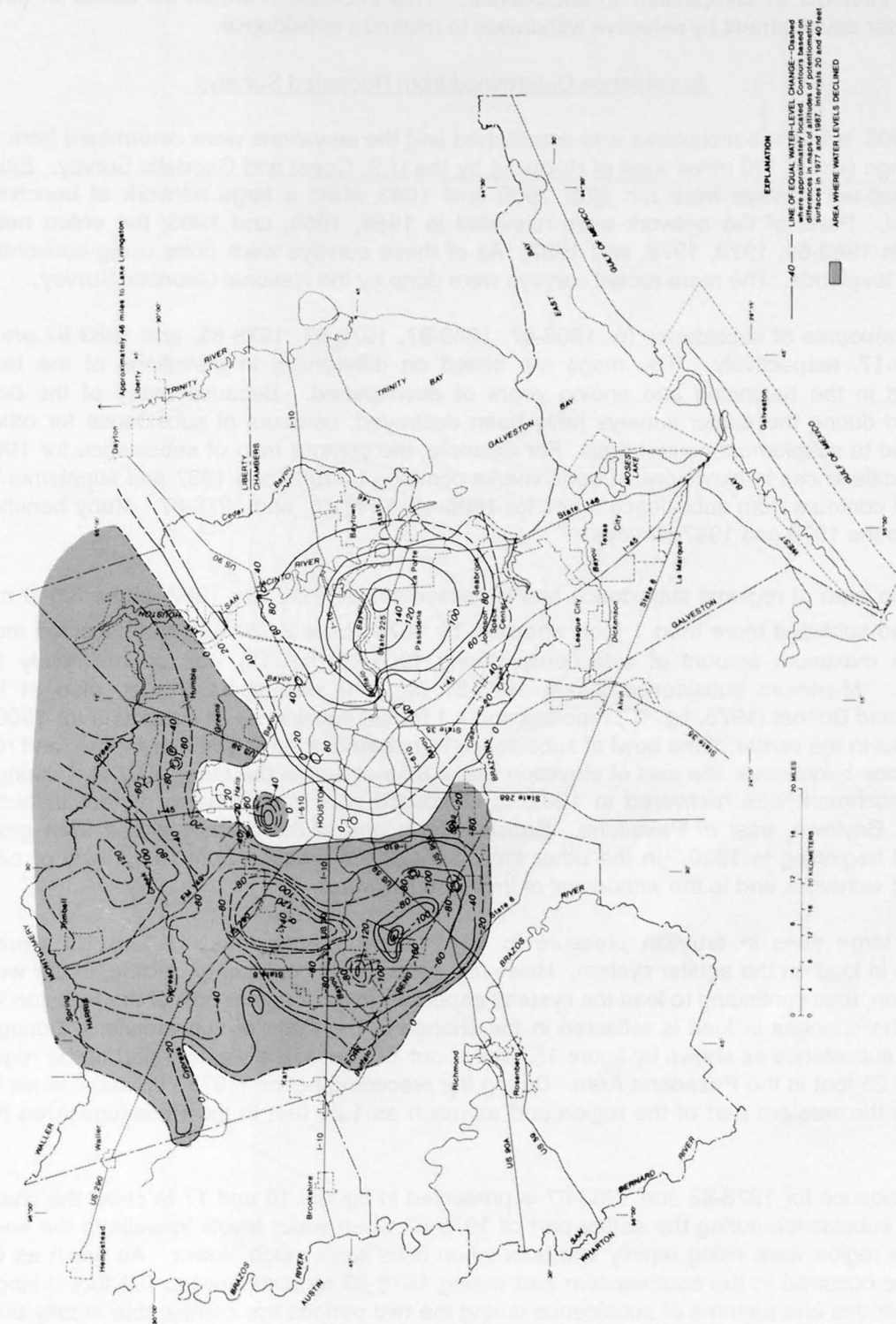


Figure 12.--Approximate changes in water levels in wells completed in the Evangeline aquifer, 1977-87.

the depth intervals of compaction to subsidence. This information would be useful in strategies of ground-water development by selective withdrawal to minimize subsidence.

Subsidence Determined from Repeated Surveys

In 1906, a line of benchmarks was established and the elevations were determined from Galveston to La Grange (about 100 miles west of Houston) by the U.S. Coast and Geodetic Survey. Either single-line or small-net surveys were run after 1906 until 1943 when a large network of benchmarks was established. Parts of the network were releveled in 1954, 1958, and 1983; the entire network was releveled in 1963-64, 1973, 1978, and 1987. All of these surveys were done using conventional spirit levels and level rods. The more recent surveys were done by the National Geodetic Survey.

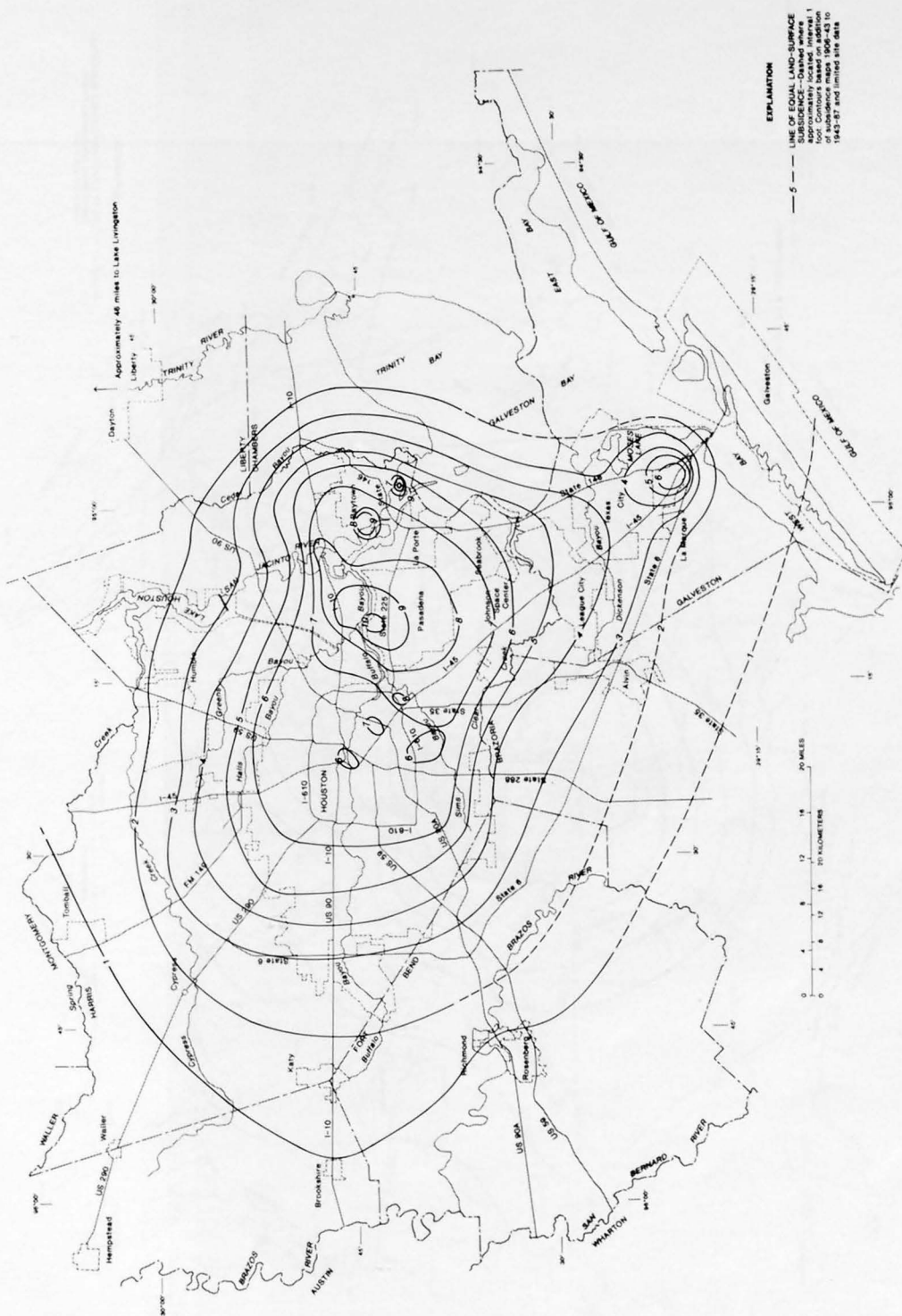
The amounts of subsidence for 1906-87, 1943-87, 1978-87, 1978-83, and 1983-87 are shown in figures 13-17, respectively. The maps are based on differences in elevations of the benchmarks determined in the beginning and ending years of each period. Because many of the benchmarks established during the earlier surveys have been destroyed, contours of subsidence for other periods were added to supplement control data. For example, the contour map of subsidence for 1906-87 was based on differences in elevations of benchmarks common to 1906 and 1987 and supplemented by the addition of contours from subsidence maps for 1906-43, 1943-78, and 1978-87. Many benchmarks are common to the 1978 and 1987 surveys.

The area of regional subsidence has increased since 1978. By 1987, about 3,640 mi² of land surface had subsided more than 1 foot; whereas, by 1978 about 2,620 mi² had subsided more than 1 foot. The maximum amount of subsidence during 1906-87 (fig. 13) was approximately 10 feet at Pasadena. Maximum subsidence during 1943-87 (fig. 14) was about 9 feet, also at Pasadena. Gabrysch and Bonnet (1975, fig. 10) reported about 1 foot of subsidence at Pasadena for 1906-43. Two benchmarks in the center of the bowl of subsidence were established in 1943, or before, and releveled in 1978. At one benchmark, the loss of elevation was 8.87 feet and at the other, 8.97 feet during 1943-78. Neither benchmark was recovered in 1987. Subsidence was approximately 9 feet in two localized centers at Baytown, east of Pasadena. Subsidence in one of the areas resulted from ground-water withdrawal beginning in 1920. In the other area, subsidence resulted from withdrawal of oil, gas and associated saltwater, and to the withdrawal of fresh ground water.

The large rises in artesian pressure in the Pasadena Area (figs. 11 and 12) were effective decreases in load on the aquifer system. However, water levels continue to decline, in the western part of the region, thus continuing to load the system, especially in the western part of the Houston Area. The effect of the changes in load is reflected in the change in the rates of subsidence. During 1978-87, maximum subsidence as shown by figure 15, was about 2.0 feet in the western part of the region and as small as 0.25 foot in the Pasadena Area. During the preceding period (1973-78), subsidence was about 1.0 foot in the western part of the region and as much as 1.25 feet in the Pasadena Area (Gabrysch, 1984).

Subsidence for 1978-83 and 1983-87 is presented in figures 16 and 17 to show the change in the pattern of subsidence during the earlier part of 1978-87 when water levels in wells in the southeastern part of the region were rising rapidly and later when rises were much slower. As much as 0.3 foot of subsidence occurred in the southeastern part during 1978-83 as compared to 0.2 foot during 1983-87. The magnitudes and patterns of subsidence during the two periods are comparable areally but localized differences occurred.

The rates of subsidence in the southeastern part of the region have decreased dramatically since 1978. The maximum subsidence of a benchmark at Pasadena during 1973-78 was 1.4 feet (Gabrysch, 1984, p. 29)--an average rate of almost 0.30 ft/yr. During 1978-83, the maximum subsidence at the same location was 0.10 foot and during 1983-87, the maximum subsidence was 0.20 foot.



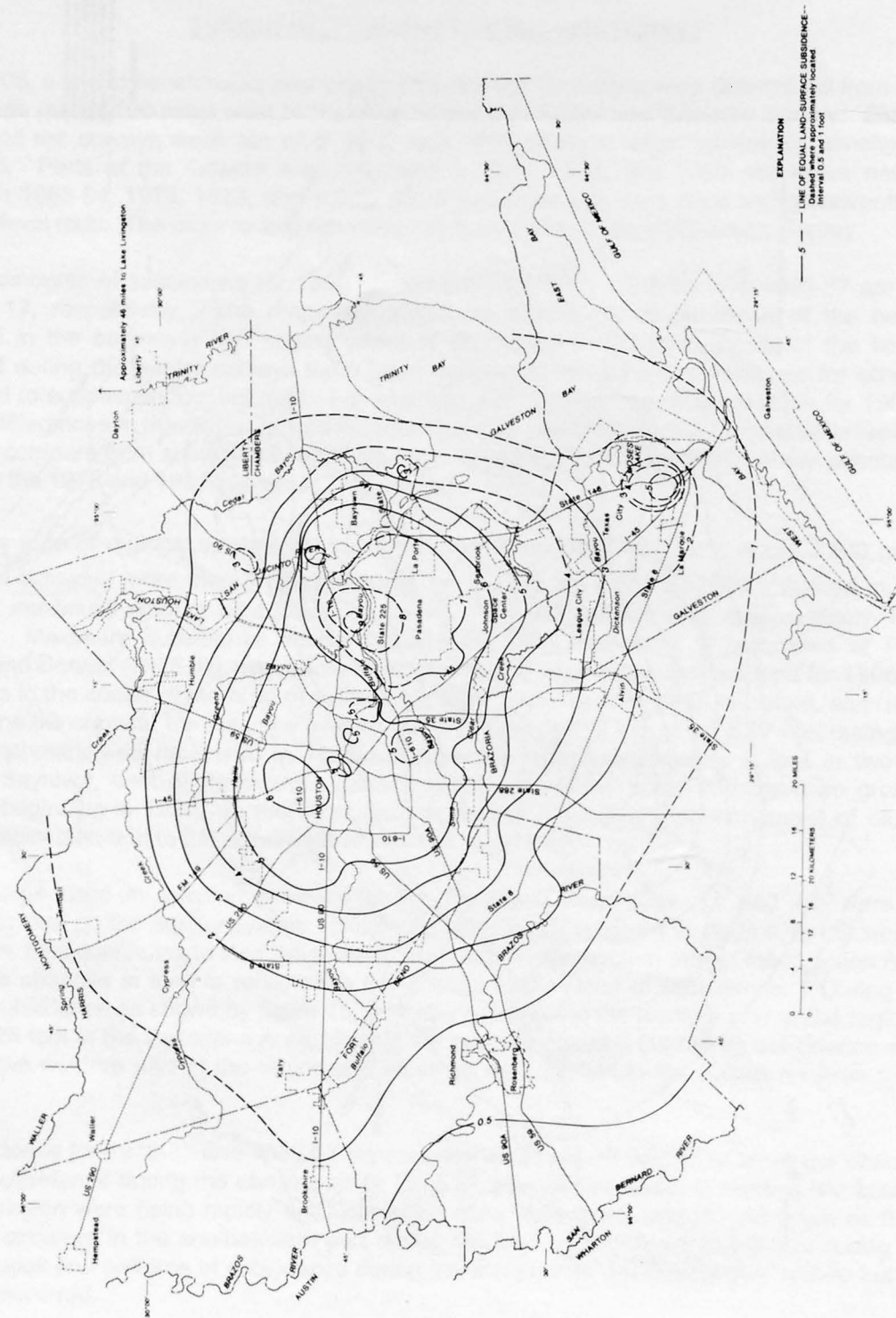
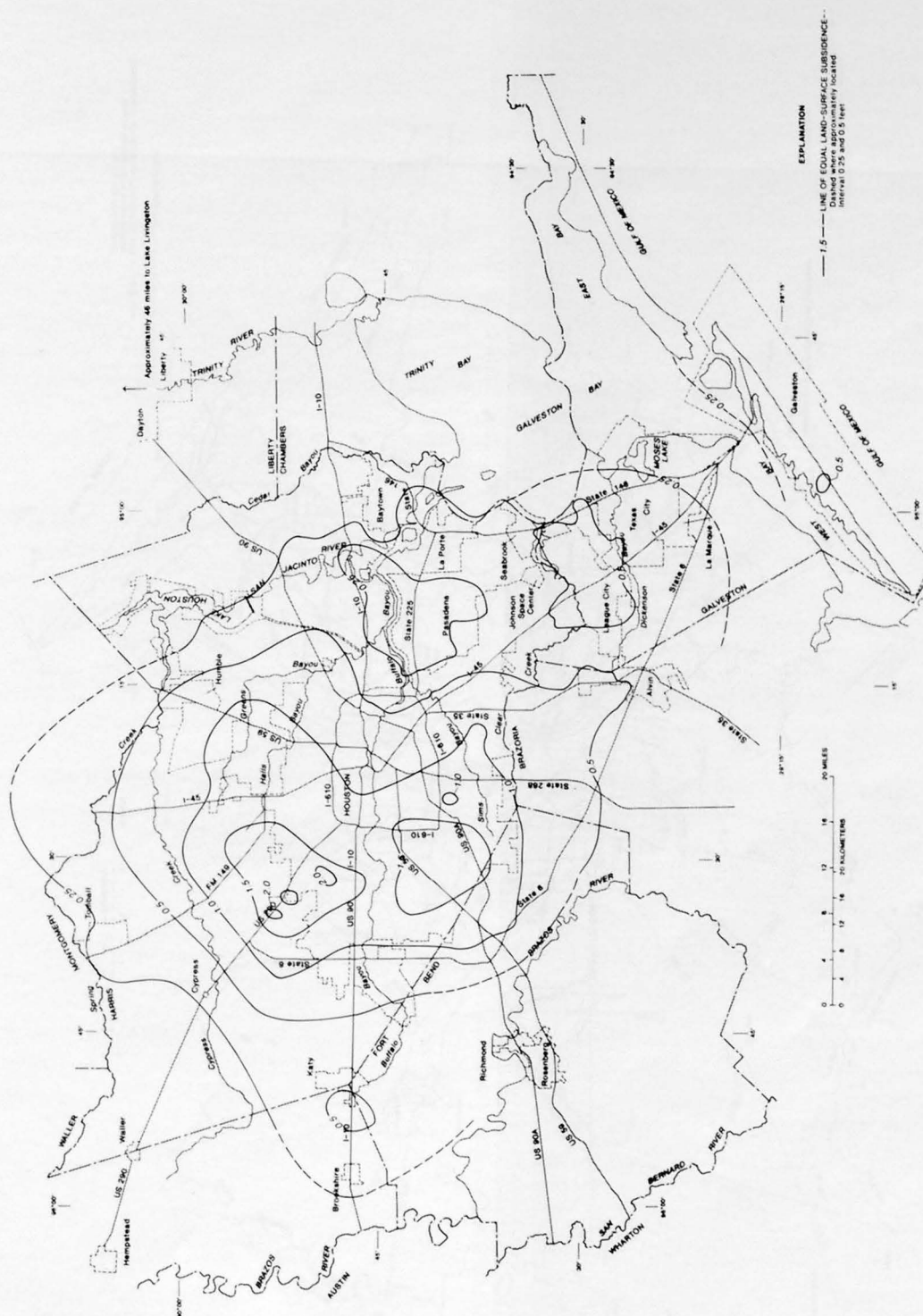
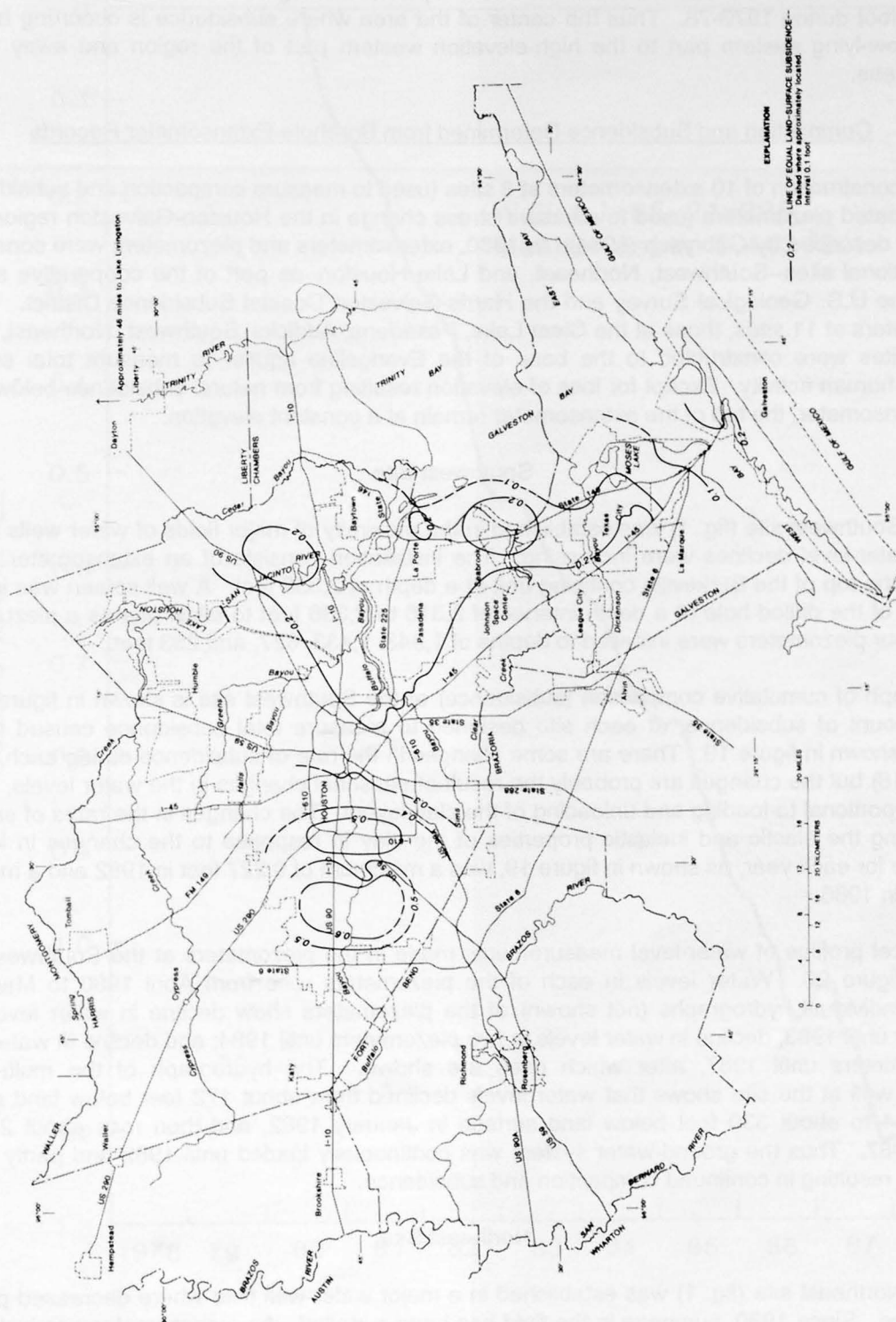


Figure 14 -- Approximate land-surface subsidence 1943-87





During 1978-87, maximum subsidence in the western part of the region was about 2.0 feet compared to about 1.0 foot during 1973-78. Thus the center of the area where subsidence is occurring has shifted from the low-lying eastern part to the high-elevation western part of the region and away from tide-affected areas.

Compaction and Subsidence Determined from Borehole-Extensometer Records

The construction of 10 extensometers at 8 sites (used to measure compaction and subsidence) and their associated piezometers (used to measure stress change in the Houston-Galveston region to 1980) have been described by Gabrysch (1984). In 1980, extensometers and piezometers were constructed at three additional sites--Southwest, Northeast, and Lake Houston--as part of the cooperative agreement between the U.S. Geological Survey and the Harris-Galveston Coastal Subsidence District. Of the 13 extensometers at 11 sites, those at the Clear Lake, Pasadena, Addicks, Southwest, Northeast, and Lake Houston sites were constructed to the base of the Evangeline aquifer to measure total subsidence caused by human activity. Except for loss of elevation resulting from natural subsidence below the base of the extensometer, the top of the extensometer remain at a constant elevation.

Southwest Site

The Southwest site (fig. 1) was established in the proximity of major fields of water wells where the rates of water-level declines were increasing. The installation consists of an extensometer from land surface to the top of the Burkeville confining unit at a depth of 2,358 feet. A well screen was installed in the casing of the drilled hole at a depth interval of 2,316 to 2,336 feet to allow use as a piezometer. In addition, four piezometers were installed to depths of 1,943, 1,433, 627, and 253 feet.

A graph of cumulative compaction (subsidence) at the Southwest site is shown in figure 18. The annual amount of subsidence, at each site designed to measure total subsidence caused by human activity, is shown in figure 19. There are some changes in the rate of subsidence during each year after 1982 (fig. 19) but the changes are probably the result of seasonal changes in the water levels, which are directly proportional to loading and unloading of the clay layers. The changes in the rates of subsidence are reflecting the elastic and inelastic properties of the clay in response to the changes in load. Net subsidence for each year, as shown in figure 19, was a maximum of 0.227 foot in 1982 and a minimum of 0.091 foot in 1986.

Vertical profiles of water-level measurements made in the piezometers at the Southwest site are shown in figure 20. Water levels in each of the piezometers rose from April 1980 to March 1987. However, individual hydrographs (not shown) of the piezometers show decline in water levels in one piezometer until 1983; decline in water levels in two piezometers until 1984; and decline in water levels in two piezometers until 1987, after which rises are shown. The hydrograph of the multi-screened production well at the site shows that water levels declined from about 172 feet below land surface in March 1954 to about 330 feet below land surface in January 1982, and then rose about 22 feet by January 1987. Thus the ground-water system was continuously loaded until 1982 and partly unloaded since then, resulting in continued compaction and subsidence.

Northeast Site

The Northeast site (fig. 1) was established in a major water-well field where decreased production was planned. Since 1980, pumpage in the field has been curtailed. An extensometer was installed to a depth of 2,170 feet. A well screen was installed in the casing at a depth interval of 2,099 to 2,119 feet to allow use of the well as a piezometer. Four other piezometers drilled at the site are completed to depths of 1,596, 1,035, 487, and 298 feet. A graph of cumulative compaction (subsidence) at the site is shown in figure 21. A relatively constant rate of subsidence (fig. 19) was recorded since 1980, except for 1982, when the subsidence was maximum at 0.101 foot. The minimum amount during the period of measurement was 0.050 foot in 1983. The average rate of subsidence from the slope of the compaction

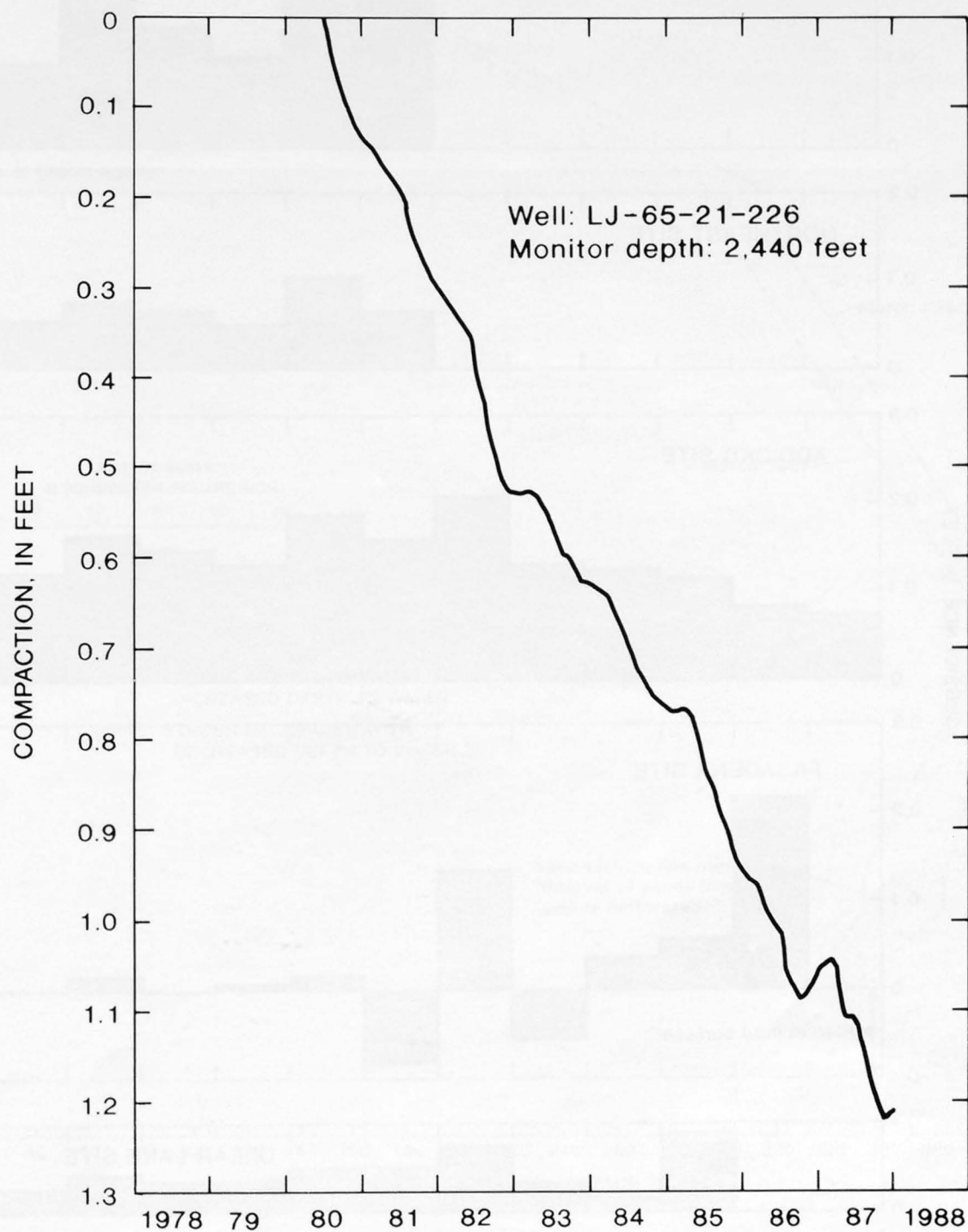


Figure 18.--Cumulative compaction at the Southwest site.

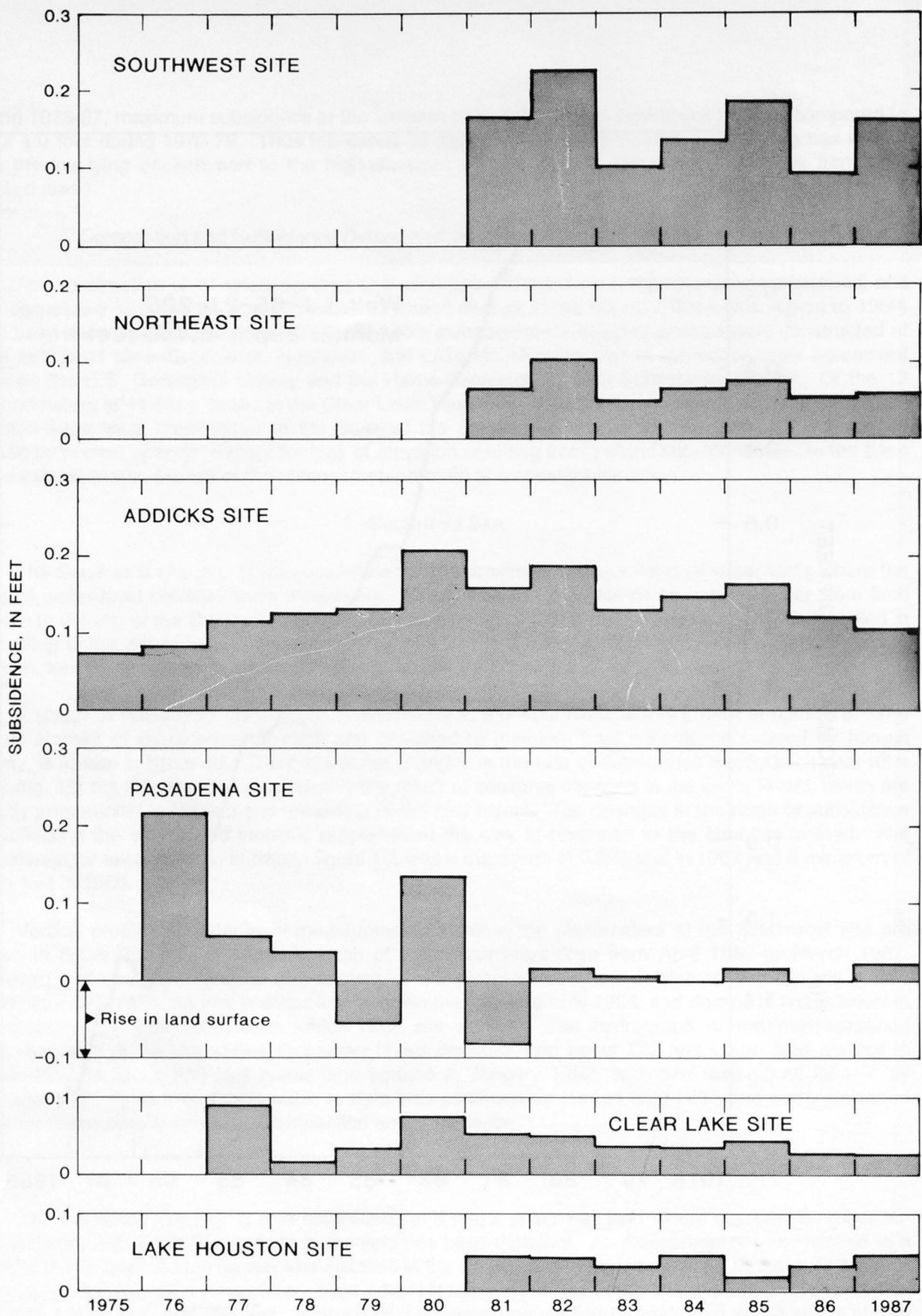


Figure 19.--Annual subsidence measured by extensometers at sites in the Houston-Galveston region.

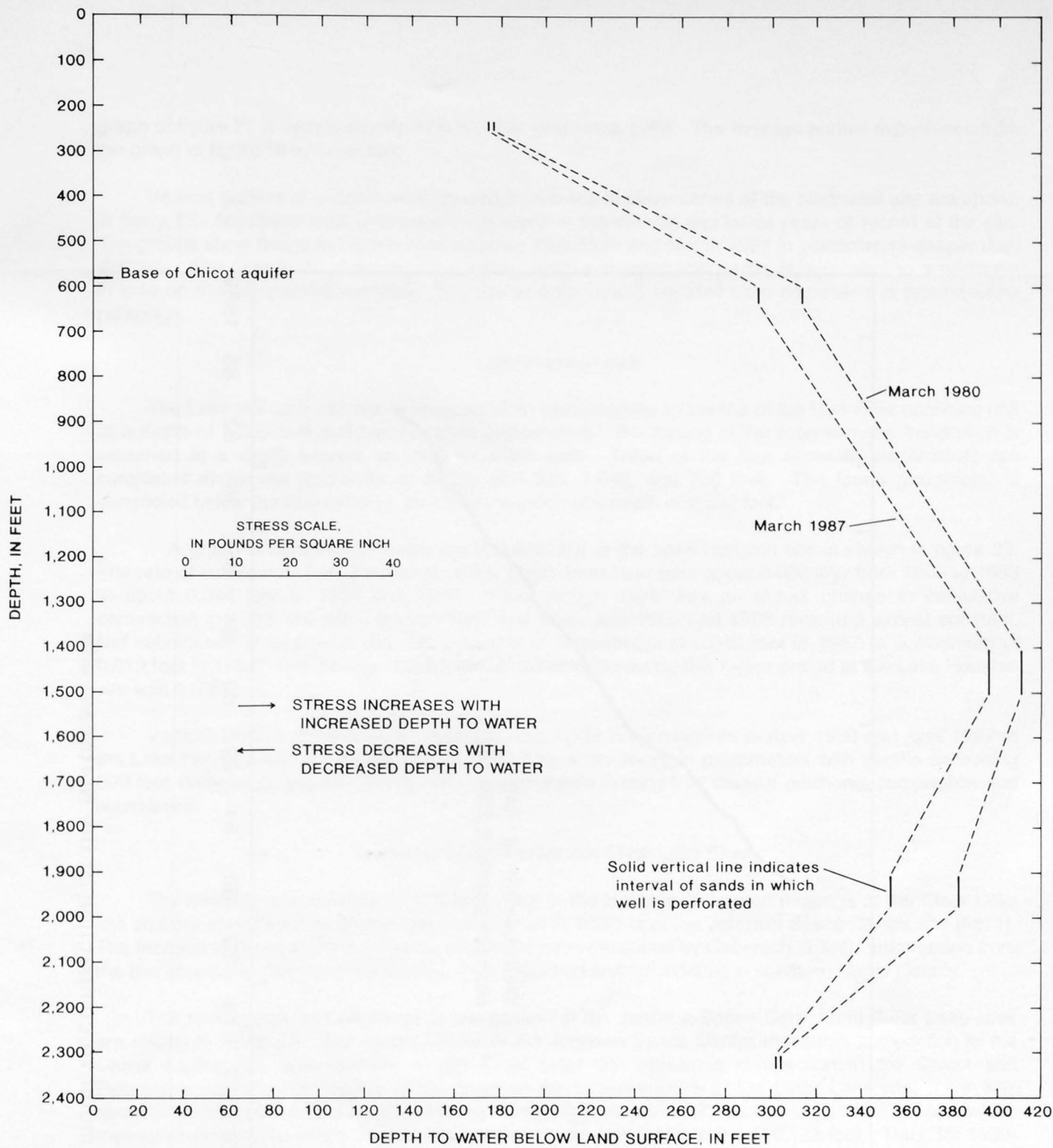


Figure 20.--Potentiometric profiles and changes in effective stress at the Southwest site.

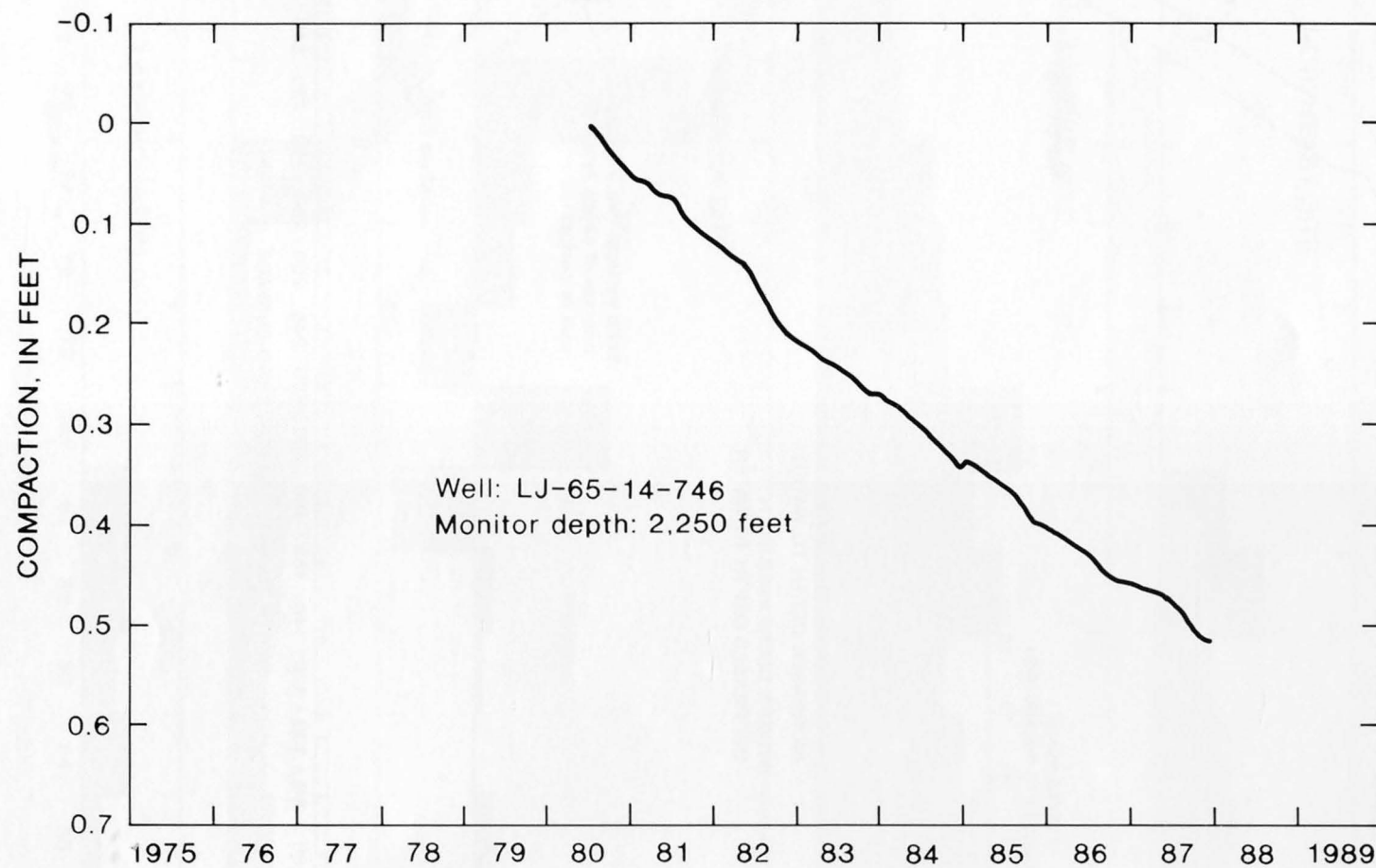


Figure 21.--Cumulative compaction at the Northeast site.

graph of figure 21 is approximately 0.06 foot per year since 1982. The average annual subsidence from the graph of figure 19 is 0.066 foot.

Vertical profiles of water-level measurements made in piezometers at the Northeast site are shown in figure 22. Measurements presented were made in the earliest and latest years of record at the site. The graphs show that water levels rose between April 1980 and March 1987 in piezometers deeper than 450 feet. The magnitude of rise in water levels, which increased with depth, is equivalent to a decrease in load on the compacting material. The rise in water levels resulted from decreases in ground-water pumpage.

Lake Houston Site

The Lake Houston site (fig. 1) consists of an extensometer to the top of the Burkeville confining unit at a depth of 1,940 feet and four separate piezometers. The casing of the extensometer installation is screened at a depth interval of 1,861 to 1,871 feet. Three of the four separate piezometers are completed above the Burkeville at depths of 1,503, 1,048, and 700 feet. The fourth piezometer is completed below the Burkeville (in the Jasper aquifer) at a depth of 2,592 feet.

A graph of compaction (subsidence) measured at the Lake Houston site is shown in figure 23. The rate of subsidence from the slopes of the graph decreased from about 0.050 ft/yr from 1980 to 1983 to about 0.044 ft/yr in 1986 and 1987. Even though there was an abrupt change in cumulative compaction in 1985, the rate between 1982 and 1985, and 1985 and 1988 remained almost constant. Net subsidence in each year (fig. 19) ranged from a maximum of 0.049 foot in 1987 to a minimum of 0.019 foot in 1985. The average annual rate of subsidence during the 7-year period at the Lake Houston site was 0.039 foot.

Vertical profiles of water-level measurements made in piezometers in April 1980 and April 1987 at the Lake Houston site are shown in figure 24. The water levels in piezometers with depths exceeding 300 feet declined during the period, reflecting increased loading that caused additional compaction and subsidence.

Johnson Space Center and Clear Lake Sites

The deepest extensometer (3,072 feet deep) in the Houston-Galveston region is at the Clear Lake site and the oldest existing piezometer (established in 1962) is at the Johnson Space Center site (fig. 1). The facilities at these and the following sites have been described by Gabrysch (1984). Information from the two sites have been coupled to evaluate compaction and subsidence in southern Harris County.

The compaction and difference in compaction at the Johnson Space Center and Clear Lake sites are shown in figure 25. The extensometer at the Johnson Space Center measures compaction in the Chicot aquifer; the extensometer at the Clear Lake site measures compaction in the Chicot and Evangeline aquifers. According to the graph of the extensometers at the Clear Lake site, there was about 0.175 foot of compaction (subsidence) during 1980-82 and 0.172 foot during 1983-87. Meanwhile, measured compaction at the Johnson Space Center site was 0.108 foot and 0.123 foot. Thus, for 1980-82, about 62 percent of the subsidence resulted from compaction of sediments in the Chicot aquifer and 38 percent resulted from compaction in the Evangeline aquifer. Likewise, 72 percent of the subsidence for 1983-87 resulted from compaction in the Chicot aquifer and only 28 percent resulted from compaction in the Evangeline aquifer. The rate of subsidence has decreased significantly at the Clear Lake site as indicated by the decreasing slope in figure 25. According to monitor records, subsidence decreased from 0.075 foot in 1980 to 0.026 foot in 1987 (fig. 19).

Vertical profiles of water-level measurements at the Johnson Space Center and Clear Lake sites are shown in figure 26. The earliest measurements for the graphs (March 1978) were selected to precede the phenomenal rise in water levels associated with increased pressure resulting from an escape

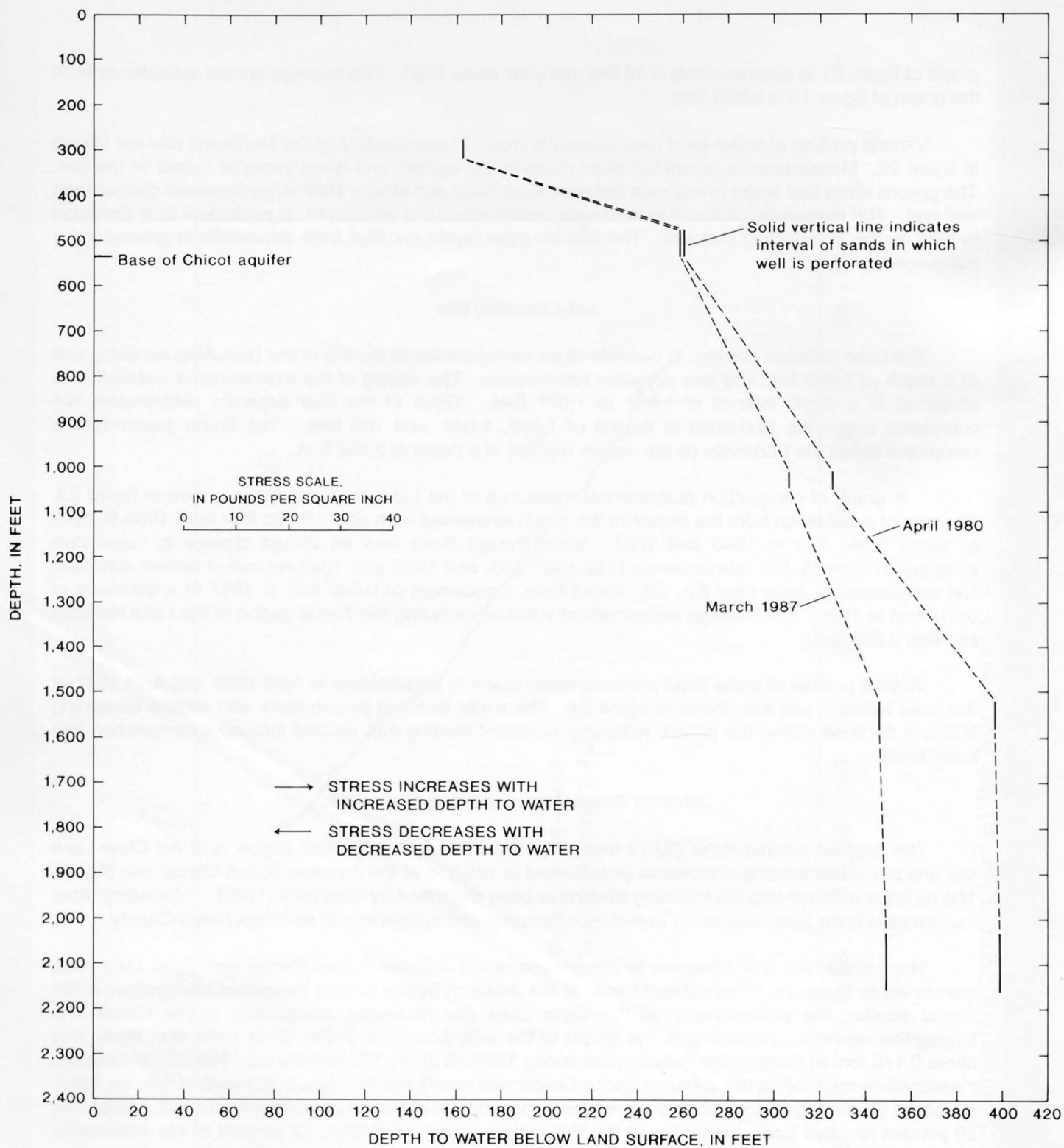


Figure 22.--Potentiometric profiles and changes in effective stress at the Northeast site.

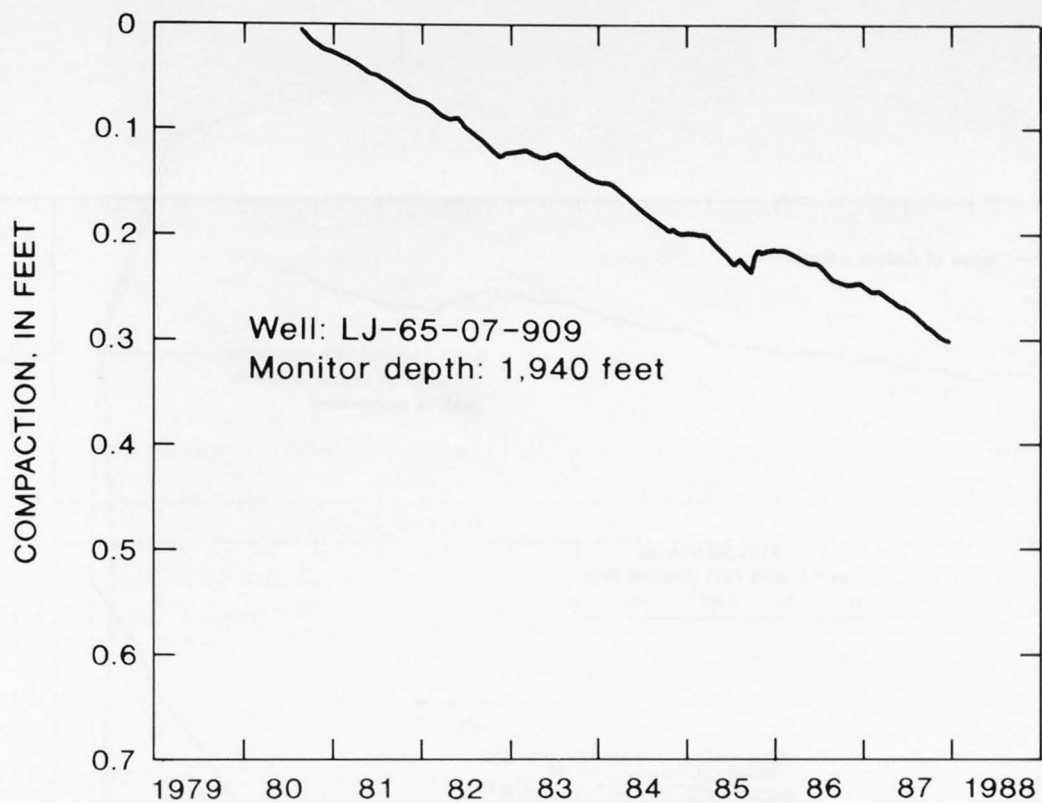


Figure 23.--Cumulative compaction at the Lake Houston site.

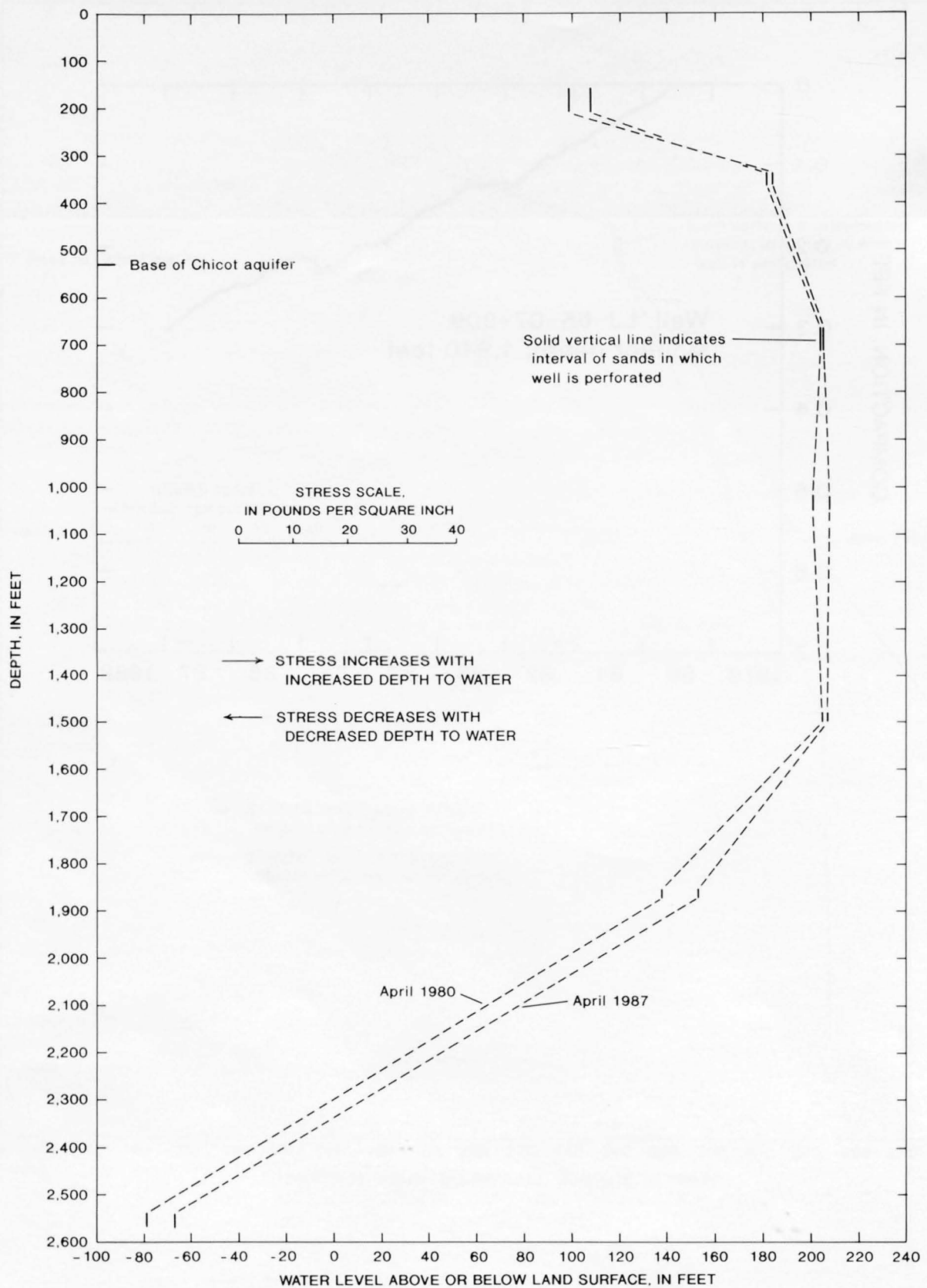


Figure 24.--Potentiometric profiles and changes in effective stress at the Lake Houston site.

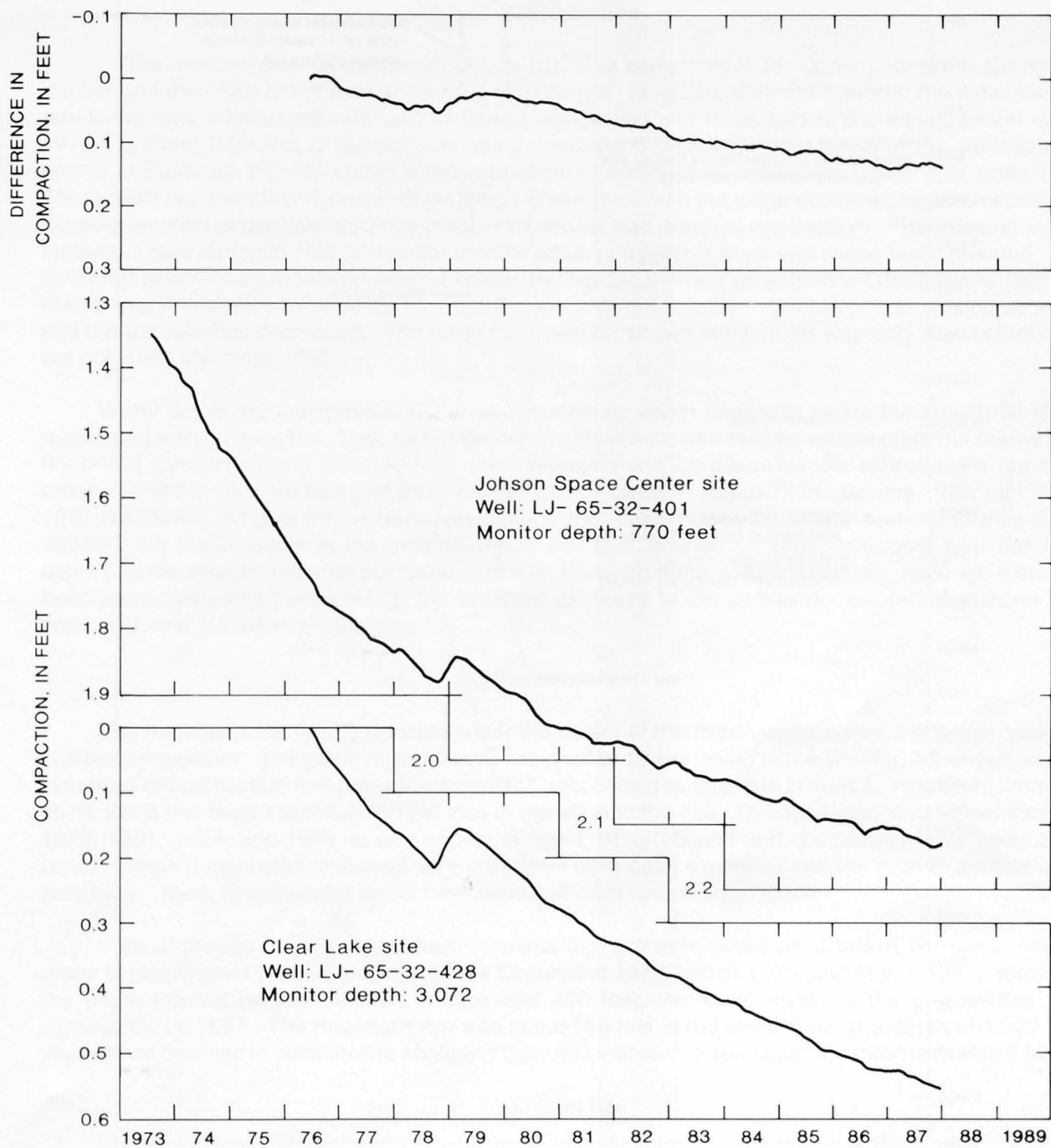


Figure 25.--Measured compaction and cumulative difference at the Johnson Space Center and Clear Lake sites.

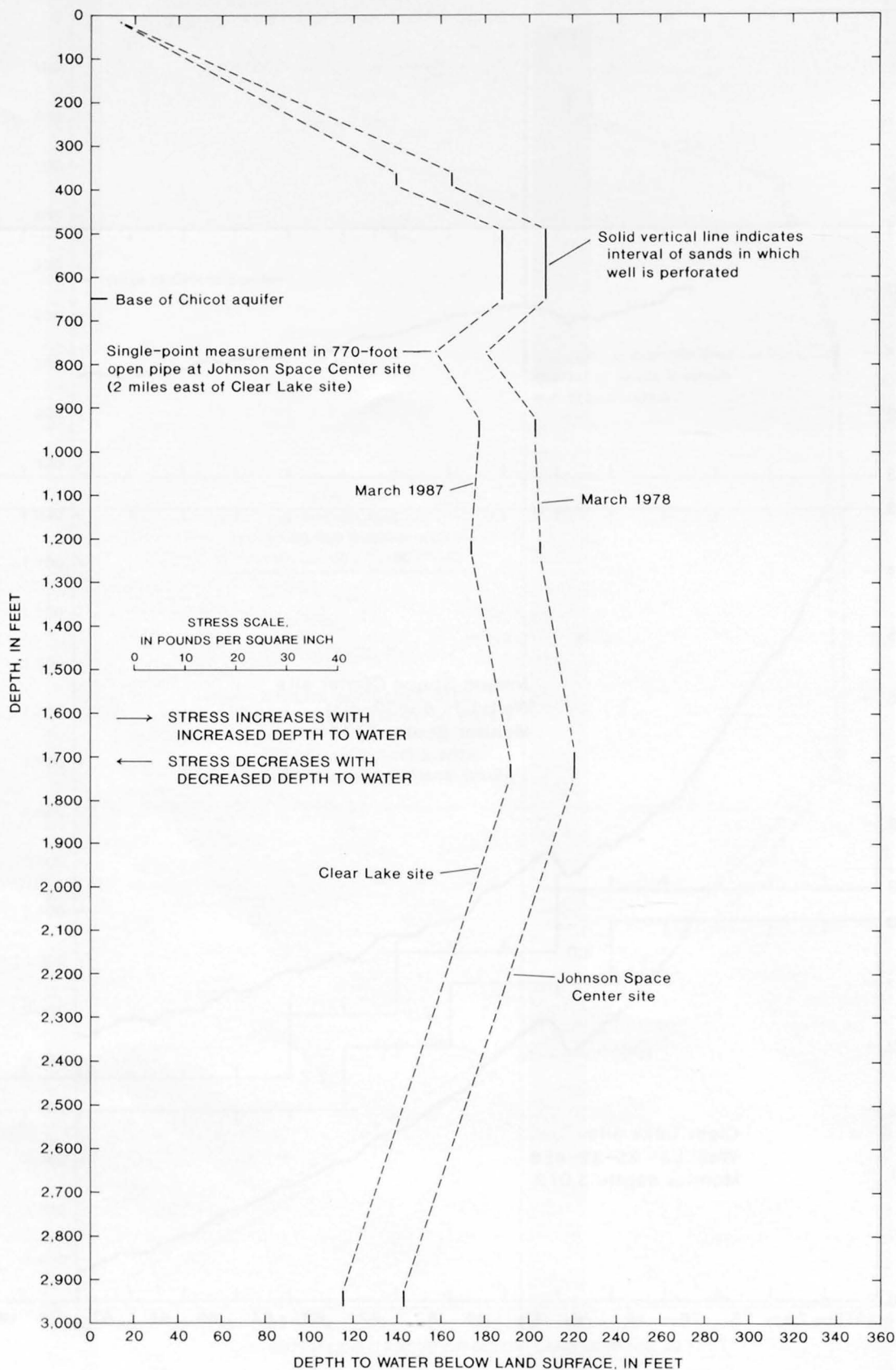


Figure 26.--Potentiometric profiles and changes in effective stress at the Johnson Space Center and Clear Lake sites.

of gas from a ruptured gas well described by Gabrysch (1984). The rise in water level, typical for the event, is shown by the hydrograph of figure 27. The sharp rise of the water level in late 1978 was followed by the dissipation of pressure (lowering of the water level) in 1979-80. Since 1980, the water levels have risen as before the event reflecting the regional response to decreased ground-water pumpage. Water levels rose in all piezometers until March 1987 as shown in figure 26.

Seabrook Site

The extensometer at the Seabrook site (fig. 1) is completed in the upper part of the Evangeline aquifer and therefore is not measuring total subsidence. However, data indicate that the extensometer measures most subsidence. About 0.51 foot of compaction was measured by the extensometer during 1978-87; about 0.50 foot of subsidence was determined by leveling. The graph of the extensometer record at Seabrook (fig. 28) shows a distinct pattern of compaction and rebound each year since 1977. The pattern is a reflection of seasonal pumpage where maximum pumpage occurs in the summer months causing greatest water-level declines (maximum stress) and greatest compaction. The rebound in land surface occurs during the fall and winter months when pumpage is least and water levels rebound. The seasonal pattern was not demonstrated before 1977 when the rate of water-level decline was high and elastic properties were masked by inelastic (permanent) deformation. Subsidence is continuing at the site but the rate has decreased. The rate of compaction shown in figure 28 was 0.21 ft/yr before 1978 but only 0.03 ft/yr since 1982.

Water levels are being measured in piezometers at seven depths to define the change in stress associated with compaction. Until 1986, measurements were made in eight piezometers but the well LJ-65-32-601 (screen interval 364-540 feet) was destroyed and maximum depths to water are not being measured at the site. Vertical profiles of measurements made in March 1978, January 1986, and March 1987 are shown in figure 29. Artesian pressure in the material above 300 feet declined slightly during 1978-87 but the pressure in the material below 300 feet increased. Thus, additional load has been applied to the shallow material but some load was taken from the deeper material. Although there has been more unloading than loading, the resultant decrease in stress has not exceeded residual pore pressures, and subsidence continues.

Pasadena Site

The Pasadena site (fig. 1) is located near the center of the region of subsidence where subsidence has been maximum. The graph of cumulative compaction (subsidence) at the site (fig. 30) shows several instances of compaction and rebound since 1977, responding to changes in stress. However, since late 1978, there has been essentially no net loss in elevation at the site. Rebound (negative subsidence) for 1979, 1981, 1984, and 1986, is also shown in figure 19. Rebound and compaction have been about equal indicating that residual excess pore pressures have been exceeded and the system is responding elastically. Thus, rises in water levels have been sufficient to stop subsidence.

Vertical profiles of water-level measurements (fig. 31) were constructed based on measurements made in piezometers at the Pasadena site in September 1976, March 1978, and March 1987. Except in the depth interval between ground surface and 400 feet, the water levels in the piezometers rose significantly by 1987. The maximum rise was about 152 feet in the piezometer at a depth of 1,330 feet. Water-level declines in piezometers shallower than 400 feet have been small; the maximum was 6 feet.

Addicks Site

Monitoring of compaction (subsidence) at the Addicks site (fig. 1) began in 1974. A graph of subsidence from extensometer records since installation of the monitor is shown in figure 32. Subsidence increased from about 0.08 foot in 1975 to about 0.21 foot in 1980, then decreased to about 0.12 foot in 1987, as shown in figure 19. The average rate of subsidence for 1983-87 from the slope of the graph of figure 32 was about 0.14 ft/yr.

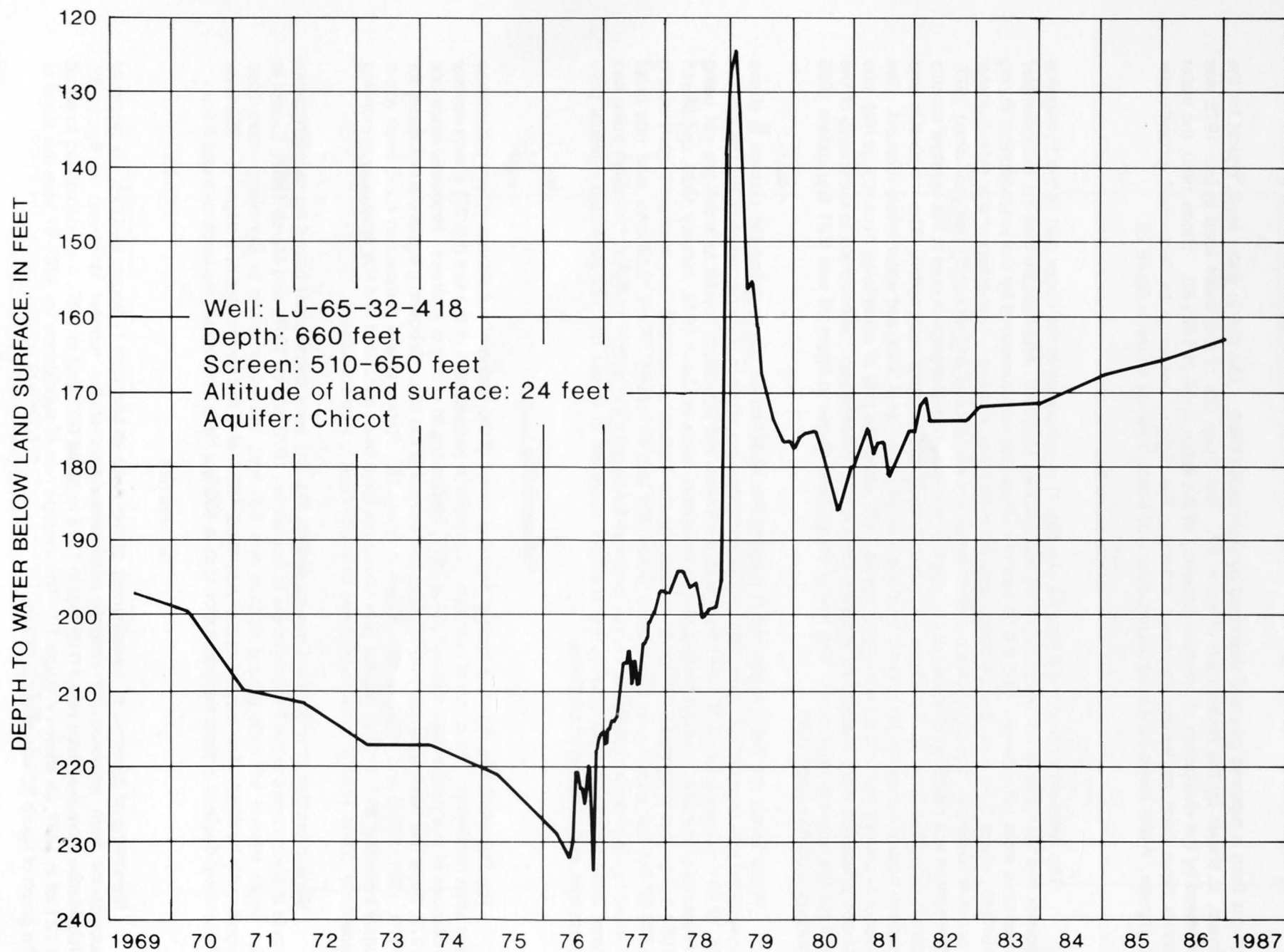


Figure 27.--Hydrograph of a well in southeastern Harris County showing water-level rise caused by gas pressure.

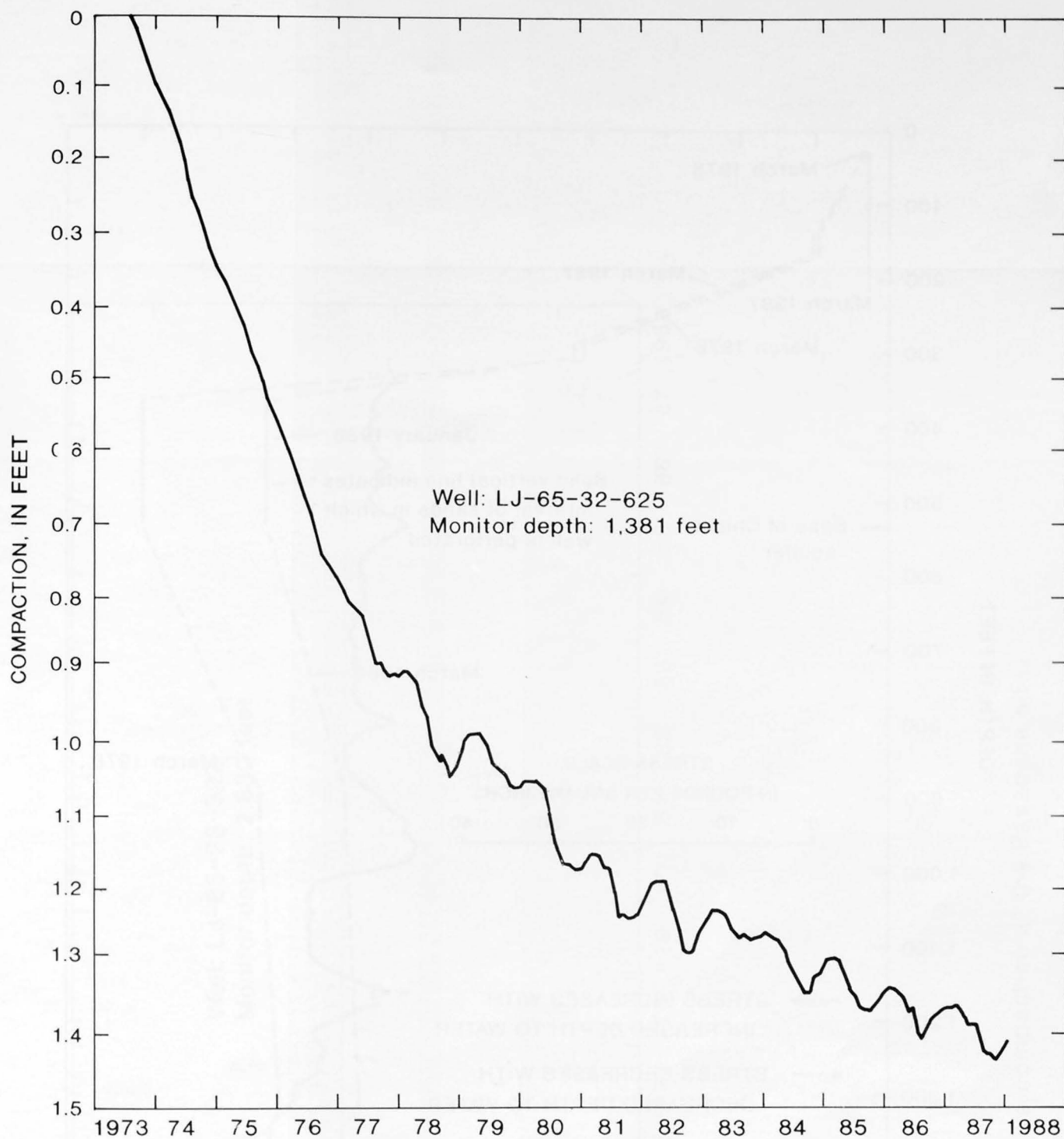


Figure 28.--Cumulative compaction at the Seabrook site.

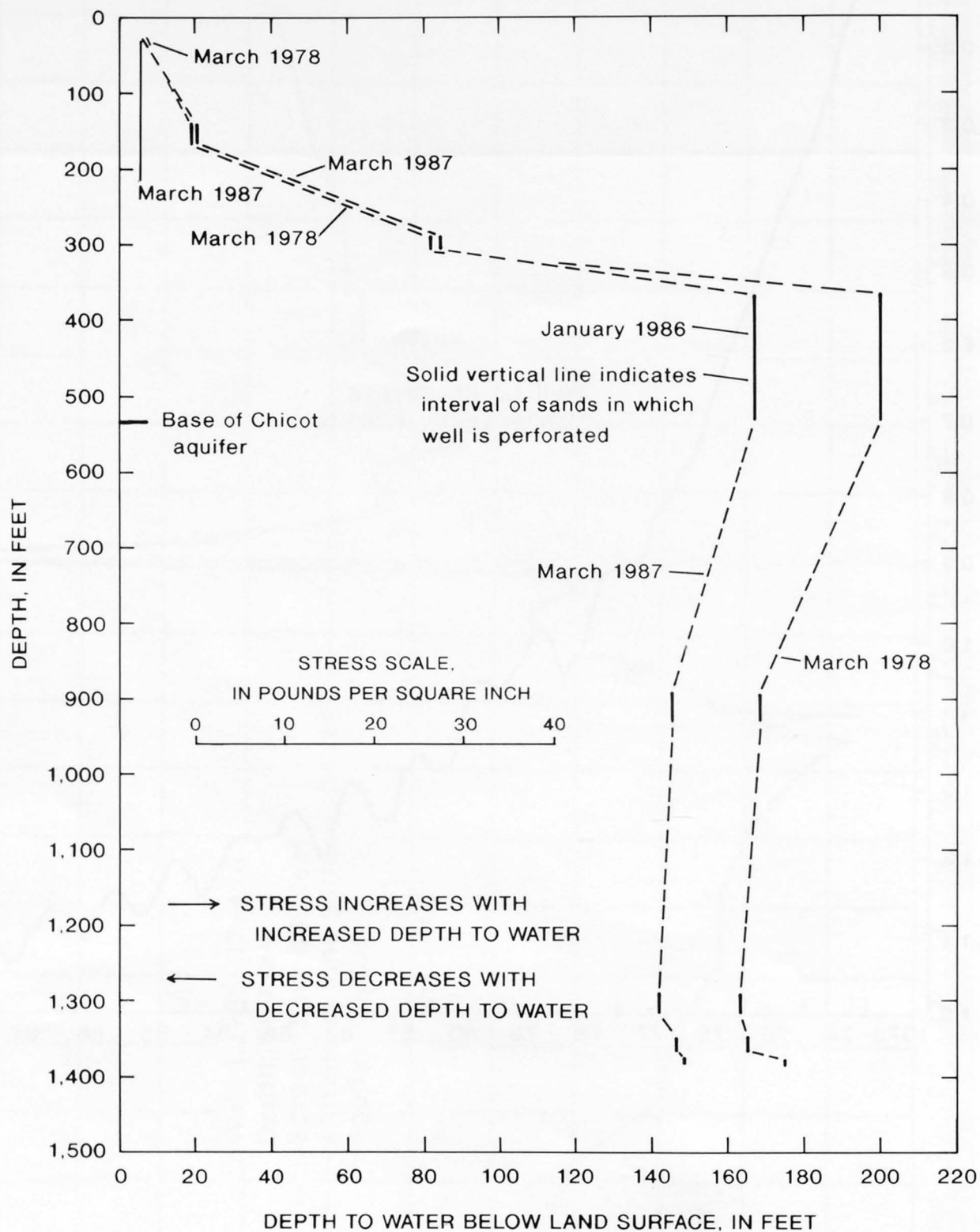


Figure 29.--Potentiometric profiles and changes in effective stress at the Seabrook site.

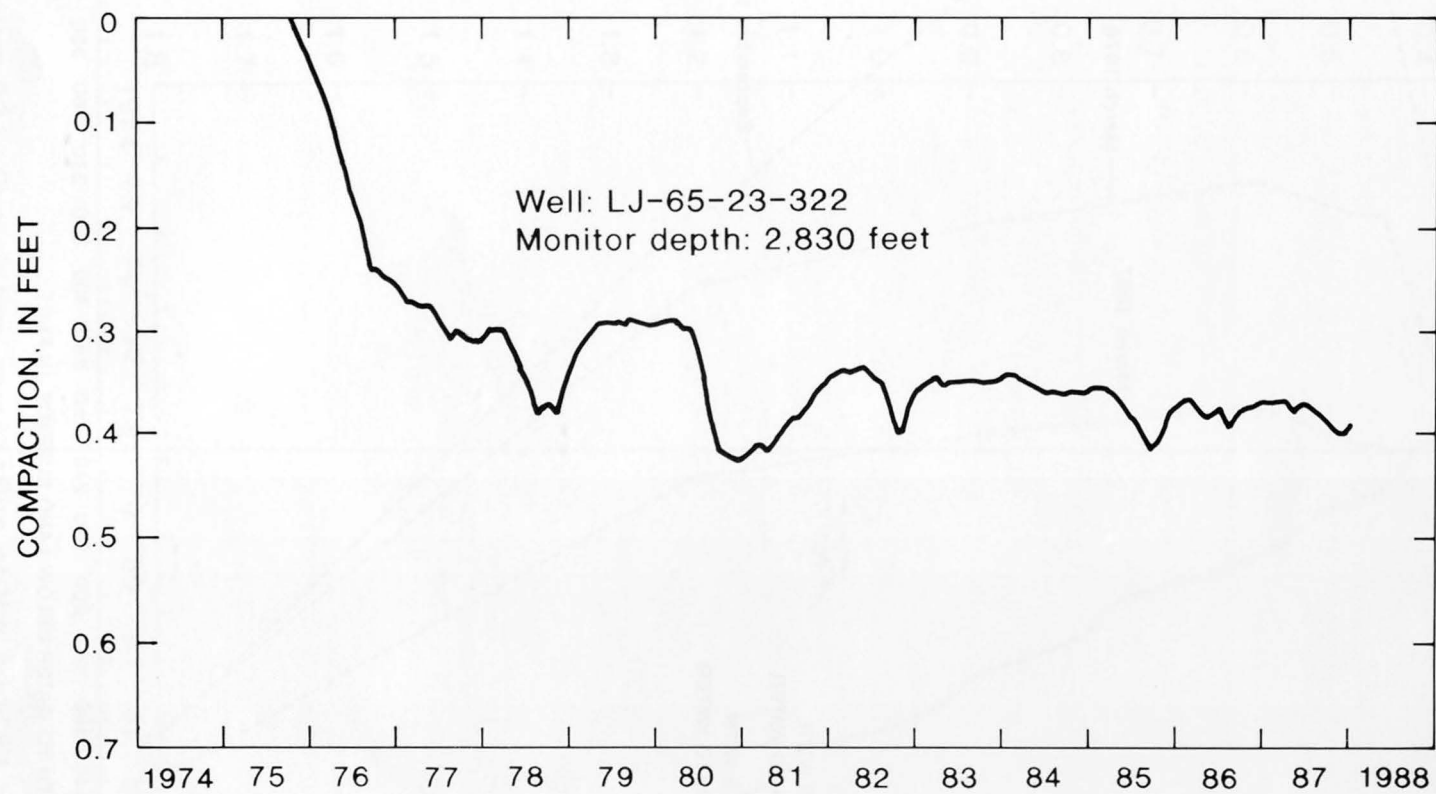


Figure 30.--Cumulative compaction at the Pasadena site.

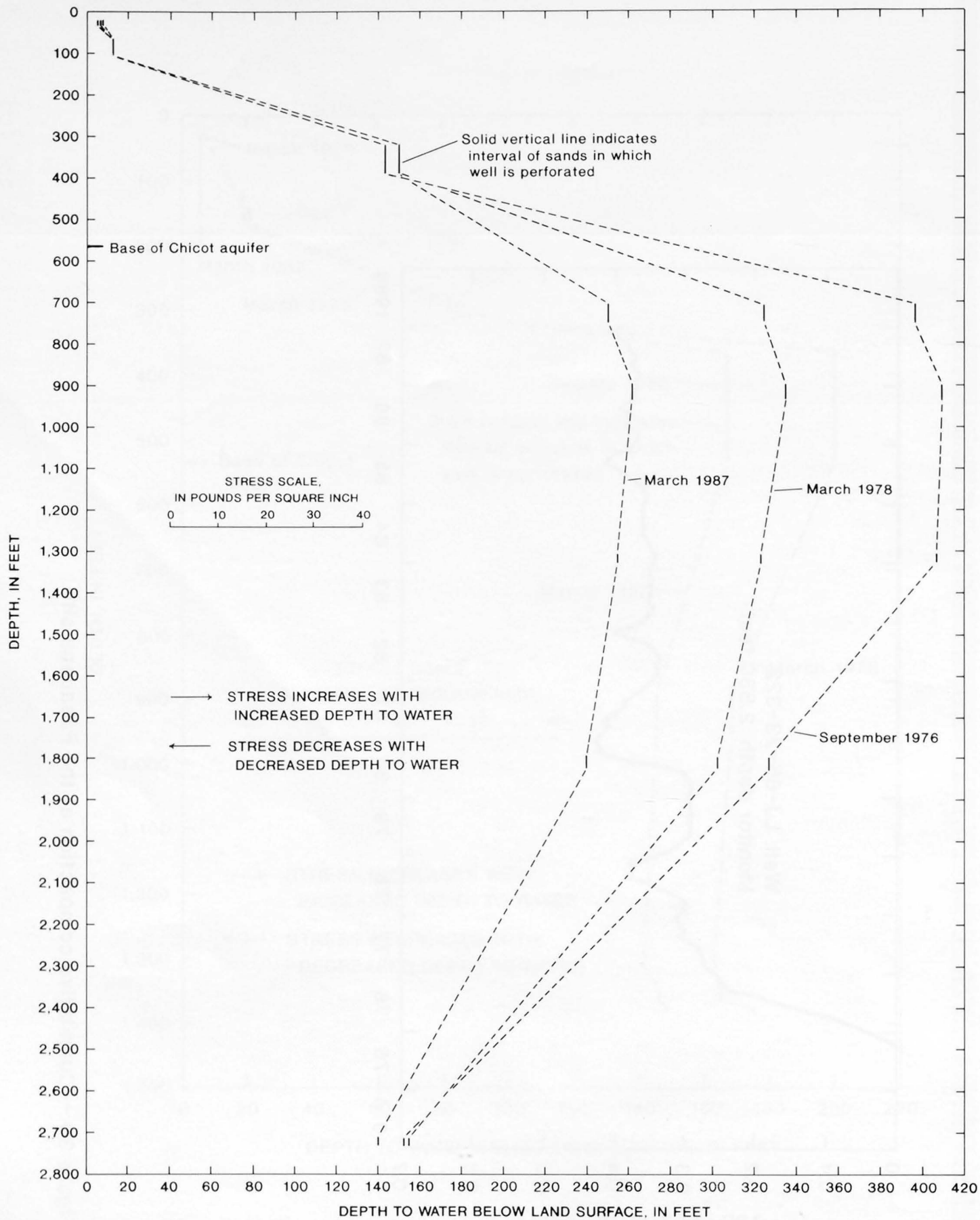


Figure 31.--Potentiometric profiles and changes in effective stress at the Pasadena site.

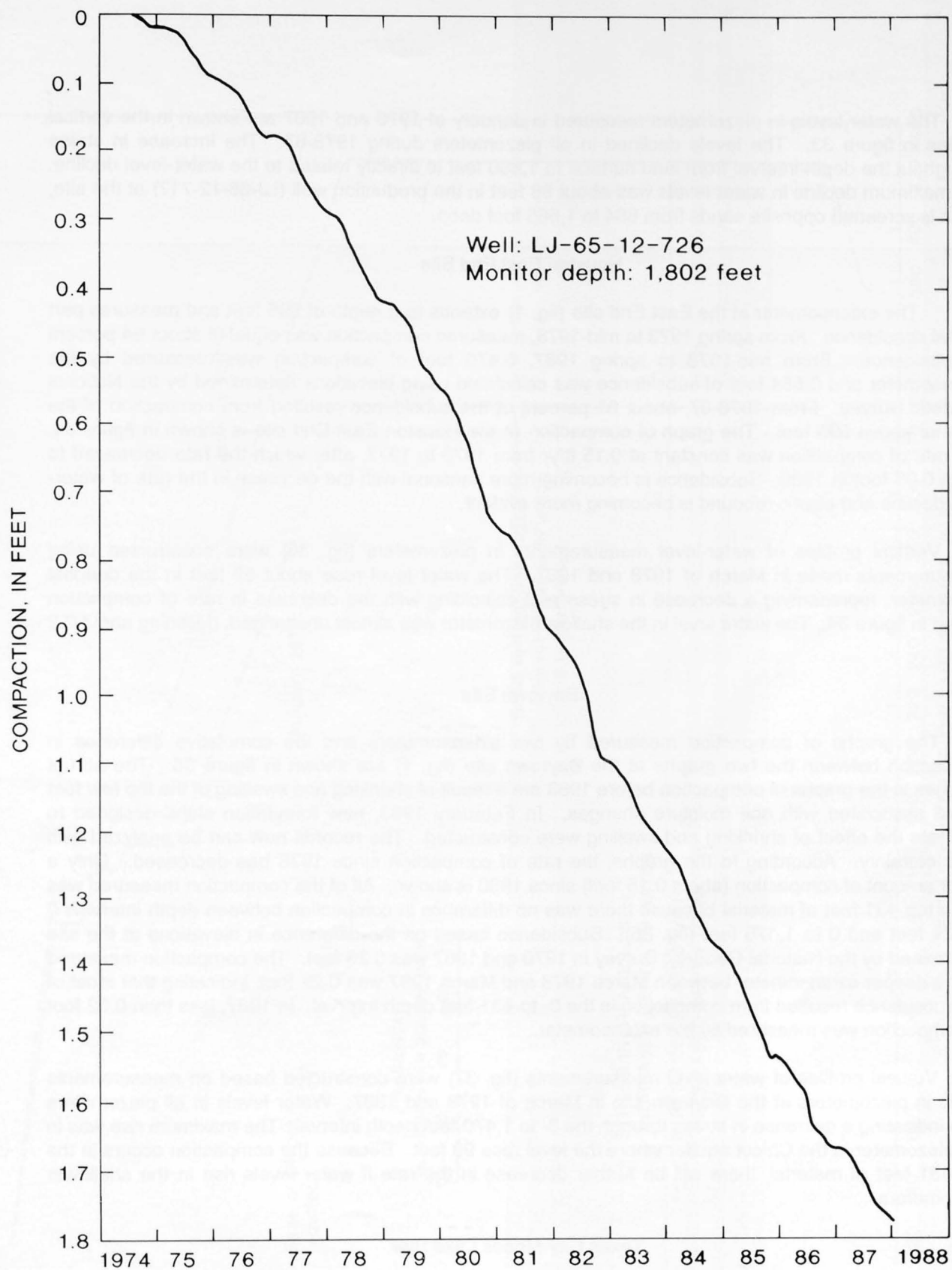


Figure 32.--Cumulative compaction at the Addicks site.

The water levels in piezometers measured in January of 1978 and 1987 are shown in the vertical profiles in figure 33. The levels declined in all piezometers during 1978-87. The increase in stress throughout the depth interval from land surface to 1,660 feet is directly related to the water-level decline. The maximum decline in water levels was about 88 feet in the production well (LJ-65-12-717) at the site, which is screened opposite sands from 664 to 1,565 feet deep.

Houston East End Site

The extensometer at the East End site (fig. 1) extends to a depth of 995 feet and measures part of total subsidence. From spring 1973 to mid-1978, measured compaction was equal to about 84 percent of subsidence. From mid-1978 to spring 1987, 0.470 foot of compaction was measured by the extensometer and 0.554 foot of subsidence was calculated using elevations determined by the National Geodetic Survey. From 1978-87, about 85 percent of the subsidence resulted from compaction of the material above 995 feet. The graph of compaction at the Houston East End site is shown in figure 34. The rate of compaction was constant at 0.15 ft/yr from 1973 to 1977, after which the rate decreased to about 0.03 foot in 1986. Subsidence is becoming more seasonal with the decrease in the rate of water-level decline and elastic rebound is becoming more evident.

Vertical profiles of water-level measurements in piezometers (fig. 35) were constructed using measurements made in March of 1978 and 1987. The water level rose about 59 feet in the deepest piezometer, representing a decrease in stress and coinciding with the decrease in rate of compaction shown in figure 34. The water level in the shallow piezometer was almost unchanged, declining about 0.2 foot.

Baytown Site

The graphs of compaction measured by two extensometers and the cumulative difference in compaction between the two graphs at the Baytown site (fig. 1) are shown in figure 36. The abrupt changes in the graphs of compaction before 1983 are a result of shrinking and swelling of the top few feet of soil associated with soil moisture changes. In February 1983, new foundation slabs designed to eliminate the effect of shrinking and swelling were constructed. The records now can be analyzed with more certainty. According to the graphs, the rate of compaction since 1978 has decreased. Only a minor amount of compaction (about 0.15 foot) since 1980 is shown. All of the compaction measured was in the top 431 feet of material because there was no difference in compaction between depth intervals 0 to 431 feet and 0 to 1,475 feet (fig. 36). Subsidence based on the difference in elevations at the site determined by the National Geodetic Survey in 1978 and 1987 was 0.23 foot. The compaction measured by the deeper extensometer between March 1978 and March 1987 was 0.22 foot, indicating that most of the subsidence resulted from compaction in the 0- to 431-feet depth interval. In 1987, less than 0.02 foot of compaction was measured by the extensometer.

Vertical profiles of water-level measurements (fig. 37) were constructed based on measurements made in piezometers at the Baytown site in March of 1978 and 1987. Water levels in all piezometers rose indicating a decrease in stress through the 0- to 1,470-foot depth interval. The maximum rise was in the piezometer in the Chicot aquifer where the level rose 98 feet. Because the compaction occurs in the top 431 feet of material, there will be further decrease in the rate if water levels rise in the shallower piezometers.

Texas City-Moses Lake Site

The graph of compaction at the Texas City-Moses Lake site (fig. 1) is shown in figure 38. The rate of compaction from 1973 to 1977 was almost constant at about 0.04 ft/yr. The rate of compaction decreased beginning in 1977 until 1981; then the material began to rebound because of decreased stress resulting from rising water levels. Since 1980, the elastic rebound as measured by the extensometer was

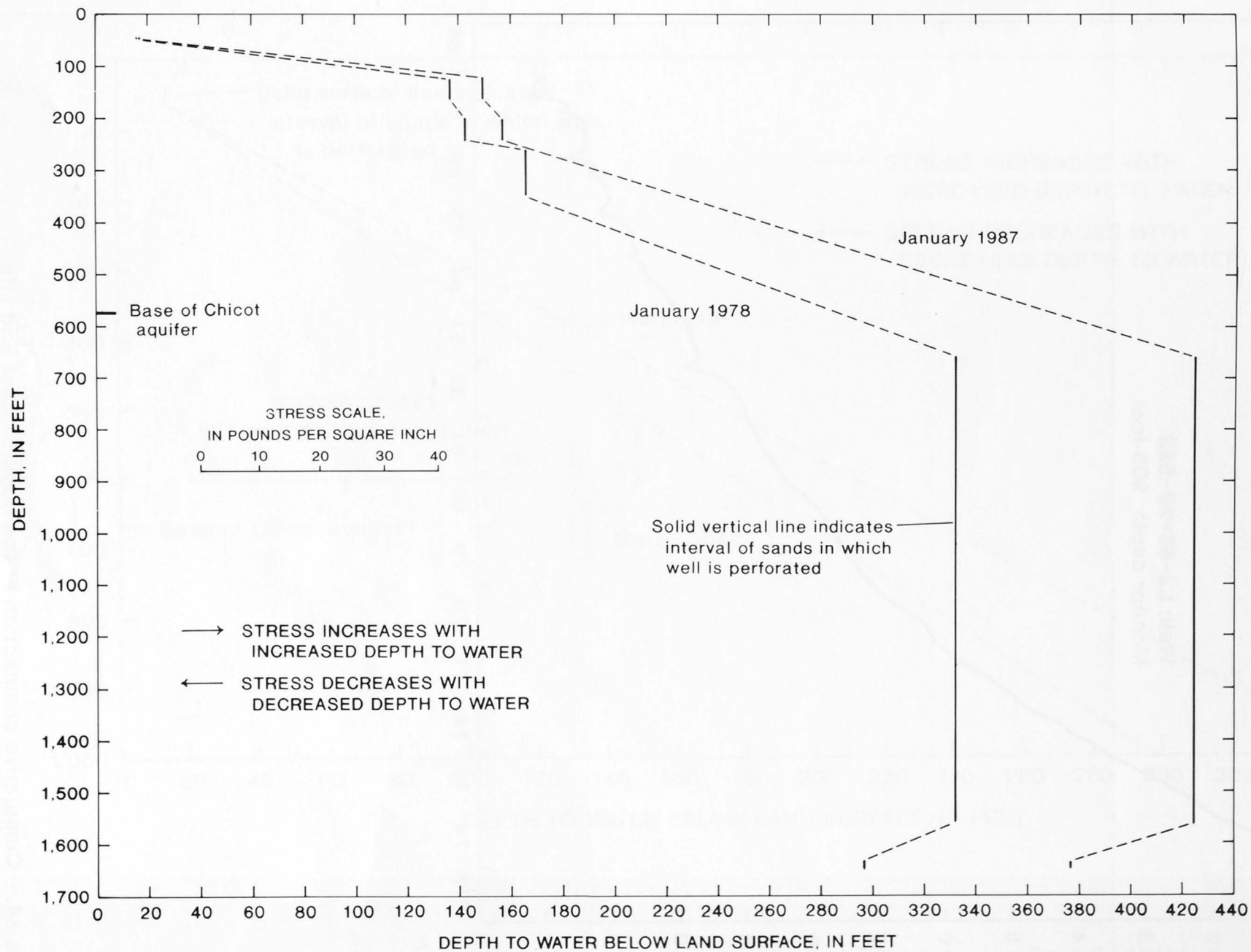


Figure 33.--Potentiometric profiles and changes in effective stress at the Addicks site.

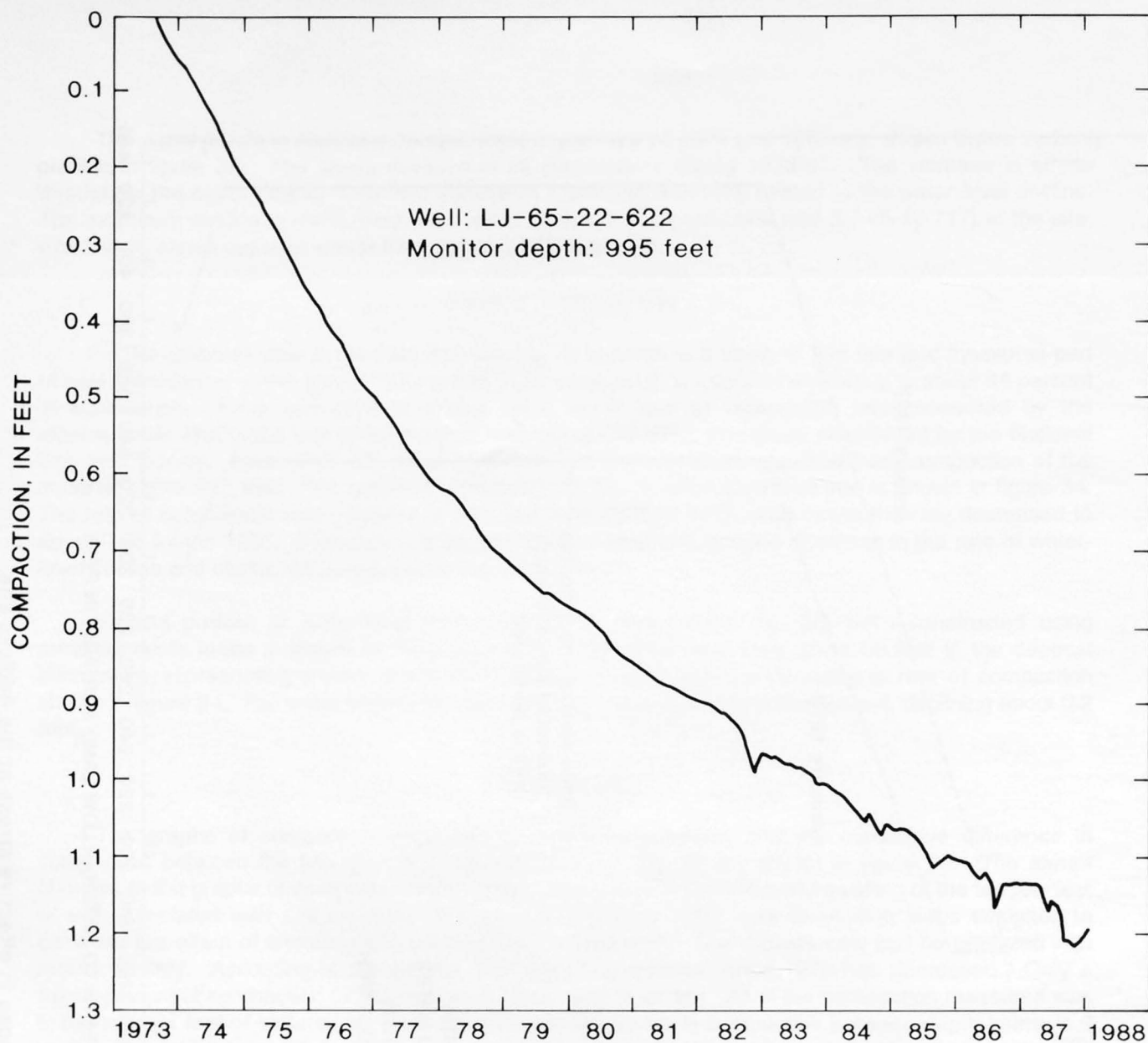


Figure 34.--Cumulative compaction at the Houston East End site.

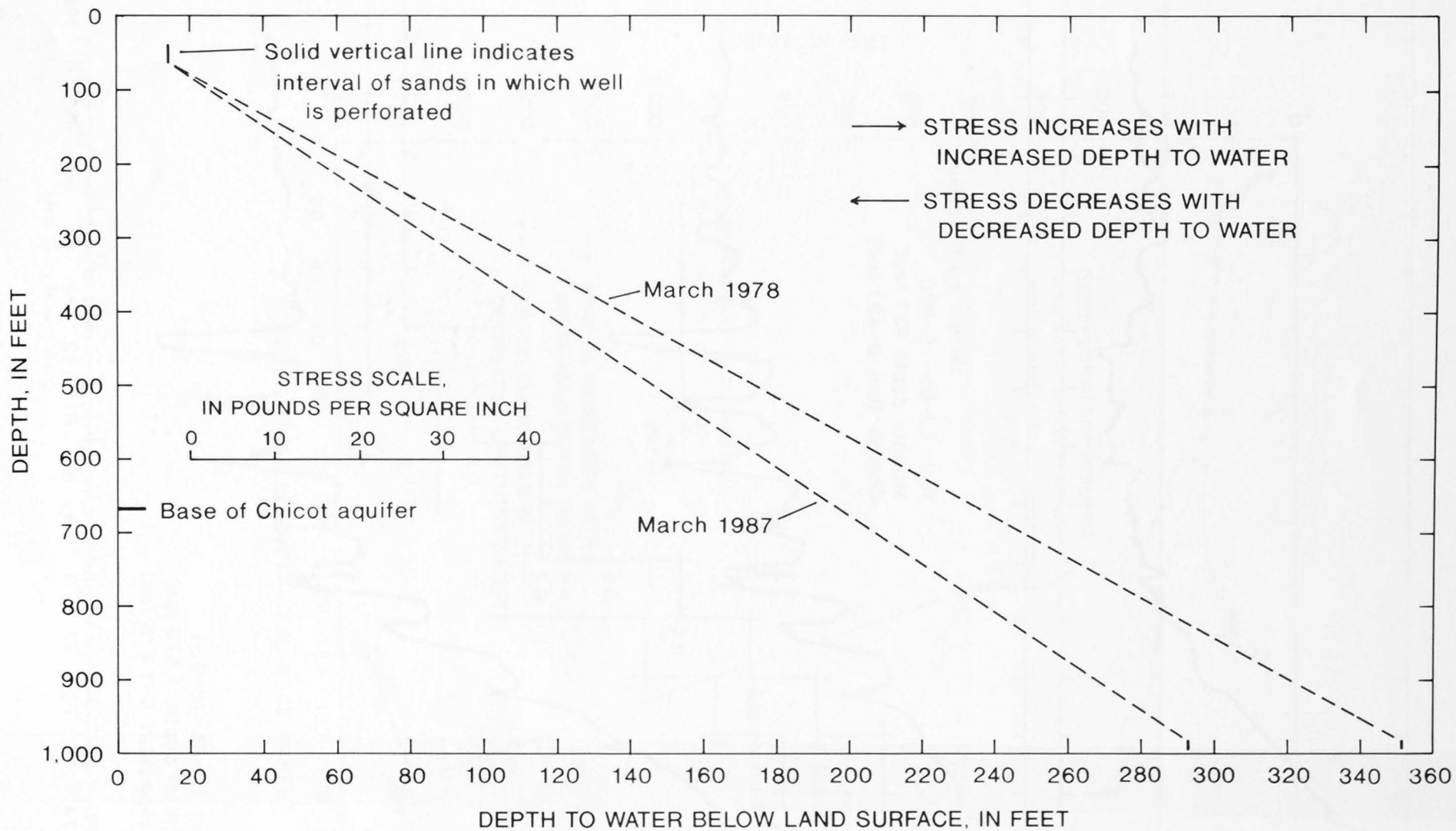


Figure 35.--Potentiometric profiles and changes in effective stress at the Houston East End site.

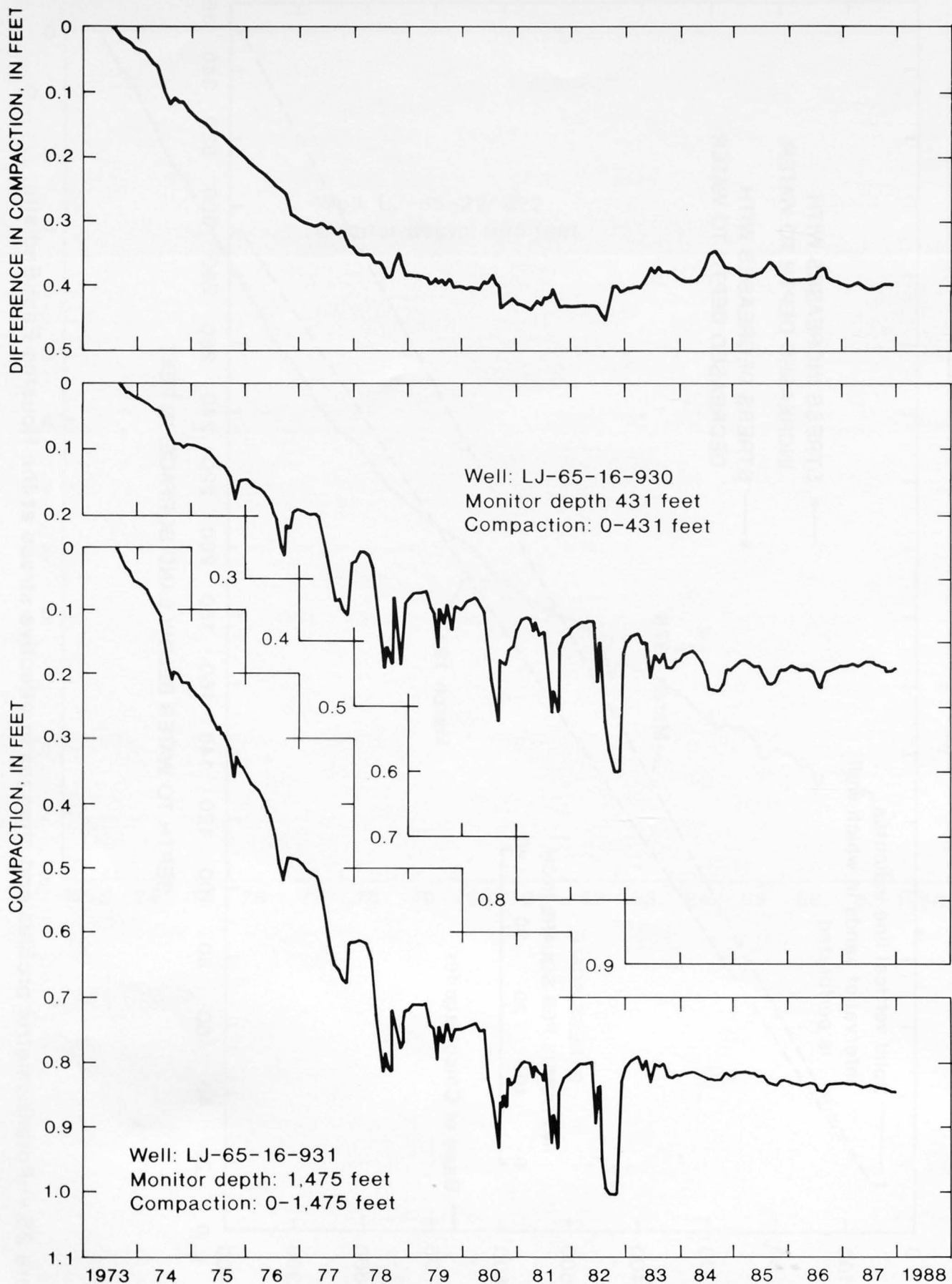


Figure 36.--Measured compaction and cumulative difference at the Baytown site.

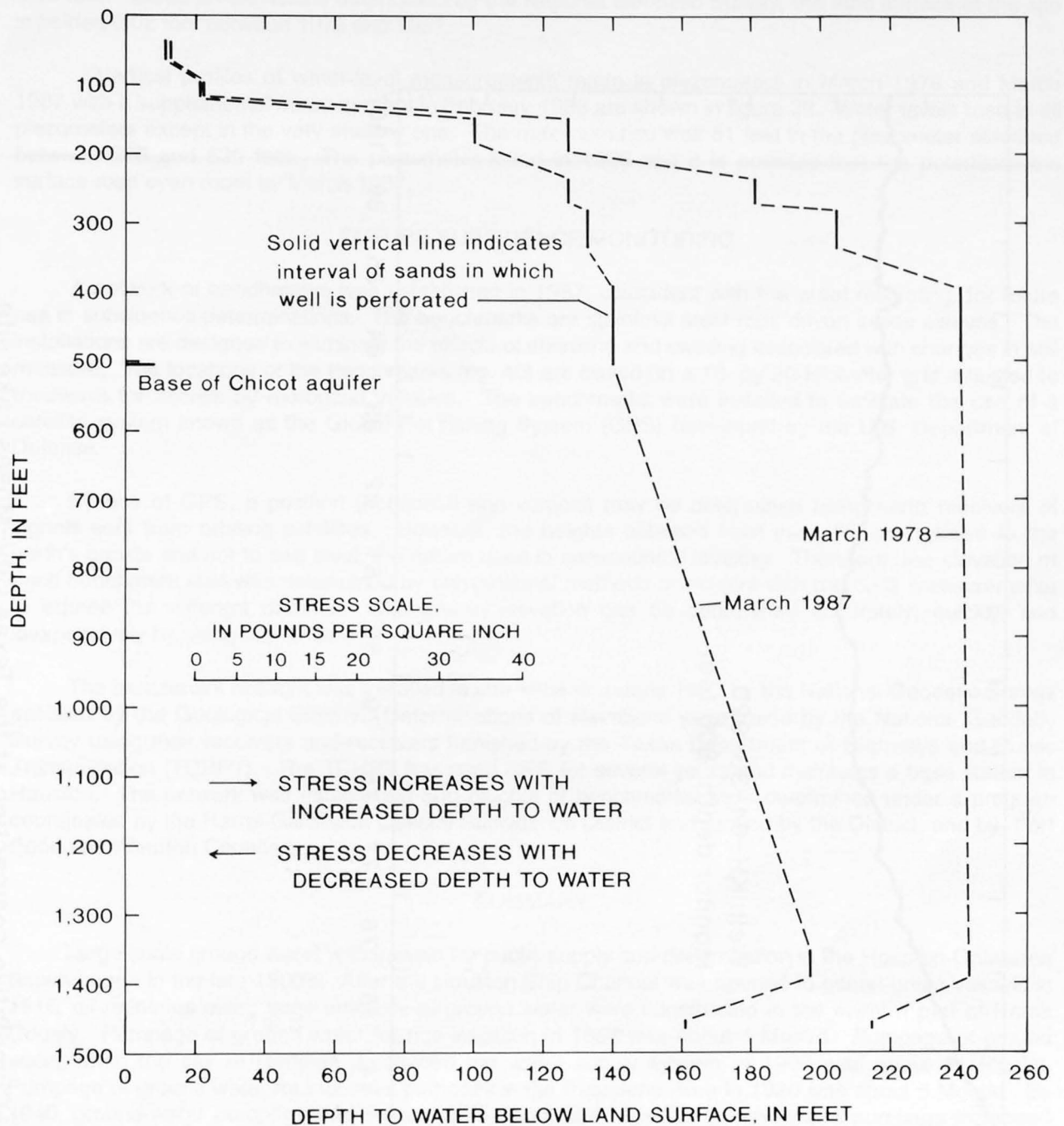


Figure 37.--Potentiometric profiles and changes in effective stress at the Baytown site.

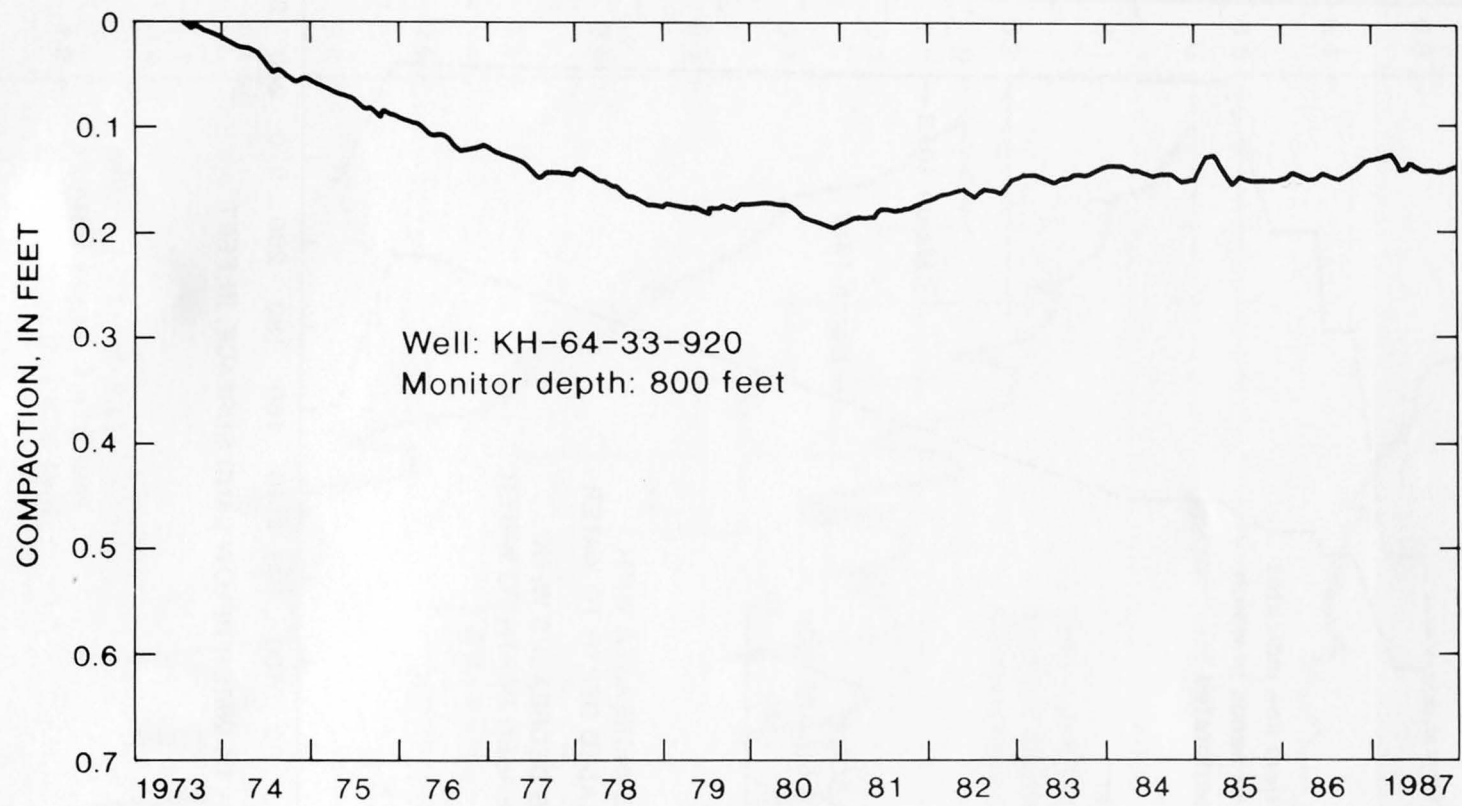


Figure 38.--Cumulative compaction at the Texas City-Moses Lake site.

0.06 foot. Based on elevations determined by the National Geodetic Survey, the land surface at the site subsided 0.02 foot between 1978 and 1987.

Vertical profiles of water-level measurements made in piezometers in March 1978 and March 1987 with a supplemental measurement in February 1986 are shown in figure 39. Water levels rose in all piezometers except in the very shallow one. The maximum rise was 51 feet in the piezometer screened between 525 and 535 feet. The piezometer failed in 1986 and it is possible that the potentiometric surface rose even more by March 1987.

FUTURE SUBSIDENCE MONITORING

A network of benchmarks was established in 1987, coincident with the areal releveled, for future use in subsidence determinations. The benchmarks are stainless steel rods driven inside sleeves. The installations are designed to eliminate the effects of shrinking and swelling associated with changes in soil moisture. The locations of the benchmarks (fig. 40) are based on a 10- by 20-kilometer grid adjusted to roadways for access by motorized vehicles. The benchmarks were installed to facilitate the use of a satellite system known as the Global Positioning System (GPS) developed by the U.S. Department of Defense.

By use of GPS, a position (horizontal and vertical) may be determined using earth receivers of signals sent from orbiting satellites. However, the heights obtained from the GPS are relative to the earth's geoids and not to sea level, the datum used in conventional leveling. Therefore, the elevation of each benchmark also was determined by conventional methods coincident with the GPS measurements to equate the different datums. Changes in elevation can be determined accurately, quickly, and inexpensively by using the GPS.

The benchmark network was installed in late 1986 and early 1987 by the National Geodetic Survey assisted by the Geological Survey. Determinations of elevations were made by the National Geodetic Survey using their receivers and receivers furnished by the Texas Department of Highways and Public Transportation (TDHPT). The TDHPT has used GPS for several years and maintains a base station in Houston. The network was established and heights of benchmarks were determined under a program coordinated by the Harris-Galveston Coastal Subsidence District and funded by the District, and by Fort Bend and Wharton Counties.

SUMMARY

Large-scale ground-water withdrawals for public supply and rice irrigation in the Houston-Galveston region began in the late 1800's. After the Houston Ship Channel was opened to ocean-going vessels in 1915, oil refineries using large amounts of ground water were constructed in the eastern part of Harris County. Pumpage of ground water for rice irrigation in 1887 was about 1 Mgal/d. Pumpage of ground water when the city of Houston purchased the water supply system in 1906 was about 11 Mgal/d. Pumpage of ground water for industrial purposes in the Pasadena Area in 1920 was about 5 Mgal/d. By 1940, ground-water pumpage had increased to about 154 Mgal/d. Ground-water pumpage increased rapidly in the 1940's because of the need by war industries located in the region.

The growing demand for water for increased population, rice irrigation, and industrial uses was met by increased pumpage from wells. In 1954, when water from Lake Houston became available, the city of Houston was the largest city in the United States using ground water exclusively for public supply. In 1954, ground-water pumpage in the region was 388 Mgal/d. Ground-water withdrawal remained comparatively stable from 1955 to 1962. Pumpage increased from 398 Mgal/d in 1962 to 507 Mgal/d in 1969, and remained relatively constant at 500 Mgal/d through 1982. Ground-water pumpage was 416 Mgal/d in 1987.

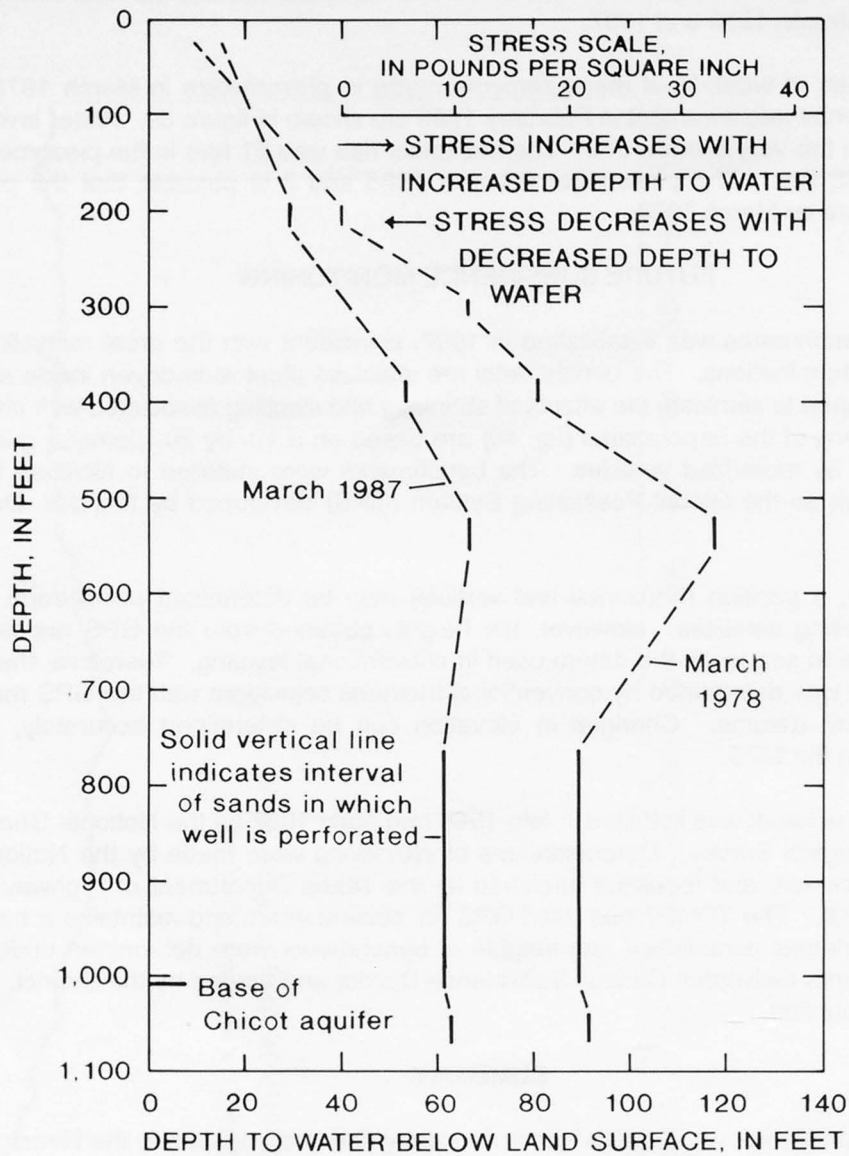


Figure 39.--Potentiometric profiles and changes in effective stress at the Texas City-Moses Lake site.

The rates of ground-water pumpage in the areas changed significantly after the importation of surface water from Lake Livingston began and the withdrawals shifted from the eastern to the western parts of the region. Ground-water pumpage decreased in the Houston Area from a historical high of 257 Mgal/d in 1980 to 206 Mgal/d in 1987. The city of Houston pumped 176 Mgal/d or 85 percent of the total in 1987. Pumpage in the Katy Area fluctuated widely between about 112 Mgal/d and 170 Mgal/d in 1970-87.

Ground-water use has changed from principally irrigation to public supply. Pumpage was about 119 Mgal/d in 1970 and about 138 Mgal/d in 1987. Ground-water use decreased from 1970 to 1987 in the Pasadena, Baytown-La Porte, Texas City, Alta Loma, and Johnson Space Center Areas, all located in the southeastern part of the region where subsidence has been critical. The largest decrease was in the Pasadena Area where ground-water withdrawal was about 121 Mgal/d in 1970 and about 37 Mgal/d in 1987.

Water levels in wells generally declined in the region until late 1976 when water from Lake Livingston was introduced. In 1977, the large cones of depression in water levels were centered in the Pasadena and Houston Areas. After 1977, the greatest water-level decline was in the western one-half of the region. Declines in water levels in wells in the Chicot aquifer generally exceeded 50 feet and were as much as 300 feet during 1943-87. Declines in water levels in wells in the Evangeline aquifer generally exceeded 50 feet and were as much as 450 feet during 1943-87. In the eastern part of the region, water levels rose during 1977-87 because of a large reduction in ground-water withdrawal following the introduction of water from Lake Livingston. Water-level rises in wells in the Chicot and Evangeline aquifers were more than 140 feet and 120 feet.

Conventional leveling at several times since 1906 has been used to determine subsidence of the land surface in the Houston-Galveston region. More recently, borehole extensometers have been used for measurement of compaction in select depth intervals at 11 locations; subsidence is being measured at six of those sites.

Maximum subsidence in the Houston-Galveston region during 1906-87 has been about 10 feet. The land surface has subsided more than 1 foot in about 3,640 mi² of the Houston-Galveston region. The bowl-shaped depression is centered in the Pasadena Area. However, the pattern of subsidence changed after 1978. The rate of subsidence decreased significantly in the southeastern part of the region where water levels in wells rose and continued the same or increased in the western part of the region where the water-level decline continued. However, subsidence did not stop until rises in water levels exceeded residual excess pore pressure. Subsidence in the Pasadena Area decreased from a rate of almost 0.3 ft/yr during 1973-78 to about 0.03 ft/yr during 1978-87. Maximum subsidence in the western part of the region increased from about 0.20 ft/yr during 1973-78 to about 0.22 ft/yr during 1978-87. Maximum subsidence during 1978-87 was about 2.0 feet.

Thirteen borehole extensometers at 11 sites are being used to monitor compaction in selected depth intervals in Harris and Galveston Counties. Extensometers at the Clear Lake, Pasadena, Addicks, Southwest, Northeast, and Lake Houston sites measure total man-caused subsidence. These extensometers yield continuous records of subsidence; conventional methods allow measurement of subsidence between times of releveling. Except for loss of elevation resulting from natural subsidence below the base of the extensometer, the top of the extensometer (the inner pipe) remains at a constant elevation. Therefore, the extensometers can be considered as stable benchmarks in the area of subsidence.

A network of benchmarks was established in 1986 and 1987 for determination of changes in elevation using a Global Positioning System (GPS). By use of the GPS, a position (horizontal and vertical) may be determined with earth receivers of signals sent from orbiting satellites. Thus, changes in elevation can be determined accurately, quickly, and inexpensively.

SELECTED REFERENCES

- Carr, J.E., Meyer, W.R., Sandeen, W.M., and McLane, I.R., 1985, Digital models for simulation of ground-water hydrology of the Chicot and Evangeline aquifers along the Gulf Coast of Texas: Texas Department of Water Resources Report 289, 101 p.
- Gabrysch, R.K., 1969, Land-surface subsidence in the Houston-Galveston region, Texas: Tokyo, Japan, 1969, Proceedings, International Symposium on Land Subsidence, Publication no. 88, AIHS, p. 43-54.
- 1980, Development of ground water in the Houston district, Texas, 1970-74: Texas Department of Water Resources Report 241, 49 p.
- 1984, Ground-water withdrawals and land-surface subsidence in the Houston-Galveston region, Texas, 1906-80: Texas Department of Water Resources Report, 287, 64 p.
- Gabrysch, R.K., and Bonnet, C.W., 1974, Land-surface subsidence in the area of Burnett, Scott, and Crystal Bays near Baytown, Texas: U.S. Geological Survey Water-Resources Investigations Report 21-74, 48 p.
- 1975, Land-surface subsidence in the Houston-Galveston region, Texas: Texas Water Development Board Report 188, 19 p.
- 1976a, Land-surface subsidence at Seabrook, Texas: U.S. Geological Survey Water-Resources Investigations Report/NTIS 76-31, 53 p.
- 1976b, Land-surface subsidence in the area of Moses Lake near Texas City, Texas: U.S. Geological Survey Water-Resources Investigations Report 76-32, 42 p.
- Jorgensen, D.G., 1975, Analog-model studies of ground-water hydrology in the Houston district, Texas: Texas Water Development Board Report 190, 84 p.
- Lang, J.W., and Winslow, A.G., 1950, Geology and ground-water resources of the Houston district, Texas: Texas State Board of Water Engineers Bulletin 5001, 55 p.
- Meyer, W.R., and Carr, J.E., 1979, A digital model for simulation of ground-water hydrology in the Houston Area, Texas: Texas Department of Water Resources LP-103, 27 p.
- Williams, J.F. III, and Ranzau, C.E., Jr., 1987, Ground-water withdrawals and changes in ground-water levels, ground-water quality, and land-surface subsidence in the Houston district, Texas, 1980-84: U.S. Geological Survey Water-Resources Investigations Report 87-4153, 56 p.
- Winslow, A.G., and Doyel, W.W., 1954, Land-surface subsidence and its relation to the withdrawal of ground water in the Houston-Galveston region, Texas: *Economic Geology*, v. 49, no. 4, p. 413-422.
- Winslow, A.G., and Wood, L.A., 1959, Relation of land subsidence to ground-water withdrawals in the upper Gulf Coast region, Texas: *Mining Engineering*, v. 11, no. 10, p. 1030-1034.
- Wood, L.A., and Gabrysch, R.K., 1965, Analog model study of ground water in the Houston district, Texas: Texas Water Commission Bulletin 6508, 103 p.

USGS LIBRARY - RESTON



3 1818 00099324 4