Case History No. 9.12. The Houston-Galveston Region, Texas, U.S.A., by R. K. Gabrysch, U.S. Geological Survey, Houston, Texas

9.12.1 INTRODUCTION

The Houston-Galveston region of Texas, as described in this report, includes all of Harris and Galveston Counties and parts of Brazoria, Fort Bend, Waller, Montgomery, Liberty, and Chambers Counties (Figure 9.12.1). Land-surface subsidence has become critical in parts of the region because some low-lying areas along Galveston Bay are subject to inundation by normal tides, and an even larger part of the region may be subject to catastrophic flooding by hurricane tides. Hurricanes resulting in tides of 3.0-4.6 metres above sea level strike the Texas coast on the average of once every 10 years.

Land-surface subsidence due to fluid withdrawals was first documented in the Goose Creek oil field in Harris County (Pratt and Johnson, 1926). Since then, numerous reports on subsidence in the Houston-Galveston region have attributed subsidence to the compaction of fine-grained material associated with the oil- and water-bearing sands. The more recent reports (Winslow and Doyel, 1954; Winslow and Wood, 1959; Gabrysch, 1969; and Gabrysch and Bonnet, 1975a) present data and interpretations of regional subsidence and its relation to the withdrawals of ground water for municipal supply, industrial use, and irrigation. The authors of these reports recognized that subsidence due to the removal of oil and gas has occurred in the region, but the data are not sufficient to describe in detail the localized areas of occurrence.

9.12.2 GEOLOGY AND HYDROLOGY OF THE HOUSTON-GALVESTON REGION

The aquifers in the Houston-Galveston region are composed of sand and clay beds that are not persistent in either lithology or thickness. The beds grade into each other both laterally and vertically within short distances; consequently, differentiation of geological formations on drillers' logs and electrical logs is almost impossible. However, by use of both the logs and the hydraulic properties of the aquifers, the subsurface units have been divided into three major aquifer systems and one confining system (Jorgensen, 1975).

The age of the geological formations composing the aquifers and the confining layer ranges from Miocene to Holocene. The deepest aquifer containing freshwater is the Jasper aquifer of Miocene age, which is separated from the overlying Evangeline and Chicot aquifers by the Burkeville confining layer. The two principal aquifer systems of the region are the Chicot aquifer of Pleistocene age and the Evangeline aquifer of Pliocene age. The Burkeville confining layer is probably part of the Fleming Formation of Miocene age.

The aquifers are under artesian conditions throughout most of the region, but little information on the hydraulic properties of the Jasper aquifer is available because it is undeveloped. Reports of test holes in the Jasper (W. F. Guyton, oral commun., 1977) indicate that the hydraulic head in the Jasper is above land surface, which probably approximates the original conditions. It is assumed that with no change in head, compaction of the deposits in the Jasper system has not occurred; therefore, the discussion of subsidence in this report will be restricted to a discussion of the Evangeline and Chicot aquifer systems.

The Evangeline aquifer system is composed of the Goliad Sand and possibly the upper part of the Fleming Formation. The system contains sands that yield freshwater of good quality in about the inland two-thirds of the region. The transmissivity of the aquifer system ranges from less than 460m^2/d to about 1,400 m^{2}d. The horizontal hydraulic conductivity is about 4.57 metres per day, and the storage coefficient ranges from about 0.00005 to more than 0.001.

The Chicot aquifer system is composed of the Willis Sand, Bentley Formation, Montgomery Formation, Beaumont Clay, and the Quaternary alluvium and includes the deposits from the land surface to the top of the Evangeline aquifer. The transmissivity of the Chicot aquifer ranges from 0 to about 1,858 m^2/d. The horizontal hydraulic conductivity is about twice that of the Evangeline aquifer, and the storage coefficient ranges from 0.00004 to 0.20. The larger values

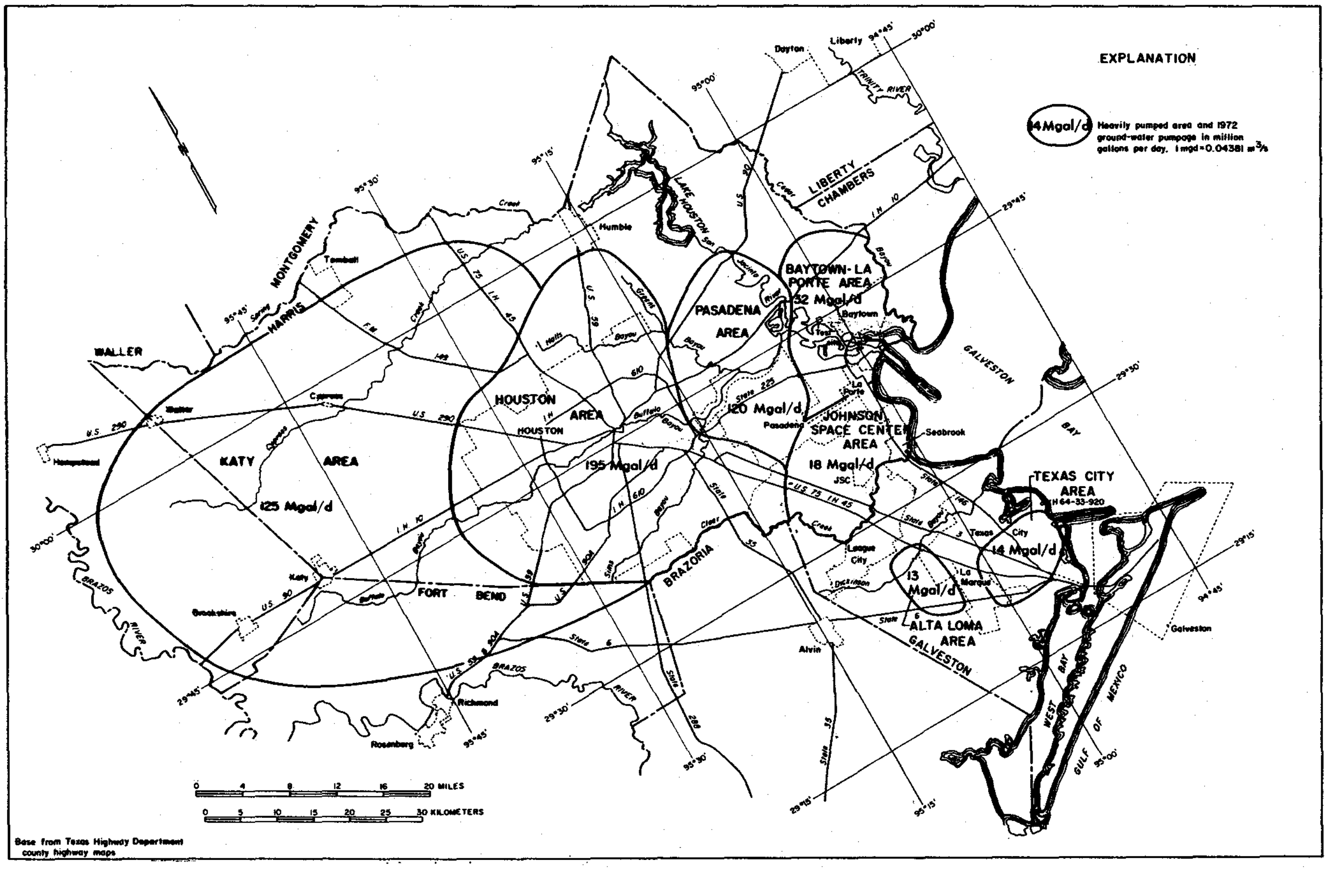

Figure 9.12.1 Locations of principal areas of ground-water withdrawals and average rates of pumping in 1972.

of the storage coefficient occur in the northern part of the region where the aquifer crops out and is partly under water-table conditions.

Both the Evangeline and the Chicot aquifer systems contain many layers of clay interbedded with the water-bearing sands. The clay beds are generally less than 6 metres thick, but locally they retard the vertical movement of water. Every sand bed, therefore, has a different hydraulic head. Data from cores of the clay beds were obtained at six sites for evaluation of subsidence in the Houston-Galveston region. The mineral composition of 27 samples from 5 sites were also determined (Gabrysch and Bonnet, 1975b and unpublished data). Montmorillonite is the principal mineral constituent of the clay beds, which also contain smaller amounts of illite, chlorite, and kaolinite.

9.12.3 DEVELOPMENT OF GROUND WATER

Development of ground water in the Houston-Galveston region for municipal supply and irrigation began in the 1890's. Ground-water withdrawals increased gradually to about 4.4 M^3/s (cubic metres per second) with population growth, increased irrigation, and industrial use until the late 1930's. Construction of the large industrial complex in the region began in 1937, and by 1954 ground-water pumping had increased to about 18 m^3/s.

Ground-water pumping decreased to about 14 m^3/s by 1959 because of the introduction of a supply of surface water in 1954 from nearby Lake Houston on the San Jacinto River. By 1962, ground-water pumping was again at a rate of about 18 m^3/s.

Pumping of ground water for municipal supply, industrial use, and irrigation was approximately 46 per cent, 33 per cent, and 21 per cent, respectively, of the total of 23 m^3/s pumped in 1972. The principal areas of pumping and the average daily rates of pumping in 1972 in each area are shown on Figure 9.12.1. Pumping in 1975 for all uses was 22 m^3/s.

The pumping of larger amounts of ground water has resulted in water-level declines during 1943-73 of as much as 61 metres in wells completed in the Chicot aquifer and as much as 99 metres in wells completed in the Evangeline aquifer (Figures 9.12.2 and 9.12.3). The maximum average annual rate of water-level decline for 1943-73 was 2.0 metres in the Chicot aquifer and 3.3 metres in the Evangeline aquifer. During 1964-73, the maximum rate of decline was 3.0 metres in the Chicot and 5.4 metres in the Evangeline.

9.12.4 SUBSIDENCE OF THE LAND SURFACE

The area of the greatest amount of subsidence coincides with the area of the greatest amount of artesian-pressure decline, which is east-southeast of Houston at Pasadena. Figure 9.12.4 shows that as much as 2.3 metres of subsidence occurred at Pasadena between 1943 and 1973. It should be noted, however, that within the entire region of subsidence, more than one center occurs. These areas are indicated by the closed contours on Figure 9.12.4.

Some of the centers of subsidence may be associated with the pumping of oil and gas and some may be associated with the pumping of ground water. Additional complications in analyzing the causes and areal distribution of subsidence result from the varying thicknesses of individual beds of fine-grained material, the varying total thickness of fine-grained material, the vertical distribution of changes in artesian head, and the relation of compressibility to depth of burial. An example of the effects of compressibility and depth of burial occurs in the southern part of Harris County where about 55 per cent of the subsidence is due to compaction in the Chicot aquifer, which composes only the upper one-fourth of the estimated compacting interval.

Figure 9.12.5 shows subsidence for 1964-73. The maximum amount of subsidence during this period was about 1.1 metres. The indicated maximum average rate for the 9-year period is about 0.12 metre per year as compared to the maximum average rate of 0.08 metre per year for the 30 year period 1943-73. During the last part of the 1943-73 period, the rate of subsidence accelerated, and the area of subsidence increased. The area in which subsidence is 0.3 metre or more increased from about 906 square kilometres in 1954 to about 6,475 square kilometres in 1973.

The maps showing the amounts of subsidence (Figures 9.12.4 through 9.12-6) were constructed from data obtained from the leveling program of the National Geodetic Survey (formerly the U.S. Coast and Geodetic Survey) supplemented by data obtained from local industries. Some subsidence occurred before 1943, but the amount is difficult to determine. However, an approximation of the amount and extent of the subsidence that occurred between 1906 and 1943 is shown on Figure 9.12.6. By 1943, four centers of subsidence were apparent. The centers at Pasadena, Baytown, and Texas City were the result of ground-water pumping; and the center in the Goose Creek oil field resulted from the production of oil, gas, and saltwater.

Because of the nature of deposition of the aquifer systems, each sand bed has a different hydraulic head, and each clay layer is under a different amount of stress. The water-level declines shown by Figures 9.12.2 and 9.12.3 are the maximum declines that have occurred in each of the aquifers. Water-level measurements indicate that the water table is approximately at its original position (about 2 to 6 metres below land surface). Piezometers installed at different depths at each of eight sites are used to define the potentiometric profiles. The differences between the measurements in the piezometers and the original potentiometric surfaces define the stress profile. As an example, at a site in the Pasadena area, the depths to water below land surface in January 1978 were as follows:

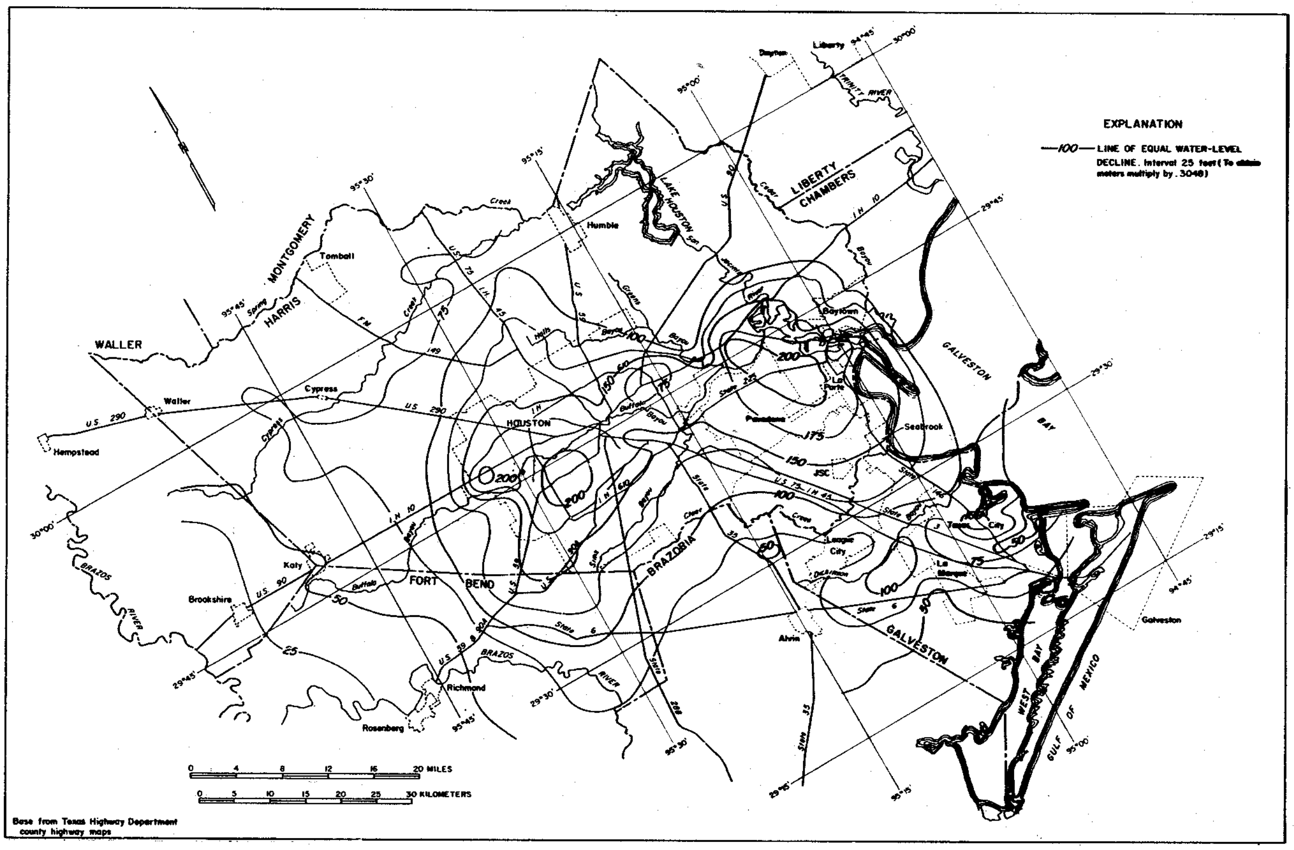

Figure 9.12.2 Approximate declines of water levels in wells completed in the Chicot aquifer, 1943-73.

Piezometer depth (metres)	Depth to water (metres)
10	1.85
30	4.31
119	45.21
221	100.31
284	102.74
403	100.44
552	93.20
828	47.28

The potentiometric surface in each of the two aquifer systems was 15 to 30 metres above land surface before large withdrawals began.

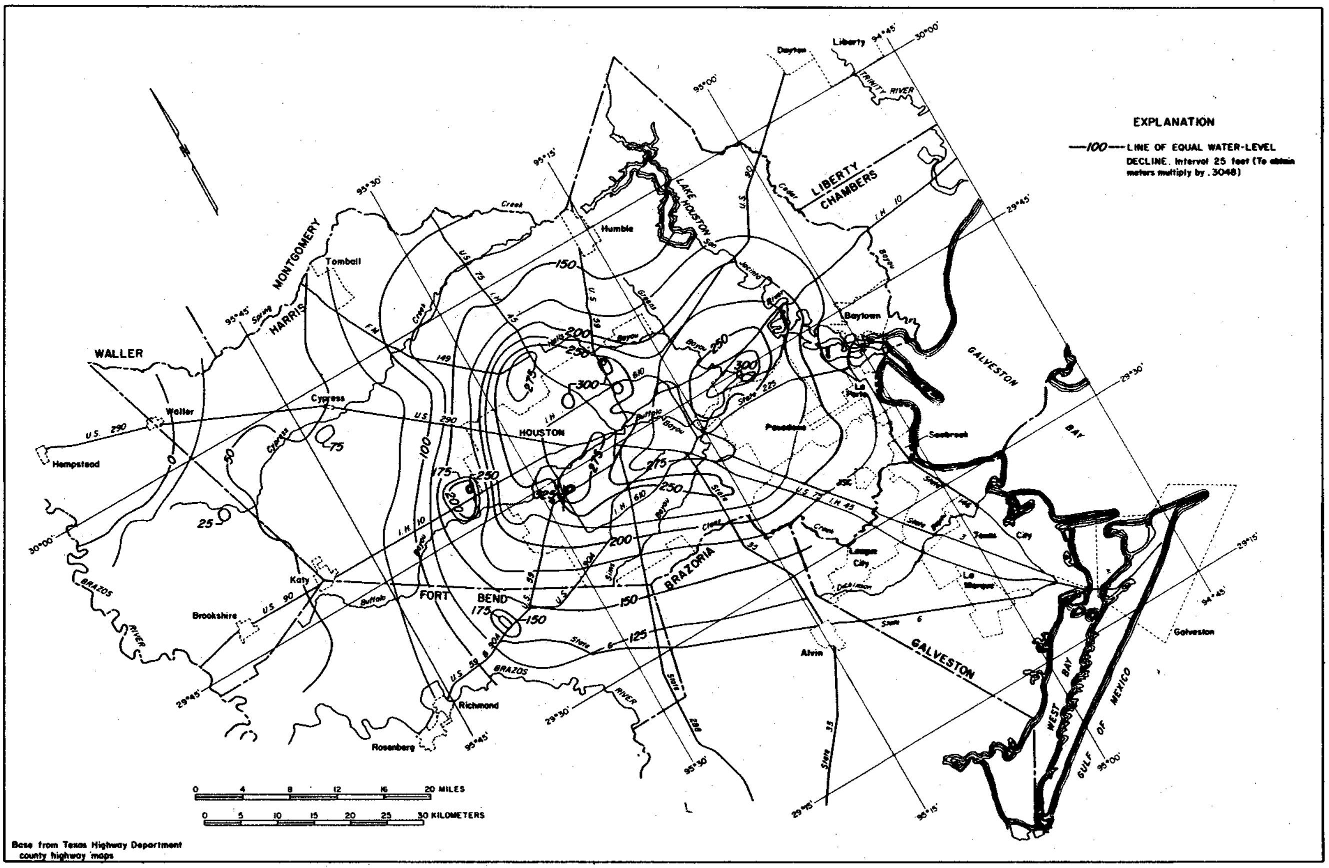

Figure 9.12.3 Approximate declines of water levels in wells completed in the Evangeline aquifer, 1943-73.

The compressibility of the aquifer system has been estimated at two locations. At Seabrook, it is assumed that no compaction due to ground-water pumping occurred below a depth of about 610 metres. Above 610 metres, the sediments include about 243.5 metres of fine-grained material, and the average stress applied to the system during 1943-73 was estimated to be a change in head of 38.6 metres of water. Subsidence during 1943-73 was 0.91 metre; therefore, the compressibility of the fine-grained materials was determined to be

$$0.91 \text{ m}/(243.5 \text{ m})\ (38.6) = 9.7 \times 10^{-5}\text{m}^{-1}.$$

At Texas City, it is assumed that no compaction due to ground-water pumping occurred below a depth of 506 metres. Above 506 metres, the sediments include about 151.5 metres of fine-

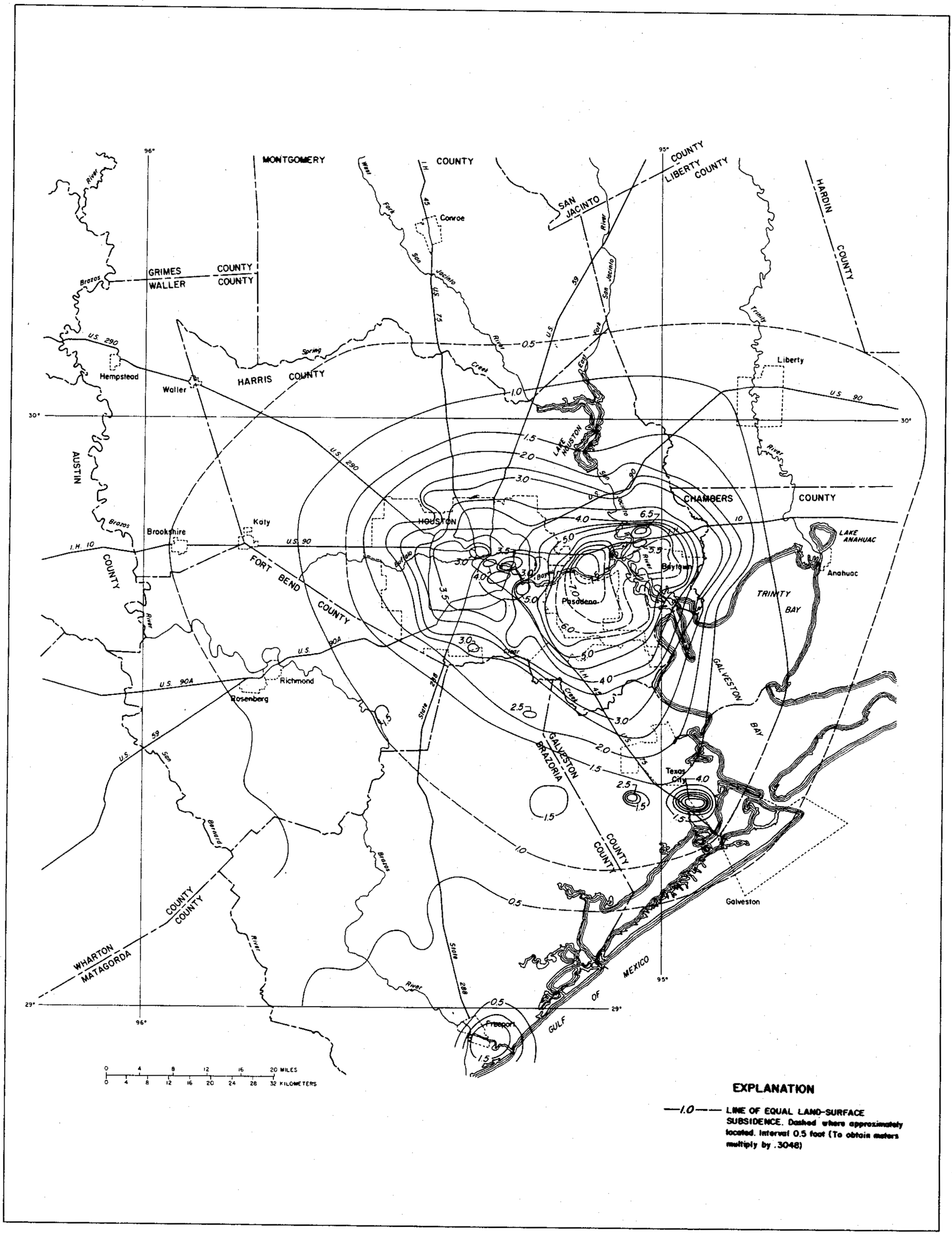

Figure 9.12.4 Subsidence of the land surface, 1943-73.

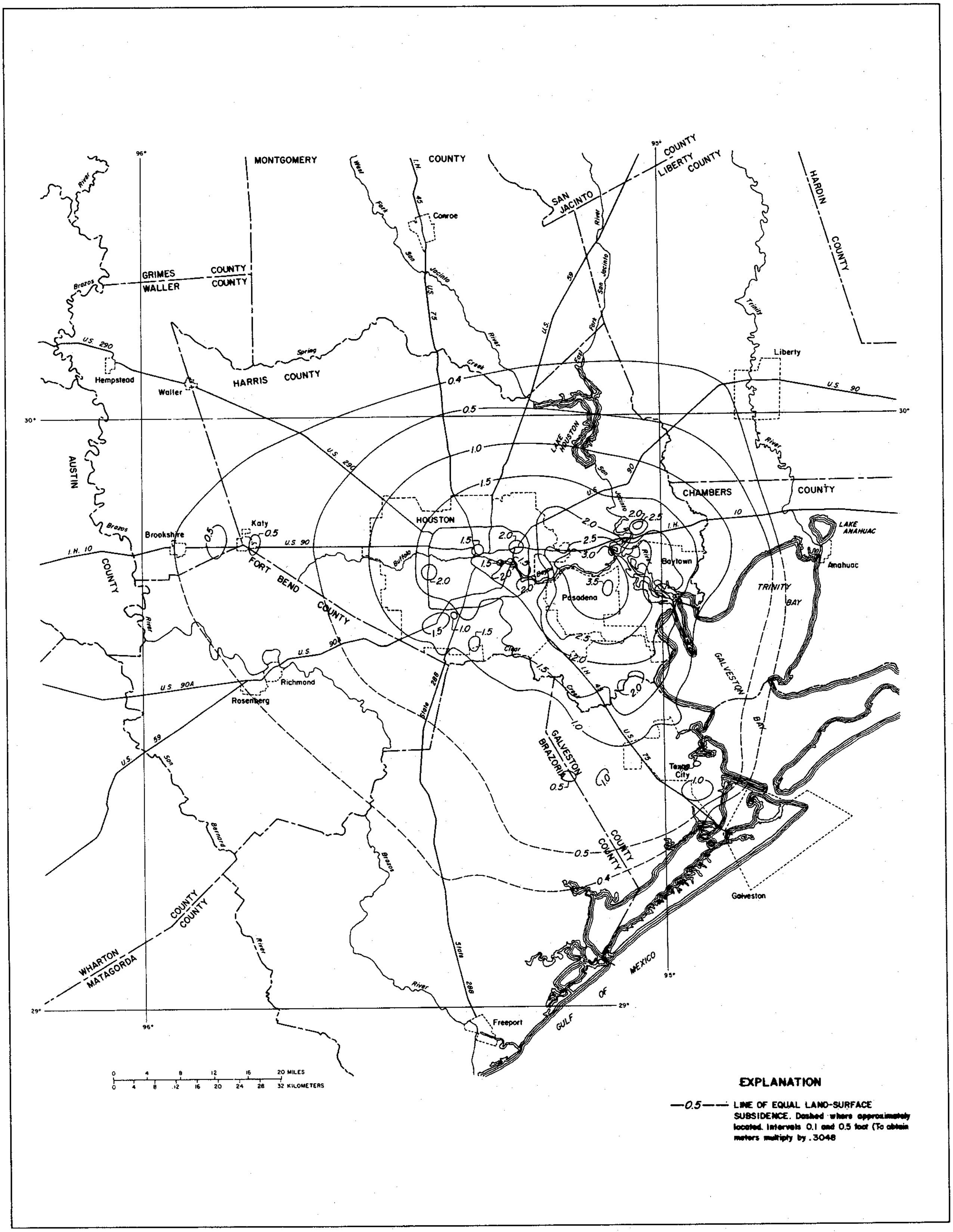

Figure 9.12.5 Subsidence of the land surface, 1964-73.

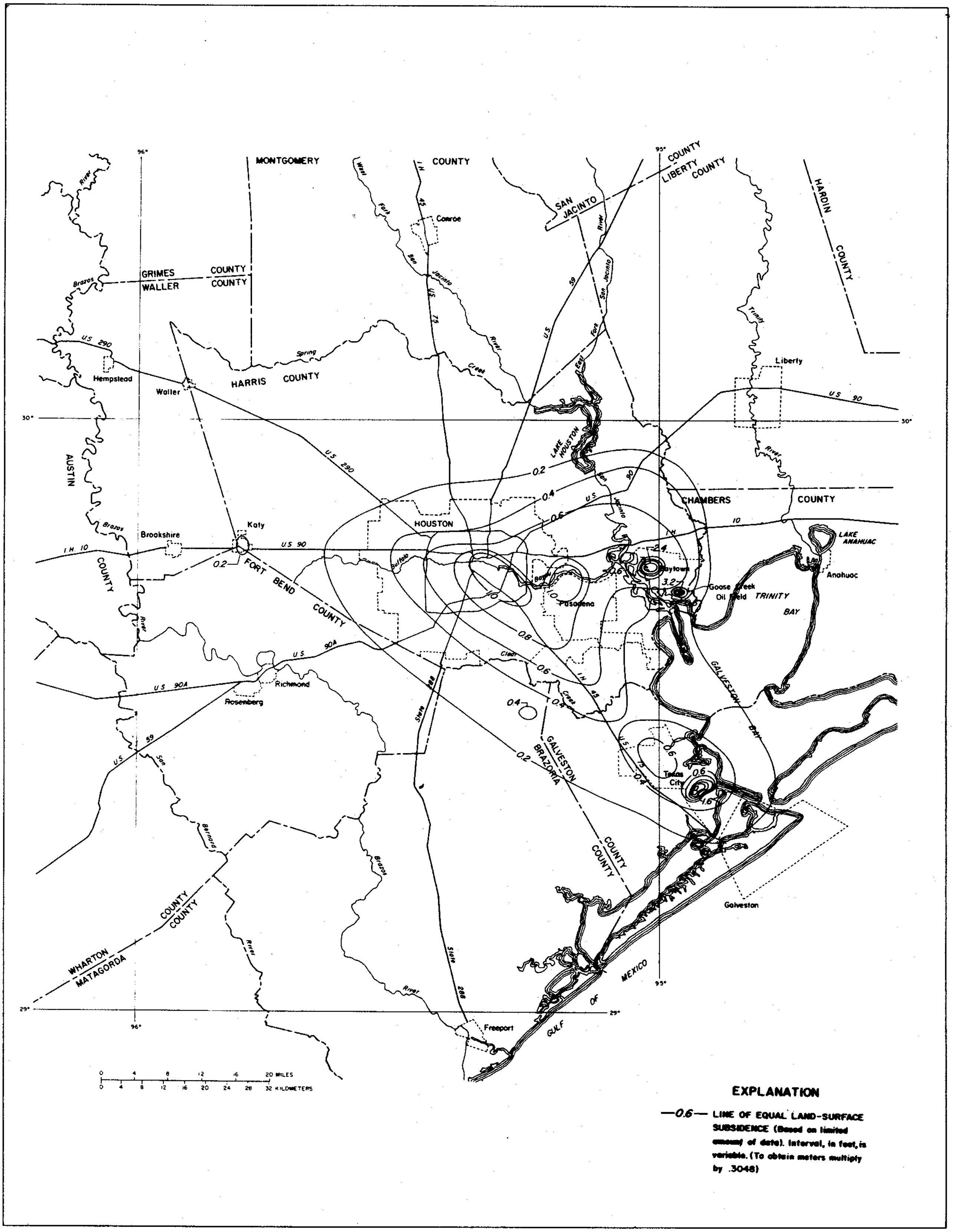

Figure 9.12.6 Approximate subsidence of the land surface, 1906-43.

grained material, and the average stress applied to the system during 1964-73 was estimated to be a change in head of 5.7 metres of water. Subsidence during 1964-73 was 0.18 metre; therefore, the compressibility of the fine-grained material was determined to be:

$$0.18/(151.5 \text{ m}) (5.7 \text{ m}) = 2.1 \times 10^{-4} \text{m}^{-1}.$$

The weighted average compressibility as determined by laboratory consolidation tests of 15 cores from three sites was 3.2 x 10^{-4}m^{-1}. Because the sediments were still undergoing compression, the compressibilities determined at the Seabrook and Texas City sites are minimum estimates of specific storage.

It has been suggested by some investigators that, in addition to inundation of land by tidal waters, some if not all of the numerous existing faults in the Houston-Galveston region are reactivated by man-caused land-surface subsidence. Attempts have been made to relate the fault activity to subsidence, but because of a lack of data the relationships are not clear.

In 1977, a network of measurement stations, about 0.6 kilometre apart, were established along a line about 70 kilometres long from the approximate center of subsidence westward along U.S. Highway 90 to the Harris County boundary. In addition, closely spaced marks for horizontal and vertical control will be established at three active faults. The purpose of this network is to measure horizontal strain associated with subsidence and to relate this strain to movement along the fault planes.

It has also been hypothesized (Kreitler, 1977) that the numerous faults act as partial barriers to ground-water flow and therefore control or "compartmentalize" subsidence; however, the data on artesian-pressure fluctuations in the area do not support this hypothesis.

Most of the damage resulting from subsidence is related to the lowering of land-surface elevations in the vicinity of Galveston Bay and the subsequent inundation by tidal waters. Several roadways have been rebuilt at higher elevations; ferry landings have been rebuilt; and levees have been constructed to reclaim or protect some areas. The cost of the damages resulting from subsidence have been estimated in some areas, but comprehensive studies for the entire region have not been made. Jones and Larson (1975, table 5) estimated the annual cost of subsidence during 1969-74 to be $31,705,040 in 2,448 square kilometres of the area most severely affected by subsidence. In their estimate of costs, Jones and Larson attributed fault-caused structural damage to man-caused subsidence.

One outstanding example of both the social and economic impacts of subsidence is in the Brownwood subdivision on the west side of Baytown. The area of the subdivision has subsided more than 2.4 metres since 1915, and some homes in the subdivision are permanently flooded by water from the bay. The U.S. Army Corps of Engineers has recommended that the entire subdivision, consisting of 448 homes occupied by 1,550 residents, be purchased by the Federal Government and the inhabitants be relocated at a cost of about $40 million.

9.12.5 FUTURE SUBSIDENCE IN THE REGION

Ground-water pumping in the Houston-Galveston region increased at a rate of about 6 per cent per year before about 1967. Since then, ground-water pumping has been at an almost stable rate, possibly because of recirculation of cooling water by industry and increased use of surface water from Lake Houston. As a result, the rate of decline in water levels has decreased significantly in many parts of the region since the early 1970’s. Records from borehole extensometers (compaction monitors) indicate a decreased rate of subsidence at seven sites scattered throughout the region. The decrease in the rate of subsidence, which began about September 1976, strongly suggests a reflection of the decreased rate of water-level decline.

Water from a new source, Lake Livingston on the Trinity River, about 97 kilometres east of Houston has become available recently; and voluntary commitments to purchase this water have been made by all major industries using ground water in the southern half of Harris County. As a result, ground-water pumping will decrease by about 3.1 m^3/s in the area of maximum artesian-pressure decline and subsidence. An analog-model study of the effects of the decreased pumping suggests a maximum water-level recovery of about 30 metres in the center of the bowl of subsidence. Data are not sufficient to determine the head recovery necessary to stop subsidence, but the rate of subsidence is expected to decrease substantially. By June 1977, the increased use of surface water had caused a decrease in ground-water pumping of about 0.8 m^3/s. Locally, the recovery in artesian head has been as much as 18 metres.

The Harris-Galveston Coastal Subsidence District was created by the Texas Legislature in 1975 to "provide for the regulation of the withdrawal of ground water within the boundaries of the District for the purpose of ending subsidence which contributes to or precipitates flooding, inundation, or overflow of any area within the District, including without limitation rising waters resulting from storms or hurricanes." The District plans to monitor the stress-strain relationships with additional compaction monitors and piezometers designed for installation prior to the expected voluntary decrease in ground-water pumping. The data collected will be the basis for controlling pumping by the issuance of well permits.

The constitutionality of the subsidence district has been tested in a Texas District Court in a suit titled Sammy Beckendorf, et al., versus the Harris-Galveston Coastal Subsidence District. The District prevailed, but Beckendorf, et al., have appealed the ruling of the court. Other lawsuits against the District have been filed but have not come to trial. Two other lawsuits (Smith-Southwest Industries, et al., versus Friendswood Development Company, et al.; and E. R. Brown, et al., versus Exxon Company, U.S.A., et al.), whereby the plaintiffs seek to establish blame and recover damages from subsidence, have not come to trial.

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