

Introduction

Land-surface subsidence, or land subsidence, in Harris County, Texas, which encompasses much of the Houston area (fig. 1), has been occurring for decades. Land subsidence has increased the frequency and extent of flooding, damaged buildings and transportation infrastructure, and caused adverse environmental effects. The primary cause of land subsidence in the Houston area is withdrawal of groundwater, although extraction of oil and gas also has contributed (Pratt and Johnson, 1926). Throughout most of the 20th century, groundwater was the primary source of municipal, agricultural, and industrial water supply for Harris County. Currently (2009) a transition to surface water as the primary source of supply, guided by a groundwater regulatory plan developed by the Harris-Galveston Subsidence District (HGSD) (2001), is in effect. The aquifers in Harris County contain an abundant amount of potable groundwater, but they also contain layers of clay. Groundwater withdrawals caused compaction of the clay layers, which in turn resulted in the widespread, substantial land-surface subsidence that has occurred in the Houston area.

The U.S. Geological Survey (USGS), in cooperation with the HGSD, prepared a map to show the estimated (approximate amount and extent of) land subsidence that has occurred in Harris County since the early 1900s. This report presents the map, which documents subsidence in Harris County from 1915-17 to 2001, briefly describes the regional hydrogeology and the mechanisms of subsidence, and describes data and methods used to construct the map. The map was constructed using geographic information system (GIS) techniques that involved subtraction of 1915-17 land-surface (topographic map) elevations from 2001 land-surface elevations derived from Light Detection and Ranging (LIDAR) data. For comparison, contours of measured subsidence from 1906 to 2000 (Gabrysch and Neighbors, 2005, fig. 6) are overlain on the map. Subsidence as indicated on the map also is compared to cumulative clay compaction at sites of 12 extensometers in the county maintained by the USGS in cooperation with the HGSD. Although substantial subsidence also has occurred in adjacent counties, particularly Galveston County, this report is restricted to Harris County because the 2001 land-surface dataset contained data only for Harris County. The amount of subsidence shown at any specific location is considered a regional-scale estimate and is not intended for use in engineering or other design applications.

The authors thank the Texas Parks and Wildlife Department for providing 7.5-minute topographic quadrangle maps for 1915-17 in GIS digital format and the Tropical Storm Allison Recovery Project for providing the 2001 land-surface elevation data in GIS digital format.

Hydrogeology

The Chicot aquifer, Evangeline aquifer, and Jasper aquifer are the primary aquifers in the Gulf Coast aquifer system that underlies Harris County (fig. 2). Most of the groundwater withdrawn in Harris County is from the Evangeline aquifer. The Evangeline and other aquifers comprise laterally discontinuous deposits (layers) of gravel, sand, silt, and clay that dip and thicken from northwest to southeast. The aquifers thus crop out in bands inland from and approximately parallel to the coast and become progressively more deeply buried and confined toward the coast. Most recharge of water to the aquifers is through the outcrops of the aquifers. The Chicot aquifer outcrop consists of the youngest sediments and outcrops at the coast, followed farther inland by the Evangeline aquifer outcrop, and then farthest inland by the Jasper aquifer outcrop. In the natural flow system, water is recharged in the unconfined outcrop areas, moves downward through the aquifer toward the coast, and discharges as diffuse upward leakage in the confined down-dip areas (Kasmarek and Robinson, 2004).

Historical Groundwater Withdrawals and Land-Surface Subsidence

In the 1940s, groundwater withdrawals in the Houston area began to increase steadily, and in the 1950s, the steady increase became a sharp increase that continued, although at a lesser rate, through the 1960s and into the early 1970s (fig. 3). In the 1950s and 1960s, the severity and frequency of flooding in low-lying areas also increased. As scientists determined that subsidence was related to groundwater withdrawals, community leaders realized that the increased frequency and severity of flooding was because of subsidence (Harris-Galveston Subsidence District, 2009).

Although the use of surface water for municipal supply to offset the need for groundwater began as early as the 1950s, surface-water use was small relative to groundwater use, and groundwater withdrawals remained unregulated until the 1970s. In 1975, the HGSD was created by the Texas Legislature "to provide for the regulation of groundwater withdrawal throughout Harris and Galveston Counties for the purpose of preventing land subsidence, which leads to increased flooding" (Harris-Galveston Subsidence District, 2009).

After 1975, the HGSD directed a transition from groundwater to surface water and efforts to conserve water that reversed the long-term trend in groundwater withdrawals in Harris County despite continued population increases (fig. 3). By 2001, groundwater withdrawals in Harris County had decreased to about 290 million gallons per day, a 29-percent reduction from the peak withdrawal rate of 410 million gallons per day in 1976. The groundwater regulatory plan of the HGSD mandates that groundwater withdrawal account for a maximum of 20 percent of the water supply in Harris and Galveston Counties by 2030 (Harris-Galveston Subsidence District, 2001).

Subsidence trends in Harris County reflect the pattern of groundwater withdrawals. Before the 1940s, subsidence was localized and associated with oil and gas extraction primarily in the Baytown area. By the early 1940s, groundwater withdrawals for industrial and municipal use had caused measurable subsidence centered in the area of the Houston Ship Channel (Baytown-Pasadena area). By the mid-1970s, 6 feet or more of subsidence had occurred in the Baytown-Pasadena area, and by 1979 almost 3,200 square miles of the greater Houston area (in Harris County and adjacent counties) had subsided more than 1 foot (Copolin and Galloway, 1999, p. 40). Since the early 1990s, subsidence in the Baytown-Pasadena area as indicated by measured compaction data (Kasmarek and others, 2009, fig. 16) has essentially ceased because of major reductions in groundwater withdrawals in the area; but in the western Houston area (Addicks), subsidence as indicated by measured compaction data from the 1970s through 2001 was about 0.12 foot per year because of continued groundwater withdrawals in the area.

Mechanisms of Land-Surface Subsidence

The weight of aquifer material (overburden) overlying stored groundwater is supported by a combination of hydraulic pressure exerted by the water and pressure exerted by the sediment material, or "skeletal matrix," of an aquifer. When water is withdrawn, water levels in an aquifer decline and the hydraulic pressure in the aquifer decreases, which results in a corresponding increase in pressure that the skeleton must exert to support the weight of the overburden. In aquifers composed of sand and clay layers, the increase in skeletal pressure causes compaction of the clay layers (sand compacts also, but negligibly compared to clay), which in turn results in subsidence of the land surface (fig. 4). When

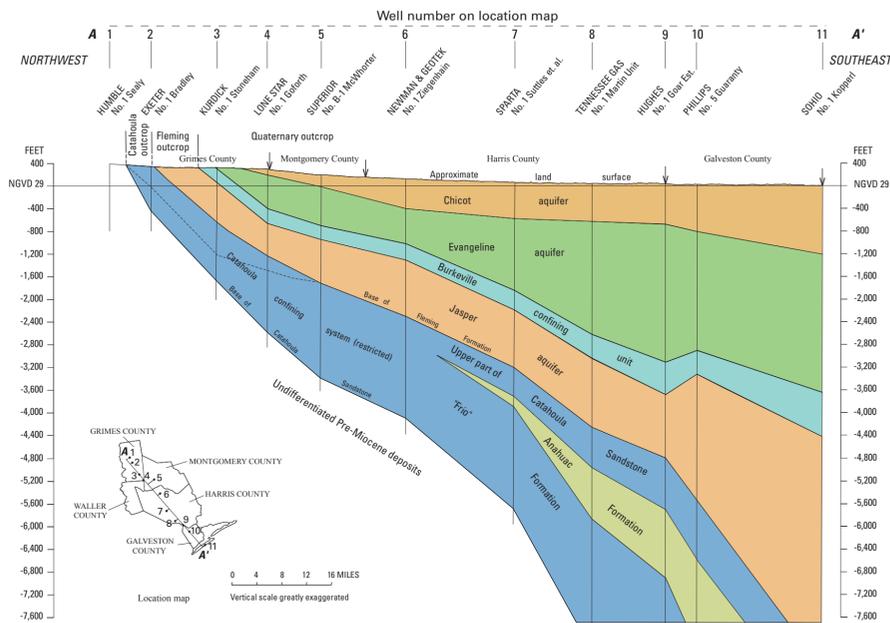


Figure 2. Hydrogeologic section of the Gulf Coast aquifer system in Harris County and adjacent counties, Texas (modified from Baker, 1979, fig. 4).

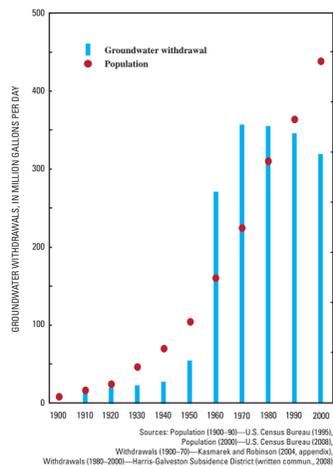


Figure 3. Trends in groundwater withdrawals and population in Harris County, Texas, 1900-2000.

recharge replenishes the aquifer and water levels and hydraulic pressure recover, a relatively small amount of uplift (rebound) of the land surface can occur; but in areas such as Harris County, where withdrawals over many years have caused substantial cones of depression in water levels of the Chicot and Evangeline aquifers (figs. 5A and 5B, respectively), most of the compaction of clay layers is inelastic and irreversible. The compaction, and thus subsidence, is essentially permanent because the skeletal matrix of the aquifer has deformed, and the individual grains within the clay layer have been reoriented or realigned (Galloway and others, 1999).

Historical 1915-17 Topographic Maps

Thirty-eight historical 7.5-minute topographic quadrangle maps that together encompass Harris County, constructed from topographic surveys done by the USGS during 1915-17, were obtained from the USGS Library in Denver, Colo. Land-surface elevation relative to mean sea level datum is indicated on the maps by contour lines at 1-foot intervals. The Texas Parks and Wildlife Department digitized these maps, creating 38 vector (x, y, z coordinate-based) datasets, each in the Lambert conformal conic projection. The USGS obtained these datasets, with metadata (Kim Ludcke, Texas Parks and Wildlife Department, written commun., 2008), reprojected them into the State Plane projection, and converted them into 38 raster (grid of cells) datasets. In other words, for each dataset a digital surface represented by contour lines connecting points of equal elevation was converted to a digital surface represented by a grid of cells, each cell with a value of elevation. This type of dataset is also known as a digital elevation model (DEM). A DEM is a digital file (GIS layer) of land-surface elevations at regularly spaced intervals. The 38 datasets were then edge matched by interpolating between adjacent edge values to create a combined, single DEM with a cell size of 15 feet square using GIS techniques (Hutchinson, 1988).

Examination of 1915-17 Contours

The dataset of elevation contours extracted from the quadrangles was checked for line placement accuracy, elevation accuracy, and quality of edge matching across the paper map sheets. Overall, the elevation lines and associated values match the raster map images. Where the original quadrangle sheet borders another quadrangle, shifts in the contour placement and discrepancies in elevation values occurred. The error types in the dataset were characterized as edge-matching errors, human errors, and mislabeled contours. The edge-matching errors exist in areas where individual quadrangles converge and the respective contours are misaligned or are offset compared to the adjacent quadrangle. Errors introduced during the digital conversion from quadrangles to GIS contours are classified as human errors and include the combining of the quadrangle boundary with the topographic contours. Mislabeled contours were a result of erroneously classifying a topographic depression as an area of rise and labeling the contours accordingly.

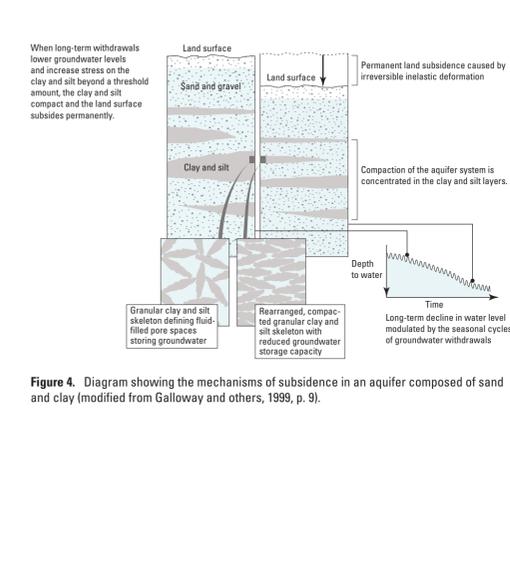


Figure 4. Diagram showing the mechanisms of subsidence in an aquifer composed of sand and clay (modified from Galloway and others, 1999, p. 9).

A subset of thirty 1-square-mile areas was randomly selected and examined for the effects of edge-matching errors, human errors, and mislabeled contours. The absolute value of the maximum error, or difference in elevation, and the percentage of the area in the cell that was affected were noted. The resultant values were then used to compute an area-weighted average absolute error of 0.01 foot. The elevation accuracy associated with the contours on a quadrangle is plus or minus one-half the contour interval, or 0.5 foot. A comprehensive data evaluation and data modification to correct all errors in the dataset were beyond the scope of this report.

Vertical Datum Conversion

The North American Vertical Datum of 1988 (NAVD 88) currently (2009) is the official vertical datum for the United States (National Oceanic and Atmospheric Administration, 2007) and the datum of choice for USGS data. Because the datum of the historical quadrangle maps is mean sea level, conversion to NAVD 88 was necessary. The mean sea level vertical datum was determined to be the Fourth General Adjustment of 1912. Through time, vertical datums related to sea level have undergone numerous adjustments as additional benchmarks were established, historical benchmarks were reoccupied, leveling techniques improved, and technology evolved. The Sea Level Datum of 1929 was based on 26 tidal stations and in 1973 was renamed National Geodetic Vertical Datum of 1929 (NGVD 29) because the vertical datum used did not reflect mean sea level.

The 1915-17 USGS quadrangles were produced from leveling surveys done by the USGS in cooperation with Harris County on the basis of benchmark locations and elevations in accordance with the Fourth General Adjustment of 1912 (Bowie and Avers, 1914; Marshall, 1916a, b). The current (2009) National Geodetic Survey (NGS) benchmark database was queried for these benchmarks. Many of these benchmarks had been reoccupied in subsequent survey leveling studies.

A set of 62 benchmarks from the historical leveling surveys was obtained for Harris County and the surrounding area from the NGS (National Geodetic Survey, 2009a). Of these, seven were selected to estimate the adjustment from 1912 to NGVD 29. Most of the 62 benchmarks were not used because they were located in areas of historical subsidence; the seven selected were not. The mean difference between the Fourth General Adjustment of 1912 and NGVD 29 was used to adjust the 1915-17 raster elevations from the elevations related to mean sea level from the 1915-17 USGS 7.5-minute quadrangles. An adjustment factor of 0.105 foot was calculated and subtracted from each DEM grid-cell value to compensate for the difference in vertical datums between the Fourth General Adjustment of 1912 and NGVD 29.

The change in elevation corresponding to the change in vertical datum for Harris County from NGVD 29 to NAVD 88 was determined using Corposon version 6 software. The Corposon software uses the NGS software "Vercon" to convert between NGVD 29 and NAVD 88 (National Geodetic Survey, 2009b; U.S. Army Corps of Engineers, 2009). The changes in elevations resulting from the change in vertical datum ranged from -0.04 foot in eastern Harris County to 0.18 foot in western Harris County.

2001 Light Detection and Ranging (LIDAR) Data

LIDAR is a laser-based scanning technology that is used to obtain three-dimensional topography. The technology is particularly useful when it is important to obtain a large amount of high-resolution land-surface elevation data in a relatively short time over a large geographic area. LIDAR has been used in areas of glacial advance and retreat or river sandbar accretion and erosion (Collins and Kaye, 2006); and in coastal areas for shoreline mapping and change analysis, storm-surge modeling, and sea-level-rise scenarios (National Oceanic and Atmospheric Administration Coastal Services Center, 2009). Instrumented aircraft transmit laser pulses to land surface and record the time it takes for the pulses to return to a receiver sensor. Millions of data points are recorded as the pulses are reflected back from points at various distances from the sensor. The sensor is integrated with a global positioning system (GPS) and an inertial navigation system to obtain exact locations of the point measurements. After post-processing the data to relate recorded laser pulse times to distances, the multitude of point-measurement data collectively define a detailed DEM of land-surface topography.

Tropical Storm Allison produced record amounts of rain in southeastern Texas in June 2001. Nearly 57 inches of rain fell in Houston (National Weather Service Hydrometeorological Prediction Center, 2009), causing widespread flooding that resulted in 22 deaths and more than \$5 billion of damages (Harris County Flood Control District Tropical Storm Allison Recovery Project, 2009). In October 2001, LIDAR technology was applied in Harris County by the Tropical Storm Allison Recovery Project (TSARP) to obtain detailed land-surface elevation data for use in studies to identify areas of high flood risk in Harris County. The 2001 LIDAR dataset was collected using stringent quality-assurance protocols (Peggy Cobb, TerraPoint USA, Inc., written commun., 2009). The result of the LIDAR mapping, provided to the USGS by the TSARP, was a series of 157 DEMs (vertical datum NAVD 88), with metadata, covering Harris County (Harris County Flood Control District Tropical Storm Allison Recovery Project, 2002). The DEM cell size is 30 centimeters (about 1 foot) by 30 centimeters. The surface elevation accuracy is about 15 centimeters (about 0.5 foot). Thus, the DEMs provided detailed representations of land-surface elevation, including the effect on elevation of essentially all natural and anthropogenic features. Positive relief features in the DEMs, such as buildings, cars, tree canopy, highway overpasses, and so forth, were removed from the DEMs through post-processing filtering techniques to yield "bare-earth" representations of land surface. Nevertheless, it is unlikely that every positive relief feature that could result in erroneous bare-earth elevations was eliminated. Subsequently, using standard GIS techniques (see "Downloads Directory" at <http://pubs.usgs.gov/sim/3097/>), the USGS combined the separate DEMs into a single DEM for all of Harris County.

Map Showing Estimated Land-Surface Subsidence in Harris County, 1915-17 to 2001

The map (DEM) showing estimated subsidence from 1915-17 to 2001 in Harris County (fig. 6) was created by subtracting the 1915-17 DEM from the 2001 DEM using GIS techniques. The metadata for the subsidence map contain a detailed description of the GIS techniques involved (see "Downloads Directory"). Although each of the two DEMs is accurate on a regional scale, each has potential inherent inaccuracies on a local or site-specific scale. As noted in the "Examination of 1915-17 Contours" section, for the thirty-eight 1915-17 topographic quadrangle datasets, a random sampling of thirty 1-square-mile areas yielded an area-weighted average absolute error of 0.01 foot relative to the original quadrangle elevations; and the elevation accuracy associated with the contours on a quadrangle is 0.5 foot. As noted in the "2001 Light Detection and Ranging (LIDAR) Data" section, the metadata-reported accuracy for the LIDAR data was about 15 centimeters or about 0.5 foot. The accuracy of the values in the 1915-17 to 2001 subsidence dataset, and thus the subsidence map, is a combination of the accuracies of the two source datasets.

The dataset contains subsidence values ranging from 0 to -30 feet. However, estimated maximum subsidence (fig. 6) is in the range of 12-13 feet. Areas visible on the map in the ranges from 13 to 20 feet likely are the result of subsidence combined with erosion associated with flooding, or the result of subsidence combined with other anthropogenic activity. Isolated, local areas of actual subsidence in the ranges from 13 to 20 feet are contained in the dataset but are too small to be visible at the scale of the map.

Null values—white areas on the subsidence map (fig. 6)—primarily indicate areas where the land-surface elevation in 2001 was greater than the elevation in 1915-17, areas covered by water bodies, or areas where subsidence exceeded 20 feet. Elevation differences in areas where 2001 elevations were greater than 1915-17 elevations generally were small, ranging from 1 to 2 feet and likely are attributable to inaccuracies in the source data. Numerous null-value areas are in the northeastern and northwestern parts of Harris County where development is relatively less and densely wooded areas could have attenuated the LIDAR signal, which would cause a misrepresentation of the bare-earth elevation. In the northeastern part of the county, Lake Houston is an example of a null area caused by a water body. The many rivers, creeks, canals, and bayous in Harris County also are null areas. Some other null areas result from anthropogenic influences involving landscape modification, such as water-detention structures for flood control. Addicks and Barker Reservoirs flood-detention basins in the southwestern part of the county are null because the fill for the earthen dams was excavated from within the basin areas.

Subsidence Map Compared with Contours of Measured Subsidence, 1906-2000

The GIS-developed 1915-17 to 2001 subsidence map shows broad agreement with overlain contours of measured subsidence from 1906 to 2000 (Gabrysch and Neighbors, 2005, fig. 2). In the part of the county where the most historical subsidence has occurred, the Baytown-Pasadena area, the map shows estimated subsidence mostly in the ranges from 6 to 10 feet with localized subsidence as much as 13 feet (fig. 6 inset area). The 1906-2000 contours indicate measured subsidence in that area mostly in the ranges from 7 to 10 feet. In much of the central and southern parts of the county, estimated mapped subsidence in the ranges from 3 to 6 feet is most prevalent, with numerous small areas in the ranges from 6 to 10 feet in the central part of the county. Much of the same central part of the county and some of the southern part are enclosed between the 5- and 7-foot 1906-2000 contours of measured subsidence. The rest of the county, the northwestern and northeastern parts, shows estimated historical subsidence of 0 to 3 feet. Measured 1906-2000 subsidence in the northwestern and northeastern parts of the county ranges from less than 1 to 5 feet, as indicated by the overlain contours, with subsidence lessening with distance away from the Baytown-Pasadena area of greatest subsidence.

Subsidence Map Compared with Measured Cumulative Clay Compaction at 10 Extensometer Sites

The USGS measures cumulative clay compaction continuously at 10 sites in Harris County (fig. 6) using borehole extensometers (Kasmarek and others, 2009). Two extensometers, one relatively shallow and one relatively deep, are at each of two sites, making a total of 12 in the county (table 1). The extensometers were installed during July 1973-July 1980. As noted in the "Historical Groundwater Withdrawals and Land-Surface Subsidence" section, regulation of groundwater withdrawals by the HGSD starting in the 1970s substantially reduced withdrawals throughout much of the county. Installation of the extensometers generally coincided with the start of regulation that reduced withdrawals. Data in table 1 are evidence that reducing withdrawals reduces subsidence. Assuming extensometer installation and the start of groundwater regulation occurred at the same time, on average at the extensometer sites, 77 percent of the 1915-17 to 2001 subsidence occurred before regulation (during the first 69 percent of the historical period of record). The average annual rate of subsidence at the sites before regulation was 0.08 foot per year; after regulation, it was 0.05 foot per year. At the Pasadena and Baytown sites, in the area of maximum subsidence, 97 and 92 percent (Baytown shallow), respectively, of the subsidence occurred before regulation. The only site where a greater percentage of total subsidence occurred after regulation, and the annual rate of subsidence between the mid-1970s and 2001 was substantially greater after regulation, was Addicks in the western Houston area, where appreciable groundwater withdrawals continued after the mid-1970s (Harris-Galveston Subsidence District, 2009).

Summary

Withdrawal of groundwater has caused compaction of clay layers in the aquifers underlying Harris County, Texas, which in turn has resulted in widespread, substantial land-surface (land) subsidence. The U.S. Geological Survey (USGS), in cooperation with the Harris-Galveston Subsidence District (HGSD), prepared a map to show the estimated land subsidence that has occurred in Harris County since the early 1900s. The map was constructed using geographic information system (GIS) techniques that involved subtraction of 1915-17 land-surface (topographic map) elevations from 2001 land-surface elevations derived from Light Detection and Ranging (LIDAR) data.

Groundwater withdrawals in the Houston area increased from the 1940s into the early 1970s, accompanied by increased frequency and severity of flooding. Created by the Texas Legislature in 1975, the HGSD directed a transition from groundwater to surface water and efforts to conserve water that reversed the long-term trend in groundwater withdrawals in Harris County despite continued population increases.

Subsidence trends in Harris County reflect the pattern of groundwater withdrawals. By the mid-1970s, 6 feet or more of subsidence had occurred throughout the area of the Houston Ship Channel (Baytown-Pasadena area), and by 1979 hundreds of square miles of the greater Houston area had subsided more than 1 foot. Since the early 1990s, subsidence in the Baytown-Pasadena area has essentially ceased because of major reductions in groundwater withdrawals in the area; but in the western Houston area (Addicks), subsidence continued because of continued groundwater withdrawals in the area.

The USGS obtained 38 historical 7.5-minute topographic quadrangle maps (contour lines at 1-foot interval) that together encompass Harris County; the maps were constructed from topographic surveys done by the USGS during 1915-17. The Texas Parks and Wildlife Department digitized these maps, creating 38 vector datasets. The USGS converted the vector datasets into raster datasets (digital elevation models [DEMs]) and combined them into a single DEM using GIS techniques. Because the datum of the historical quadrangle maps is mean sea level (Fourth General Adjustment of 1912), elevation adjustments were applied to convert the vertical datum of the DEM to North American Vertical Datum of 1988 (NAVD 88), the current (2009) datum of choice for USGS data.

After Tropical Storm Allison in June 2001, LIDAR technology was applied in Harris County by the Tropical Storm Allison Recovery Project (TSARP) to obtain detailed land-surface elevation data. The TSARP provided the USGS a series of 157 LIDAR-based "bare-earth" DEMs. The USGS combined the separate DEMs into a single DEM (vertical datum NAVD 88) for all of Harris County using GIS techniques.

The map (DEM) showing estimated subsidence from 1915-17 to 2001 in Harris County was created by subtracting the 1915-17 DEM from the 2001 DEM using GIS techniques. The GIS-developed 1915-17 to 2001 subsidence map shows broad agreement with overlain contours of measured subsidence from 1906 to 2000. In the part of the county where the most historical subsidence has occurred, the Baytown-Pasadena area, the map shows estimated subsidence mostly in the ranges from 6 to 10 feet with localized subsidence as much as 13 feet. In much of the central and southern parts of the county, estimated mapped subsidence in the ranges from 3 to 6 feet is most prevalent. The rest of the county, the northwestern and northeastern parts, shows estimated historical subsidence of 0 to 3 feet.

The USGS measures cumulative clay compaction continuously at 10 sites in Harris County using 12 borehole extensometers (two at each of two sites). Extensometer installation and the start of groundwater regulation occurred at about the same time (mid-1970s). On average at the extensometer sites, 77 percent of the 1915-17 to 2001 subsidence occurred before regulation (during the first 69 percent of the historical period of record). The average annual rate of subsidence at the sites before regulation was 0.08 foot per year; after regulation, it was 0.05 foot per year. The only site where a greater percentage of total subsidence occurred after regulation, and the annual rate of subsidence between the mid-1970s and 2001 was substantially greater after regulation, was Addicks in the western Houston area, where appreciable groundwater withdrawals continued after the mid-1970s.

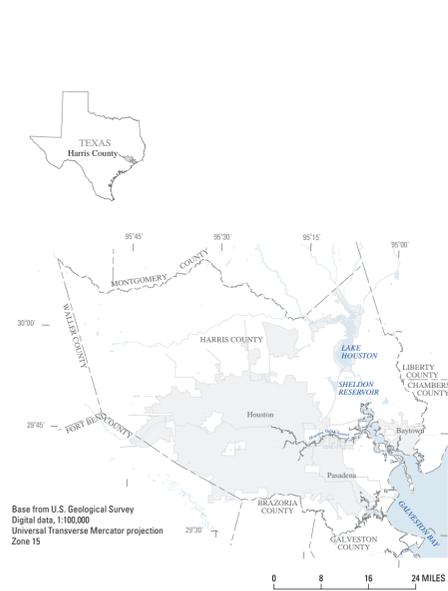


Figure 1. Location of Harris County and Houston, Texas.

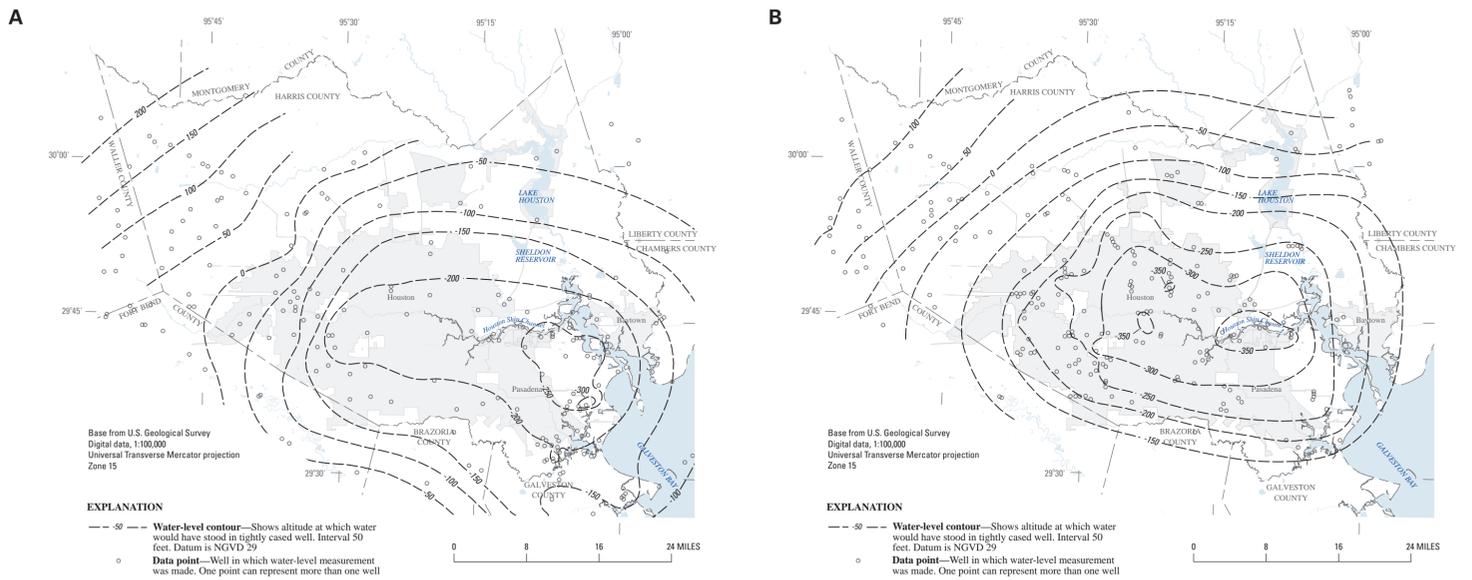


Figure 5. Water-level altitudes for 1977 in Harris County and surrounding counties, Texas, in the (A) Chicot aquifer (modified from Gabrysch, 1979, sheet 1) and (B) Evangeline aquifer (modified from Gabrysch, 1979, sheet 2).

Estimated Land-Surface Subsidence in Harris County, Texas, 1915-17 to 2001

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