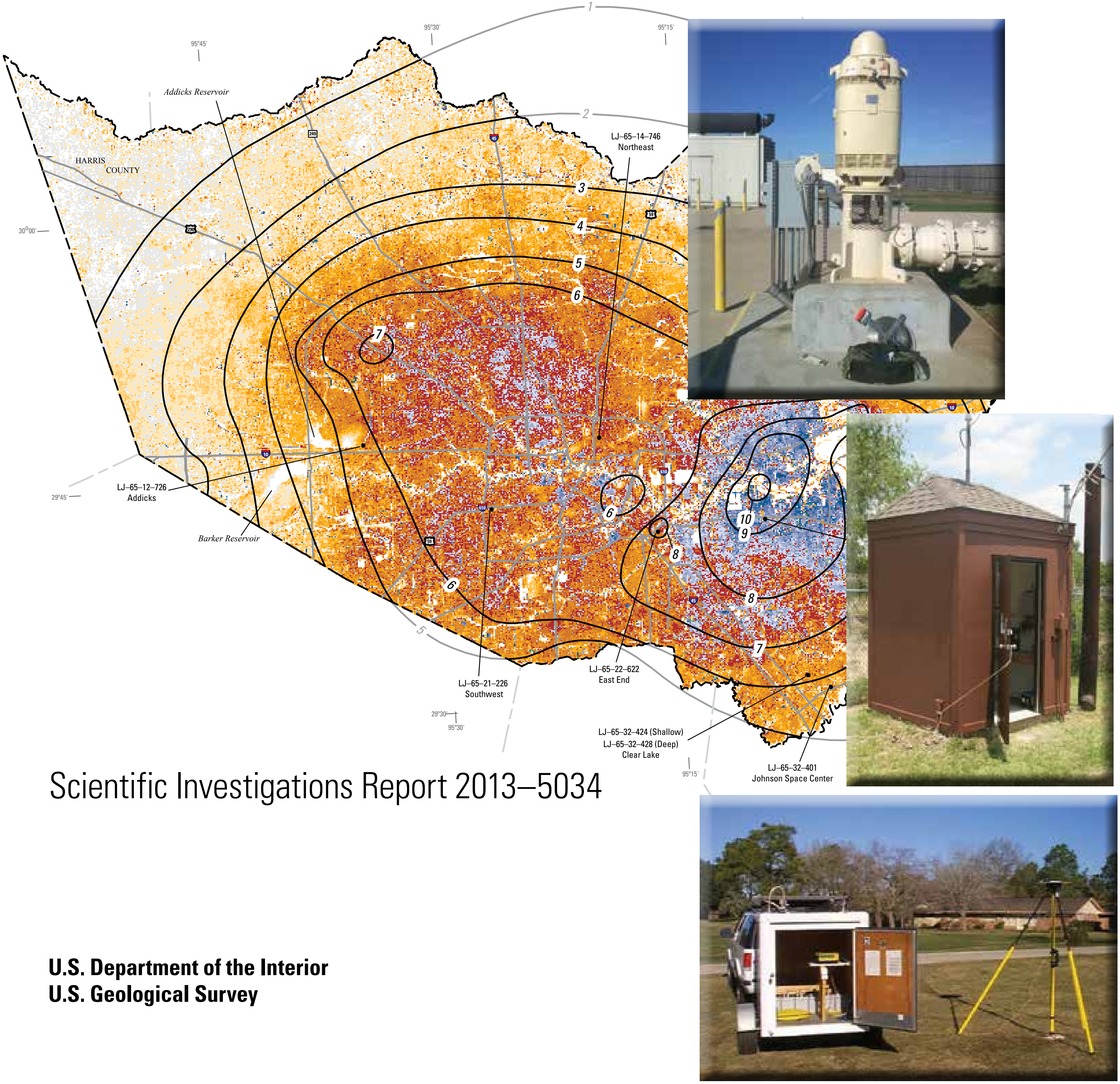
Prepared in cooperation with the Harris-Galveston Subsidence District

Groundwater Withdrawals 1976, 1990, and 2000–10 and Land-Surface-Elevation Changes 2000–10 in Harris, Galveston, Fort Bend, Montgomery, and Brazoria Counties, Texas



Scientific Investigations Report 2013–5034

U.S. Department of the Interior
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Cover:

Top right, Typical turbine public-supply production well in the study area, southeastern Texas (2011).

Center, U.S. Geological Survey borehole extensometer located at the Addicks extensometer site in Harris County, Texas (2010).

Bottom right, Typical Port-A-Measure trailer and associated equipment operated by the Harris-Galveston Subsidence District (2001; photograph used with permission from the Harris-Galveston Subsidence District).

Left, Estimated land-surface subsidence in Harris County, Texas (from sheet 2 of Kasmarek and others, 2009).

Groundwater Withdrawals 1976, 1990, and 2000–10 and Land-Surface-Elevation Changes 2000–10 in Harris, Galveston, Fort Bend, Montgomery, and Brazoria Counties, Texas

By Mark C. Kasmarek and Michaela R. Johnson

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U.S. Department of the Interior
U.S. Geological Survey

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
	Flow Rate	
gallon per day (gal/d)	0.003785	cubic meter per day (m^3/d)

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1927 (NAD 27).

Groundwater Withdrawals 1976, 1990, and 2000–10 and Land-Surface-Elevation Changes 2000–10 in Harris, Galveston, Fort Bend, Montgomery, and Brazoria Counties, Texas

By Mark C. Kasmarek and Michaela R. Johnson

Abstract

The study area comprising Harris County and parts of Galveston, Fort Bend, Montgomery, and Brazoria Counties in southeastern Texas forms part of one of the largest areas of land-surface-elevation change in the United States. Land-surface-elevation change in the study area primarily is caused by the withdrawal of groundwater. Groundwater withdrawn from the Chicot and Evangeline aquifers has been the primary source of water for municipal supply, industrial and commercial use, and irrigation in the study area. Groundwater withdrawals cause compaction of clay and silt layers abundant in the aquifers, which has in turn resulted in the widespread, substantial land-surface-elevation changes in the region with increased flooding. To estimate land-surface-elevation changes, the U.S. Geological Survey (USGS), in cooperation with the Harris-Galveston Subsidence District (HGSD), documented land-surface-elevation changes in the study area that occurred during 2000–10 and 2005–10 based on elevation data measured by 11 USGS borehole-extensometer sites, a National Geodetic Survey Continuously Operating Reference Station, and Global Positioning System Port-A-Measure (PAM) sites operated by the HGSD and the Fort Bend Subsidence District. Groundwater withdrawals in the study area also were documented for 1976, 1990, and 2000–10.

In 1976, about 428.9 million gallons per day (Mgal/d) were withdrawn from the aquifer system in Harris County, but by 2000, because of HGSD regulation, withdrawals had decreased to about 337.8 Mgal/d, or about a 21-percent reduction since 1976. By 2010, withdrawals had decreased to about 227.1 Mgal/d, or about a 47-percent reduction since 1976. Among the counties in the study area, the largest decrease in groundwater withdrawals has occurred in Galveston County since 1976. In 1976, about 27.4 Mgal/d were withdrawn from the aquifer system, and by 2000, withdrawals had decreased to about 4.12 Mgal/d, or about an 85-percent reduction since 1976. By 2010, withdrawals had decreased to about 0.626 Mgal/d, or about a 98-percent decrease since 1976.

Since the mid-1970s, Fort Bend and Montgomery Counties have undergone extensive urban development and corresponding large increases in groundwater withdrawals. Total groundwater withdrawal for Fort Bend County in 1976 was about 16.0 Mgal/d, and by 2000, withdrawals had increased to about 86.5 Mgal/d, or about a 441-percent increase since 1976. By 2010, withdrawals in Fort Bend County had increased to about 99.8 Mgal/d, or about a 524-percent increase since 1976. Total groundwater withdrawal for Montgomery County in 1976 was about 7.84 Mgal/d, and by 2000, withdrawals had increased to about 43.6 Mgal/d, or about a 456-percent increase since 1976. By 2010, withdrawals in Montgomery County had increased to about 64.2 Mgal/d, or about a 719-percent increase since 1976. Total groundwater withdrawal in Brazoria County in 1976 was about 18.0 Mgal/d, and by 2000, withdrawals had increased to about 26.0 Mgal/d, or about a 44-percent increase. By 2010, withdrawals in Brazoria County had increased to about 24.7 Mgal/d, or about a 37-percent increase since 1976.

Measured land-surface-elevation changes from December 31, 2000, to December 31, 2010, ranged from an elevation increase of 0.06 feet (ft), or an average increase in elevation of 0.006 ft per year, at the Seabrook borehole extensometer located near Seabrook, Tex., to an elevation decrease of 1.28 ft, or an average decrease in elevation of 0.128 ft per year, at a PAM station north of Jersey Village, Tex. (PAM 07). Measured land-surface-elevation changes from December 31, 2005, to December 31, 2010, ranged from an elevation increase of 0.07 ft, or an average increase in elevation of 0.014 ft per year, at PAM 09 in far northeastern Harris County to an elevation decrease of 0.51 ft, or an average decrease in elevation of 0.102 ft per year, at PAM 07.

Introduction

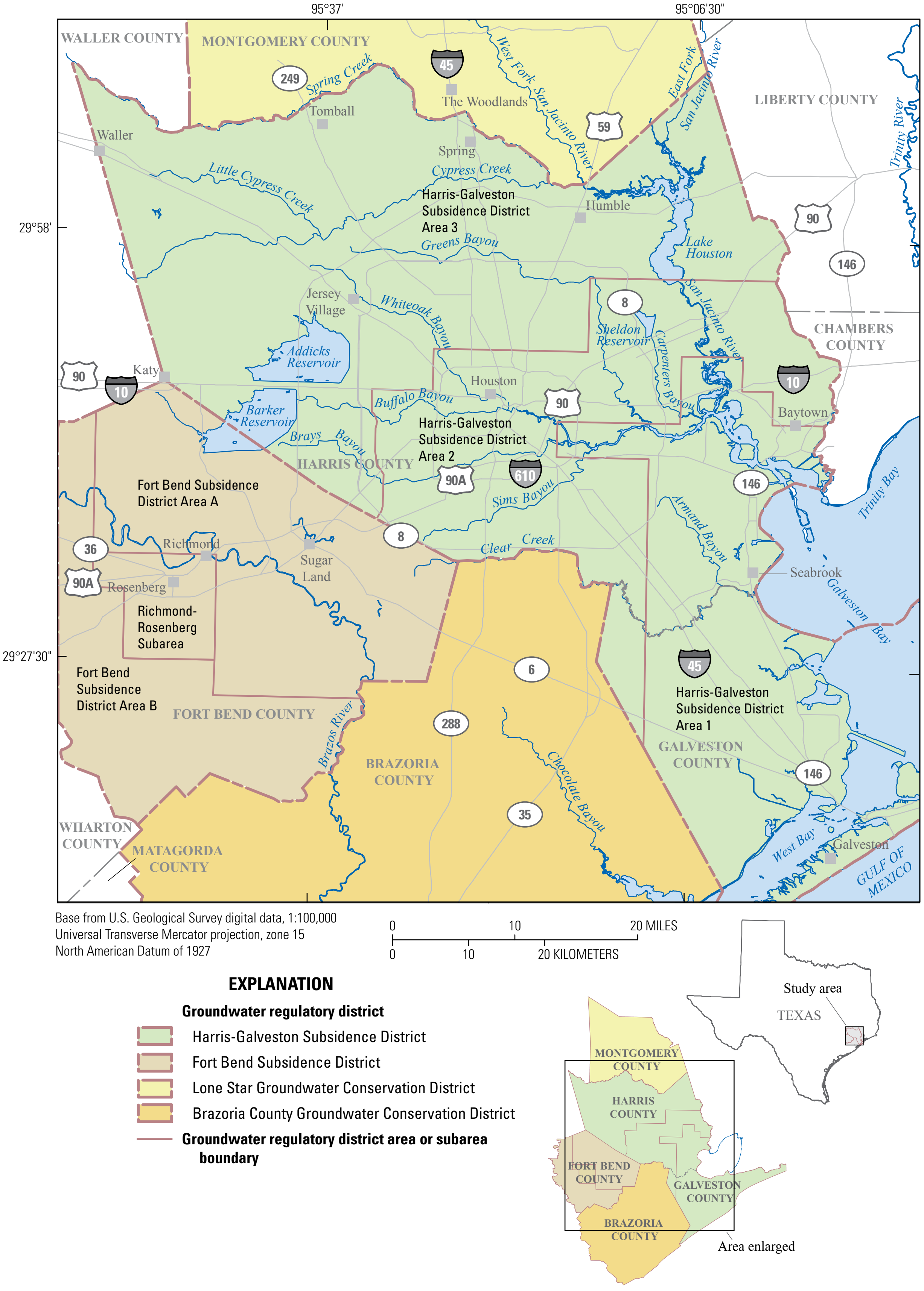
The study area comprising Harris County and parts of Galveston, Fort Bend, Montgomery, and Brazoria Counties in southeastern Texas forms part of one of the largest areas of land-surface-elevation change in the United States (fig. 1) (Coplin and Galloway, 1999). Land-surface subsidence, which causes a decrease in land-surface elevation, was first documented in the study area in 1906 in Galveston County (Coplin and Galloway, 1999). Allen (1969) described ground-surface displacement (land-surface-elevation change) as the result of a variety of subsurface displacement mechanisms that included (among others) compaction of sediments by loading, drainage, vibration, and hydrocompaction. Land-surface-elevation change in the study area primarily is caused by the withdrawal of groundwater (Kasmarek, 2012, p. 13). Groundwater withdrawn from the Chicot, Evangeline, and Jasper aquifers has been the primary source of water for municipal supply, industrial and commercial use, and irrigation in the study area. Groundwater withdrawals cause compaction of clay and silt layers abundant in the aquifers, which has in turn resulted in the widespread, substantial land-surface-elevation changes in the region with increased flooding. Groundwater withdrawals in the area began as early as the 1890s (Kasmarek, 2012). By 1979, as much as 10 feet (ft) of subsidence had occurred in the study area, and about one-third of the study area had subsided more than 1 ft (Coplin and Galloway, 1999, p. 40). Comparison of the earliest measured land-surface elevations for 1915–17 to the Tropical Storm Allison Recovery Project (Harris County Flood Control District, 2012) elevations of 2001indicated that as much as 13 ft of subsidence has occurred in southeastern Harris County (Kasmarek and others, 2009). This decrease in land-surface elevation has allowed saltwater inundation of coastal areas (Coplin and Galloway, 1999) and has increased the frequency and extent of flooding, such as the widespread, devastating flooding in the study area that resulted from Tropical Storm Allison in 2001 (Federal Emergency Management Agency and Harris County Flood Control District, 2002). Another effect of land-surface-elevation change is protrusion above land surface of wells and other fixed infrastructure (fig. 2), which is common in the study area. When the water well shown in figure 2 was initially constructed, the lower section of the slab and well casing were below land surface. As land-surface elevation decreased, the bottom section of the slab and casing protruded above the land surface, and by 2004, it was protruding more than 1ft.

The effects of groundwater withdrawals on land-surface-elevation changes and subsequent increased flooding prompted the Texas State Legislature in 1975 to authorize the establishment of the Harris-Galveston Subsidence District (HGSD) (Harris-Galveston Subsidence District, 2013) to regulate and reduce groundwater withdrawals in Harris and Galveston Counties. After the HGSD adopted a regulatory plan (Harris-Galveston Subsidence District, 2013), Harris and Galveston Counties were subdivided into Regulatory Areas 1, 2, and 3 (fig. 1). In 1976, the first groundwater regulations were implemented in the study area in Harris and Galveston Counties. Later, in 1989, the Texas State Legislature established the Fort Bend Subsidence District (FBSD) to regulate groundwater withdrawals in Fort Bend County. After the FBSD adopted a regulatory plan (Fort Bend Subsidence District, 2009), Fort Bend County was subdivided into Area A, Area B, and the Richmond-Rosenberg Subarea (fig. 1). In 1990, the first groundwater regulations were implemented in Fort Bend County. In 2001, the Lone Star Groundwater Conservation District (LSGCD) was established by the Texas State Legislature to regulate groundwater withdrawals in Montgomery County (Lone Star Groundwater Conservation District, 2011). In 2003, the Brazoria County Groundwater Conservation District (BCGCD) was established by the Texas State Legislature with the purpose to maintain the quality and availability of the county's groundwater resource for current users and future generations (Brazoria County Groundwater Conservation District, 2008). Currently (2013), a transition to surface water as the primary source of supply in Harris and Galveston Counties is in effect as stipulated by the groundwater-regulatory plan developed by the HGSD in 2001. This regulatory plan gradually decreases groundwater withdrawals while increasing usage of surface-water supplies.

To estimate the spatial distribution of land-surface-elevation changes in the study area, the U.S. Geological Survey (USGS), in cooperation with the HGSD, documented land-surface-elevation changes in the study area that occurred during 2000–10 and 2005–10 based on elevation data measured by 11 USGS borehole-extensometer sites, a National Geodetic Survey (NGS) Continuously Operating Reference Station (CORS), and Global Positioning System (GPS) Port-A-Measure (PAM) sites operated by the HGSD and the FBSD. Groundwater withdrawals in the study area also were documented for 1976, 1990, and 2000–10 based on written communication in 2012 of withdrawal data from the HGSD, the Texas Water Development Board, and the LSGCD.

Purpose and Scope

This report describes total groundwater withdrawals in the study area for 1976, 1990, and 2000–10 and depicts land-surface-elevation changes during 2005–10 and 2000–10 in parts of Harris, Galveston, Fort Bend, Montgomery, and Brazoria Counties. Changes in land-surface elevation were determined from land-surface-elevation data measured by the USGS borehole-extensometer network, an NGS CORS, and PAM sites operated by the HGSD and the FBSD in the study area. The hydrogeology of the study area is described, along with an overview of the mechanism of compaction. This report is intended to provide water-district managers and regional resource planners a means of evaluating the effect of changes in groundwater use on the occurrence of land-surface-elevation change in the study area.



Base from U.S. Geological Survey digital data, 1:100,000
Universal Transverse Mercator projection, zone 15
North American Datum of 1927

Figure 1. Locations of the study area and groundwater-regulatory districts in Harris, Galveston, Fort Bend, Montgomery, and Brazoria Counties, Texas.

Figure 2. Damaged water well with the lower section of slab and well casing protruding above land surface because of a decrease in land-surface elevation in Baytown, Texas, September 2004.

Land-Surface-Elevation Loss and Compaction Processes

Land-surface subsidence, a decrease in land-surface elevation, can occur because of potentiometric-surface declines in the affected sections of the unconsolidated confined aquifers (Galloway and others, 1999). From the 1890s to 1979, as much as 10 ft of land-surface-elevation loss had occurred in the study area, and approximately 3,200 square miles (mi^2) of the 11,000-mi^2 geographic area had subsided more than 1 ft (Coplin and Galloway, 1999). Potentiometric-surface declines related to groundwater withdrawal cause a decrease in hydraulic pressure (depressuring) that creates a load on the skeletal matrix of the sediments in the aquifer and adjacent confining units (fig. 3). Because sand layers are more transmissive and less compressible compared to clay and silt layers (referred to hereinafter as "clay layers"), sand layers depressure more rapidly compared to clay layers. In addition, when groundwater withdrawals decrease, pressure equilibrium is reestablished more rapidly in the sand layers compared to the clay layers, with the amount of compaction of the sand layers usually being minor compared to the amount of compaction of the clay layers (Trahan, 1982; Galloway and others, 1999). The clay layers are often interbedded within the sand layers, and when depressuring occurs, the clay layers dewater more slowly compared to the sand layers. Some of the factors controlling land-surface-elevation change are (1) the percentage and age of clay composing the affected aquifer sediment, (2) the rate that withdrawal changes (decreases or increases), (3) the thicknesses of the individual clay layers controlling the time required for equilibrium of excess-residual-pore pressure, (4) the historical preconsolidation head, (5) the vertical stress of the saturated and unsaturated sediment overburden, and (6) the heterogeneity of the affected aquifer sediments (Coplin and Galloway, 1999; Kasmarek, 2012; Kasmarek and others, 2012). As depressuring caused by groundwater withdrawals progresses, slow drainage of the clay layers continues to occur until the excess-residual-pore pressure in the clay layers equilibrates with the pore pressure of the adjacent sand layers. Adjacent sand layers undergo a similar loading process but are more transmissive and less compressible and therefore are more resistant to compaction than are clay layers (Kasmarek, 2012, p. 13). Clay layers compact more for a given water-level decline because, when the aquifer sediments are initially deposited, the individual flat and platy clay grains composing the clay layers are randomly oriented. After the clay layers depressurize, the orientation of the clay grains realigns, becoming perpendicular to the applied vertical overburden load (Galloway and others, 1999).

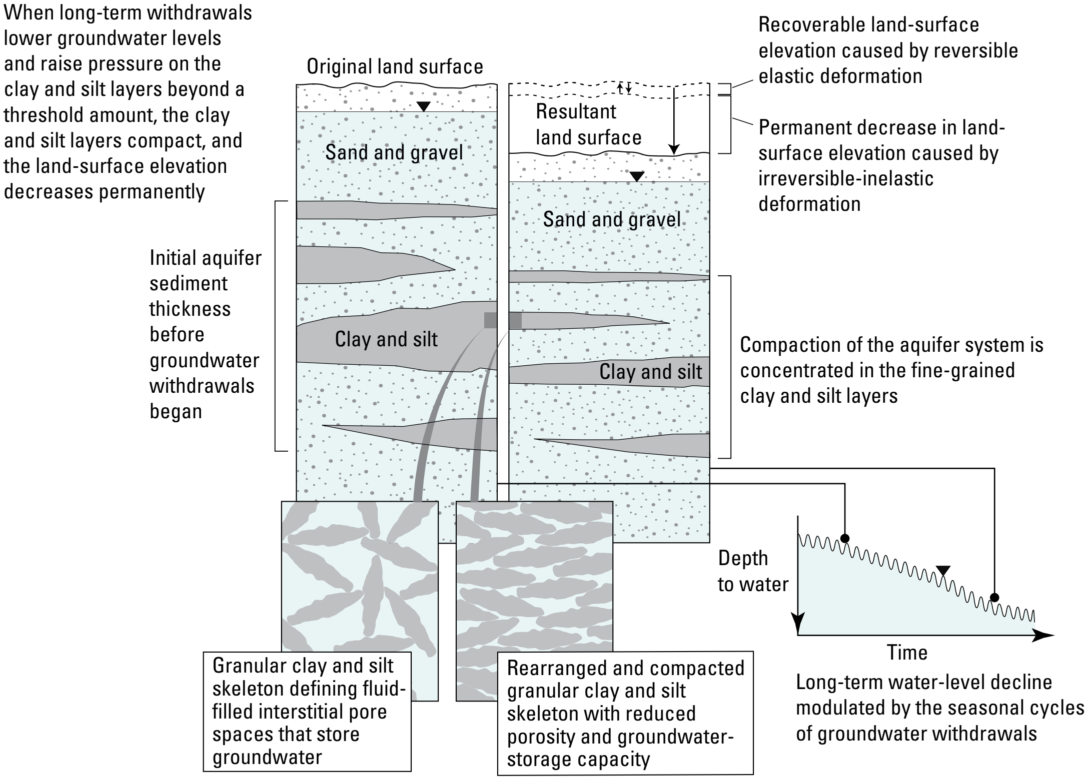


Figure 3. Diagram depicting the mechanism of aquifer compaction and resultant decrease in land-surface elevation in an aquifer composed of sand, clay, and silt (modified from Galloway and others, 1999, p. 9).

Essentially, the water stored in the sand and clay layers prior to depressuring provides interstitial pore-space support for the sand- and clay-skeleton matrixes but provides more structural support to the clay-layer matrix compared to the sand-layer matrix. Additionally, compaction of the clay layers reduces the porosity and groundwater-storage capacity of the clay layers (fig. 3). Because most compaction of the clay layers is inelastic, about 90 percent of the compaction is permanent (Gabrysch and Bonnet, 1975). In areas where groundwater withdrawals decrease, the water level in the aquifers rises and repressures the compacted clay layers, but only a small amount of rebound of the land-surface elevation occurs (Gabrysch and Bonnet, 1975) (fig. 3). The compaction of one thin clay layer generally will not cause a measureable decrease in the land-surface elevation, but when thousands of feet of stacked clay- and sand-layer sequences (characteristic of the aquifer system in the study area) depressure and compact, a decrease in land-surface elevation often occurs (Gabrysch and Bonnet, 1975).

Description of Study Area

The study area (fig. 1) includes all of Harris County and parts of Galveston, Fort Bend, Montgomery, and Brazoria Counties. The study area is a gently sloping coastal plain, and land-surface elevations are topographically highest along the northwestern boundary. The vegetation in the northern parts of the study area generally is composed of hardwood and pine forests, but as land-surface elevation decreases toward the coast, the vegetation becomes increasingly dominated by shrubs and grasses. Surficial water bodies in the study area include Sheldon, Addicks, and Barker Reservoirs and Lake Houston; parts of the Brazos and San Jacinto River Basins; Trinity and Galveston Bays; and the Gulf of Mexico. The Gulf of Mexico, Trinity Bay, and Galveston Bay have a large effect on the downdip groundwater-flow system and climate of the area. Winters in the area generally have few days of freezing temperatures. During winter, moisture-laden Pacific and Canadian air masses produce regionally extensive bands of moderate rainfall. In contrast, summers generally have high relative humidity, and prevailing winds are from the southwest. During summer, atmospheric convective cells can produce low to high rates of localized rainfall, and infrequently, moisture-laden tropical air masses produce moderate to extremely high rates of rainfall (Kasmarek and Robinson, 2004). The average annual rainfall over the area is about 48 inches, and the average annual temperature is about 68 degrees Fahrenheit (Larkin and Bomar, 1983).

Hydrogeology

The three primary aquifers in the Gulf Coast aquifer system are the Chicot, Evangeline, and Jasper (fig. 4), which are composed of laterally discontinuous deposits of gravel, sand, silt, and clay. The Chicot aquifer, the youngest and uppermost, consists of Holocene- and Pleistocene-age sediments; the Evangeline aquifer, which underlies the Chicot aquifer, consists of Pliocene- and Miocene-age sediments; and the Jasper aquifer, the oldest and most deeply buried, consists of Miocene-age sediments. Additionally, the Burkeville confining unit and Catahoula confining system consist of Miocene-age sediments (fig. 4) (Baker, 1979, 1986). Through time, geologic and hydrologic processes created accretionary-sediment wedges (stacked sequences of sediments) more than 7,600 ft thick at the coast (fig. 4) (Chowdhury and Turco, 2006). The sediments composing the Gulf Coast aquifer system were deposited by fluvial-deltaic processes and subsequently were eroded and redeposited (reworked) by reoccurring eustatic changes in sea level that occurred as a result of oscillations between glacial and interglacial climate conditions (Lambeck and others, 2002). The hydrogeologic units that dip and thicken from northwest to southeast compose the Gulf Coast aquifer system (fig. 4); the aquifers thus crop out in bands inland from and approximately parallel to the coast of the Gulf of Mexico (hereinafter the coast) and become progressively more deeply buried and confined toward the coast. Because of the paleodepositional environment, the highest percentage of clay in the sediments in the Chicot, Evangeline, and Jasper aquifers is adjacent to the coast; the percentage of clay progressively decreases towards the outcrop areas (Kasmarek and Robinson, 2004). The Burkeville confining unit separates the Evangeline and Jasper aquifers and restricts groundwater flow between the two aquifers. The Chicot aquifer can be differentiated from the geologically similar Evangeline aquifer based on hydraulic conductivity differences (Carr and others, 1985, p. 10) and where each aquifer outcrops—the Chicot aquifer outcrops closer to the coast compared to the Evangeline aquifer. The Chicot and Evangeline aquifers are hydraulically connected, which allows groundwater flow between the aquifers (fig. 4) allowing water-level changes in one of the aquifers to affect water levels in the adjacent aquifer (Kasmarek and Robinson, 2004). Evidence of this exchange of flow between the aquifers is substantiated by two long-term (1977–2012) water-level-change maps (Kasmarek and others, 2012, sheets 5 and 10) that show that the geographic areas where water levels have declined or risen in the Chicot and the Evangeline aquifers are approximately coincident.

The hydrogeologic cross section *A–A′* (fig. 4) extends from Grimes County through Montgomery and Harris Counties, terminates at the coast in Galveston County, and shows the three aquifers thickening and dipping toward the coast. Each aquifer becomes progressively thinner in the updip outcrop areas, and even though the aquifers exist in these areas, the saturated thickness of the sediments composing the aquifers is effectively insufficient to supply substantial quantities of groundwater. Most groundwater withdrawn in the updip outcrop areas is pumped from individual wells for domestic purposes.

Groundwater Withdrawals

Since the 1890s, groundwater withdrawals from the Chicot and Evangeline aquifers have been the primary source of water for development in Harris, Galveston, Fort Bend, Montgomery, and Brazoria Counties (Kasmarek, 2012). Groundwater withdrawals from the Jasper aquifer also are an important source of water in northern Harris County and in Montgomery County. Because of and coinciding with the establishment of the HGSD in 1975 and its subsequent regulatory plan, reductions in groundwater withdrawals began in 1976 because water levels of the Chicot and Evangeline aquifers had declined as much as 250 and 350 below sea level, respectively, (Gabrysch, 1979) and the relation between water-level declines and land-surface-elevation loss had been established and documented (Coplin and Galloway, 1999). Similarly, the FBSD, the LSGCD, and the BCGCD were established in 1990, 2000, and 2003, respectively, and have groundwater regulatory plans in effect. Hence, temporal and spatial changes in water use, use of surface-water sources, or conservation have resulted in appreciable changes in the volume and location of groundwater withdrawn in the study area. Additionally, the spatial distribution and amount of precipitation for any given year or period have an important effect on the volume of water withdrawn from the aquifer system. Even though withdrawals are regulated in the study area, an appreciable increase or decrease in withdrawals can occur for any given year or period when precipitation is below average or above average, respectively. For example, during 2011, the total precipitation in the study area was below average, causing increased groundwater withdrawals and a subsequent decrease in water levels in the Chicot, Evangeline, Jasper aquifers (Kasmarek and others, 2012) compared to water levels in 2010 (Johnson and others, 2011).

Because of the establishment of the HGSD in 1975, groundwater withdrawals have been restricted in Harris and Galveston Counties. In 1976, a total of about 428.9 million gallons per day (Mgal/d) were withdrawn from the aquifer system in Harris County (Greg Lackey, Harris-Galveston Subsidence District, written commun., 2012) (table 1). By 1990, because of HGSD regulation, withdrawals had decreased to about 363.4 Mgal/d, or about a 15-percent reduction since 1976, and by 2000, withdrawals had decreased to about 337.8 Mgal/d (fig. 5), or about a 21-percent reduction since 1976. By 2010, withdrawals had decreased to about 227.1 Mgal/d, or about a 47-percent reduction since 1976. For 2000–10, withdrawals ranged from a maximum of about 337.8 Mgal/d in 2000 to a minimum of about 213.8 Mgal/d in 2007. The average withdrawal for 2000–10 was 263.7 Mgal/d, or about a 38-percent reduction compared to withdrawals in 1976.

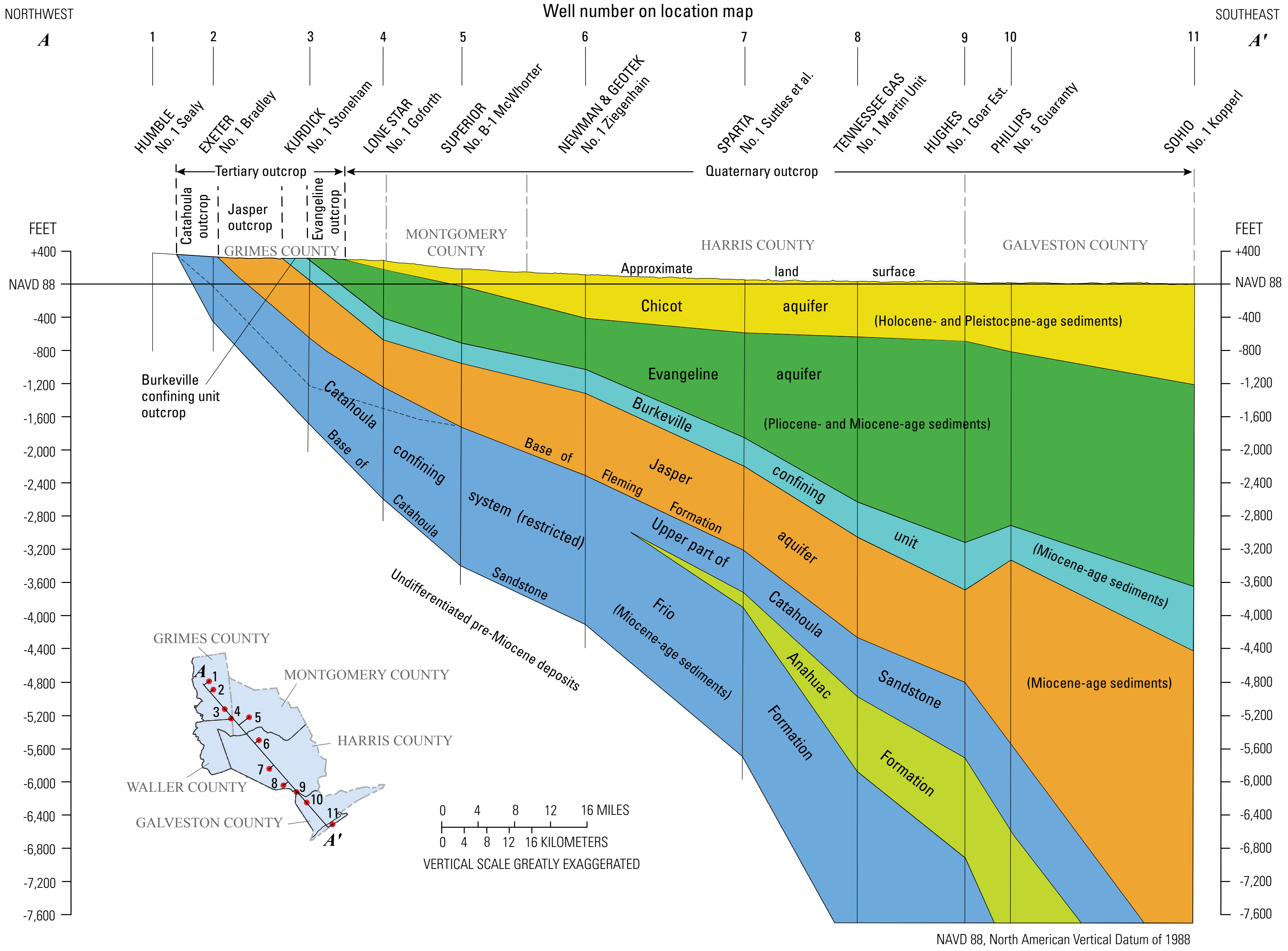


Figure 4. Hydrogeologic section of the Gulf Coast aquifer system in Grimes, Montgomery, Harris, and Galveston Counties, Texas (modified from Baker, 1979, fig. 4).

Table 1. Total groundwater withdrawals in Harris, Galveston, Fort Bend, Montgomery, and Brazoria Counties, Texas, 1976, 1990, and 2000–10.

[Groundwater withdrawal values are in million gallons per day]

Year	Harris County[1]	Galveston County[1]	Fort Bend County[2]	Montgomery County[2, 3]	Brazoria County[2]
1976	428.9	27.4	16.0	7.84	18.0
1990	363.4	4.56	62.6	24.9	15.4
2000	337.8	4.12	86.5	43.6	26.0
2001	289.6	1.63	74.6	40.3	21.7
2002	276.9	1.03	78.7	42.7	21.5
2003	276.5	1.01	80.5	47.0	21.7
2004	233.6	0.692	82.0	47.0	24.1
2005	295.8	0.820	100.5	58.8	24.8
2006	246.6	0.751	94.2	59.6	31.5
2007	213.8	0.630	79.1	54.0	34.6
2008	256.4	0.783	101.1	64.7	49.2
2009	246.9	1.21	111.3	64.1	43.2
2010	227.1	0.626	99.8	64.2	24.7

[1] Greg Lakey, Harris-Galveston Subsidence District, written commun., 2012.

[2] Bill Billingsley, Texas Water Development Board, written commun., 2012.

[3] Samantha Reiter, Lone Star Groundwater Conservation District, written commun., 2012.

Groundwater withdrawals have decreased more in Galveston County since 1976 compared to all of the other counties in the study area. In 1976, about 27.4 Mgal/d were withdrawn from the aquifer system in Galveston County (Greg Lackey, Harris-Galveston Subsidence District, written commun., 2013) (table 1). By 1990, withdrawals had decreased to 4.56 Mgal/d, or about an 83-percent reduction since 1976, and by 2000, withdrawals had decreased to about 4.12 Mgal/d (fig. 5), or about an 85-percent reduction since 1976. By 2010, withdrawals had decreased to about 0.626 Mgal/d, or about a 98-percent decrease since 1976. For 2000–10, withdrawals ranged from a maximum of about 4.12 Mgal/d in 2000 to a minimum of about 0.626 Mgal/d in 2010. The average withdrawal for 2000–10 was about 1.21 Mgal/d, or about a 96-percent reduction compared to withdrawals in 1976.

Since the mid-1970s, Fort Bend and Montgomery Counties have undergone extensive urban development and corresponding large increases in groundwater withdrawals. Total groundwater withdrawal for Fort Bend County in 1976 was about 16.0 Mgal/d (Bill Billingsley, Texas Water Development Board, written commun., 2012) (table 1). By 1990, as development and groundwater use in the county continued to increase, withdrawals had increased to about 62.6 Mgal/d, or about a 291-percent increase since 1976, and by 2000, withdrawals had increased to about 86.5 Mgal/d (fig. 5), or about a 441-percent increase since 1976. By 2010, withdrawals had further increased to about 99.8 Mgal/d, or about a 524-percent increase. For 2000–10, withdrawals ranged from a maximum of about 111.3 Mgal/d in 2009 to a minimum of about 74.6 Mgal/d in 2001. The average withdrawal for 2000–10 was about 89.8 Mgal/d or about a 461-percent increase compared to withdrawals in 1976.

Total groundwater withdrawal for Montgomery County in 1976 was about 7.84 Mgal/d (Bill Billingsley, Texas Water Development Board, written commun., 2012) (table 1). By 1990, as development and groundwater use in the county continued to increase, withdrawals had increased to about 24.9 Mgal/d, or about 218-percent increase since 1976, and by 2000, withdrawals had increased to about 43.6 Mgal/d (fig. 5) (Samantha Reiter, Lone Star Groundwater Conservation District, written commun., 2012) (table 1), or about a 456-percent increase since 1976. By 2010, withdrawals had increased to about 64.2 Mgal/d, or about a 719-percent increase since 1976. For 2000–10, withdrawals ranged from a maximum of about 64.7 Mgal/d in 2008 to a minimum of about 40.3 Mgal/d in 2001. The average withdrawal for 2000–10 was about 53.3 Mgal/d, or about a 580-percent increase compared to withdrawals in 1976.

Total groundwater withdrawals in Brazoria County exceeded withdrawals in Fort Bend and Montgomery Counties in 1976, with a withdrawal of about 18.0 Mgal/d (Bill Billingsley, Texas Water Development Board, written commun., 2012) (table 1). By 1990, withdrawals had decreased to 15.4 Mgal/d, or about a 14-percent decrease since 1976, but by 2000, withdrawals had increased to about 26.0 Mgal/d, or about a 44-percent increase since 1976. By 2010, withdrawals had decreased to about 24.7 Mgal/d (fig. 5), or about a 37-percent increase since 1976 (table 1). For 2000–10, withdrawals ranged from a maximum of about 49.2 Mgal/d in 2008 to a minimum of about 21.5 Mgal/d in 2002. The average withdrawal for 2000–10 was about 29.4 Mgal/d, or about a 63-percent increase compared to withdrawals in 1976.

Methods for Determining Land-Surface-Elevation Changes

Since mid-1973, the USGS has been collecting land-surface-elevation data (subsurface clay compaction) at borehole-extensometer sites in Harris and Galveston Counties. The HGSD has been monitoring land-surface elevation with the NGS by periodically conducting first-order leveling surveys and by using land-based GPS methods; one NGS CORS was used in this report. In 2000, the HGSD in cooperation with the FBSD began to establish a network of PAM sites in the study area based on land-surface-based GPS technology. Subsequently, in 2011 the LSGCD initiated PAM site installations in Montgomery County. The PAM network

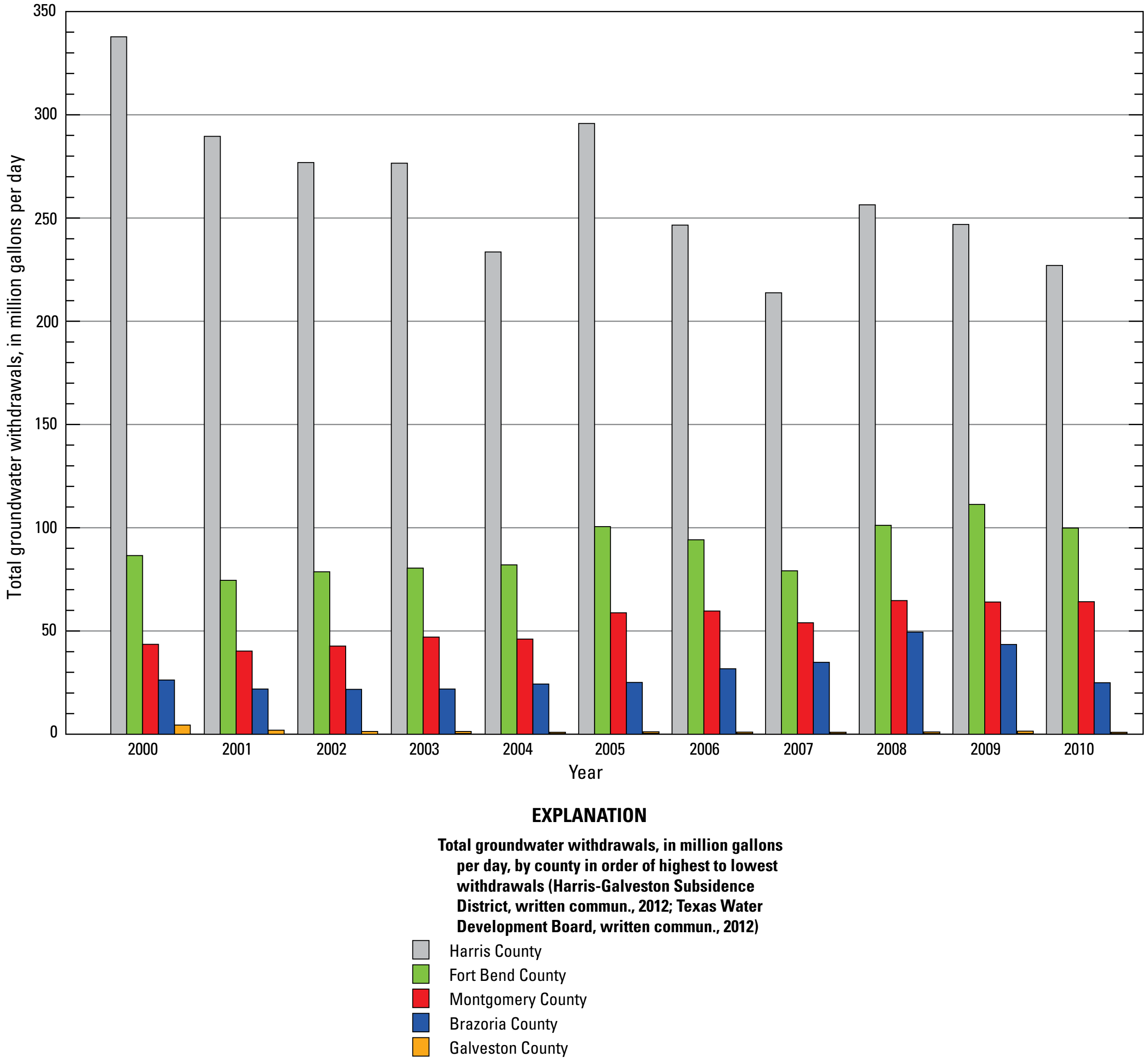
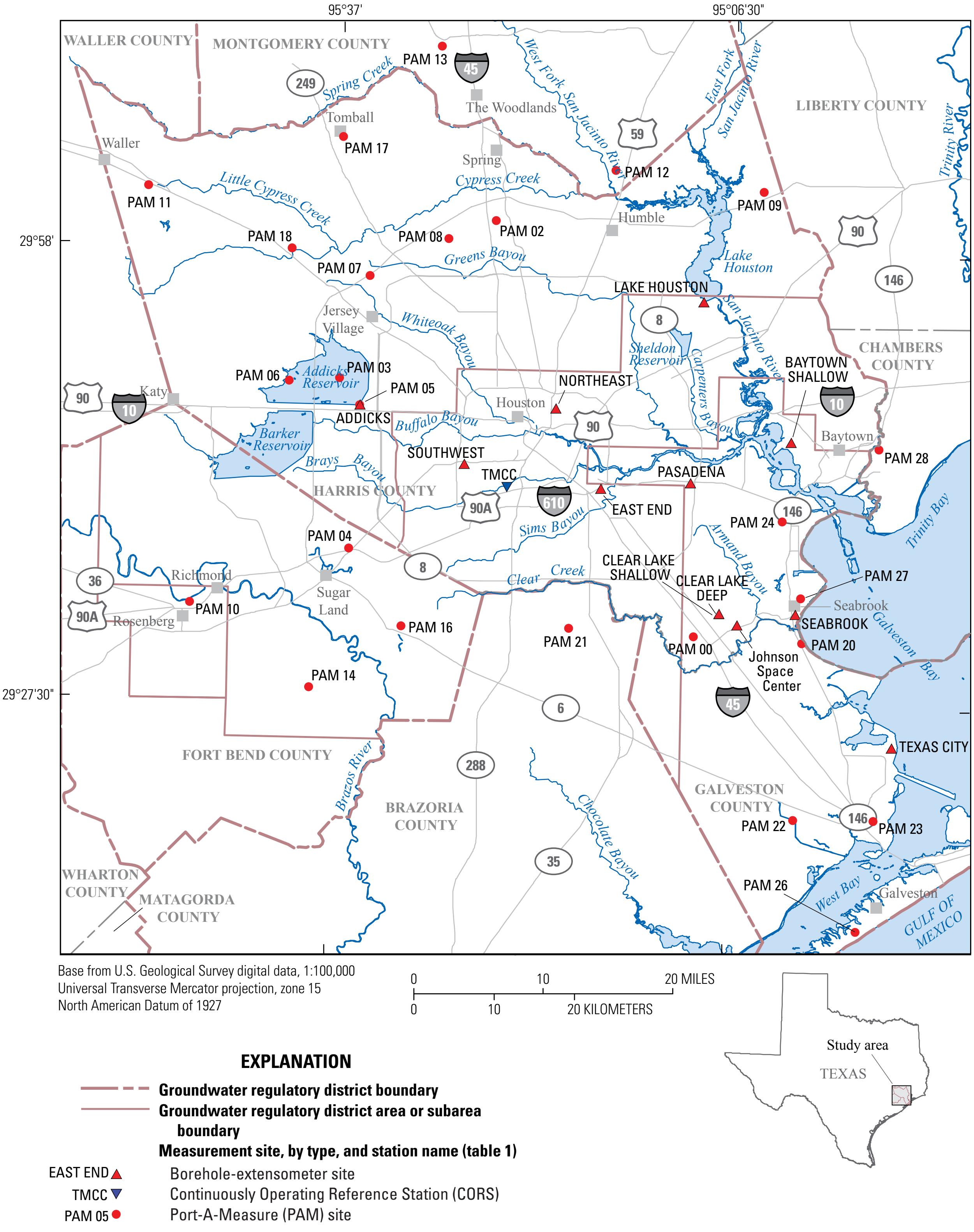


Figure 5. Total groundwater withdrawals in order from highest to lowest in Harris, Fort Bend, Montgomery, Brazoria, and Galveston Counties, Texas, 2000–10 (Harris-Galveston Subsidence District, written commun., 2012; Texas Water Development Board, written commun., 2012; Lone Star Groundwater Conservation District, written commun., 2012).

continues to be expanded into other areas of interest as time and resources become available.

To define the geographic areas subject to land-surface-elevation change and to quantify land-surface-elevation changes, data obtained from a combined monitoring network of 11 USGS borehole-extensometer sites, 1 NGS CORS, and 25 PAM sites were analyzed. The extensometer sites are located in Harris and Galveston Counties, the CORS is located in south-central Harris County, and the PAM sites are located in Harris, Galveston, Fort Bend, Brazoria, and Montgomery Counties (fig. 6). The USGS borehole-extensometer network was installed between 1973 and 1980 and continues to provide site-specific continuous land-surface-elevation-change data at 11 sites with an accuracy of 0.001 ft. At each extensometer site, an analog recorder is mounted to a steel table that is attached to the borehole-extensometer slab. A calibrated steel tape connects the recorder to the top of the 2.5-inch diameter inner pipe that is installed within the 4.5-inch-diameter outer casing. The outer casing is effectively a sleeve that isolates the inner casing from the adjacent borehole sediments. Because the steel table is anchored to the slab, land-surface-elevation changes can be accurately measured and recorded. These recorded values represent land-surface-elevation changes caused by compaction of subsurface sediment from the base of the slab (land surface) to the total depth of the extensometer. Detailed information on the scientific theory, operation, and construction of a borehole extensometer is presented in Gabrysch (1984) and Kasmarek and others (2012).



Base from U.S. Geological Survey digital data, 1:100,000
Universal Transverse Mercator projection, zone 15
North American Datum of 1927

Figure 6. Locations of the U.S. Geological Survey borehole-extensometer sites, National Geodetic Survey Continuously Operating Reference Station, and Global Positioning System Port-A-Measure sites in Harris, Galveston, Fort Bend, Montgomery, and Brazoria Counties, Texas.

Because the installation of additional borehole extensometers is cost prohibitive, in late 1993, the HGSD and the NGS cooperatively pioneered an improved, less expensive method of monitoring land-surface-elevation changes in the study area with the installation of PAM sites. The PAM sites measure land-surface-elevation changes by using GPS technology with dual-frequency, full-wavelength GPS receivers and geodetic fixed-height antennas. These data are collected at 30-second intervals and averaged over a 24-hour period. Subsequently, these data are post processed and analyzed and have a differential vertical accuracy of less than 1 centimeter (Zilkowski and others, 2012). The CORS uses the same technology and has the same accuracy as do the PAM sites. Unlike the permanently located borehole-extensometer network, each PAM is mounted on a portable trailer and continually relocated among its four predetermined reference sites, each PAM occupying each of its reference sites for 1 week. This continuous and repetitive process allows one PAM trailer to provide measurements of land-surface-elevation changes at each of its four reference sites on a monthly basis.

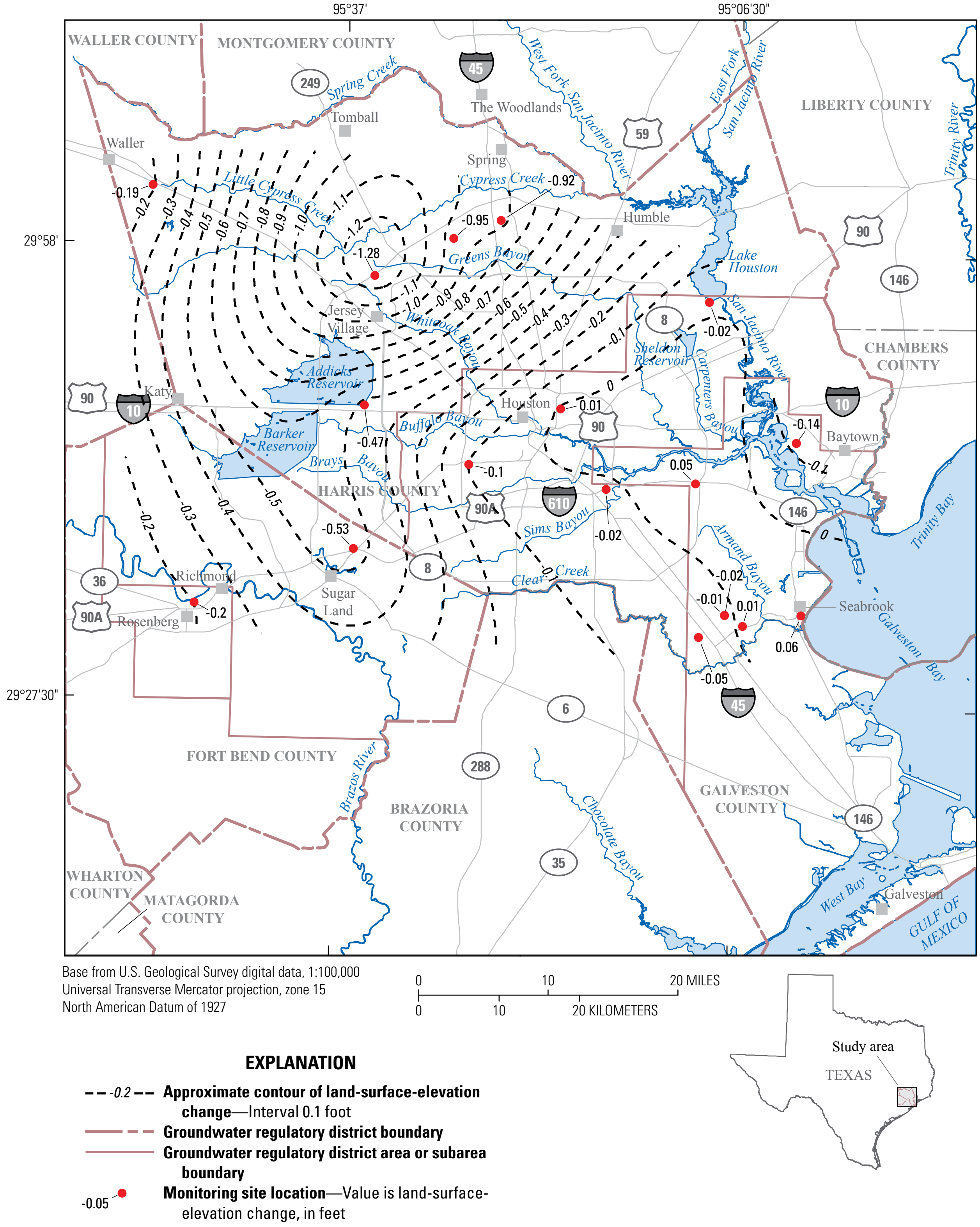
Land-Surface-Elevation Changes

To define the geographic areas that were undergoing land-surface-elevation changes and to quantify the rates of land-surface-elevation changes, data were obtained from the combined monitoring network from the 11 USGS borehole extensometers, 1 CORS, and 25 PAM sites (fig. 6) and contours of land-surface elevation were created. The contoured depictions of land-surface-elevation change were created by converting the point values of land-surface-elevation change to digital-elevation models (DEMs) for 2000–10 and 2005–10. These DEMs were then used to generate contours within a geographic information system (GIS) for the two periods of interest. Subsequently, all contours were evaluated for accuracy and spatial location and manually modified as needed to ensure that they honored the point values of land-surface-elevation change.

The contour creation technique used the Topo to Raster tool in the Environmental Systems Research Institute, Inc. (Redlands, Calif.), software package ArcGIS 9.3.1. (Environmental Systems Research Institute, Inc., 2012). Topo to Raster is based on the ANUDEM program that uses iterative finite-difference interpolation (Hutchinson, 1988, 1989). Topo to Raster is the same method in ArcGIS 9.x that was migrated from TopoGrid from ArcInfo Workstation 7.x (Environmental Systems Research Institute, Inc., 2012).

To estimate the spatial distribution of land-surface-elevation changes in the study area, measured changes in land-surface elevation from 2000 to 2010 were calculated as the difference between the land-surface elevations on December 31, 2000, and December 31, 2010. For the 10-year period, land-surface-elevation changes ranged from an increase of 0.06 ft, or an average increase in elevation of 0.006 ft per year, at the Seabrook borehole extensometer located near Seabrook, Tex., to a decrease of 1.28 ft, or an average decrease in elevation of 0.128 ft per year, at PAM 07 located north of Jersey Village, Tex. (fig. 7) (table 2). Measured land-surface-elevation changes during 2005–10 (December 31, 2005, to December 31, 2010) ranged from an increase of 0.07 ft, or an average increase in elevation of 0.014 ft per year, at PAM 09 located in far northeastern Harris County to a decrease of 0.51 ft, or an average decrease in elevation of 0.102 ft per year, at PAM 07 located north of Jersey Village (fig. 8) (table 2). The spatial distribution of the land-surface-elevation changes (figs. 7 and 8) are either related to areas affected by increases in groundwater withdrawals such as HGSD Area 3 and Fort Bend, Montgomery, and Brazoria Counties (areas where decreases in land-surface elevation occurred) or related to areas affected by decreases in withdrawals such as HGSD Area 1 and the extreme northeastern part of HGSD Area 3 adjacent to Liberty County (areas undergoing no change in elevation or increases in land-surface elevation). These land-surface-elevation changes occur slowly and nonuniformly across the study area because of a variety of reasons. Some of the reasons for differences in land-surface-elevation changes include (1) the heterogeneity of the aquifer system; (2) inconsistent distribution and variable rates of precipitation that cause more groundwater to be withdrawn during below average periods or, conversely, less water withdrawn during above average periods; and most importantly (3) the spatial and temporal patterns of groundwater withdrawals stipulated by the regulatory policies of the HGSD, FBSD, BCGCD, and LSGCD. Therefore, in areas where withdrawals were restricted or areas where withdrawals were unrestricted, decreases and increases (respectively) in land-surface elevation can occur.

Groundwater withdrawals in Harris and Galveston Counties have been restricted in HGSD Area 1 since the mid-1970s with a mandate by the HGSD that withdrawals were not to exceed more than 10 percent of total water demand (Harris-Galveston Subsidence District, 2013). Consequently, during 2000–10, at the sites in HGSD Area 1 where water levels in the Chicot and Evangeline aquifers had been restricted and water levels rose, the affected numerous clay and silt layers responded elastically (fig. 3). This water-level rise caused a slight rise in land-surface elevation ranging from 0.01 ft to 0.06 ft at the Northeast, Pasadena, Seabrook, and Johnson Space Center extensometer sites in the eastern part of the study area (fig. 7). Similarly, for 2005–10, a slight rise in land-surface elevation of as much as 0.05 ft at PAM 24 and PAM 28 and as much as 0.07 ft at PAM 09 was measured (fig. 8). Conversely, during 2000–10 in HGSD Area 3, where groundwater withdrawals were not restricted until 2010 (Harris-Galveston Subsidence District, 2013), water levels in the aquifers declined, and a general decrease in land-surface elevation occurred (figs. 7 and 8) as the clay and silt layers responded inelastically (fig. 3).



Base from U.S. Geological Survey digital data, 1:100,000
Universal Transverse Mercator projection, zone 15
North American Datum of 1927

EXPLANATION

- - -0.2 - - **Approximate contour of land-surface-elevation change**—Interval 0.1 foot

Groundwater regulatory district boundary

Groundwater regulatory district area or subarea boundary

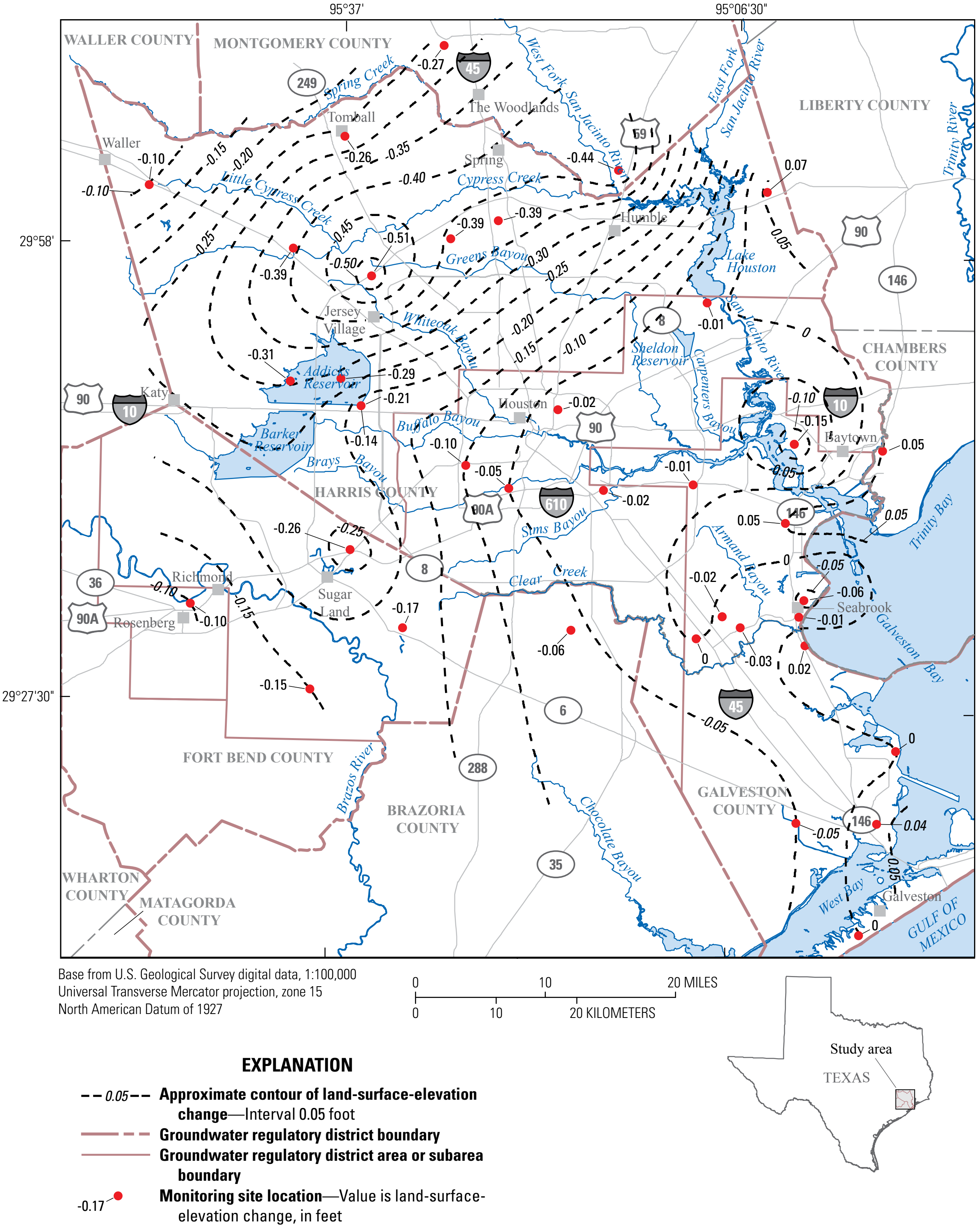
-0.05 ● **Monitoring site location**—Value is land-surface-elevation change, in feet

Figure 7. Approximate land-surface-elevation changes caused by groundwater withdrawals and subsequent compaction of subsurface sediments in Harris, Galveston, Fort Bend, and Brazoria Counties, Texas, 2000–10.

Table 2. Land-surface-elevation-change data from monitoring sites in Harris, Galveston, Fort Bend, Montgomery, and Brazoria Counties, Texas.

[----, no change value determined because measurement(s) not available in date range; PAM, Harris-Galveston Subsidence District Port-A-Measure station; ****, no January measurements were available at the beginning or ending of the year; CORS, National Geodetic Survey Continuously Operating Reference Station. Sites with site type "extensometer" represent data measured by the U.S. Geological Survey by using borehole extensometers. PAM and CORS station names and site types are from National Geodetic Survey CORS site search (http://www.ngs.noaa.gov/CORS/) or Harris-Galveston Subsidence District subsidence charts (http://mapper.subsidence.org/Chartindex.htm)]

Station name	Site type	Latitude	Longitude	Beginning year of measurements	Land-surface-elevation change, 2000–10 (feet)	Land-surface-elevation change, 2005–10 (feet)
Addicks	Extensometer	29° 47′ 27.47″ N	95° 35′ 11.04″ W	1974	-0.47	-0.14
Baytown C–1	Extensometer	29° 45′ 28.28″ N	95° 1′ 50.38″ W	1973	-0.14	-0.15
Clear Lake (shallow)	Extensometer	29° 33′ 50.21″ N	95° 7′ 10.16″ W	1976	-0.01	----
Clear Lake (deep)	Extensometer	29° 33′ 49.14″ N	95° 7′ 9.03″ W	1976	-0.02	-0.02
East End	Extensometer	29° 42′ 7.32″ N	95° 16′ 27.43″ W	1973	-0.02	-0.02
Lake Houston	Extensometer	29° 54′ 48.44″ N	95° 8′ 44.69″ W	1980	-0.02	-0.01
Johnson Space Center	Extensometer	29° 33′ 7.01″ N	95° 5′ 46.44″ W	1973	0.01	-0.03
Northeast	Extensometer	29° 47′ 28.14″ N	95° 20′ 3.17″ W	1980	0.01	-0.02
Pasadena	Extensometer	29° 42′ 36.63″ N	95° 9′ 33.40″ W	1975	0.05	-0.01
Seabrook	Extensometer	29° 33′ 53.24″ N	95° 1′ 17.27″ W	1973	0.06	-0.01
Southwest	Extensometer	29° 43′ 38.00″ N	95° 27′ 3.00″ W	1980	-0.10	-0.10
Texas City	Extensometer	29° 24′ 58.80″ N	94° 53′ 42.01″ W	1973	0.00	0.00
PAM 00	PAM	29° 32′ 19.01″ N	95° 9′ 8.02″ W	1999	-0.05	0.00
PAM 02	PAM	30° 0′ 2.34″ N	95° 24′ 57.09″ W	1996	-0.92	-0.39
PAM 03	PAM	29° 49′ 14.91″ N	95° 36′ 48.15″ W	1999	****	-0.29
PAM 04	PAM	29° 37′ 49.40″ N	95° 35′ 48.68″ W	1996	-0.53	-0.26
PAM 05	PAM	29° 47′ 28.33″ N	95° 35′ 9.24″ W	1996	****	-0.21
PAM 06	PAM	29° 48′ 58.92″ N	95° 40′ 40.00″ W	1997	****	-0.31
PAM 07	PAM	29° 56′ 10.65″ N	95° 34′ 35.91″ W	1999	-1.28	-0.51
PAM 08	PAM	29° 58′ 46.82″ N	95° 28′ 34.54″ W	1999	-0.95	-0.39
PAM 09	PAM	30° 2′ 17.23″ N	95° 4′ 17.24″ W	1999	****	0.07
PAM 10	PAM	29° 33′ 58.97″ N	95° 47′ 57.01″ W	1999	-0.20	-0.10
PAM 11	PAM	30° 1′ 55.77″ N	95° 51′ 54.78″ W	1999	-0.19	-0.10
PAM 12	PAM	30° 3′ 34.89″ N	95° 15′ 47.04″ W	2000	****	-0.44
PAM 13	PAM	30° 11′ 41.29″ N	95° 29′ 23.94″ W	2000	****	-0.27
PAM 14	PAM	29° 28′ 25.14″ N	95° 38′ 38.75″ W	2001	----	-0.15
PAM 16	PAM	29° 32′ 40.05″ N	95° 31′ 38.05″ W	2000	****	-0.17
PAM 17	PAM	30° 5′ 28.17″ N	95° 36′ 55.03″ W	2000	****	-0.26
PAM 18	PAM	29° 57′ 53.75″ N	95° 40′ 41.59″ W	2000	****	-0.39
PAM 20	PAM	29° 31′ 58.44″ N	95° 0′ 47.64″ W	2002	----	0.02
PAM 21	PAM	29° 32′ 43.66″ N	95° 18′ 43.44″ W	2002	----	-0.06
PAM 22	PAM	29° 20′ 4.26″ N	95° 1′ 14.53″ W	2002	----	-0.05
PAM 23	PAM	29° 20′ 6.27″ N	94° 55′ 3.97″ W	2002	----	0.04
PAM 24	PAM	29° 40′ 7.65″ N	95° 2′ 26.78″ W	2002	----	0.05
PAM 26	PAM	29° 12′ 37.12″ N	94° 56′ 17.94″ W	2002	----	0.00
PAM 27	PAM	29° 34′ 59.28″ N	95° 0′ 55.95″ W	2002	----	-0.06
PAM 28	PAM	29° 45′ 4.37″ N	94° 55′ 3.44″ W	2002	----	0.05
TMCC	CORS	29° 42′ 8.42″ N	95° 23′ 42.82″ W	2003	----	-0.05



Base from U.S. Geological Survey digital data, 1:100,000
Universal Transverse Mercator projection, zone 15
North American Datum of 1927

EXPLANATION

- *0.05* **Approximate contour of land-surface-elevation change**—Interval 0.05 foot
- **Groundwater regulatory district boundary**
- **Groundwater regulatory district area or subarea boundary**
- -0.17 ● **Monitoring site location**—Value is land-surface-elevation change, in feet

Figure 8. Approximate land-surface-elevation changes caused by groundwater withdrawals and subsequent compaction of subsurface sediments in Harris, Galveston, Fort Bend, Brazoria, and Montgomery Counties, Texas, 2005–10.

Data Limitations

The contour depictions of land-surface-elevation changes at any specific location are approximate. As such, these depictions are not intended for use in site-specific engineering or other design applications. Because the locations of the land-surface-elevation-monitoring sites are widely spaced in the study area, all contours are considered approximate. In addition to the different rates of groundwater withdrawals in the areas adjacent to each monitoring site, there is a difference in the clay-to-sand ratio at each site, and thus the rate of land-surface-elevation change varies from one monitoring site to another. Therefore, it is not possible to extrapolate or infer a rate of land-surface-elevation change between two adjacent monitoring sites. Users need to exercise discretion when drawing conclusions or making policy decisions based on these contoured depictions, with full awareness of the data limitations.

Summary

The study area comprising Harris County and parts of Galveston, Fort Bend, Montgomery, and Brazoria Counties in southeastern Texas forms part of one of the largest areas of land-surface-elevation change in the United States. Land-surface subsidence, which causes a decrease in land-surface elevation, was first documented in the study area in 1906 in Galveston County. Groundwater withdrawn from the Chicot and Evangeline aquifers has been the primary source of water for municipal supply, industrial and commercial use, and irrigation in the study area. Groundwater withdrawals cause compaction of clay and silt layers abundant in the aquifers, which has resulted in the widespread, substantial land-surface-elevation changes in the region. Groundwater withdrawals in the area began as early as the 1890s. By 1979, as much as 10 ft of subsidence had occurred in the study area, and about one-third of the study area had subsided more than 1 ft.

The effects of groundwater withdrawals on land-surface-elevation change and the subsequent increased flooding prompted the Texas State Legislature in 1975 to authorize the establishment of the Harris-Galveston Subsidence District (HGSD) to regulate and reduce groundwater withdrawals in Harris and Galveston Counties. Subsequently, the Texas State Legislature established the Fort Bend Subsidence District (FBSD) in 1989, the Lone Star Groundwater Conservation District (LSGCD) in 2001, and the Brazoria County Groundwater Conservation District (BCGCD) in 2003 to regulate groundwater withdrawals.

The three primary aquifers in the Gulf Coast aquifer system are the Chicot, Evangeline, and Jasper, which are composed of laterally discontinuous deposits of gravel, sand, silt, and clay. The Chicot aquifer, the youngest and uppermost, consists of Holocene- and Pleistocene-age sediments; the Evangeline aquifer, which underlies the Chicot aquifer, consists of Pliocene- and Miocene-age sediments; and the Jasper aquifer, the oldest and most deeply buried, consists of Miocene-age sediments. Through time, geologic and hydrologic processes created accretionary-sediment wedges (stacked sequences of sediments) more than 7,600 ft thick at the coast.

Since the 1890s, groundwater withdrawals from the Chicot and Evangeline aquifers have been the primary source of water for development in Harris, Galveston, Fort Bend, Montgomery, and Brazoria Counties. Groundwater withdrawals from the Jasper aquifer also are an important source of water in northern Harris County, and in Montgomery County. Temporal and spatial changes in water use, through regulation, use of surface-water sources, or conservation, have resulted in appreciable changes in the volume and location of groundwater withdrawn in the study area.

Because of and coinciding with the establishment of the HGSD in 1975, groundwater withdrawals have been restricted in Harris and Galveston Counties. In 1976, a total of about 428.9 million gallons per day (Mgal/d) were withdrawn in Harris County. By 2000, withdrawals had decreased to about 337.8 Mgal/d, or about a 21-percent reduction since 1976. The average withdrawal for 2000–10 was 263.7 Mgal/d, or about a 38-percent reduction compared to withdrawals in 1976. Galveston County has had the greatest decrease in groundwater withdrawal of all the counties in the study area. In 1976, about 27.4 Mgal/d were withdrawn in Galveston County from the aquifer system. By 2000, withdrawals had decreased to about 4.12 Mgal/d, or about an 85-percent reduction since 1976. The average withdrawal for 2000–10 was about 1.21 Mgal/d, or about a 96-percent reduction compared to withdrawals in 1976.

Since the mid-1970s, Fort Bend and Montgomery Counties have undergone extensive urban development and corresponding large increases in groundwater withdrawals. Total groundwater withdrawal for Fort Bend County in 1976 was about 16.0 Mgal/d. By 2000, withdrawals had increased to about 86.5 Mgal/d, or about a 441-percent increase since 1976. The average withdrawal for 2000–10 was about 89.8 Mgal/d, or about a 461-percent increase compared to withdrawals in 1976. Total groundwater withdrawal for Montgomery County in 1976 was about 7.84 Mgal/d. By 2000, withdrawals had increased to about 43.6 Mgal/d, or about a 456-percent increase since 1976. The average withdrawal for 2000–10 was about 53.3 Mgal/d, or about a 580-percent increase compared to withdrawals in 1976. Total groundwater withdrawal in Brazoria County in 1976 was about 18.0 Mgal/d. By 2000, withdrawals had increased to about 26.0 Mgal/d, or about a 44-percent increase. The average withdrawal for 2000–10 was about 29.4 Mgal/d, or about a 63-percent increase compared to withdrawals in 1976.

To define the geographic areas that were undergoing land-surface-elevation changes and to quantify the rates of land-surface-elevation changes, data were obtained from the combined monitoring network of 11 U.S. Geological Survey (USGS) borehole-extensometer sites, 1 National Geodetic

Survey (NGS) Continuously Operating Reference Station (CORS), and 25 Global Positioning System Port-A-Measure (PAM) sites. Measured changes in land-surface elevation from 2000 to 2010 were calculated as the difference between the land-surface elevations on December 31, 2000, and December 31, 2010. For the 10-year period, land-surface-elevation changes ranged from an increase of 0.06 ft, or an average increase in elevation of 0.006 ft per year, at the Seabrook borehole extensometer located near Seabrook, Tex., to a decrease of 1.28 ft, or an average decrease in elevation of 0.128 ft per year, at PAM 07 located north of Jersey Village, Tex.

Measured land-surface-elevation changes during 2005–10 (December 31, 2005, to December 31, 2010) ranged from an increase of 0.07 ft, or an average increase in elevation of 0.014 ft per year, at PAM 09 located in far northeastern Harris County to a decrease of 0.51 ft, or an average decrease in elevation of 0.102 ft per year, at PAM 07 located north of Jersey Village. The spatial distribution of the land-surface-elevation changes are related to areas affected by increases in groundwater withdrawals such as HGSD Regulatory Area 3 and Fort Bend, Montgomery, and Brazoria Counties (areas undergoing decreases in land-surface elevation) or areas affected by decreases in withdrawals such as HGSD Area 1 (areas undergoing increases in land-surface elevation or no change in elevation).

These land-surface-elevation changes occur slowly and nonuniformly across the study area because of a variety of reasons. Some of the reasons for differences in land-surface-elevation changes include (1) the heterogeneity of the aquifer system; (2) inconsistent distribution and variable rates of precipitation that cause more groundwater to be withdrawn during below average periods or, conversely, less water withdrawn during above average periods; and most importantly (3) the spatial and temporal patterns of groundwater withdrawals stipulated by the regulatory policies of the HGSD, FBSD, LSGCD, and BCGCD. Therefore, in areas where withdrawals were restricted or areas where withdrawals were unrestricted, decreases and increases (respectively) in land-surface elevation can occur.

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