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Prepared in cooperation with the Harris-Galveston Subsidence District, City of Houston, Fort Bend Subsidence District, Lone Star Groundwater Conservation District, and Brazoria County Groundwater Conservation District

Water-Level Altitudes 2017 and Water-Level Changes in the Chicot, Evangeline, and Jasper Aquifers and Compaction 1973–2016 in the Chicot and Evangeline Aquifers, Houston-Galveston Region, Texas

Scientific Investigations Report 2017–5080

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

Front cover:

Top left, Abandoned well, Grimes County, Tex., 1987 (photograph by Dexter W. Brown, U.S. Geological Survey).

Top middle, Piezometer and steel tape near Texas City, Tex., July 22, 2005 (photograph by Dexter W. Brown, U.S. Geological Survey).

Top right, U.S. Geological Survey hydrologist Jason Ramage taking a water-level measurement with a steel tape near Freeport, Tex., January 3, 2016 (photograph by Sachin D. Shah, U.S. Geological Survey).

Bottom right, Abandoned well showing the effects of subsidence near Houston, Texas (photograph by the U.S. Geological Survey).

Bottom left, San Jacinto River Authority piezometer near Conroe, Tex., June 2014 (photograph by Dexter W. Brown, U.S. Geological Survey).

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RYAN K. ZINKE, Secretary

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Transmissivity	
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)

International System of Units to U.S. customary units

Multiply	By	To obtain
	Volume	
liter (L)	33.81	ounce, fluid (fl. oz)
liter (L)	2.113	pint (pt)
liter (L)	1.057	quart (qt)
liter (L)	0.2642	gallon (gal)
liter (L)	61.02	cubic inch (in^3)
	Mass	
milligram (mg)	0. 00003527	ounce, avoirdupois (oz)

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C = (°F - 32) / 1.8.$$

Datum

Vertical coordinate information is referenced to either the National Geodetic Vertical Datum of 1929 (NGVD 29) or the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Water-Level Altitudes 2017 and Water-Level Changes in the Chicot, Evangeline, and Jasper Aquifers and Compaction 1973–2016 in the Chicot and Evangeline Aquifers, Houston-Galveston Region, Texas

By Mark C. Kasmarek and Jason K. Ramage

Abstract

Most of the land-surface subsidence in the Houston-Galveston region, Texas, has occurred as a direct result of groundwater withdrawals for municipal supply, commercial and industrial use, and irrigation that depressured and dewatered the Chicot and Evangeline aquifers, thereby causing compaction of the aquifer sediments, mostly in the fine-grained silt and clay layers. This report, prepared by the U.S. Geological Survey in cooperation with the Harris-Galveston Subsidence District, City of Houston, Fort Bend Subsidence District, Lone Star Groundwater Conservation District, and Brazoria County Groundwater Conservation District, is one in an annual series of reports depicting water-level altitudes and water-level changes in the Chicot, Evangeline, and Jasper aquifers and measured cumulative compaction of subsurface sediments in the Chicot and Evangeline aquifers in the Houston-Galveston region. This report contains regional-scale maps depicting approximate 2017 water-level altitudes (represented by measurements made during December 2016 through March 2017) and long-term water-level changes for the Chicot, Evangeline, and Jasper aquifers; a map depicting locations of borehole-extensometer (hereinafter referred to as "extensometer") sites; and graphs depicting measured long-term cumulative compaction of subsurface sediments at the extensometers during 1973–2016.

In 2017, water-level-altitude contours for the Chicot aquifer ranged from 200 feet (ft) below the North American Vertical Datum of 1988 (hereinafter referred to as "datum") in two localized areas in southwestern and northwestern Harris County to 200 ft above datum in west-central Montgomery County. The largest water-level-altitude decline (120 ft) depicted by the 1977–2017 water-level-change contours for the Chicot aquifer was in northwestern Harris County. A broad area where water-level altitudes declined in the Chicot aquifer extends from northwestern, north-central, and southwestern Harris County across parts of north-central, eastern, and south-central Fort Bend County into southeastern Waller County. Adjacent to the areas where water levels declined was a broad area where water levels rose in central, eastern, and southeastern Harris County, most of Galveston County, eastern and northernmost Brazoria County, and northeastern Fort Bend County. The largest rise (200 ft) in water-level altitudes in the Chicot aquifer from 1977 to 2017 was in southeastern Harris County.

The water-level-altitude contours for the Evangeline aquifer in 2017 indicated two areas where the water-level altitudes were 250 ft below datum—one area extending from south-central Montgomery County into north-central Harris County and another area in western Harris County. Water-level altitudes in the Evangeline aquifer ranged from 50 to 200 ft below datum throughout most of Harris County in 2017. In Montgomery County, water-level altitudes in the Evangeline aquifer in 2017 ranged from the aforementioned area where they were 250 ft below datum to an area where they were 200 ft above datum in the northwestern part of the county. The 1977–2017 water-level-change contours for the Evangeline aquifer depict a broad area where water-level altitudes declined in north-central Harris and south-central Montgomery Counties, extending through north-central, northwestern, and southwestern Harris County into western Liberty, southeastern and northeastern Waller, and northeastern and east-central Fort Bend Counties. The largest water-level-altitude decline (280 ft) was in north-central Harris and south-central Montgomery Counties. Water-level altitudes rose in a broad area from central, east-central, and southern Harris County extending into the northernmost part of Brazoria County, the northernmost part of Galveston County, and the southwestern area of Liberty County. The largest rise in water-level altitudes in the Evangeline aquifer from 1977 to 2017 (240 ft) was in southeastern Harris County.

Water-level-altitude contours for the Jasper aquifer in 2017 ranged from 200 ft below datum in three isolated areas of south-central Montgomery County (the westernmost of these areas extended slightly into north-central Harris County) to 250 ft above datum in extreme northwestern Montgomery County, northeastern Grimes County, and southwestern Walker County. The 2000–17 water-level-change contours

for the Jasper aquifer depict water-level declines in a broad area throughout most of Montgomery County and in parts of Waller, Grimes, and Harris Counties, with the largest decline (220 ft) in an isolated area in south-central Montgomery County.

Compaction of subsurface sediments (mostly in the fine-grained silt and clay layers) in the Chicot and Evangeline aquifers was recorded continuously by using 13 extensometers at 11 sites that were either activated or installed between 1973 and 1980. During the period of record beginning in 1973 (or later depending on activation or installation date) and ending in late November or December 2016, measured cumulative compaction at the 13 extensometers ranged from 0.096 ft at the Texas City-Moses Lake extensometer to 3.700 ft at the Addicks extensometer. From January through late November or December 2016, the Addicks, Lake Houston, Southwest, and Northeast extensometers recorded net decreases in land-surface elevation, but the Baytown C–1 (shallow), Baytown C–2 (deep), Clear Lake (shallow), Clear Lake (deep), East End, Johnson Space Center, Pasadena, Seabrook, and Texas City-Moses Lake extensometers recorded net increases in land-surface elevation.

The rate of compaction varies from site to site because of differences in rates of groundwater withdrawal in the areas adjacent to each extensometer site; differences among sites in the ratios of sand, silt, and clay and their corresponding compressibilities; and previously established preconsolidation heads. It is not appropriate, therefore, to extrapolate or infer a rate of compaction for an adjacent area on the basis of the rate of compaction recorded by proximal extensometers.

Introduction

Allen (1969) described ground-surface displacement as the last step of a variety of subsurface displacement mechanisms that included (among others) compaction of aquifer sediments by loading, drainage, vibration, and hydrocompaction. The Houston-Galveston region, Texas—consisting of Harris, Galveston, Fort Bend, Montgomery, Brazoria, Chambers, Grimes, Liberty, San Jacinto, Walker, and Waller Counties (fig. 1)—represents one of the largest areas of ground-surface displacement (also called land-surface subsidence and hereinafter referred to as "subsidence") in the United States (Coplin and Galloway, 1999). According to Coplin and Galloway (1999, p. 40), by 1979, as much as 10 feet (ft) of subsidence had occurred in the Houston-Galveston region, and approximately 3,200 square miles (mi^2) of the 11,000-mi^2 geographic area had subsided more than 1 ft. Comparing land-surface elevations for 1915–17 to those for 2001, Kasmarek, Gabrysch, and Johnson (2010, sheet 2) determined that as much as 13 ft of subsidence in a small, localized area had occurred in southeastern Harris County during the historical period.

Subsidence has been linked to hydrocarbon extraction and groundwater withdrawals in the Houston-Galveston region and was first documented in the region in 1926, at the Goose Creek Oil Field in southeastern Harris County (fig. 1) (Pratt and Johnson, 1926). Although subsidence was first identified in the Houston-Galveston region as a result of hydrocarbon extraction at this particular oil field, most of the subsidence in the Houston-Galveston region is a direct result of groundwater withdrawals that have depressured and dewatered the Chicot and Evangeline aquifers, thereby causing compaction of the aquifer sediments (Winslow and Doyel, 1954; Winslow and Wood, 1959; Gabrysch and Bonnet, 1975; Gabrysch, 1984; Holzer and Bluntzer, 1984; Kasmarek, Gabrysch, and Johnson, 2010).

Groundwater withdrawn from the Chicot, Evangeline, and Jasper aquifers has been the primary source of water for municipal supply, commercial and industrial use, and irrigation in the Houston-Galveston region since the early 1900s (Kasmarek and Robinson, 2004). Prior to 1975, the withdrawal of groundwater from the Chicot and Evangeline aquifers was unregulated, and water levels in the aquifers were declining with associated depressuring, dewatering, and compaction resulting in subsidence (Coplin and Galloway, 1999). By 1977, groundwater withdrawals had caused water-level altitudes in southeastern Harris County to decline by as much as 300 ft in the Chicot aquifer and by as much as 350 ft in the Evangeline aquifer (as indicated by long-term changes in water-level-altitude contours referenced to the North American Vertical Datum of 1988 [NAVD 88]) (Gabrysch, 1979). Attendant with these declines in water-level altitudes, by 1979, as much as 10 ft of subsidence had occurred in the Houston-Galveston region (Coplin and Galloway, 1999).

Subsidence is of particular concern in low-lying coastal areas such as the Houston-Galveston region. Subsidence in the region has increased the frequency and severity of flooding (Coplin and Galloway, 1999). Low-pressure weather systems such as tropical storms and hurricanes result in high rates of precipitation and cause high tides to reach farther inland. Storm surge is an abnormal rise of water generated by a storm, over and above the normal astronomical tides (National Oceanic and Atmospheric Administration, 2001, 2015). Subsidence exacerbates the effects of storm surge and impedes stormwater runoff by creating areas of decreased land-surface elevations where water accumulates. Subsidence has shifted the shoreline along Galveston Bay, as evidenced by the inundation of the Brownwood Subdivision associated with Hurricane Alicia in August 1983 near Baytown, Tex., and adjacent areas in the Houston-Galveston region (fig. 1), thereby changing the distribution of wetlands and aquatic vegetation (Coplin and Galloway, 1999).

To address the issues associated with subsidence and subsequent increased flooding, the 64th Texas State Legislature in 1975 authorized the establishment of the Harris-Galveston Subsidence District (HGSD) (fig. 1) to regulate and reduce groundwater withdrawals in Harris and Galveston Counties (Harris-Galveston Subsidence District, 2013). In cooperation with the HGSD, the U.S. Geological Survey (USGS) has monitored water levels in wells screened

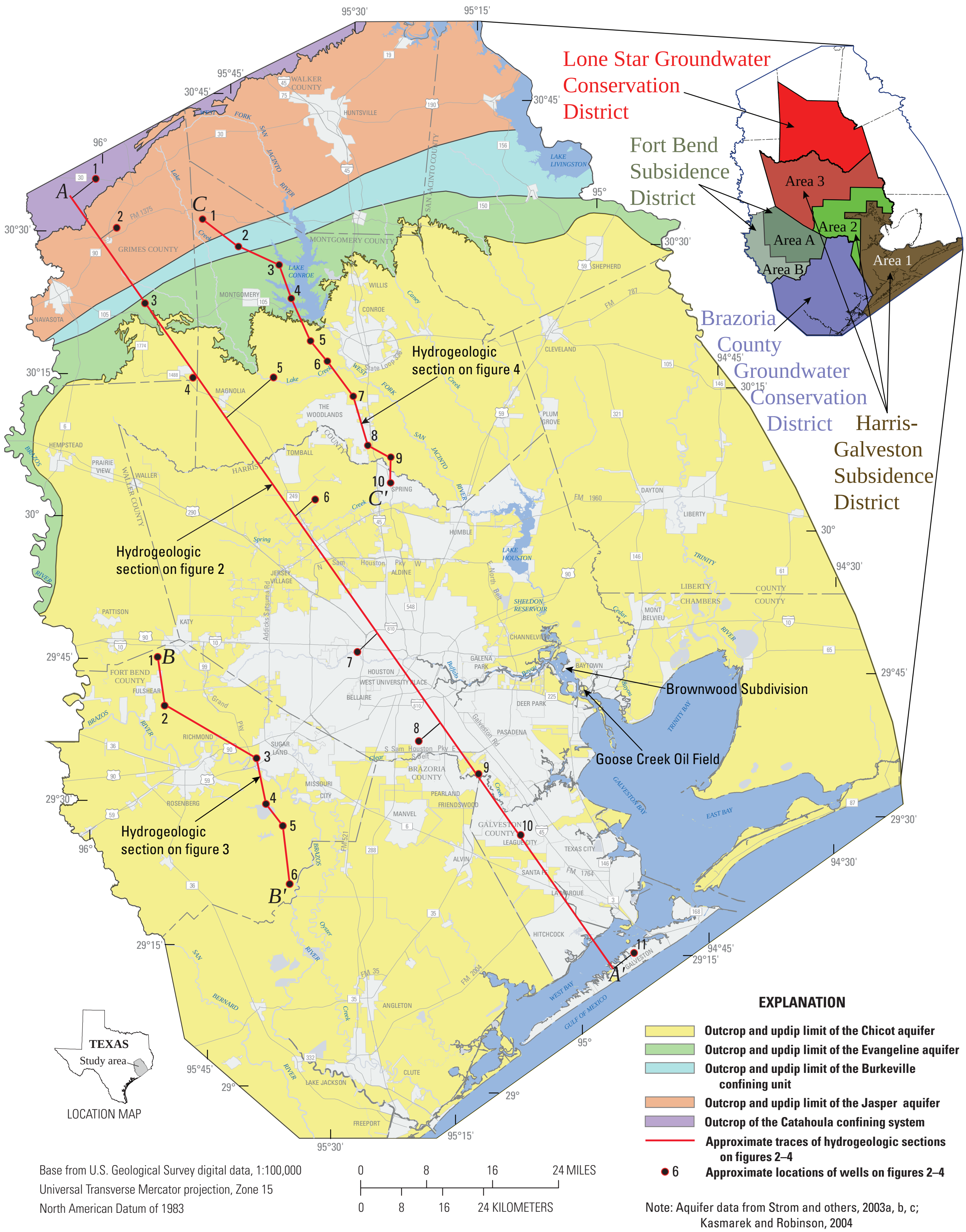


Figure 1. Locations of groundwater regulatory districts; approximate traces of hydrogeologic sections *A–A′*, *B–B′*, and *C–C′*; and outcrops and updip limits of the aquifers in the Gulf Coast aquifer system in the Houston-Galveston region study area, Texas, 2017 (modified from Strom and others, 2003a, b, c; Kasmarek and Robinson, 2004).

in the Chicot and Evangeline aquifers and compaction of subsurface sediments in Harris and Galveston Counties since 1976. The USGS has published annual reports depicting water-level altitudes and water-level changes for the Chicot and Evangeline aquifers in the Houston-Galveston region beginning with the 1977 water-level-altitude maps (Gabrysch, 1979). Subsequently, the monitoring of groundwater levels was expanded into the Fort Bend subregion (encompassing Fort Bend County and adjacent areas), and the first water-level-altitude maps for this area were created and presented in the 1991 water-level report (Barbie and others, 1991) and subsequently revised in 1997 (Kasmarek, 1997). The USGS published its first report on water-level altitudes and water-level changes for the Jasper aquifer in the Houston-Galveston region (primarily Montgomery County) in 2001 (Coplin, 2001). Water-level altitudes and water-level changes for the Jasper aquifer were subsequently the subject of a detailed assessment on water-level altitudes in 2007 and water-level changes in the Chicot, Evangeline, and Jasper aquifers; this assessment was part of report that also depicted compaction during 1973–2006 in the Chicot and Evangeline aquifers (Kasmarek and Houston, 2007).

The cumulative compaction data from a network of 13 borehole extensometers (hereinafter referred to as "extensometers") in the Houston-Galveston region have been presented in USGS reports of annual water-level altitudes and water-level changes since 1981 (cumulative compaction during 1973–81; Gabrysch and Ranzau, 1981). Earlier USGS reports documented the occurrence of subsidence in the study area determined by the reoccupation and releveling of a network of benchmarks by using spirit-leveling techniques during the periods 1906–51 (Winslow and Doyel, 1954), 1906–78, 1943–78, and 1973–78 (Gabrysch, 1984). Most recently, Kasmarek and others (2016) depicted 2016 water-level altitudes and changes for various periods in the Chicot, Evangeline, and Jasper aquifers and cumulative compaction recorded by the 13 extensometers during 1973–2015 in the Chicot and Evangeline aquifers.

Subsequent to establishing the HGSD, the Texas State Legislature established an additional subsidence district (Fort Bend Subsidence District [FBSD]) and two groundwater conservation districts (Lone Star Groundwater Conservation District [LSGCD] and, most recently, Brazoria County Groundwater Conservation District [BCGCD]) in the Houston-Galveston region to provide for the regulation of groundwater withdrawals in areas within their jurisdiction. The FBSD was established by the 71st Texas State Legislature in 1989 and has jurisdiction throughout Fort Bend County (fig. 1). The FBSD is divided into area A, which includes the Richmond-Rosenberg subarea, and area B. The primary purpose of the FBSD is to regulate groundwater withdrawals to prevent subsidence that contributes to flooding (Fort Bend Subsidence District, 2013). The LSGCD was established by the 77th Texas State Legislature in 2001 and has jurisdiction throughout Montgomery County (fig. 1). The purpose of the LSGCD is to conserve, protect, and enhance the groundwater resources of Montgomery County (Lone Star Groundwater Conservation District, 2013). The BCGCD was established by the 78th Texas State Legislature in 2003 with the purpose to maintain the quality and availability of Brazoria County's (fig. 1) groundwater resources for current users and future generations (Brazoria County Groundwater Conservation District, 2012). Regulatory plans to gradually decrease groundwater withdrawals by increased usage of alternative surface-water supplies are being phased in; the current (2017) groundwater management plans of each district are available on their respective websites (Brazoria County Groundwater Conservation District, 2012; Fort Bend Subsidence District, 2013; Harris-Galveston Subsidence District, 2013; Lone Star Groundwater Conservation District, 2013). Currently (2017), groundwater withdrawals are not being regulated by a groundwater conservation district in Liberty and Chambers Counties.

In 1976, the HGSD began implementing its first groundwater regulatory plan (Harris-Galveston Subsidence District, 2013). An extensive well-monitoring network was established by 1977, and water-level data were collected and used to create the first published water-level-altitude maps of the Chicot and Evangeline aquifers in the Houston-Galveston region (Gabrysch, 1979). The FBSD adopted its groundwater management plan in 1990 (Fort Bend Subsidence District, 2013), and in cooperation with the FBSD, an increased number of wells were inventoried by the USGS in Fort Bend, Harris, Brazoria, and Waller Counties in 1989 and 1990. A more comprehensive water-level-altitude report for the Chicot and Evangeline aquifers was published by the USGS in 1991 (Barbie and others, 1991), and when updated well data became available, that water-level-altitude report was revised in 1997 (Kasmarek, 1997). Similarly, after the establishment of the LSGCD in 2001, the USGS first published a water-level-altitude map of the Jasper aquifer in the Houston-Galveston region (primarily Montgomery County) (Coplin, 2001). In 2004, 2006, and 2007, as additional wells with reliable water-level data were inventoried, revised water-level-altitude maps for the Jasper aquifer were prepared (Kasmarek and Lanning-Rush, 2004; Kasmarek and others, 2006; Kasmarek and Houston, 2007). In comparison to the 2001 (Coplin, 2001) and 2004 (Kasmarek and Lanning-Rush, 2004) reports, the 2007 water-level-altitude map (Kasmarek and Houston, 2007) was the most comprehensive for the Jasper aquifer in the study area prepared at that time. Since 2007, similarly comprehensive maps for the Jasper aquifer have been included in an annual series of reports that depict water-level altitudes and water-level changes in the Chicot, Evangeline, and Jasper aquifers and cumulative compaction in the Chicot and Evangeline aquifers in the Houston-Galveston region (Kasmarek and Houston, 2008; Kasmarek, Johnson, and Ramage, 2010; Johnson and others, 2011; Kasmarek and others, 2011, 2012, 2013, 2014, 2015, 2016).

Purpose and Scope

This report, prepared by the USGS in cooperation with the HGSD, City of Houston, FBSD, LSGCD, and BCGCD, is one in an annual series of reports depicting water-level altitudes and water-level changes (the differences between water-level altitudes at specific points [wells]) in the Chicot, Evangeline, and Jasper aquifers and measured cumulative compaction (hereinafter referred to as “cumulative compaction”) of fine-grained subsurface sediments in the Chicot and Evangeline aquifers in the Houston-Galveston region. A summary of the hydrogeology of the study area is provided, and the mechanism of compaction and subsidence is described. Regional-scale maps depicting approximate contoured 2017 water-level altitudes in the Chicot, Evangeline, and Jasper aquifers are featured, along with maps depicting approximate contoured long-term (1977–2017) water-level changes for the Chicot and Evangeline aquifers and a map depicting approximate contoured long-term (2000–17) water-level changes for the Jasper aquifer.

In addition to maps depicting water-level altitudes and long-term water-level changes in the Chicot, Evangeline, and Jasper aquifers, this report contains a map depicting the locations of the 13 extensometers at 11 sites in Harris and Galveston Counties that were activated or installed between 1973 and 1980. At these sites, the 13 extensometers continuously record cumulative compaction of subsurface sediments of the Chicot and Evangeline aquifers. Graphs are presented of the long-term cumulative compaction data recorded by the 13 extensometers from 1973 (or later depending on activation or installation date) through 2016. For all three aquifers (Chicot, Evangeline, and Jasper), the point data (individual water-level altitudes measured at each well), contour data, and associated metadata are available for download in a companion data release (Kasmarek and Ramage, 2017). The metadata are compliant with geospatial metadata standards (Federal Geographic Data Committee, 2015). Compaction data for the 13 extensometers are available in a second companion data release (Ramage, 2017).

Hydrogeology of the Study Area

The three primary aquifers in the Gulf Coast aquifer system in the Houston-Galveston region study area are the Chicot, Evangeline, and Jasper (figs. 2–5), which are composed of laterally discontinuous deposits of gravel, sand, silt, and clay. The youngest and uppermost aquifer, the Chicot aquifer, consists of Holocene- and Pleistocene-age sediments; the underlying Evangeline aquifer consists of Pliocene- and Miocene-age sediments; and the oldest and most deeply buried of the three aquifers, the Jasper aquifer, consists of Miocene-age sediments (fig. 2) (Baker, 1979, 1986). The lowermost unit of the Gulf Coast aquifer system is the Miocene-age Catahoula confining system, which includes the Catahoula Sandstone. The Catahoula confining system consists of sands in the upper section and clay and tuff interbedded with sand in the lower section (figs. 2 and 4).

The percentage of clay and other fine-grained clastic material generally increases with depth downdip (Baker, 1979). Through time, geologic and hydrologic processes created accretionary sediment wedges (stacked sequences of sediments) more than 7,600 ft thick at the coast (fig. 2) (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 worldwide episodic changes in sea level (eustasy) that occurred as a result of oscillations between glacial and interglacial climate conditions (Lambeck and others, 2002). The Gulf Coast aquifer system consists of hydrogeologic units that dip and thicken from northwest to southeast (fig. 2); 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 (Kasmarek, 2013, figs. 4–7). The Burkeville confining unit is stratigraphically positioned between the Evangeline and Jasper aquifers (figs. 2–5), thereby restricting groundwater flow between the Evangeline and Jasper aquifers. There is no confining unit between the Chicot and Evangeline aquifers; therefore, the aquifers are hydraulically connected, which allows groundwater flow between the aquifers (figs. 2–4). Because of this hydraulic connection, water-level changes that occur in one aquifer can affect water levels in the adjoining aquifer (Kasmarek and Robinson, 2004). Supporting evidence of the interaction of groundwater flow between the Chicot and Evangeline aquifers is demonstrated by comparing the two long-term (1977–2016) water-level-change maps (Kasmarek and others, 2016, sheets 5 and 10), which indicate that the areas where water levels have risen or declined are approximately spatially coincident. Hydraulic properties of the Chicot aquifer do not differ appreciably from the hydrogeologically similar Evangeline aquifer but can be differentiated on the basis of hydraulic conductivity (Carr and others, 1985, p. 10). From aquifer-test data, Meyer and Carr (1979) estimated that the transmissivity of the Chicot aquifer ranges from 3,000 to 25,000 feet squared per day (ft^2/d) and that the transmissivity of the Evangeline aquifer ranges from 3,000 to 15,000 ft^2/d. The Chicot aquifer outcrops and extends inland from the Gulf of Mexico coast and terminates at the northernmost updip limit of the aquifer. Proceeding updip and inland of the Chicot aquifer, the older hydrogeologic units of the Evangeline aquifer, the Burkeville confining unit, the Jasper aquifer, and the Catahoula confining system sequentially outcrop (fig. 1). In the outcrop and updip areas of the Jasper aquifer, the aquifer can be differentiated from the Evangeline aquifer on the basis of the depths to water below land-surface datum (blsd), which are shallower (closer to land surface) in the Jasper aquifer compared to those in the Evangeline aquifer. Additionally, in the downdip parts of the aquifer system, the Jasper aquifer can be differentiated from the Evangeline aquifer on the basis of stratigraphic position relative to the elevation of the Burkeville confining unit (figs. 2–4).

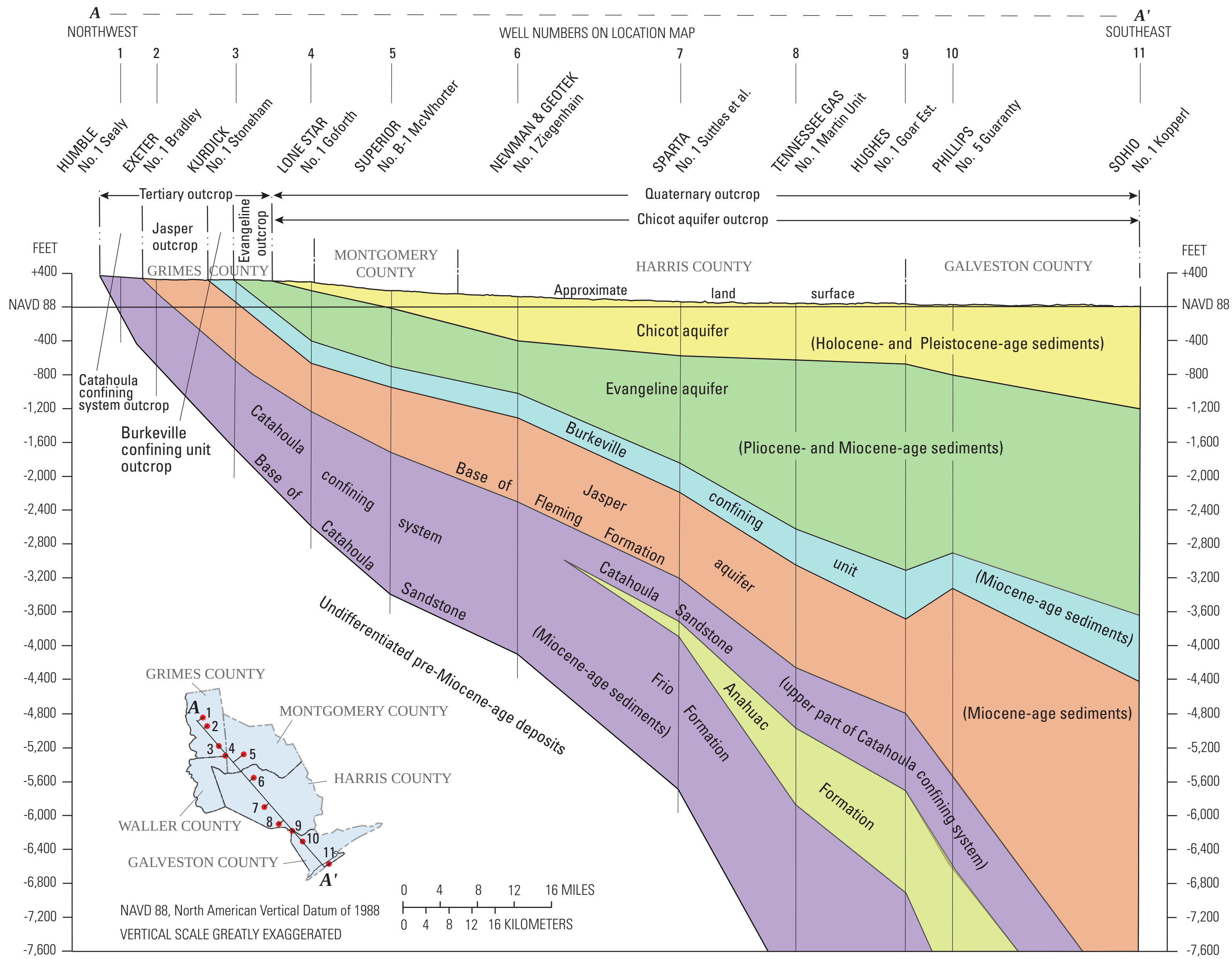


Figure 2. Hydrogeologic section *A–A′* of the Gulf Coast aquifer system in Grimes, Montgomery, Harris, and Galveston Counties, Texas (modified from Baker, 1979, fig. 4).

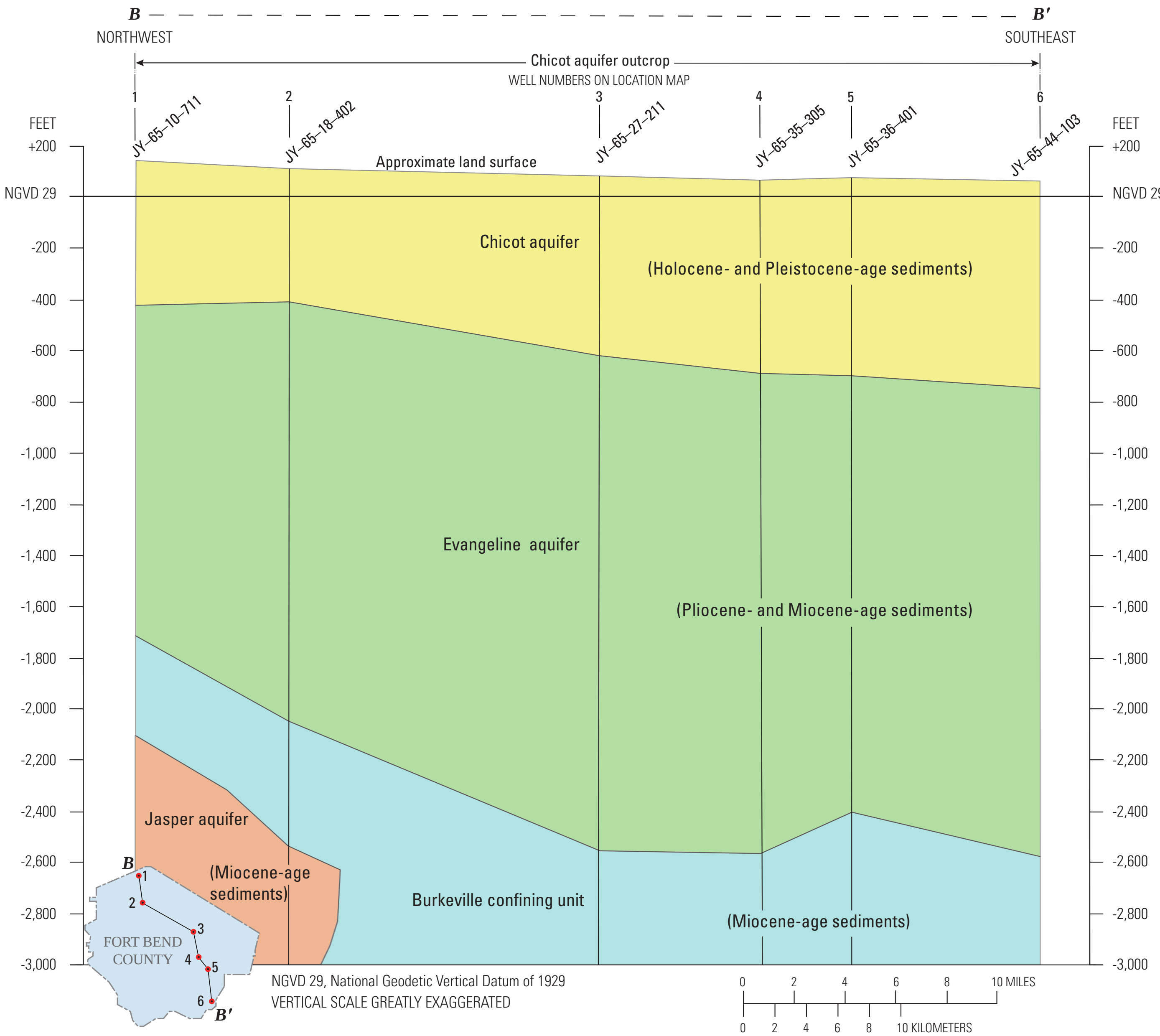


Figure 3. Hydrogeologic section *B–B′* of the Gulf Coast aquifer system in Fort Bend County, Texas (modified from Wesselman, 1972, fig. 30).

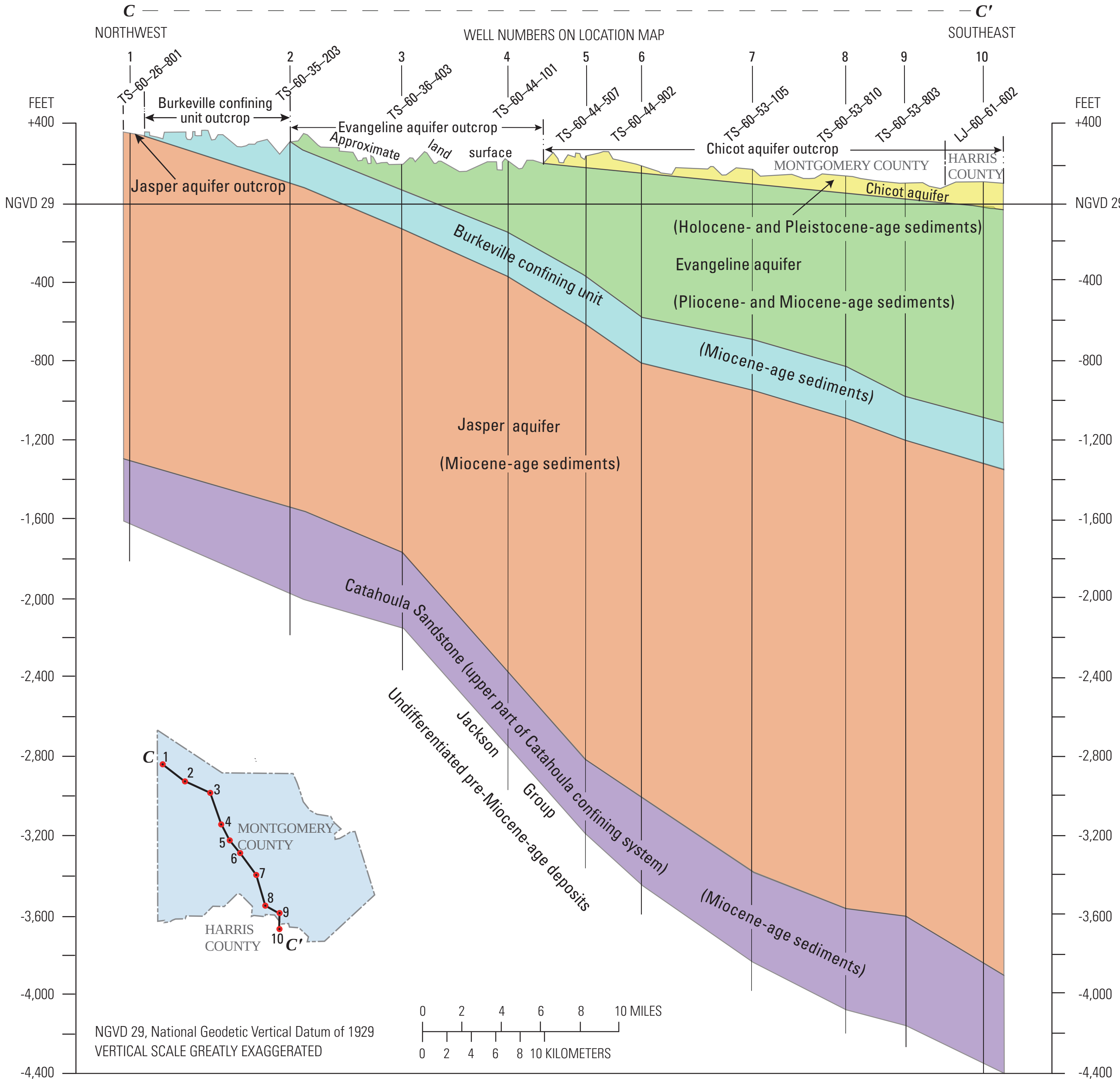
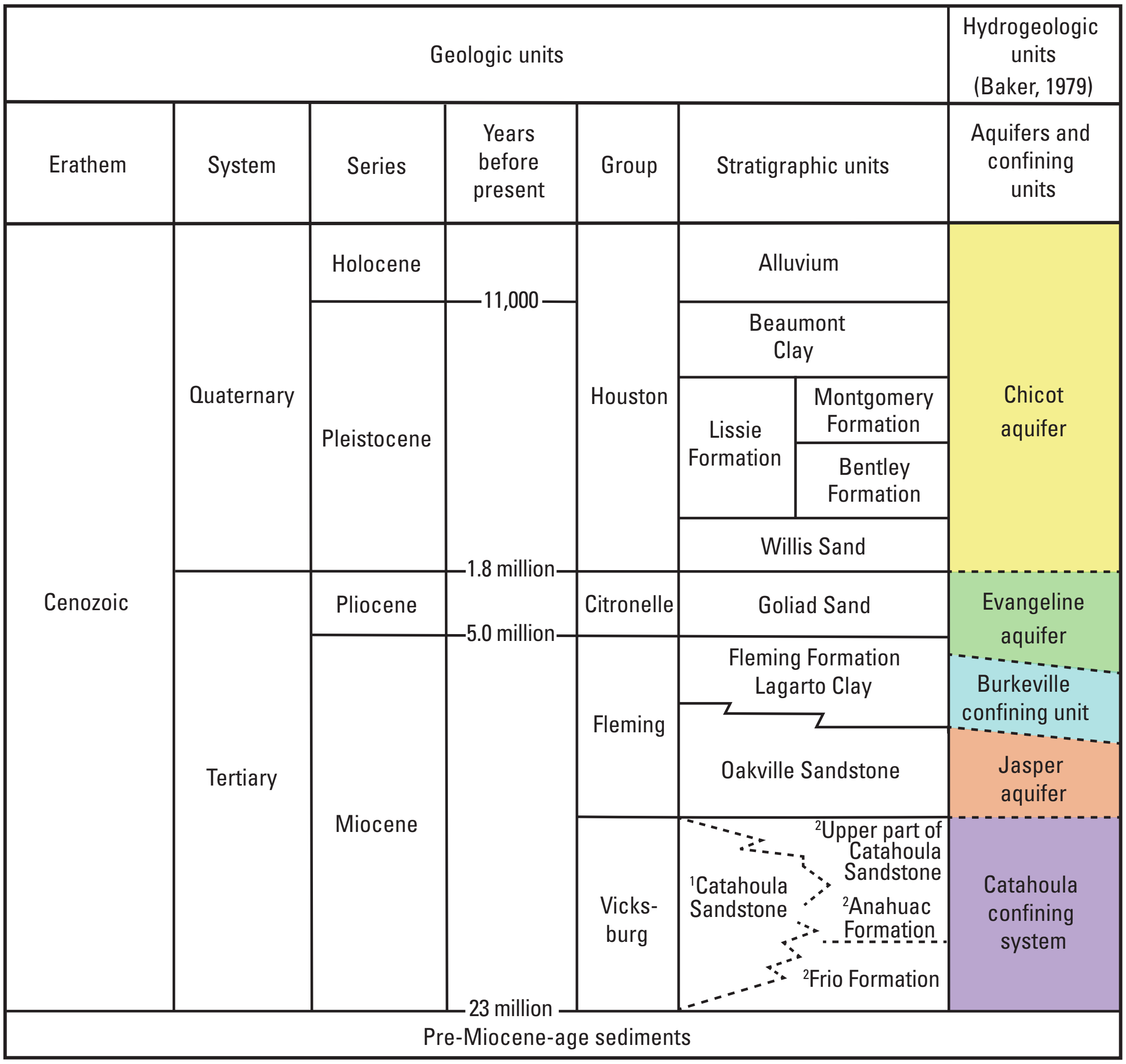


Figure 4. Hydrogeologic section *C–C′* of the Gulf Coast aquifer system in Montgomery and Harris Counties, Texas (modified from Popkin, 1971, fig. 29).



[1]Located in the outcrop.
[2]Located in the subcrop.

Figure 5. Geologic and hydrogeologic units of the Gulf Coast aquifer system in the Houston-Galveston region study area, Texas (modified from Sellards and others, 1932; Baker, 1979; Meyer and Carr, 1979).

The hydrogeologic cross section *A–A′* (fig. 2) extends through the Houston-Galveston region from northwestern Grimes County southeastward through Montgomery and Harris Counties before terminating at the coast in Galveston County; the Chicot, Evangeline, and Jasper aquifers thicken and dip toward the coast from their updip (outcrop) limits. Comparisons of cross sections *A–A′* (fig. 2) and *C–C′* (fig. 4) indicate that the thicknesses of the three aquifers similarly increase downdip towards the coast. In Montgomery and Grimes Counties, the saturated thickness of the sediments composing the Chicot aquifer (figs. 2 and 4) is effectively insufficient for most groundwater withdrawals except for low-volume domestic withdrawals. The hydrogeologic cross section *C–C′* (fig. 4) extends through Montgomery County into extreme northern Harris County and similarly indicates that sediment thickness of the aquifers progressively decreases towards the northwest updip limit. Compared to the appreciable downdip changes in saturated thicknesses of the Chicot and Evangeline aquifers depicted in hydrogeologic cross sections *A–A′* and *C–C′*, the saturated thicknesses of the Chicot and Evangeline aquifers moving downdip along hydrogeologic cross section *B–B′* are relatively constant (only a small part of the Jasper aquifer is present in hydrogeologic cross section *B–B′*) (fig. 3).

The water quality of the Chicot, Evangeline, and Jasper aquifers in the Houston-Galveston region varies spatially and with depth. For the most part, the groundwater is classified as fresh (less than 1,000 milligrams per liter [mg/L] dissolved-solids concentration [Freeze and Cherry, 1979]). Concentrations of dissolved solids range from less than 500 mg/L in the updip parts of the aquifers to more than 10,000 mg/L in the downdip and more deeply buried, confined parts of the aquifers near the coast (Baker, 1979; Peter and others, 2011). Precipitation falling on the land surface overlying these aquifers returns to the atmosphere as evapotranspiration, discharges to streams, or infiltrates as groundwater recharge to the unconfined updip sediments composing the aquifers. The infiltrating water moves downgradient, reaching the intermediate and deep zones of the aquifers southeastward of the outcrop areas; regionally, the recharged water also moves downgradient toward the coast into the intermediate and deep zones of the aquifers, where it can be withdrawn and discharged by wells or is naturally discharged by diffuse upward leakage in topographically low areas near the coast (Kasmarek and Robinson, 2004). Water in the coastal, deep zones of the aquifers is denser, and this higher density water causes the fresher, lower density water that has not been captured and withdrawn by wells to be redirected as diffuse upward leakage to shallow zones of the confined downdip areas of the aquifer system. Remaining water not withdrawn by wells ultimately discharges along the coast, providing inflows to the brackish (dissolved-solids concentrations of 1,000–10,000 mg/L [Freeze and Cherry, 1979]) waters of the coastal bays and estuaries (Kasmarek and Robinson, 2004).

Subsidence and Compaction Processes

Subsidence can occur as a result of potentiometric surface declines in unconsolidated confined aquifers (Galloway and others, 1999). Potentiometric surface declines 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. 6). Because sand layers are more transmissive and less compressible than are fine-grained silt and clay layers, sand layers depressure more rapidly compared to silt and clay layers. In addition, when groundwater withdrawals are decreased, pressure equilibrium is reestablished more rapidly in the sand layers compared to the silt and clay layers, and the amount of compaction of the sand layers is usually minor compared to the amount of compaction of the silt and clay layers (Trahan, 1982; Galloway and others, 1999). The silt and clay layers are often interbedded within the sand layers, and when depressuring occurs, the silt and clay layers dewater more slowly compared to the sand layers. The compressibility of the silt and clay layers is dependent on the thickness and hydraulic characteristics of the silt and clay layers and the vertical stress of the saturated and unsaturated sediment overburden. Slow drainage of the silt and clay layers continues to occur until the residual excess pore pressure in the silt and clay layers equilibrates with the pore pressure of the adjacent sand layers (Kasmarek, 2013). As dewatering progresses, compaction of the silt and clay layers continues until hydraulic pressure equilibrium is attained. A similar loading process occurs in the sand layers; however, the major difference is that the individual silt and clay grains spatially rearrange as depressuring and dewatering progress, finally becoming perpendicular to the applied vertical overburden load (Galloway and others, 1999). Essentially, the water stored in the silt and clay layers prior to depressuring provides interstitial pore-space support to the skeletal matrix of the silt and clay grains. As water levels continue to decline, the silt and clay layers continue to dewater, depressure, and compact. Additionally, compaction of the silt and clay layers reduces the porosity and groundwater-storage capacity of the silt and clay layers (fig. 6). Because most compaction of subsurface sediments is inelastic, with about 90 percent of the compaction considered permanent, only a small amount of rebound of the land-surface elevation can occur (Gabrysch and Bonnet, 1975). Although the compaction of one thin silt and clay layer generally will not cause a measureable decrease in the land-surface elevation, when numerous stratigraphic sequences of sand layers and silt and clay layers (characteristic of the Gulf Coast aquifer system) depressure and compact, a measureable amount of subsidence often occurs (Gabrysch and Bonnet, 1975).

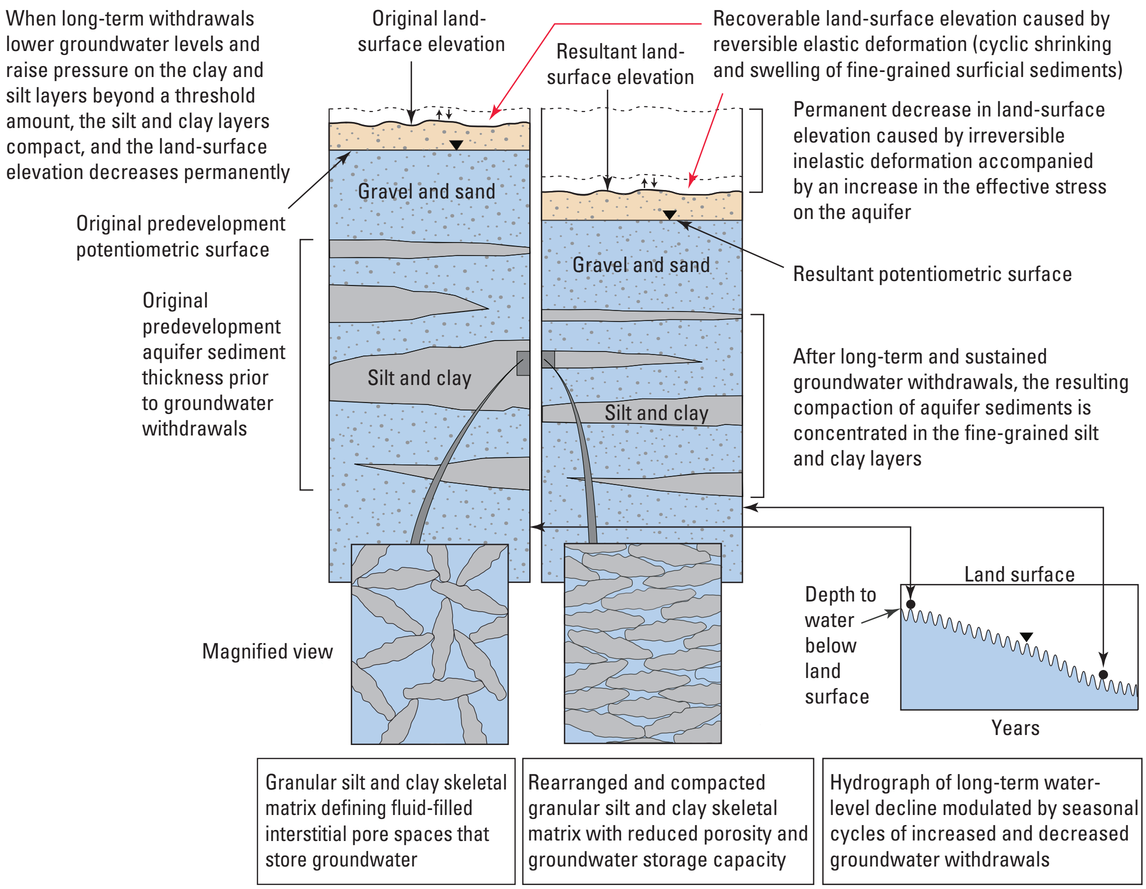


Figure 6. Mechanism of subsidence caused by potentiometric surface declines induced by groundwater withdrawals in an aquifer composed of gravel, sand, silt, and clay (modified from Galloway and others, 1999, p. 9).

Data-Collection and Analysis Methods

Water-level data were obtained from observation wells by measuring the depth to water blsd at each well. Measurements were made by USGS personnel by using a calibrated steel tape, airline, or electric water-level tape in accordance with methods described in Cunningham and Schalk (2011). Water-level data also were provided by industrial entities and powerplants within the study area that use water for hydrocarbon processing and electrical power generation, respectively. Most of the measured wells were being pumped at least once daily and some more frequently during the period of this study. Well pumps were inoperative for at least 1 hour before the water-level measurements were made in order to obtain a water-level measurement that approximates the static conditions within the aquifer. Antecedent withdrawal rates and pumping status of nearby wells were not always known, however, and in such instances could have affected the representativeness of the water-level data that were collected. To ensure that the water-level measurement recorded was accurate, at least two water-level-altitude measurements were made at each well while the well was not being pumped.

To represent the annual water-level altitudes of the Chicot, Evangeline, and Jasper aquifers, water-level altitudes are usually measured from December through March; the 2017 water-level altitudes discussed in this report were measured from December 2016 through March 2017. Water-level altitudes in the Houston-Galveston region are usually higher during December through March compared to the rest of the year because groundwater withdrawals during these months generally are at an annual minimum; during these winter months, the temperatures are cooler, and less water is used for agricultural and residential (lawn) irrigation purposes compared to the rest of the year. Conversely, water-level altitudes in the aquifers decline during the warm summer and early fall months because there is usually less precipitation and groundwater withdrawals are much larger compared to other months of the year. After the water-level-measurement data were collected during December 2016 through March 2017, they were thoroughly evaluated and incorporated into a geographic information system (GIS) as point-data layers and subsequently used for the construction of water-level-altitude and water-level-change maps (Kasmarek and Ramage, 2017).

Determination of Water-Level Altitudes

The annual (2017) regional-scale depictions of water-level altitudes presented in this report were derived from water-level-measurement data collected during December 2016 through March 2017 throughout the 11-county study area. The water levels in the aquifers are constantly changing in response to changes in hydrologic conditions, groundwater withdrawal rates, and precipitation. Therefore, the depictions of water-level altitude represent aquifer conditions at the time the water-level data were collected. These water-level-altitude data were calculated by subtracting the water-level measurement from the land-surface elevation value at each well referenced to NAVD 88 (National Oceanic and Atmospheric Administration, 2008). To determine land-surface elevations, a corresponding land-surface-datum value for each well was obtained by using USGS National Geospatial Program 3D Elevation Program (3DEP) values referenced to NAVD 88 (U.S. Geological Survey, 2017b). The height above land-surface elevation of the water-level measuring point of each well was measured by using an engineering ruler. The accuracy of the land-surface-elevation data has gradually improved over time, and the most accurate land-surface data available were used by the USGS for each historical annual depiction of water-level altitudes in the study area. Prior to 2016, water-level altitudes published in this annual series of USGS reports were referenced to either the National Geodetic Vertical Datum of 1929 or NAVD 88.

The 2017 water-level altitudes measured in wells completed in the Chicot, Evangeline, and Jasper aquifers are depicted on contour maps with 50-ft contour intervals. The approximate water-level-altitude contours are regional-scale depictions of the water levels in wells in the Chicot, Evangeline, and Jasper aquifers, and the areal extents and locations of these contours represent the combined effects of total groundwater withdrawals from all groundwater wells screened in the Gulf Coast aquifer system.

Quality Assurance

Protocols for the collection and review of water-level data were in accordance with the USGS Texas Water Science Center internal document “Quality Assurance and Data Management Plan for Groundwater Activities” dated January 2017 (section 5.0, “Data collection,” and section 6.0, “Data review and processing” [Christopher L. Braun, U.S. Geological Survey, written commun., 2017]). All collected data were archived in the USGS National Water Information System (NWIS) (U.S. Geological Survey, 2017a).

Depicting Changes in Water-Level Altitudes

Maps depicting changes in water-level altitudes in the Chicot, Evangeline, and Jasper aquifers were constructed for the long-term (1977–2017 [Chicot and Evangeline aquifers] and 2000–17 [Jasper aquifer]) periods. Water-level changes were computed as the difference between water-level altitudes at each point (well) for which a water-level measurement was made in 1977 or 2000 and in 2017. For wells measured in 2017 that had no corresponding measurement in 1977 or 2000, a GIS raster (gridded surface) (Worboys, 1995) was created from published 1977 (Gabrysch, 1979) or 2000 (Kasmarek and Houston, 2007) water-level-altitude contours. The maps were constructed by contouring the set of mapped point values computed either as the difference in water-level altitude at each point (well) for which a water-level measurement was made in 2017 and in 1977 or 2000 or as the difference in water-level altitude at that point in 2017 and the water-level altitude on a gridded surface of the 1977 (Gabrysch, 1979) or 2000 (Kasmarek and Houston, 2007) water-level-altitude maps. Gridded-surface values (rather than actual measured values) for the historical year were used to compute differences (mapped point values) because many of the wells measured in 1977 or 2000 have been destroyed or were not measured in 2017. For the subset of wells measured both in 2017 and in 1977 or 2000, the mapped point values used were the differences in water-level-altitude values between 2017 and 1977 or 2000 rather than the differences between the 2017 water-level-altitude values and the gridded-surface values from 1977 or 2000. The datasets of water-level-change values (difference between 2017 and 1977 or 2000 water-level-altitude values) are available in Kasmarek and Ramage (2017).

Borehole Extensometers

To construct an extensometer (example shown in fig. 7), a borehole is first drilled to a predetermined depth, generally below the depth of expected water-level decline. A steel outer casing with one or more slip joints and a screened interval is installed in the previously drilled borehole. The slip joint(s) helps to prevent crumpling and collapse of the well casing as compaction of subsurface sediments occurs, and the screened interval allows groundwater to enter the outer casing and inner casing of the piezometer, a type of small-diameter well with a screened interval that is used to measure the depth to water blsd. A substantial cement plug is installed and set at the base of the extensometer, and after the cement plug hardens, the smaller diameter inner pipe (often referred to as the “extensometer pipe”) is inserted down hole inside the outer casing and positioned to rest on the upper surface of the cement plug at depth. This rigid inner pipe, therefore, extends vertically from the top of the cement plug to slightly above land surface, thus providing a fixed reference elevation above land surface for measuring changes in land-surface elevation. At land surface, a concrete slab is poured and connected to an array of vertical concrete piers extending down into the water table. The concrete piers connect the slab to the underlying unconsolidated sediments penetrated by the borehole; this construction design helps to eliminate the continuous shrink and swell of the surficial clayey sediments associated with soil-moisture changes. A metal gage house (not depicted

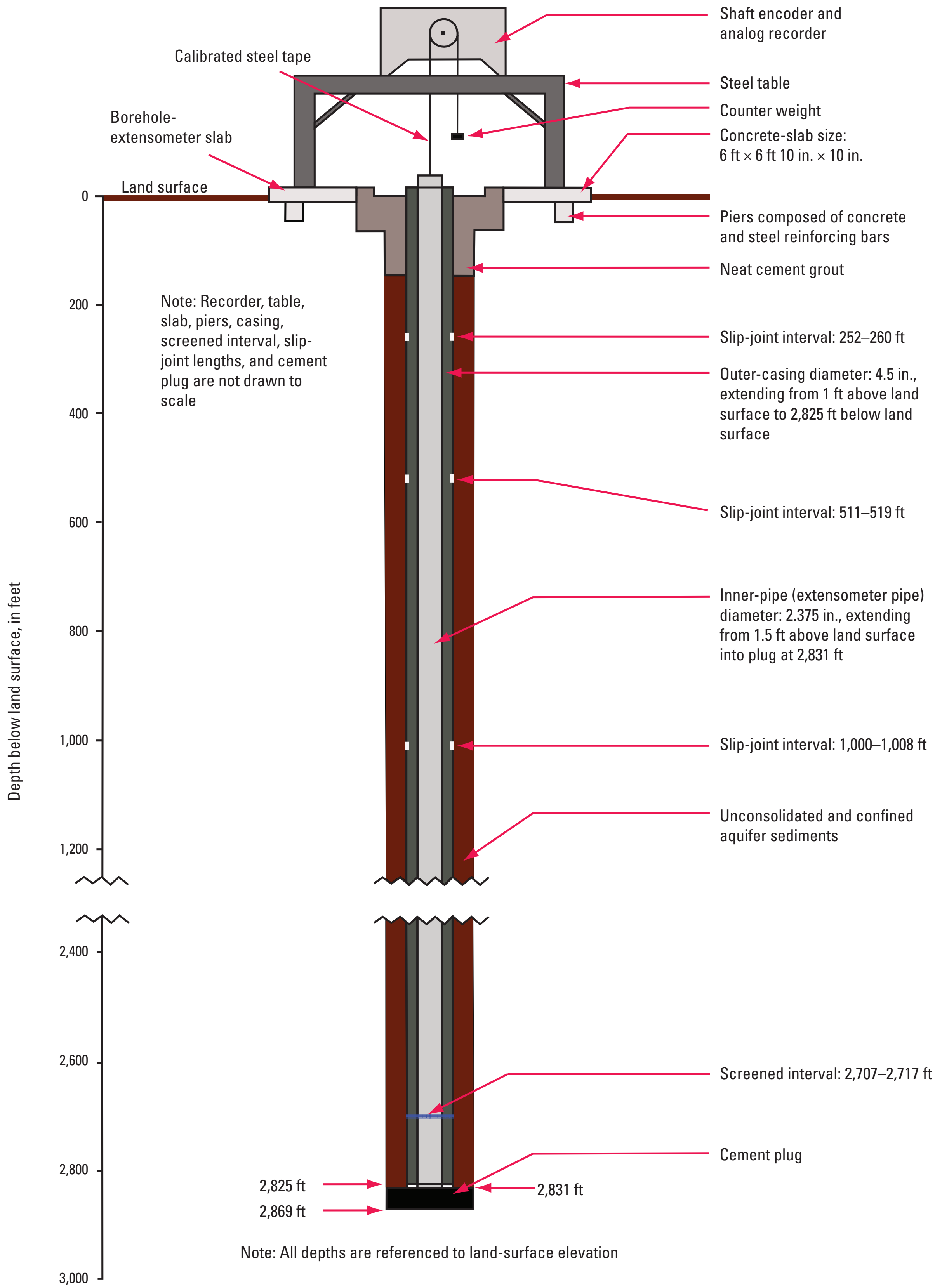


Figure 7. Cross-sectional perspective of the borehole extensometer/piezometer (LJ–65–23–322) located at Pasadena, Texas (ft, foot; in., inch).

in fig. 7) is constructed on the concrete slab, and a shaft encoder and analog recorder are mounted to a steel table that is attached to the concrete slab. A calibrated steel tape connects the recorder to the top of the inner pipe; because the steel table is anchored to the concrete slab, changes in land-surface elevation can be accurately measured and recorded. These recorded values through time represent the cumulative compaction that has occurred at the extensometer site. Because the extensometer functions as a piezometer and an extensometer, the cause-and-effect relation between the changes in water level in the aquifer and the changes in land-surface elevation can be established. Detailed information on the scientific theory, construction, and operation of extensometers is presented in Gabrysch (1984).

For this report, extensometer data of the cumulative compaction in the Chicot and Evangeline aquifers were collected from and evaluated for 13 extensometers at 11 sites in Harris and Galveston Counties (fig. 8) and are available in Ramage (2017). The extensometer data recorded at these 11 sites are used to quantify the rate of compaction in the Chicot and Evangeline aquifers on an ongoing basis, thereby providing water-resource managers a tool for evaluating the effects on subsidence rates caused by changes in the volume of groundwater withdrawn from the Chicot and Evangeline aquifers.

To quantify the rates of compaction in the aquifers, a network of extensometers was installed beginning in 1973 at selected sites throughout Harris and Galveston Counties. Five extensometers were installed (four in Harris County and one in Galveston County) and began recording cumulative compaction data in July 1973: LJ–65–22–622 (East End), LJ–65–16–930 (Baytown C–1 [shallow]), LJ–65–16–931 (Baytown C–2 [deep]), and LJ–65–32–625 (Seabrook) in Harris County and KH–64–33–920 (Texas City-Moses Lake) in Galveston County. An extensometer initially installed in 1962 in Harris County (LJ–65–32–401 [Johnson Space Center]) was also included in the network. Since July 1973, routine measurements of compaction at the Johnson Space Center extensometer have been recorded and collected and are included in this report. Additional extensometers were added to the network during 1974–76 in Harris County: LJ–65–12–726 (Addicks) in 1974, LJ–65–23–322 (Pasadena) in 1975, and LJ–65–32–424 (Clear Lake [shallow]) and LJ–65–32–428 (Clear Lake [deep]) in 1976. The most recent extensometers added to the network were installed in Harris County in 1980: LJ–65–07–909 (Lake Houston), LJ–65–14–746 (Northeast), and LJ–65–21–226 (Southwest). Since activation or installation between 1973 and 1980, cumulative compaction data have been continuously recorded and periodically collected about every 28 days at the 13 extensometers, thereby providing site-specific rates of compaction accurate to within 0.001 ft. From late 1973 to late 1982, a noticeable amount of seasonal variation occurred at the two extensometers at the Baytown site (fig. 8). This variation was determined to be caused by surficial clayey sediments that expand (swell) during periods of precipitation and contract (shrink) during hot and dry periods, which is characteristic of the montmorillonitic clay within the aquifer sediments. Consequently, in 1982, to reduce the excessive recorded fluctuation of the land surface, both extensometers were modified by installing a system of more deeply penetrating vertical piers into the sediments at the depth of the water table. Compaction data collected at the Baytown site after 1982 indicate that these design modifications reduced these fluctuations and improved the accuracy of the data (Ramage, 2017).

Each extensometer has a 10- to 20-ft screened interval that is located above the cement plug, which allows water to flow into the center pipe and thus functions as a piezometer (fig. 7). A water-level measurement is made during each extensometer site visit. If the depth of the screened interval is positioned entirely within the Chicot aquifer or Evangeline aquifer, these water-level measurements are evaluated to determine if they are representative of water levels in the adjacent area and, when verified, are used in the creation of the water-level-altitude maps.

Water-Level Altitudes and Changes

During years when rainfall and temperature are near normal, total groundwater withdrawals in the study area typically do not change appreciably from the previous year; therefore, water-level altitudes in the aquifer system typically do not fluctuate appreciably from the previous year (Kasmarek and Houston, 2007; Kasmarek and others, 2011, 2016). During years of drought or abundant rainfall, however, water-level altitudes in the aquifer system can be appreciably different compared to the previous year because of changes in recharge and groundwater withdrawals (Kasmarek and Houston, 2008; Johnson and others, 2011; Kasmarek and others, 2012, 2013). The water-level altitudes in the Chicot, Evangeline, and Jasper aquifers depicted in this report for 2017 were measured following a year of abundant rainfall. The National Oceanic and Atmospheric Administration (2017) reported that 60.96 inches (in.) of precipitation fell in Houston during 2016 compared to the average annual precipitation amount of 49.77 in. for 1981–2010. The wetter-than-normal conditions were accompanied by warmer-than-normal temperatures; the average annual temperature in 2016 for Houston was 1.6 degrees Fahrenheit above normal (1981–2010; National Oceanic and Atmospheric Administration, 2017). Because more groundwater might be withdrawn for irrigation purposes if the weather is warmer than normal during the irrigation season, the warmer-than-normal temperatures in 2016 might somewhat counteract the wetter-than-normal conditions in terms of groundwater withdrawals. Compared to 2016, water levels in 2017 increased in about 54, 48, and 80 percent of the wells screened in the Chicot, Evangeline, and Jasper aquifers, respectively. Water levels in 2017 decreased compared to 2016 in about 27, 43, and 18 percent of the wells screened in the Chicot, Evangeline, and Jasper aquifers, respectively (Kasmarek and others, 2016; Kasmarek and Ramage, 2017).

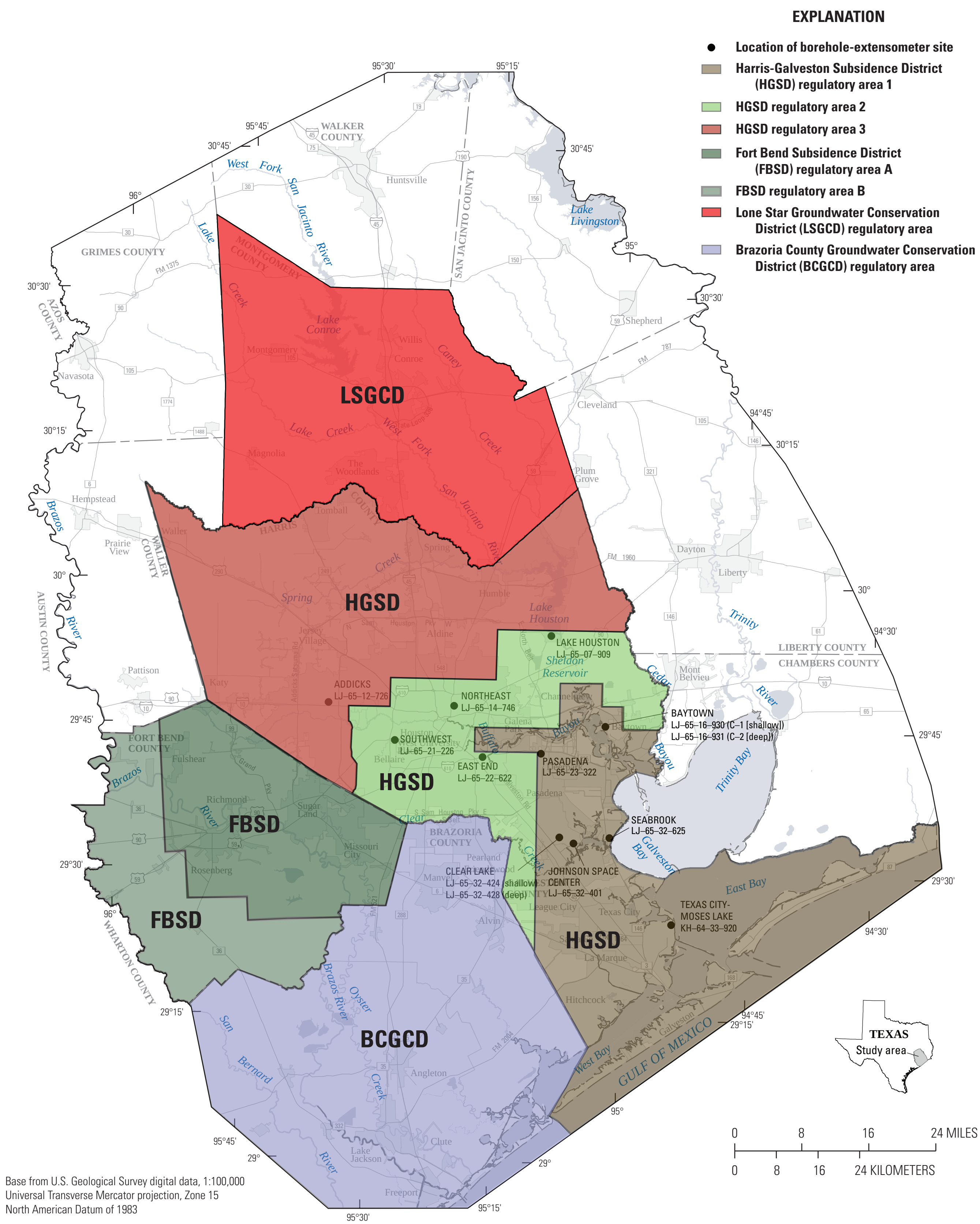


Figure 8. Locations of borehole-extensometer sites and respective areas of jurisdiction for each groundwater regulatory district, Houston-Galveston region, Texas, 2016.

Locations of wells used to construct the 2017 water-level-altitude maps for the Chicot, Evangeline, and Jasper aquifers are presented in Kasmarek and Ramage (2017). The water-level altitudes in 2017 and 2016 (Kasmarek and others, 2016) were generally similar. The Chicot, Evangeline, and Jasper aquifer maps in this report depict approximate water-level altitudes for 2017 and water-level-altitude changes for 1977–2017 in the Chicot and Evangeline aquifers and for 2000–17 in the Jasper aquifer.

Chicot Aquifer

Water-level-measurement data from 164 wells were used to depict the approximate 2017 water-level-altitude contours for the Chicot aquifer (fig. 9) (all of the water-level contours in this report are considered approximate). In 2017, water-level-altitude contours for the Chicot aquifer ranged from 200 ft below NAVD 88 (hereinafter referred to as “datum”) in two localized areas in southwestern and northwestern Harris County to 200 ft above datum in west-central Montgomery County.

The largest water-level-altitude decline (120 ft) depicted by the 1977–2017 water-level-change contours for the Chicot aquifer was in northwestern Harris County (fig. 10). A broad area where water-level altitudes declined in the Chicot aquifer extends from northwestern, north-central, and southwestern Harris County across parts of north-central, eastern, and south-central Fort Bend County into southeastern Waller County. In addition to the broad area of decline, water-level altitudes also declined from Fort Bend County into northwestern Brazoria County (fig. 10). Adjacent to the areas where water levels declined was a broad area where water levels rose in central, eastern, and southeastern Harris County, most of Galveston County, eastern and northernmost Brazoria County, and northeastern Fort Bend County. There were also small isolated areas in northwestern and southwestern Fort Bend County where water-level altitudes rose 20 ft (fig. 10). The largest rise (200 ft) in water-level altitudes in the Chicot aquifer from 1977 to 2017 was in southeastern Harris County (fig. 10).

Evangeline Aquifer

Water-level-measurement data from 305 wells were used to depict the approximate 2017 water-level-altitude contours for the Evangeline aquifer (fig. 11). In 2017, the water-level-altitude contours for the Evangeline aquifer indicated two areas where the water-level altitudes were 250 ft below datum—one of these areas extended from south-central Montgomery County into north-central Harris County, and the other was in western Harris County. Water-level altitudes in the Evangeline aquifer ranged from 50 to 200 ft below datum throughout most of Harris County in 2017. In Montgomery County, water-level altitudes in the Evangeline aquifer in 2017 ranged from the aforementioned area where they were 250 ft below datum to an area where they were 200 ft above datum in the northwestern part of the county. The water-level-altitude contour of 200 ft above datum extended from southern Grimes County, through a small part of northern Waller County, into northwestern Montgomery County (fig. 11).

The 1977–2017 water-level-change contours for the Evangeline aquifer (fig. 12) depict a broad area where water-level altitudes declined in north-central Harris and south-central Montgomery Counties, extending through north-central, northwestern, and southwestern Harris County into western Liberty, southeastern and northeastern Waller, and northeastern and east-central Fort Bend Counties (fig. 12). The largest water-level-altitude decline (280 ft) was in north-central Harris and south-central Montgomery Counties. Water-level altitudes rose in a broad area from central, east-central, and southern Harris County extending into the northernmost part of Brazoria County, the northernmost part of Galveston County, and the southwestern area of Liberty County. The largest rise in water-level altitudes in the Evangeline aquifer from 1977 to 2017 (240 ft) was in southeastern Harris County (fig. 12).

Jasper Aquifer

Water-level-measurement data from 102 wells were used to depict the approximate 2017 water-level-altitude contours for the Jasper aquifer (fig. 13). In 2017, water-level-altitude contours for the Jasper aquifer ranged from 200 ft below datum in three isolated areas of south-central Montgomery County (the westernmost of these areas extended slightly into north-central Harris County) to 250 ft above datum in extreme northwestern Montgomery County, northeastern Grimes County, and southwestern Walker County (fig. 13).

Whereas annual water-level-altitude data have been collected since 1977 from wells completed in the Chicot and Evangeline aquifers, annual water-level-altitude data have been collected since only 2000 from wells completed in the Jasper aquifer. The 2000–17 water-level-change contours for the Jasper aquifer (fig. 14) depict water-level declines in a broad area throughout most of Montgomery County and in parts of Waller, Grimes, and Harris Counties, with the largest decline (220 ft) in an isolated area in south-central Montgomery County.

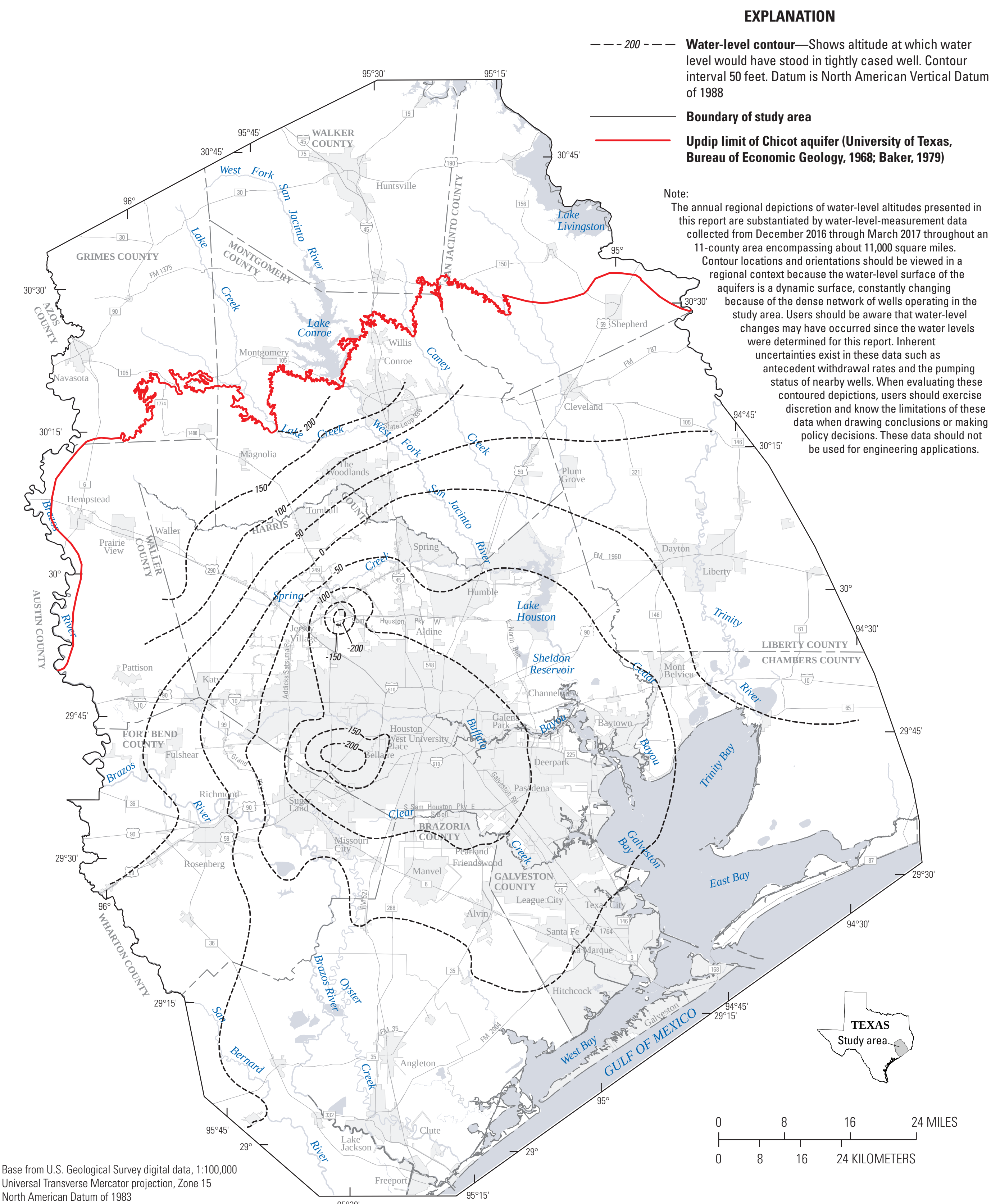


Figure 9. Approximate 2017 water-level altitudes and updip limit of the Chicot aquifer, Houston-Galveston region, Texas (water-level-measurement data collected during December 2016 through March 2017).

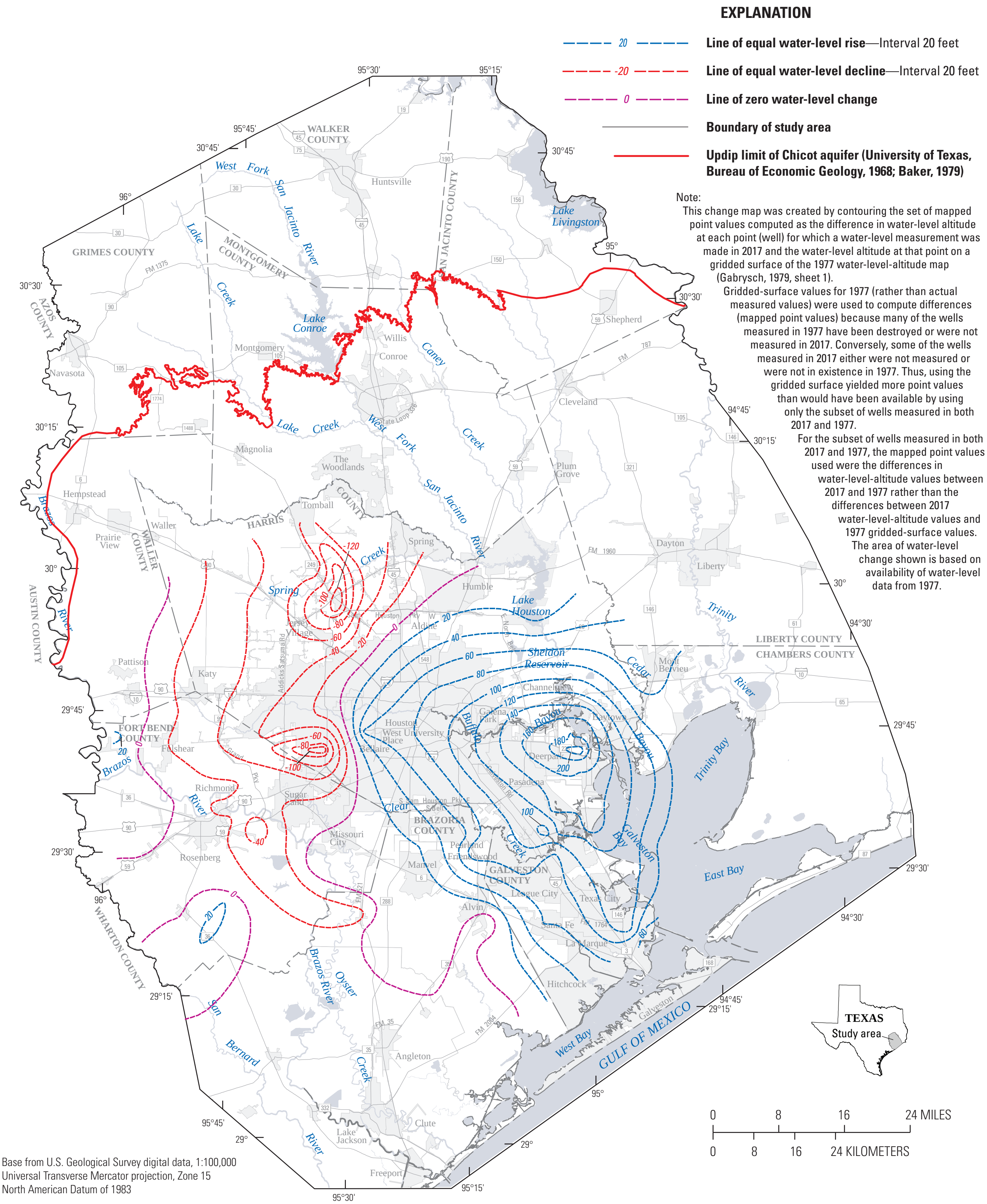


Figure 10. Approximate 1977–2017 water-level changes in the Chicot aquifer, Houston-Galveston region, Texas.

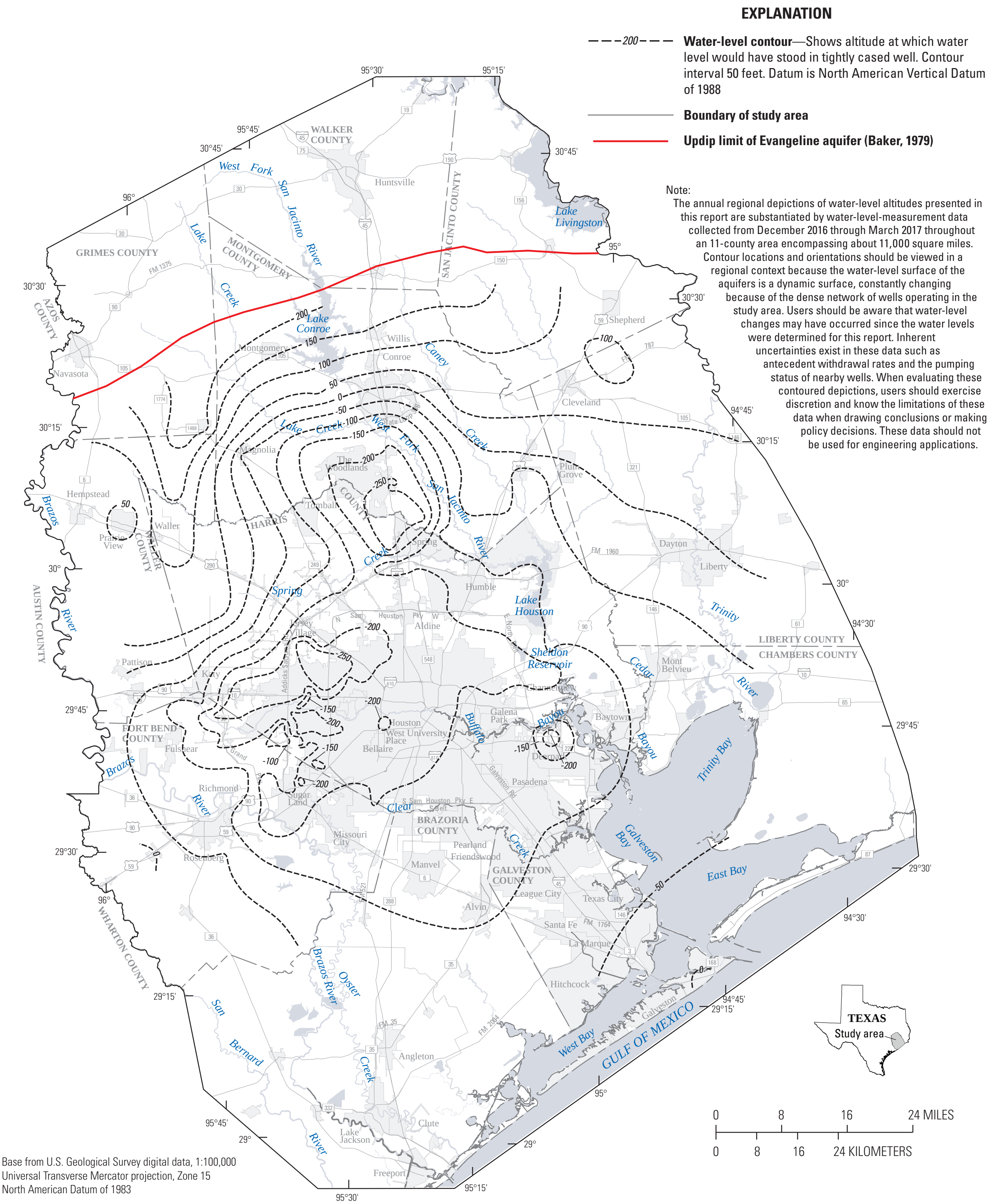


Figure 11. Approximate 2017 water-level altitudes and updip limit of the Evangeline aquifer, Houston-Galveston region, Texas (water-level-measurement data collected during December 2016 through March 2017).

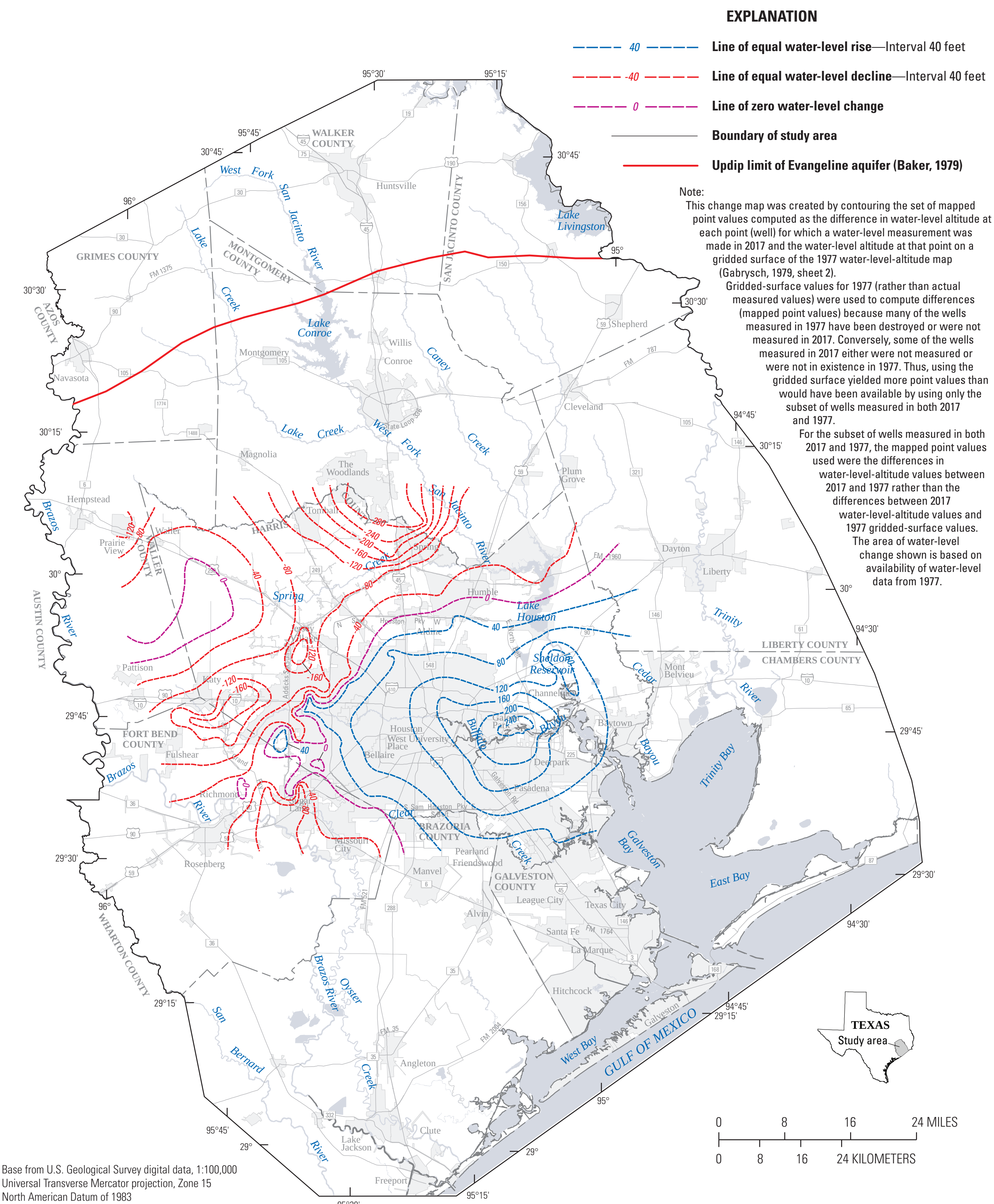


Figure 12. Approximate 1977–2017 water-level changes in the Evangeline aquifer, Houston-Galveston region, Texas.

EXPLANATION

— — 50 — — **Water-level contour**—Shows altitude at which water level would have stood in tightly cased well. Contour interval 50 feet. Datum is North American Vertical Datum of 1988

—— **Boundary of study area**

—— **Updip limit of Jasper aquifer (University of Texas, Bureau of Economic Geology, 1968, 1974; Baker, 1986)**

Note:
The annual regional depictions of water-level altitudes presented in this report are substantiated by water-level-measurement data collected from December 2016 through March 2017 throughout an 11-county area encompassing about 11,000 square miles. Contour locations and orientations should be viewed in a regional context because the water-level surface of the aquifers is a dynamic surface, constantly changing because of the dense network of wells operating in the study area. Users should be aware that water-level changes may have occurred since the water levels were determined for this report. Inherent uncertainties exist in these data such as antecedent withdrawal rates and the pumping status of nearby wells. When evaluating these contoured depictions, users should exercise discretion and know the limitations of these data when drawing conclusions or making policy decisions. These data should not be used for engineering applications.

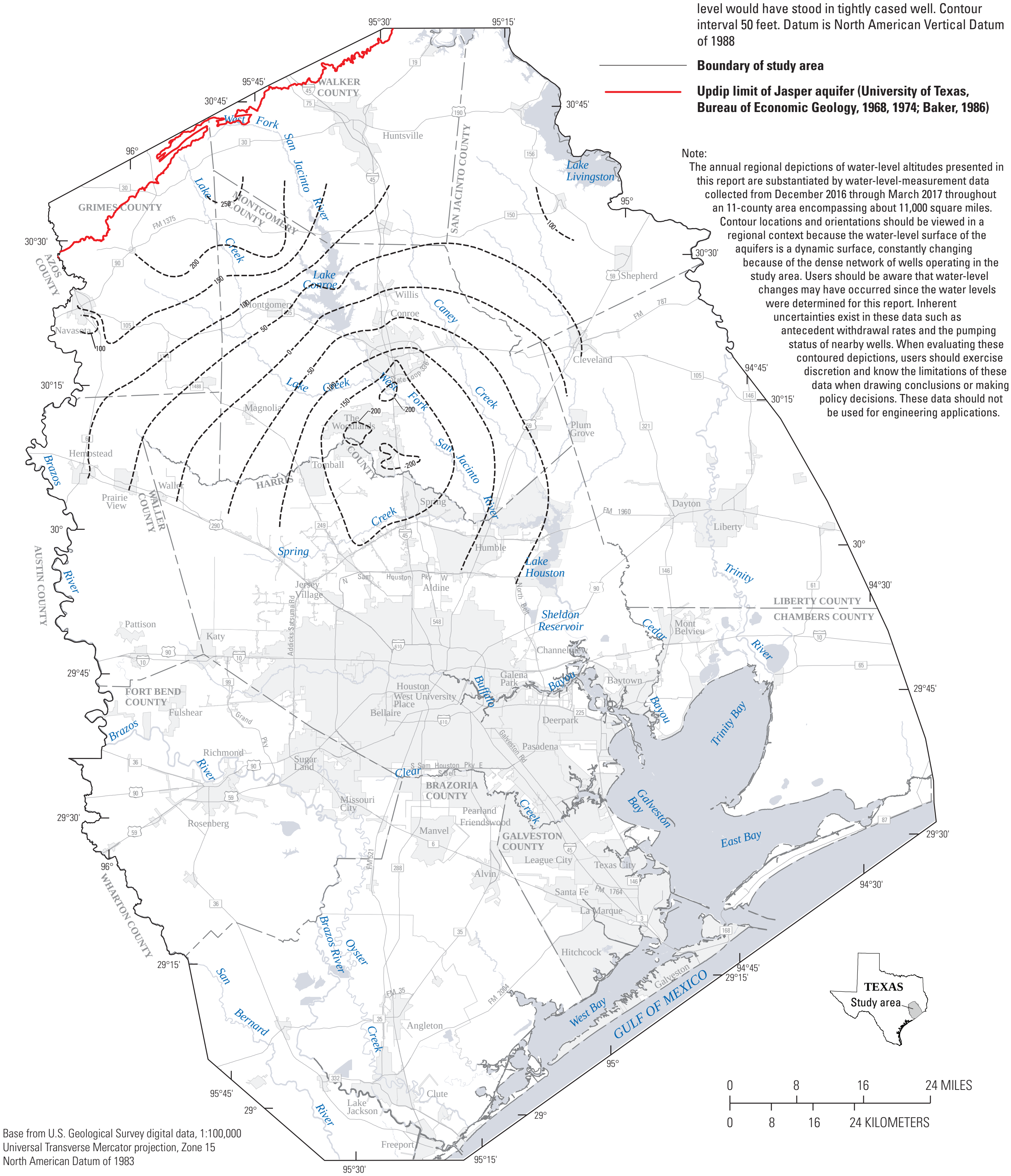


Figure 13. Approximate 2017 water-level altitudes and updip limit of the Jasper aquifer, Houston-Galveston region, Texas (water-level-measurement data collected during December 2016 through March 2017).

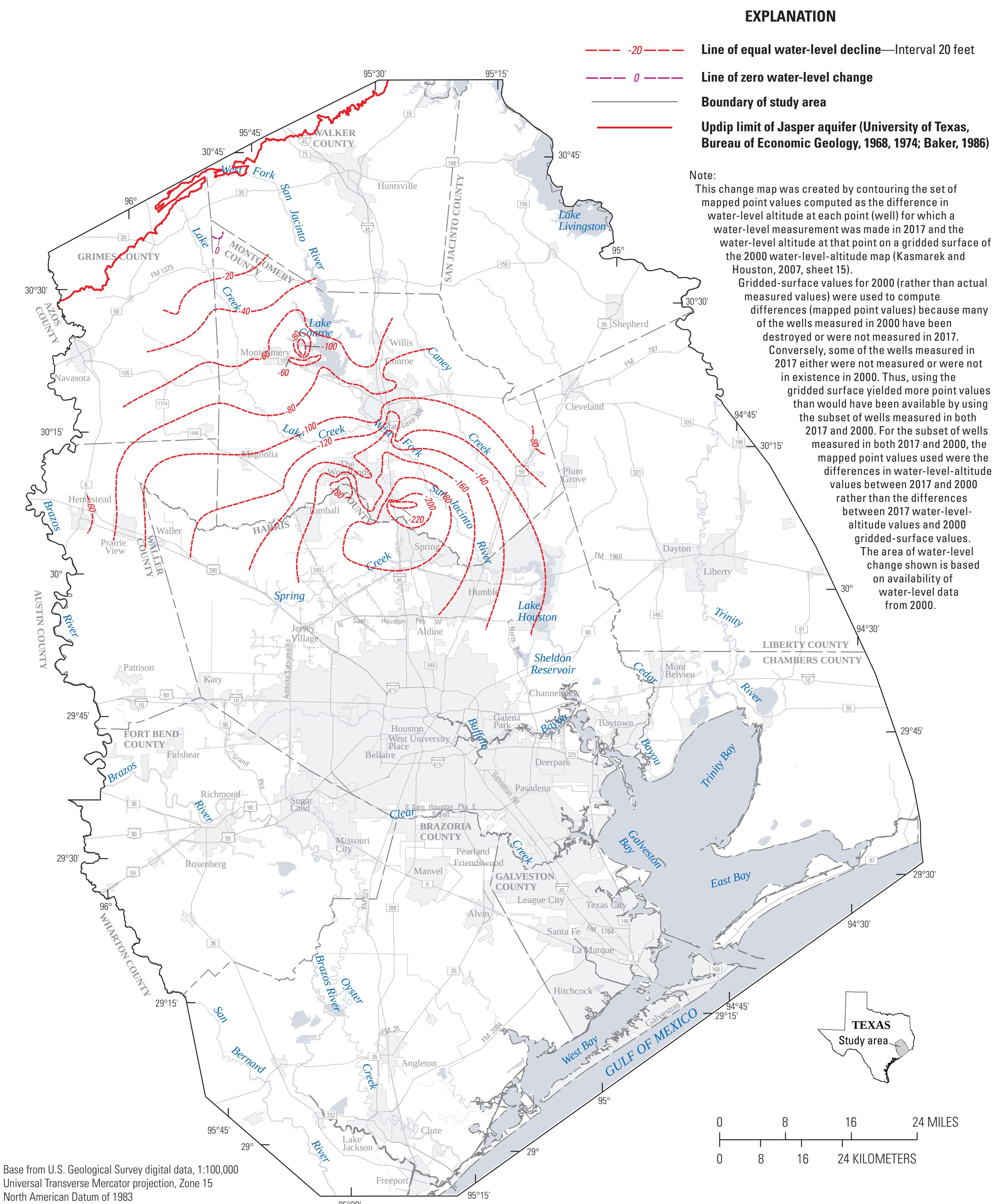


Figure 14. Approximate 2000–17 water-level changes in the Jasper aquifer, Houston-Galveston region, Texas.

Compaction of Subsurface Sediments in the Chicot and Evangeline Aquifers

Compaction of subsurface sediments (mostly in the fine-grained silt and clay layers because relatively limited compaction occurs in sand layers) in the Chicot and Evangeline aquifers was recorded continuously by using analog technology at the 13 extensometers at 11 sites (fig. 8) that were either activated or installed between 1973 and 1980. The cumulative compaction data for each extensometer are collected about 13 times per year during site visits. During each site visit, the amount of cumulative compaction at a site is determined by subtracting the previously recorded compaction value from the ending compaction value. Cumulative compaction over the course of a year is the difference between the value recorded during the first site visit in January and the value recorded during the last site visit in late November or December.

Graphs of cumulative compaction are presented for 1973 (or later depending on when each extensometer was activated or installed) through late November or December 2016 (figs. 15 and 16). The supporting cumulative compaction data used for the creation of the graphs are available in Ramage (2017). The selected depth of the extensometer (figs. 15–16) determines the total thickness of sediment over which compaction is measured by the extensometer. Six of the extensometers measure compaction that occurs in solely the Chicot aquifer (East End, Johnson Space Center, Texas City-Moses Lake, Baytown C–1 [shallow], Clear Lake [shallow], and Seabrook), and seven of the extensometers measure compaction that occurs in both the Chicot and Evangeline aquifers (Lake Houston, Northeast, Southwest, Addicks, Baytown C–2 [deep], Clear Lake [deep], and Pasadena) (figs. 15–16).

Prior to the establishment of the HGSD in 1975, the withdrawal of groundwater from the Chicot and Evangeline aquifers was unregulated, and water levels in the aquifers were declining with associated depressuring, dewatering, and compaction (Coplin and Galloway, 1999). By 1977, the withdrawals had resulted in water-level-altitude declines of as much as 300 and 350 ft below datum in the Chicot and Evangeline aquifers, respectively, in southeastern Harris County (Gabrysch, 1979), and correspondingly, by 1979, as much as 10 ft of subsidence had occurred in the Houston-Galveston region (Coplin and Galloway, 1999). A more recent USGS study determined that from the early 1900s until 2001 as much as 12–13 ft of subsidence had occurred in the Pasadena and Baytown areas in Harris County and that most (77–97 percent) of the subsidence in the Houston-Galveston region had occurred prior to the extensometer construction that began in 1973 (Kasmarek, Gabrysch, and Johnson, 2010). When reductions in groundwater withdrawals were first mandated following the establishment of the HGSD in 1975 (Harris-Galveston Subsidence District, 2015), the rate of groundwater withdrawal began to gradually decrease in Harris and Galveston Counties, and incrementally, a reduction in the rate of compaction was recorded by the extensometers (figs. 15–16). Coincident with the curtailment of groundwater withdrawals, water levels in the aquifers began to rise and recover (Kasmarek and others, 2016, sheets 5 and 10). As discussed in the “Water-Level Altitudes and Changes” section of this report, from 1977 to 2017 the decreases in groundwater withdrawals have caused water levels in the Chicot and Evangeline aquifers to rise as much as 200 and 240 ft, respectively.

For each extensometer, the cumulative compaction data discussed in this report begin on the extensometer installation date of the year it was installed, but for subsequent years, the data begin on the first site visit in January and end on the last site visit of the year (typically in late November or December) (Ramage, 2017) (figs. 15 and 16). From January through late November or December 2016, the Addicks, Lake Houston, Southwest, and Northeast extensometers recorded net decreases in land-surface elevation, but the Baytown C–1 (shallow), Baytown C–2 (deep), Clear Lake (shallow), Clear Lake (deep), East End, Johnson Space Center, Pasadena, Seabrook, and Texas City-Moses Lake extensometers recorded net increases in land-surface elevation (Ramage, 2017). For 2016, cumulative compaction data ranged from 0.096 ft (fig. 16) (Ramage, 2017) at the Texas City-Moses Lake extensometer, which measures compaction of solely the Chicot aquifer, to 3.700 ft (fig. 15) (Ramage, 2017) at the Addicks extensometer, which measures compaction of both the Chicot and Evangeline aquifers.

The graphs of cumulative compaction data indicate that the slopes of the graphs and rates of compaction were substantially higher when the extensometers were initially installed as early as 1973 compared to the slopes of the graphs and rates of compaction in the subsequent years (figs. 15 and 16). These asymptotic compaction-rate patterns are directly caused by the rise in water levels in the aquifers as groundwater withdrawals decreased in response to regulatory mandates of the HGSD (Harris-Galveston Subsidence District, 2015). As water levels in the aquifers began to rise and recover, the hydrostatic pressure increased, and residual excess pore pressure equilibrated; hence, the rates of compaction progressively decreased. Comparing the locations of the extensometers (fig. 8) to the geographic areas of the 1977–2017 long-term water-level changes in the Chicot and Evangeline aquifers (figs. 10 and 12), the relatively large areas of water-level rises coincide with the compaction-rate decreases, with the exception of the Addicks extensometer site. The rate of compaction varies from site to site because of the differences in groundwater-withdrawal rates in the adjacent areas of each site; differences in the ratios of sand, silt, and clay and corresponding compressibilities of the subsurface sediments at each site; and the previously established preconsolidation heads as discussed in Kasmarek (2013). The Pasadena and Baytown extensometer sites are proximal to the area of maximum historical subsidence rates, near Galveston Bay. The patterns of cumulative compaction at the Pasadena

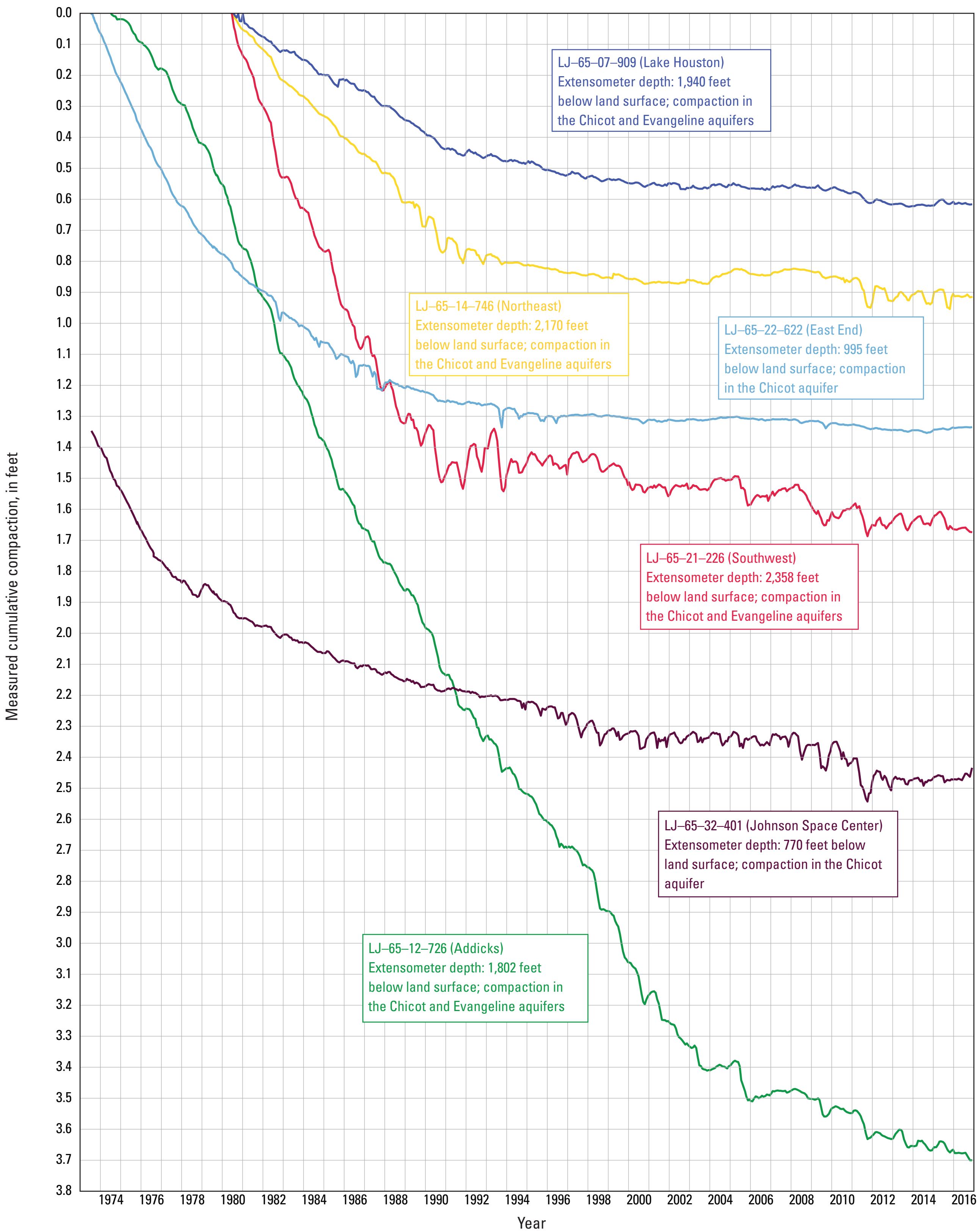


Figure 15. Measured cumulative compaction of subsurface sediments at the Lake Houston, Northeast, East End, Southwest, Johnson Space Center, and Addicks borehole-extensometer sites (sites are depicted on fig. 8), 1973–2016.

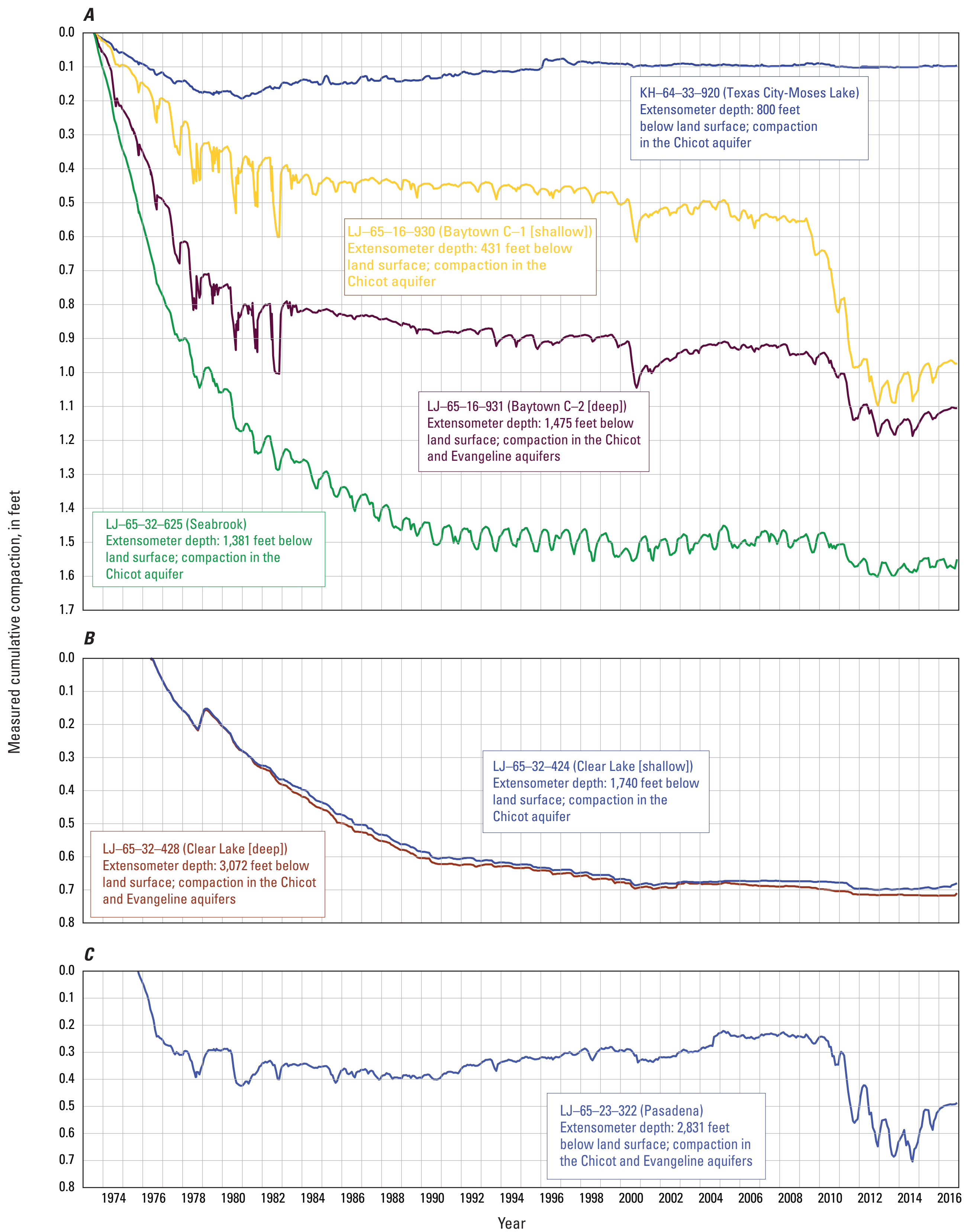


Figure 16. Measured cumulative compaction of subsurface sediments at the *A*, Texas City-Moses Lake, Baytown C–1 (shallow), Baytown C–2 (deep), and Seabrook borehole-extensometer sites; *B*, Clear Lake (shallow) and Clear Lake (deep) borehole-extensometer sites; and *C*, Pasadena borehole-extensometer site (sites are depicted on fig. 8), 1973–2016.

extensometer and both Baytown extensometers were different compared to the patterns of cumulative compaction at the other extensometer sites (fig. 16). The graphs of cumulative compaction data from installation in 1975 through 2016 for the Pasadena extensometer and from installation in 1973 through 2016 for the Baytown C–1 (shallow) and Baytown C–2 (deep) extensometers depict cumulative compaction values of 0.487 (Pasadena extensometer), 0.973 (Baytown C–1 [shallow] extensometer), and 1.105 ft (Baytown C–2 [deep] extensometer) (fig. 16) (Ramage, 2017).

The Addicks extensometer site is in regulatory area 3 (fig. 8) of the HGSD and, as such, was not scheduled for a 30-percent groundwater withdrawal reduction until 2011 (Harris-Galveston Subsidence District, 2013); therefore, the Addicks extensometer site is in a part of the study area where groundwater withdrawals remained relatively large for many years. Cumulative compaction data from the Addicks extensometer (fig. 15) indicate a consistent rate of compaction beginning from when the extensometer was installed in mid-1974 through about mid-2003. During the period from mid-1974 through mid-2003, the rate of compaction was consistent at about 0.1 ft per year, caused by continuing groundwater withdrawals in the area adjacent to the Addicks extensometer site. Additionally, the rate of compaction during August 2003 through December 2003 (Ramage, 2017) decreased to about 0.004 ft; this decrease in the rate of compaction likely was caused by changes in withdrawals, as the adjacent public-supply well field was observed by USGS personnel to be inoperative during this 5-month period. From December 2003 to about April 2005, data indicate a slight increase in land-surface elevation (rebound), followed by a decrease in land-surface elevation until February 2006. Again in March 2006, a gradual increase in land-surface elevation occurred until March 2008. Compaction resumed (albeit at a lower rate than in 2008) in May 2009, and net decrease in land-surface elevation continued to occur through October 2013. The rate of compaction recorded by the Addicks extensometer averaged about 0.025 ft per year during 2009–16 on the basis of a beginning value of 3.502 ft in January 2009 and an ending value of 3.700 ft in December 2016 (fig. 15).

The graph of cumulative compaction data obtained from the Seabrook extensometer (fig. 16) indicates a seasonal sinusoidal pattern in land-surface elevation caused by a decrease in land-surface elevation during the hot and dry months of June through September, when rates of groundwater withdrawal are higher. This decrease in land-surface elevation is followed by an increase in land-surface elevation during the cooler and wetter months of December through March, when rates of groundwater withdrawal are lower compared to the rest of year. Additionally, during the hot and dry months of June through September, the surficial clayey sediments desiccate and shrink, but as the heat of the summer dissipates and the cooler and wetter months arrive with a decrease in groundwater withdrawals, the sediments rehydrate and swell, thereby causing an increase in land-surface elevation, or rebound (U.S. Geological Survey, 2015).

The Baytown C–1 (shallow) and Baytown C–2 (deep) extensometers began recording cumulative compaction data in July 1973 (fig. 16) (Ramage, 2017). From July 1973 through about early May 2009, the cumulative compaction data recorded at the Baytown C–1 (shallow) extensometer were consistently lower than the cumulative compaction data recorded at the Baytown C–2 (deep) extensometer, with a difference as much as 0.465 ft recorded in July and August 2001. In late May 2009, however, an increase in the rate of compaction recorded at the Baytown C–1 (shallow) extensometer began, and by December 2016, the difference in cumulative compaction data for the two sites was within 0.132 ft (fig. 16). The cumulative compaction amounts recorded by the Baytown C–1 (shallow) and the Baytown C–2 (deep) extensometers have been similar since 2011 because of the increase in the rate of compaction at the Baytown C–1 (shallow) extensometer during 2009–11. The cause of the recent increase in the rate of compaction at the Baytown C–1 (shallow) extensometer is not known. Unlike the cumulative compaction amounts that were historically appreciably different at the Baytown shallow and deep extensometers, the cumulative compaction amounts recorded by the Clear Lake (shallow) and Clear Lake (deep) extensometers have been similar throughout their periods of record (fig. 16).

Cumulative compaction data for the Texas City-Moses Lake extensometer indicate not only that a halt in the rate of compaction occurred but also that, from January 1981 until December 2016, a slight rise in land-surface elevation of approximately 0.097 ft has occurred (fig. 16) (Ramage, 2017). The cumulative compaction data for the Pasadena, Clear Lake (shallow), Clear Lake (deep), Seabrook, Baytown C–1 (shallow), Baytown C–2 (deep), and Johnson Space Center extensometers indicate a slight increase in land-surface elevation from late 1978 to early 1980 (figs. 15 and 16) because a ruptured natural gas well pressurized the confined aquifer system and caused water levels to rise in the area adjacent to the ruptured well (Gabrysch, 1984). Gradually, the pressure in the aquifer dissipated, and the process of compaction subsequently returned to rates similar to those prior to the pressuring event.

Data Limitations

Before 2016, most of the land-surface elevations at wells used in the annual series of reports were derived from USGS 1:24,000-scale 7.5-minute topographic quadrangle maps, which have a 5-ft contour, or from a digital elevation model (DEM). Land-surface elevations at wells installed in Harris County were derived from a DEM obtained from the 2001 Tropical Storm Allison Recovery Project land-surface dataset that used light detection and ranging (lidar) technology (Peggy Cobb, Terrapoint USA, Inc., written commun., 2009). The land-surface elevations were referenced to NAVD 88 by using Corpscon version 6 (U.S. Army Corps of Engineers, 2006).

The lidar data were contoured at a 1-ft interval, thereby providing an accuracy of 0.5 ft. The topographic quadrangle maps for the Gulf of Mexico coastal area were typically contoured at a 5-ft interval, thereby providing 2.5-ft accuracy; thus, the lidar data provide about five times better accuracy when compared to 7.5-minute topographic quadrangle maps (Kasmarek, Gabrysch, and Johnson, 2010). Additionally, all of the topographic quadrangle maps were variously dated, and not all of the maps were updated with changes in land-surface elevations that might have occurred since their initial publication.

In 2016, the authors updated the land-surface-elevation data for the study area. To determine land-surface elevations, a corresponding land-surface-datum value for each well was obtained by using USGS National Geospatial Program 3DEP values referenced to NAVD 88 (U.S. Geological Survey, 2017b). Updated land-surface-datum values from 3DEP were applied to the site information stored in the NWIS database for all sites in the study area and were used to enhance the accuracy of the maps depicting water-level altitudes and the accuracy of subsequent calculations of point values that are used as control data during the creation of the water-level-altitude maps (figs. 9, 11, and 13) and long-term water-level-change maps (figs. 10, 12, and 14). Additionally for all sites, the values of horizontal coordinate information (latitude and longitude) were updated to the North American Datum of 1983, and these data were also used to update the NWIS database.

Land-surface elevations were not updated to adjust previously published water-level altitudes and used in the analysis of differences between current year and historical year maps of water-level altitude. Because of sediments with a prevalence of montmorillonitic clays and a large dependence on groundwater withdrawals to meet water-use demand, the land-surface elevation is not constant. Any changes in land-surface elevation could affect the accuracy of water-level-change maps depicting the differences between the current year (2017) and the historical year (1977) altitudes.

The depictions of water-level altitudes and changes at any specific location are considered to represent a regional-scale approximation and, as such, are not intended for use in engineering or other design applications. The water-level altitudes and changes presented in this report were rounded to the nearest foot; the values depicted on the maps represent a mathematical approximation that could vary as much as plus or minus 0.5 ft in addition to accuracies associated with the DEM source data. Use of these data for critical or local-scale applications is not advised without full awareness of the data limitations. Users need to exercise discretion when drawing conclusions or making policy decisions on the basis of these contoured depictions.

The graphs of long-term cumulative compaction data (figs. 15 and 16) represent compaction of subsurface sediments above the depth of the cement plug (fig. 7); by design, any compaction or vertical movement that occurs below these depths in stratigraphically lower units or resulting from tectonic processes is not recorded by the extensometers. Depending on the total depth of the extensometer, the cumulative compaction at a given extensometer could represent compaction of the sediments of solely the Chicot aquifer (for example, the Baytown C–1 [shallow] extensometer) or could represent compaction of the sediments in both the Chicot and Evangeline aquifers (for example, the Addicks extensometer).

The rate of compaction varies from site to site because of differences in groundwater withdrawals in the areas adjacent to each extensometer site; differences among sites in the ratios of sand, silt, and clay and their corresponding compressibilities; and previously established preconsolidation heads. It is not appropriate, therefore, to extrapolate or infer a rate of compaction for an adjacent area on the basis of the rate of compaction recorded by proximal extensometers.

Summary

The Houston-Galveston region, Texas—consisting of Harris, Galveston, Fort Bend, Montgomery, Brazoria, Chambers, Grimes, Liberty, San Jacinto, Walker, and Waller Counties—represents one of the largest areas of land-surface subsidence (hereinafter referred to as “subsidence”) in the United States. By 1979, as much as 10 feet (ft) of subsidence had occurred in the Houston-Galveston region, and approximately 3,200 square miles (mi^2) of the 11,000-mi^2 geographic area had subsided more than 1 ft. Most of the subsidence in the Houston-Galveston region has occurred as a direct result of groundwater withdrawals that depressured and dewatered the Chicot and Evangeline aquifers, thereby causing compaction of the aquifer sediments. Groundwater withdrawn from the Chicot, Evangeline, and Jasper aquifers has been the primary source of water for municipal supply, commercial and industrial use, and irrigation in the Houston-Galveston region since the early 1900s. To address the issues associated with subsidence and subsequent increased flooding, the 64th Texas State Legislature in 1975 authorized the establishment of the Harris-Galveston Subsidence District to regulate and reduce groundwater withdrawals in Harris and Galveston Counties. Subsequently, the Texas State Legislature established the Fort Bend Subsidence District in 1989 and the Lone Star Groundwater Conservation District in 2001 to regulate groundwater withdrawals in Fort Bend and Montgomery Counties, respectively. The Brazoria County Groundwater Conservation District was established by the Texas State Legislature in 2003 to maintain the quality and availability of the county’s groundwater resources for current users and future generations. This report, prepared by the U.S. Geological Survey in cooperation with the Harris-Galveston Subsidence District, City of Houston, Fort Bend Subsidence District, Lone Star Groundwater Conservation District, and Brazoria County Groundwater Conservation District, is one in an annual series of reports depicting water-level altitudes and water-level changes in the Chicot, Evangeline, and Jasper aquifers and measured cumulative compaction of subsurface sediments in the Chicot and Evangeline aquifers in the Houston-Galveston region. Water levels in wells screened in the Chicot, Evangeline, and Jasper aquifers were measured during December 2016 through March 2017 (water levels usually are higher during these months compared to the rest of the year).

This report contains regional-scale maps depicting approximate 2017 water-level altitudes and long-term water-level changes for the Chicot, Evangeline, and Jasper aquifers; a map depicting locations of borehole-extensometer (hereinafter referred to as "extensometer") sites; and graphs depicting cumulative compaction of subsurface sediments measured by the extensometers beginning in 1973 (or later depending on when the extensometer was activated or installed) through late November or December 2016.

The water-level altitudes in the Chicot, Evangeline, and Jasper aquifers depicted in this report for 2017 were measured following a year of abundant rainfall. The wetter-than-normal conditions were accompanied by warmer-than-normal temperatures; the average annual temperature in 2016 for Houston was 1.6 degrees Fahrenheit above normal. Because more groundwater might be withdrawn for irrigation purposes if the weather is warmer than normal during the irrigation season, the warmer-than-normal temperatures in 2016 might somewhat counteract the wetter-than-normal conditions in terms of groundwater withdrawals. Compared to 2016, water levels in 2017 increased in about 54, 48, and 80 percent of the wells screened in the Chicot, Evangeline, and Jasper aquifers, respectively. Water levels in 2017 decreased compared to 2016 in about 27, 43, and 18 percent of the wells screened in the Chicot, Evangeline, and Jasper aquifers, respectively.

Water-level-measurement data from 164 wells were used to depict the approximate 2017 water-level-altitude contours for the Chicot aquifer. In 2017, water-level-altitude contours for the Chicot aquifer ranged from 200 ft below the North American Vertical Datum of 1988 (hereinafter referred to as "datum") in two localized areas in southwestern and northwestern Harris County to 200 ft above datum in west-central Montgomery County. The largest water-level-altitude decline (120 ft) depicted by the 1977–2017 water-level-change contours for the Chicot aquifer was in northwestern Harris County. A broad area where water-level altitudes declined in the Chicot aquifer extends from northwestern, north-central, and southwestern Harris County across parts of north-central, eastern, and south-central Fort Bend County into southeastern Waller County. In addition to the broad area of decline, water-level altitudes also declined from Fort Bend County into northwestern Brazoria County. Adjacent to the areas where water levels declined was a broad area where water levels rose in central, eastern, and southeastern Harris County, most of Galveston County, eastern and northernmost Brazoria County, and northeastern Fort Bend County. There were also small isolated areas in northwestern and southwestern Fort Bend County where water-level altitudes rose 20 ft. The largest rise (200 ft) in water-level altitudes in the Chicot aquifer from 1977 to 2017 was in southeastern Harris County.

Water-level-measurement data from 305 wells were used to depict the approximate 2017 water-level-altitude contours for the Evangeline aquifer. In 2017, the water-level-altitude contours for the Evangeline aquifer indicated two areas where the water-level altitudes were 250 ft below datum—one of these areas extended from south-central Montgomery County into north-central Harris County, and the other was in western Harris County. Water-level altitudes in the Evangeline aquifer ranged from 50 to 200 ft below datum throughout most of Harris County in 2017. In Montgomery County, water-level altitudes in the Evangeline aquifer in 2017 ranged from the aforementioned area where they were 250 ft below datum to an area where they were 200 ft above datum in the northwestern part of the county. The water-level-altitude contour of 200 ft above datum extended from southern Grimes County, through a small part of northern Waller County, into northwestern Montgomery County. The 1977–2017 water-level-change contours for the Evangeline aquifer depict a broad area where water-level altitudes declined in north-central Harris and south-central Montgomery Counties, extending through north-central, northwestern, and southwestern Harris County into western Liberty, southeastern and northeastern Waller, and northeastern and east-central Fort Bend Counties. The largest water-level-altitude decline (280 ft) was in north-central Harris and south-central Montgomery Counties. Water-level altitudes rose in a broad area from central, east-central, and southern Harris County extending into the northernmost part of Brazoria County, the northernmost part of Galveston County, and the southwestern area of Liberty County. The largest rise in water level-altitudes in the Evangeline aquifer from 1977 to 2017 (240 ft) was in southeastern Harris County.

Water-level-measurement data from 102 wells were used to depict the approximate 2017 water-level-altitude contours for the Jasper aquifer. In 2017, water-level-altitude contours for the Jasper aquifer ranged from 200 ft below datum in three isolated areas of south-central Montgomery County (the westernmost of these areas extended slightly into north-central Harris County) to 250 ft above datum in extreme northwestern Montgomery County, northeastern Grimes County, and southwestern Walker County. The 2000–17 water-level-change contours for the Jasper aquifer depict water-level declines in a broad area throughout most of Montgomery County and in parts of Waller, Grimes, and Harris Counties, with the largest decline (220 ft) in an isolated area in south-central Montgomery County.

Compaction of subsurface sediments (mostly in the fine-grained silt and clay layers) in the Chicot and Evangeline aquifers was recorded continuously by using analog technology at the 13 extensometers at 11 sites that were either activated or installed between 1973 and 1980. The compaction rates measured by each extensometer were substantially higher when the extensometers were initially installed compared to compaction rates in subsequent years. When reductions in groundwater withdrawals were mandated following the establishment of the Harris-Galveston Subsidence District in 1975, the rates of groundwater withdrawal began to decrease gradually in Harris and Galveston Counties, as did the rate of compaction. Coincident with the curtailment of groundwater withdrawals, the water levels in the aquifers began to rise and recover. From 1977 to 2017 the decreases in groundwater withdrawals have caused water levels in the Chicot and Evangeline aquifers to rise as much as 200 and 240 ft, respectively. From January through December 2016, the Addicks, Lake Houston, Southwest, and Northeast extensometers recorded net decreases in land-surface elevation, but the Baytown C–1 (shallow), Baytown C–2 (deep), Clear Lake (shallow), Clear Lake (deep), East End, Johnson Space Center, Pasadena, Seabrook, and Texas City-Moses Lake extensometers recorded net increases in land-surface elevation. During the period of record beginning in 1973 (or later depending on activation or installation date) and ending in late November or December 2016, measured cumulative compaction at the 13 extensometers ranged from 0.096 ft at the Texas City-Moses Lake extensometer, which measures compaction in solely the Chicot aquifer, to 3.700 ft at the Addicks extensometer, which measures compaction in both the Chicot and Evangeline aquifers.

The rate of compaction varies from site to site because of differences in rates of groundwater withdrawal in the areas adjacent to each extensometer site; differences among sites in the ratios of sand, silt, and clay and their corresponding compressibilities; and previously established preconsolidation heads. It is not appropriate, therefore, to extrapolate or infer a rate of compaction for an adjacent area on the basis of the rate of compaction recorded by proximal extensometers.

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