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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

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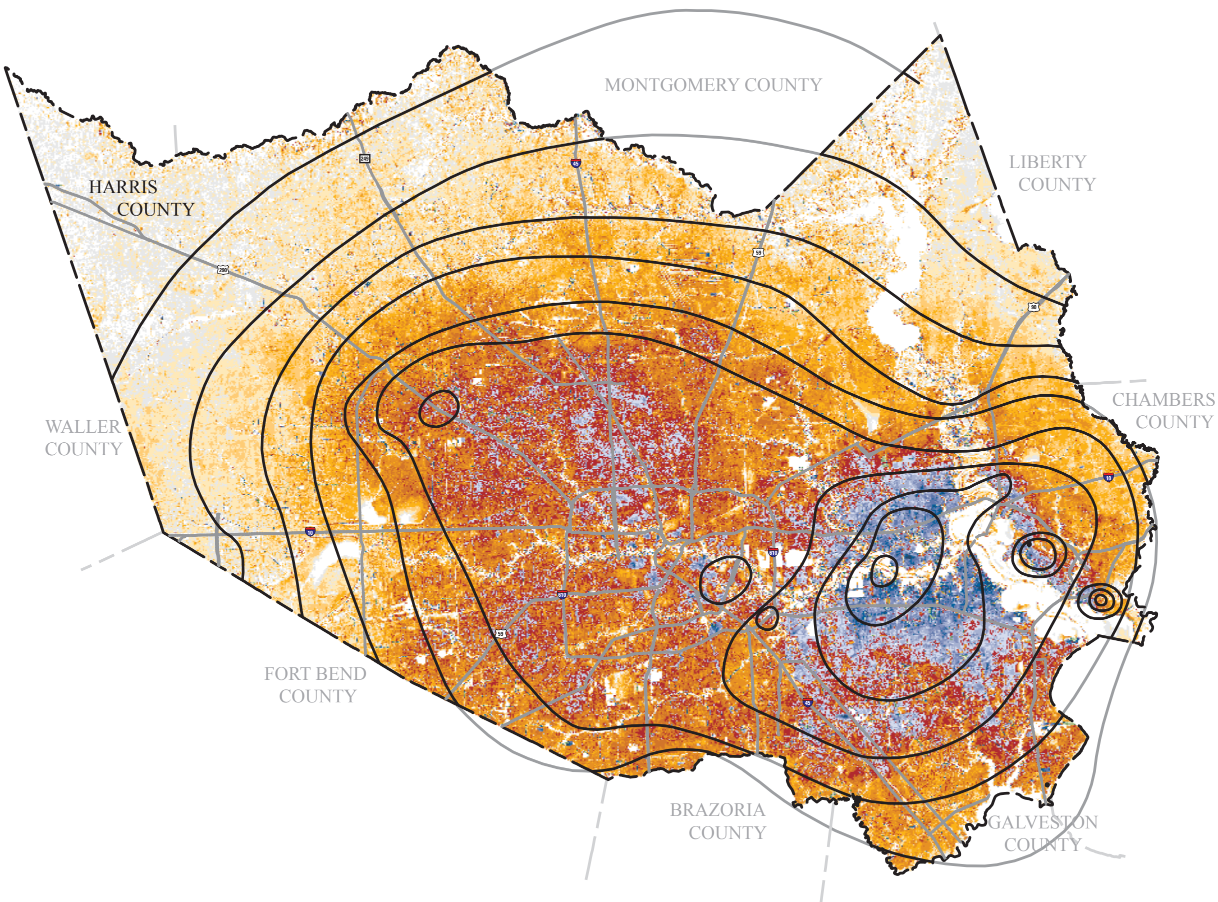

Pamphlet to accompany
Scientific Investigations Map 3365

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

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[Available at http://dx.doi.org/10.3133/sim3365.]

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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)

Datum

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 1983 (NAD 83).

Water-Level Altitudes 2016 and Water-Level Changes in the Chicot, Evangeline, and Jasper Aquifers and Compaction 1973–2015 in the Chicot and Evangeline Aquifers, Houston-Galveston Region, Texas

By Mark C. Kasmarek, Jason K. Ramage, and Michaela R. Johnson

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. The report contains regional-scale maps depicting approximate 2016 water-level altitudes (represented by measurements made during December 2015–March 2016) for the Chicot, Evangeline, and Jasper aquifers; maps depicting 1-year (2015–16) water-level changes for each aquifer; maps depicting approximate contoured 5-year (2011–16) water-level changes for each aquifer; maps depicting approximate contoured long-term (1990–2016 and 1977–2016) water-level changes for the Chicot and Evangeline aquifers; a map depicting approximate contoured long-term (2000–16) water-level changes for the Jasper aquifer; a map depicting locations of borehole-extensometer sites; and graphs depicting measured long-term cumulative compaction of subsurface sediments at the extensometers during 1973–2015. Tables listing the water-level data used to construct each water-level map for each aquifer and the measured long-term cumulative compaction data for each extensometer site are included. Graphs depicting water-level measurement data also are included; these graphs can be used to approximate changes in effective stress caused by changes in groundwater withdrawal from the Chicot and Evangeline aquifers.

In 2016, water-level-altitude contours for the Chicot aquifer ranged from 200 feet (ft) below the vertical datum (North American Vertical Datum of 1988; hereinafter, datum) in a localized area in northwestern Harris County to 200 ft above datum in west-central Montgomery County. Water-level changes during 2015–16 in the Chicot aquifer ranged from a 39-ft decline to a 26-ft rise. Contoured 5-year and long-term changes in water-level altitudes of the Chicot aquifer ranged from a 30-ft decline to a 20-ft rise (2011–16), from a 140-ft decline to a 160-ft rise (1990–2016), and from a 120-ft decline to a 200-ft rise (1977–2016). In 2016, water-level-altitude contours for the Evangeline aquifer ranged from 250 ft below datum in three separate areas in south-central Montgomery County and extending into north-central Harris County, in west-central Harris County, and in southwestern Harris County to 200 ft above datum in southeastern Grimes and northwestern Montgomery Counties. Water-level changes during 2015–16 in the Evangeline aquifer ranged from a 65-ft decline to a 61-ft rise. Contoured 5-year and long-term changes in water-level altitudes of the Evangeline aquifer ranged from a 60-ft decline to a 40-ft rise (2011–16), from a 160-ft decline to a 160-ft rise (1990–2016), and from a 320-ft decline to a 240-ft rise (1977–2016). In 2016, water-level-altitude contours for the Jasper aquifer ranged from 200 ft below datum in south-central Montgomery County extending into north-central Harris County to 250 ft above datum in northwestern Montgomery County and extending into eastern Grimes County and southwestern Walker County. Water-level changes during 2015–16 in the Jasper aquifer ranged from a 38-ft decline to a 51-ft rise. Contoured 5-year and long-term changes in water-level altitudes of the Jasper aquifer ranged from a 60-ft decline to a 40-ft rise (2011–16) and from a 220-ft decline to a 20-ft decline (2000–16).

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 December 2015, measured cumulative compaction at the 13 extensometers ranged from 0.095 ft at the Texas City-Moses Lake extensometer to 3.666 ft at the Addicks extensometer. From January through December 2015, the Northeast, Southwest, Addicks, Johnson Space Center, and Clear Lake (deep) extensometers recorded net decreases in land-surface elevation, but the Lake Houston, East End, Texas City-Moses Lake, Baytown C–1 (shallow), Baytown C–2 (deep), Seabrook, Clear Lake (shallow), and Pasadena extensometers recorded net increases in land-surface elevation. For the 11 extensometer sites during the selected years 1988, 1998, 2008, 2012, and 2015, the smallest effective stress (20.12 pounds per square inch [psi]) was estimated at the Texas City-Moses Lake extensometer site and was produced by a measured water level of 46.42 ft below land-surface datum (blsd) in January 2008. The corresponding net compaction during 2007 at this site was 0.001 ft. The largest effective stress (174.86 psi) was estimated at the Addicks extensometer site and was produced by a measured water level of 403.38 ft blsd in January 1998. The corresponding net compaction at the Addicks site was 0.067 ft in 1997.

The 2011 drought caused water-level declines in the aquifers that were documented by the water-level-measurement data collected in January 2012. During the 2011 drought, the 13 extensometers recorded varying amounts of compaction that ranged from a net compaction value of 0.002 ft recorded by the Texas City-Moses Lake extensometer to a net compaction value of 0.192 ft recorded by the Pasadena extensometer. Water-level data for 1988, 1998, 2008, 2012, and 2015 and the corresponding net compaction values recorded by the extensometers for 1987, 1997, 2007, 2011, and 2014 were used to illustrate the cause and effect relations between changes in water level caused by groundwater withdrawals and resulting changes in effective stress. Changes in effective stress are related to changes in land-surface elevations caused by compaction of the fine-grained sediments composing 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.

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. This report, prepared by the U.S. Geological Survey (USGS) in cooperation with the Harris-Galveston Subsidence District (HGSD), City of Houston, Fort Bend Subsidence District (FBSD), Lone Star Groundwater Conservation District (LSGCD), and Brazoria County Groundwater Conservation District (BCGCD), 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 fine-grained subsurface sediments in the Chicot and Evangeline aquifers in the Houston-Galveston region.

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, the withdrawals had resulted in water-level-altitude declines of 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).

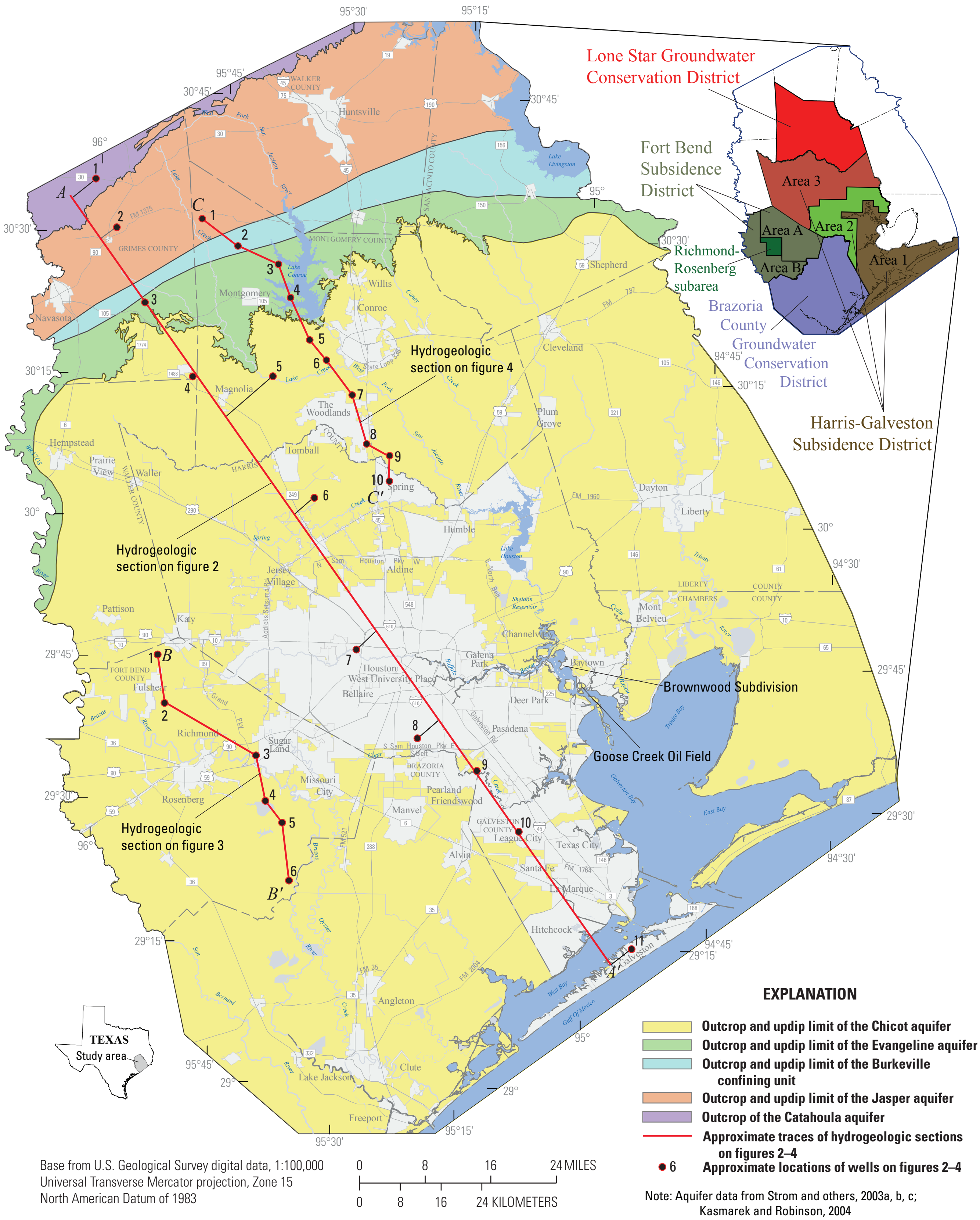

Figure 1. Locations of groundwater regulatory districts; approximate traces of hydrogeologic sections *A–A´*, *B–B´*, and *C–C´*; and the Houston-Galveston region study area, Texas, 2016 (modified from Strom and others, 2003a, b, c; Kasmarek and Robinson, 2004).

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 Weather Service, 2001; National Oceanic and Atmospheric Administration, 2015a). 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 (fig. 1), as evidenced by the inundation of the Brownwood Subdivision (fig. 1) associated with Hurricane Alicia in August 1983 near Baytown, Tex., and adjacent areas in the Houston-Galveston region, 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 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 USGS has monitored water levels in wells screened 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 annual reports of water-level altitudes and water-level changes for the Jasper aquifer (Coplin, 2001) in the Houston-Galveston region (primarily Montgomery County) beginning in 2001, and after additional data were available, an updated report was published (Kasmarek and Houston, 2007). The measured cumulative compaction (hereinafter referred to as “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 land-surface 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 (2015) depicted 2015 water-level altitudes and changes for various periods in the Chicot, Evangeline, and Jasper aquifers and cumulative compaction recorded by the 13 extensometers during 1973–2014 in the Chicot and Evangeline aquifers.

Subsequent to establishing the HGSD, the Texas State Legislature established an additional subsidence district (FBSD) and two groundwater conservation districts (LSGCD and, most recently, 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 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 (2016) groundwater management plans of each district are available on their respective Web sites (Harris-Galveston Subsidence District, 2013; Fort Bend Subsidence District, 2013; Lone Star Groundwater Conservation District, 2013; Brazoria County Groundwater Conservation District, 2012). Currently (2016), 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 the 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 and others, 2009, 2010, 2012, 2013, 2014, 2015; Johnson and others, 2011).

Purpose and Scope

This report is one in an annual series of reports depicting 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. The report also describes the hydrogeology of the study area and provides an overview of the mechanism of compaction and subsidence.

This report contains regional-scale maps (sheets 1–14) depicting approximate 2016 water-level altitudes in the Chicot, Evangeline, and Jasper aquifers (sheets 1, 6, and 11); maps depicting 1-year (2015–16) water-level changes for each aquifer (sheets 2, 7, and 12); maps depicting approximate contoured 5-year (2011–16) water-level changes for each aquifer (sheets 3, 8, and 13); maps depicting approximate contoured long-term (1990–2016 and 1977–2016) water-level changes for the Chicot and Evangeline aquifers (sheets 4, 5, 9, and 10); and a map depicting approximate contoured long-term (2000–16) water-level changes for the Jasper aquifer (sheet 14).

The point and contour data depicted on the maps for all three aquifers (Chicot, Evangeline, and Jasper) are available for download at http://dx.doi.org/10.3133/sim3365, as are the metadata compliant with Federal Geographic Data Committee-mandated guidelines (Federal Geographic Data Committee, 2015).

In addition to maps depicting water-level altitudes and changes in the Chicot, Evangeline, and Jasper aquifers, this report also contains a map that depicts the locations of the 11 extensometer sites in Harris and Galveston Counties activated or installed between 1973 and 1980 (sheet 15). At these sites, 13 extensometers continuously record cumulative compaction of subsurface sediments of the Chicot and Evangeline aquifers. Graphs of these cumulative long-term compaction data from the 13 extensometers from 1973 (or later depending on activation or installation date) through 2015 are presented on sheet 16. Tables 1–3 present the water-level data used to construct each water-level map for each aquifer, and table 4 presents the data that support the graphs of cumulative compaction of subsurface sediments. A brief description is included of the methods used for map construction. Figures are included that can be used to approximate changes in effective stress caused by changes in groundwater withdrawal from the Chicot and Evangeline aquifers.

Hydrogeology of the Study Area

The three primary aquifers in the Gulf Coast aquifer system in in the Houston-Galveston region study area are the Chicot, Evangeline, and Jasper (figs. 2–4), 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 aquifer, 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).

Since about 1932 numerous authors have contributed to the body of knowledge and understanding of the complex stratigraphic and hydrogeologic relations of the Gulf Coast aquifer system in the Houston-Galveston region study area (fig. 5). Using this information, a series of groundwater flow models were created, the most recent being Kasmarek (2013); these models provide an evaluative tool that can be used by water-resource managers to help regulate and conserve the important natural water resource of the aquifer system.

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 (eustacy) 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. 2–4), 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).

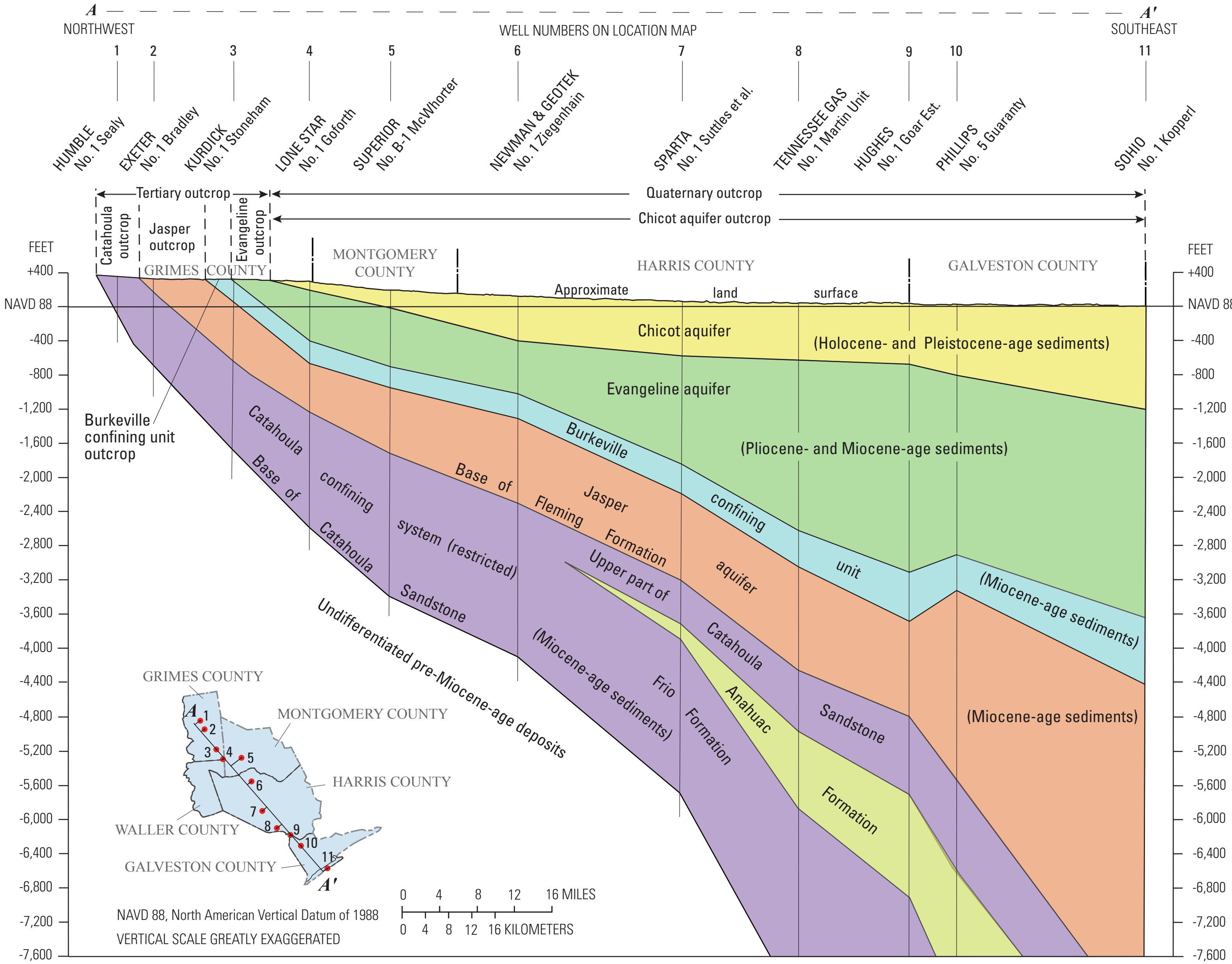

Figure 2. Hydrogeologic section *A–A´* of the Gulf Coast aquifer system in Grimes, Montgomery, Harris, and Galveston Counties, Texas (modified from Baker, 1979, fig. 4).

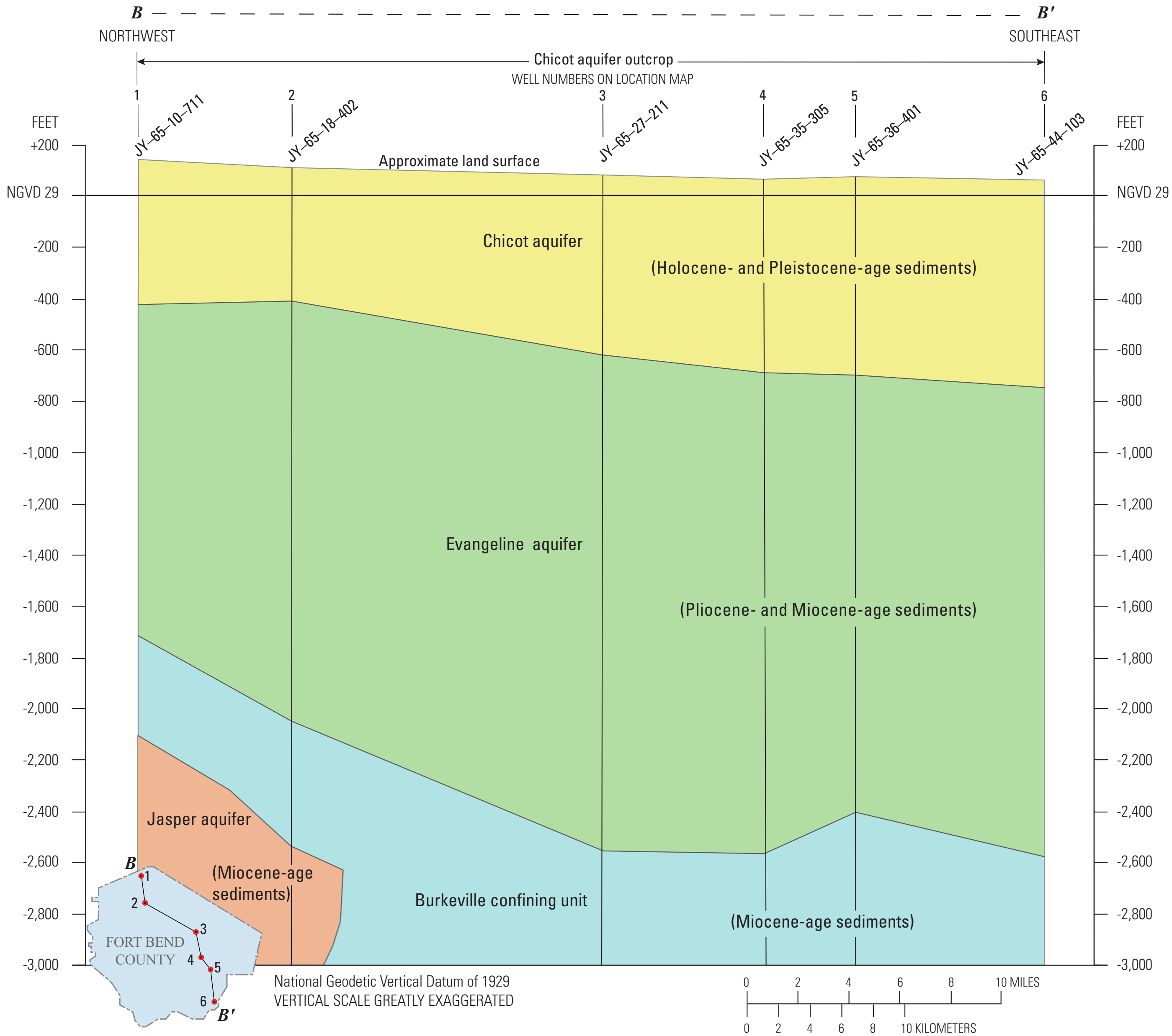

Figure 3. Hydrogeologic section *B–B´* of the Gulf Coast aquifer system in Fort Bend County, Texas (modified from Wesselman, 1972, fig. 30).

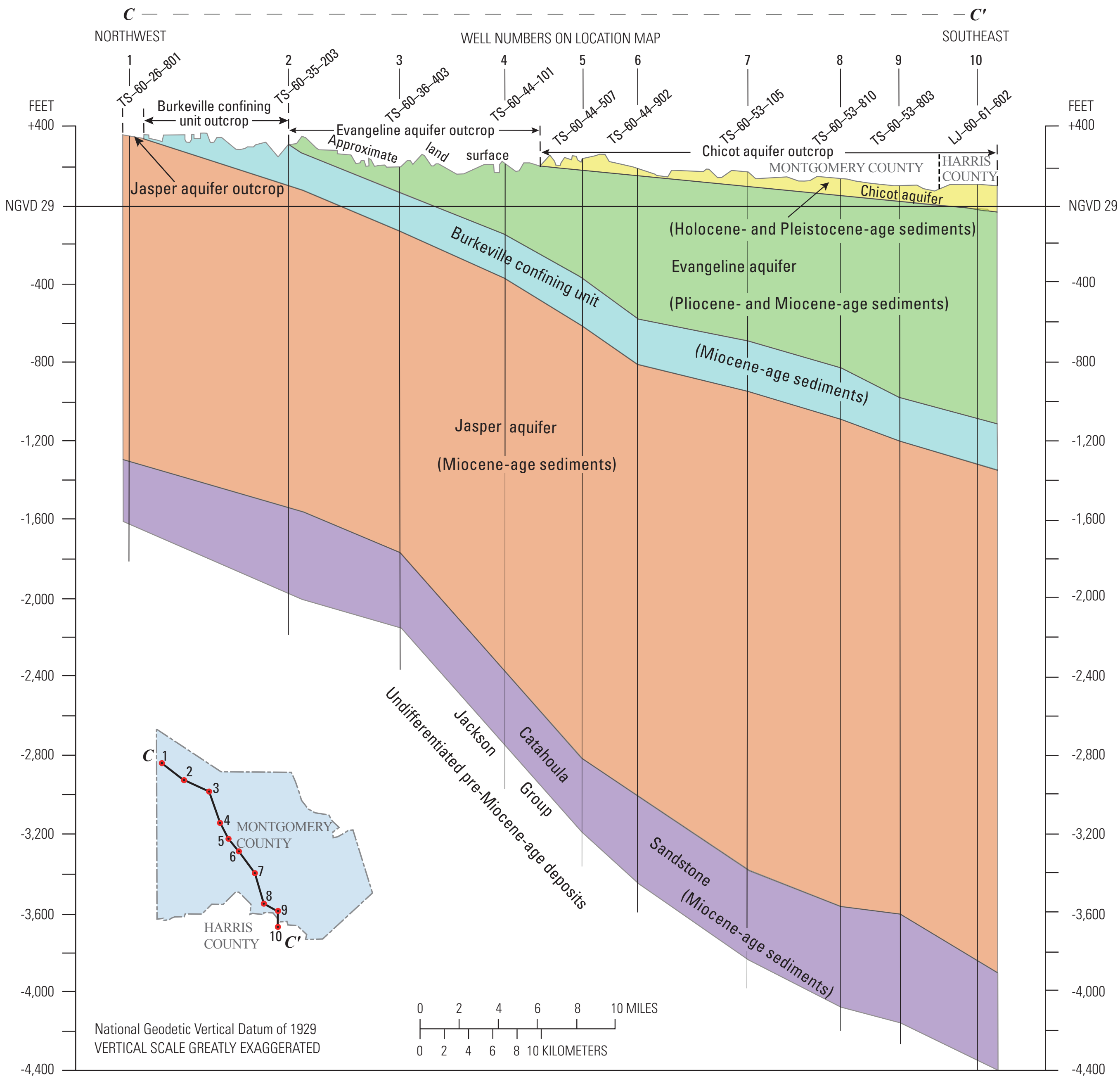

Figure 4. Hydrogeologic section *C–C´* of the Gulf Coast aquifer system in Montgomery and Harris Counties, Texas (modified from Popkin, 1971, fig. 29).

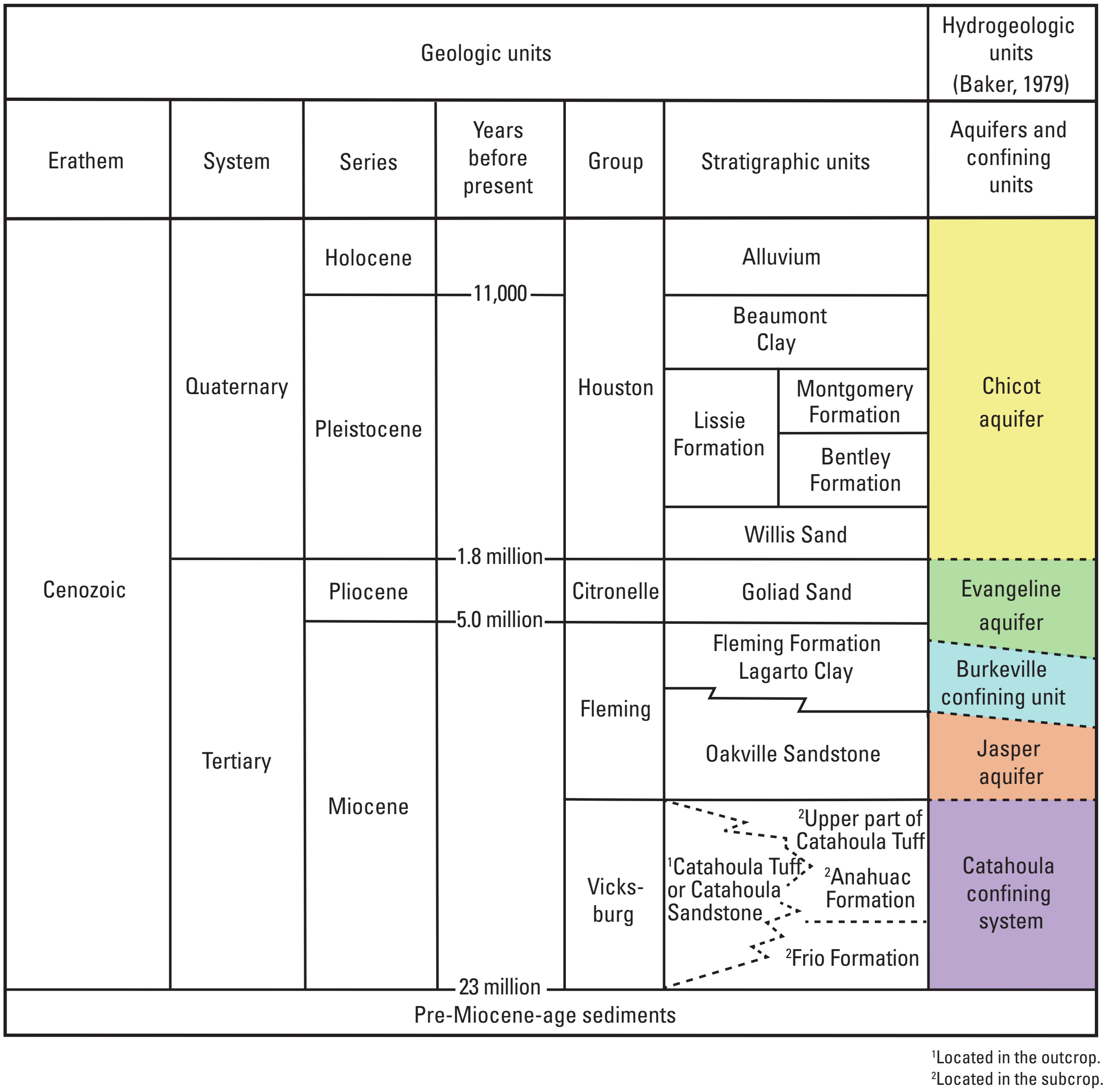

Figure 5. Geologic and hydrogeologic units of the Gulf Coast aquifer system in the Houston-Galveston region study area, Texas (modified from Sellards and others, 1932; Baker, 1979; Meyer and Carr, 1979).

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 (1977–2015) water-level-change maps (Kasmarek and others, 2015, sheets 5 and 10, respectively), 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 most northern 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, and the Jasper aquifer 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).

The hydrogeologic cross section *A–A′* (fig. 2) extends through the Houston-Galveston region from northwestern Grimes County, continues southeastward through Montgomery and Harris Counties, terminates at the coast in Galveston County, and depicts the three aquifers thickening and dipping toward the coast from their updip (outcrop) limits. Comparisons of cross sections *A–A′* (fig. 2), *B–B′* (fig. 3), and *C–C′* (fig. 4) indicate that the thicknesses of the three aquifers similarly increase downdip towards the coast. Conversely, in central Harris, southern Montgomery, and Grimes Counties, the sediments of the updip Chicot and Evangeline aquifers become progressively thinner, and in Montgomery and Grimes County, the thickness of the sediments composing the Chicot aquifer is effectively insufficient for groundwater withdrawal (figs. 2 and 4). 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.

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. This water is ultimately discharged along the coast to brackish (dissolved-solids concentrations of 1,000–10,000 mg/L [Freeze and Cherry, 1979]) water of the coastal bays and estuaries (Kasmarek and Robinson, 2004).

Subsidence and Compaction Processes

By 1979, as much as 10 ft of subsidence had occurred in the Houston-Galveston region, and approximately 3,200 mi^2 of the 11,000-mi^2 geographic area had subsided more than 1 ft (Coplin and Galloway, 1999). 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 decrease, 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

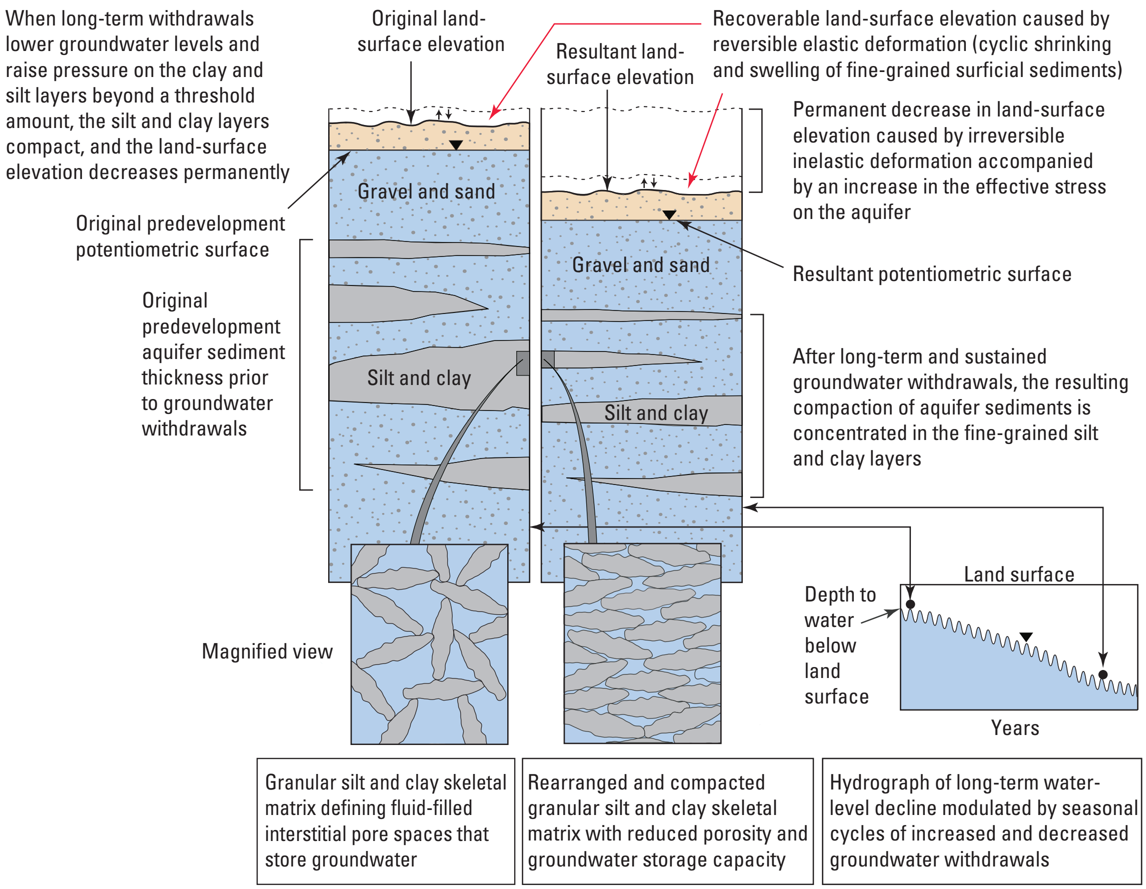

Figure 6. Mechanism of subsidence caused by potentiometric surface declines induced by groundwater withdrawals in an aquifer composed of gravel, sand, silt, and clay (modified from Galloway and others, 1999, p. 9).

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).

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 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 operating 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 measurements were made at each well while the well was not being pumped. Water-level measurements used to construct sheets 1–14 of this report were collected in wells during December 2015–March 2016 to represent 2016 water-level altitudes of the aquifers (tables 1–3; Chicot, Evangeline, and Jasper aquifers, respectively); during December through March, water levels of the aquifers in the Houston-Galveston region are usually higher compared to the rest of the year because rates of groundwater withdrawal during these months generally are at a minimum. In the study area, groundwater levels in the aquifers are generally higher in the late fall, winter, and spring months of the year because of the cooler temperatures requiring less water to be used for irrigation, increased precipitation, and, hence, decreased groundwater withdrawals used for public supply. Conversely, groundwater levels of the aquifers decline during the warmer summer months and early fall because of decreased precipitation and increased groundwater withdrawals. After a thorough evaluation, the collected data were incorporated into a geographic information system (GIS) as point-data layers and used for the construction of sheets 1–14.

Determination of Water-Level Altitudes

The annual (2016) regional-scale depictions of water-level altitudes presented in this report were derived from water-level-measurement data collected during December 2015–March 2016 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 water-level-altitude depictions presented on sheets 1, 6, and 11 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-altitude value referenced to the North American Vertical Datum of 1988 (NAVD 88) (National Oceanic and Atmospheric Administration, 2008) (hereinafter, referred to as “datum”) for each point (well). To determine land-surface elevations, a corresponding land-surface-datum value for each well is obtained from a digital elevation map (DEM), and the elevation of the measuring point is measured by using an engineering ruler at the well site. The accuracy of the land-surface-altitude data has gradually improved through time, and the most accurate land-surface-altitude data available were used by the USGS for each historical annual depiction of water-level altitudes in the study area. Previous reports in this annual series used the National Geodetic Vertical Datum of 1929 (NGVD 29) and NAVD 88. This year (2016), however, the vertical datums were converted to NAVD 88 for consistency that standardized and slightly improved the accuracy of land-surface elevations throughout the study area. Although these two datums differ geographically throughout the world, “nowhere in the study area does [the datum difference] exceed more than a couple inches” (Cliff Middleton, National Geodetic Survey, written commun., 2015).

The data for each point (well) used for contour configuration on the three approximate 2016 water-level-altitude maps (sheets 1, 6, and 11) are referenced to NAVD 88 (tables 1–3, respectively). These approximate water-level-altitude contours represent 2016 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. Water-level altitudes were depicted by using contour intervals of 50 and 100 ft.

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 Plan for Groundwater Activities” (app. 7.3, “Groundwater Data Management Plan” [Greg P. Stanton, U.S. Geological Survey, written commun., 2011]). All data were archived in the USGS National Water Information System (NWIS) (http://waterdata.usgs.gov/tx/nwis/nwis).

Depicting Changes in Water-Level Altitudes and Effects of Drought

Maps depicting changes in water-level altitudes in the Chicot, Evangeline, and Jasper aquifers were constructed for 1-year (2015–16), 5-year (2011–16), and various long-term (1990–2016 [Chicot and Evangeline aquifers], 1977–2016 [Chicot and Evangeline aquifers], and 2000–16 [Jasper aquifer]) periods (sheets 3–5 [Chicot aquifer], 8–10 [Evangeline aquifer], and 13–14 [Jasper aquifer]). To create these various water-level-change maps, datasets of water-level-change values (difference between the current year [2016] and historical water-level-altitude values) were used. Historical years (1977, 1990, and 2000) when water-level-altitude maps were created and published as part of the USGS annual map series are coincident with the creation of the HGSD, FBSD, and LSGCD, respectively.

Magnitudes of water-level changes during 1-year periods often fluctuate because groundwater levels can change appreciably in response to short-term changes in precipitation and groundwater withdrawals. Precipitation fluctuations associated with wet and dry periods can appreciably affect the volume of groundwater withdrawal as irrigation demand is reduced by increased rainfall. Given these short-term dynamics, water-level changes during the most recent 1-year period (2015–16) were not contoured but rather depicted as individual point values on sheets 2, 7, and 12. Whereas the normal annual precipitation is 49.77 inches (in.), the precipitation total during 2015 was 70.03 in., which is about 41 percent more than the normal annual precipitation total (National Oceanic and Atmospheric Administration, 2012, 2015b). In years with near-normal precipitation such as 2008 when 53.00 in.

of precipitation fell (National Oceanic and Atmospheric Administration, 2015b), the spatial distribution of 1-year water-level changes are more equally and spatially distributed compared to the spatial distribution of the current (2015–16) 1-year change maps (sheets 2, 7, and 12) that reflect the wetter than normal conditions during 2015. Conversely, in drier than normal years such as 2011 when only 24.57 in. of precipitation fell, the spatial distribution of 1-year change predominately consisted of declines (Kasmarek and others, 2012, sheets 2, 7, and 12). The study area was in an extreme drought in 2011 (National Oceanic and Atmospheric Administration, 2016), and elevated temperatures occurred throughout the year but especially during June, July, August, and September when the average high temperatures were 94.4 degrees Fahrenheit (°F), 96.9 °F, 102.0 °F, and 95.5 °F, respectively (National Oceanic and Atmospheric Administration, 2015b). The warm and dry conditions in 2011 caused increased water demand compared to years with normal precipitation amounts and temperatures, and the increase in demand was met by increased groundwater withdrawals from wells, which caused potentiometric-surface declines in the aquifers.

For the 1-year (2015–16) water-level-change maps (sheets 2, 7, and 12), water-level changes were computed as the difference between the depths to water at each point (well) for which a water-level measurement was available in 2015 and in 2016. Water-level changes on the 1-year maps (sheets 2, 7, and 12) are depicted by using upward-pointing triangles to indicate water-level rises, downward-pointing triangles to indicate water-level declines, and circles to indicate no water-level change when values range from -0.49 ft to 0.49 ft. The numbers within the rise and decline triangles indicate the amount of water-level change in feet.

For the historical 5-year (2011–16) water-level-change maps (sheets 3, 8, and 13), water-level changes were computed as the difference between water-level altitude at each point (well) for which a water-level measurement was made in 2011 and in 2016. Changes on the 5-year maps are depicted by contours of equal water-level change, and each map was constructed by contouring the set of mapped point differences.

For the historical long-term (1977–2016, 1990–2016, and 2000–16) water-level-change maps (sheets 4, 5, 9, 10, and 14), 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 the historical years (1977, 1990, and 2000) and in 2016. For wells measured in 2016 that had no corresponding measurement in the historical year, a GIS raster (gridded surface) (Worboys, 1995) was created from published historical water-level-altitude contours (1977 [Gabrysch, 1979], 1990 [Barbie and others, 1991; Kasmarek, 1997], and 2000 [Kasmarek and Houston, 2007]). 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 2016 and in the historical year or as the difference in water-level altitude at that point in 2016 and the water-level altitude on a gridded surface of the historical year water-level-altitude map (Gabrysch, 1979; Barbie and others, 1991; Kasmarek, 1997; Kasmarek and Houston, 2007) (tables 1–3). 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 the historical year have been destroyed or were not measured in 2016. For the subset of wells measured both in 2016 and in the historical year, the mapped point values used were the differences in water-level-altitude values between 2016 and the historical year rather than the differences between the 2016 water-level-altitude values and the historical year's gridded-surface values.

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 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 in the sediments penetrated 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).

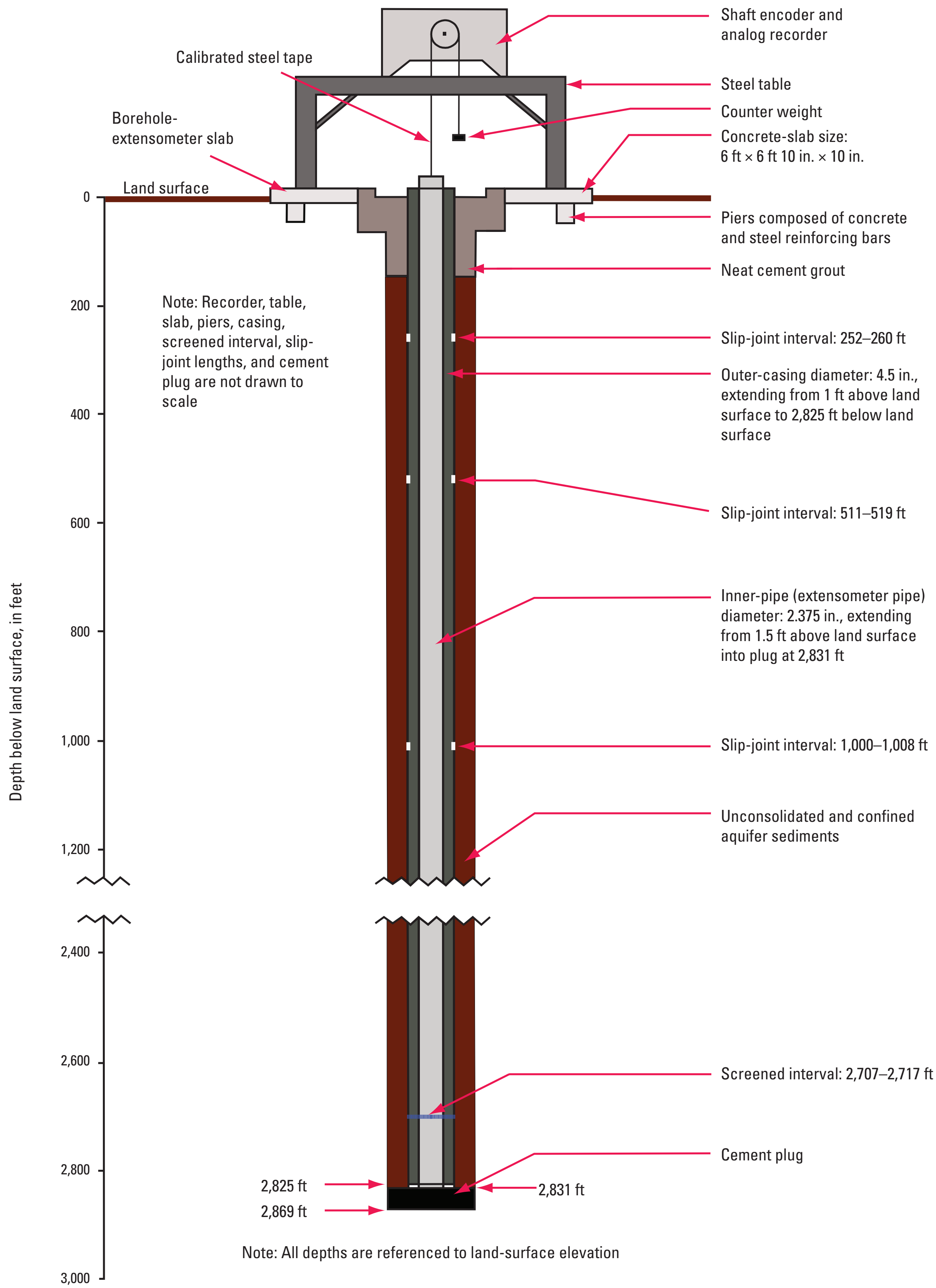

Figure 7. Cross-sectional perspective of the borehole extensometer/piezometer (LJ–65–23–322) located at Pasadena, Texas (ft, foot; in., inch).

Extensometer data recorded at the 11 sites are used to quantify the rate of compaction in the Chicot and Evangeline aquifers, 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. For this report, extensometer data of the cumulative compaction in the Chicot and Evangeline aquifers were collected from and evaluated for 13 extensometers in Harris and Galveston Counties (sheet 15; tables 4*A*–4*M*).

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 installed in 1962 in Harris County (LJ–65–32–401 [Johnson Space Center]) was 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 final three extensometers in the current (2016) 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 (table 4). From late 1973 to late 1982, a noticeable amount of seasonal variation occurred at the two extensometers at the Baytown site (sheet 16). 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. Data collected after 1982 indicate that these design modifications reduced the fluctuations and improved the accuracy of the data (sheet 16).

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

Locations of wells used to construct the water-level-altitude maps and water-level-change maps for the Chicot, Evangeline, and Jasper aquifers are shown in appendix 1. The well index numbers on the three maps (apps. 1–1, 1–2, and 1–3) correspond to tabular data (tables 1–3, respectively) for each of the maps for each aquifer. The Chicot and Evangeline aquifer maps (sheets 1–5 and 6–10, respectively) depict approximate water-level altitudes in 2016 and water-level changes during 2015–16, 2011–16, 1990–2016, and 1977–2016 in these two aquifers. The Jasper aquifer maps (sheets 11–14) depict approximate water-level altitudes in 2016 and water-level changes during 2015–16, 2011–16, and 2000–16. The contoured depictions on the maps showing approximate water-level changes were constructed by using contour intervals relative to the specific range of water-level changes for a given map. Adjusting the contour intervals in this way helped to present a clear depiction of regional-scale water-level changes.

Chicot Aquifer

Water-level measurements from 177 wells (table 1) were used to construct the approximate 2016 water-level-altitude map of the Chicot aquifer (sheet 1). In 2016, the water-level-altitude contours ranged from 200 ft below datum in a localized area in northwestern Harris County to 200 ft above datum in west-central Montgomery County (sheet 1). In one well (LJ–65–20–520) in southwestern Harris County near the Harris County and Fort Bend County border, the water-level altitude of 221 ft below datum recorded in 2016 (table 1) was not contoured because it was much lower than water-level altitudes of proximal wells. Depictions of water-level change during 2015–16, 2011–16, 1990–2016, and 1977–2016 are presented on sheets 2, 3, 4, and 5, respectively.

The total number of water-level-measurement pairs used to construct the water-level-change maps was 163 for 2015–16, 142 for 2011–16, 140 for 1990–2016, and 128 for 1977–2016 (table 1). Water-level changes for 2015–16 for wells screened in the Chicot aquifer were determined by subtracting the measured depth to water blsd in 2016 from the measured depth to water blsd in 2015 and are depicted by numbered upward-pointing triangles to indicate water-level rises, numbered downward-pointing triangles to indicate water-level declines, and circles to indicate no water-level changes. These 1-year changes ranged from a 39-ft decline in southwestern Harris County to a 26-ft rise in northern Brazoria County (sheet 2). For 2011–16, water-level-altitude contours ranged from a 30-ft decline in southeastern Harris County to a 20-ft rise in southern Fort Bend County (sheet 3). For 1990–2016, water-level-altitude contours ranged from a 140-ft decline in an isolated area in north-central Harris County to a 160-ft rise in an isolated area in south-central Harris County (sheet 4). For 1977–2016, water-level-altitude contours ranged from a 120-ft decline in an isolated area located in northwestern Harris County to a 200-ft rise in southeastern Harris County (sheet 5). The 1977–2016 water-level-change map depicts a broad area of decline in northern, north-central, and southwestern Harris County and across parts of north-central, eastern, and southeastern Fort Bend County and extending into southeastern Waller County (sheet 5). Additionally, declines extend from Fort Bend County into northwestern and northeastern Brazoria County (sheet 5). A broad area of rise is depicted in central, eastern, and southeastern Harris County, all of Galveston County, eastern and northernmost Brazoria County, and northeastern Fort Bend County (sheet 5).

Evangeline Aquifer

Water-level measurements from 320 wells (table 2) were used to construct the approximate 2016 water-level-altitude map of the Evangeline aquifer (sheet 6). In 2016, water-level-altitude contours ranged from 250 ft below datum in three separate areas located in south-central Montgomery County extending into north-central Harris County, in western-central Harris County, and in southwestern Harris County to 200 ft above datum in southeastern Grimes and northwestern Montgomery Counties (sheet 6). Depictions of water-level change for 2015–16, 2011–16, 1990–2016, and 1977–2016 are presented on sheets 7, 8, 9, and 10, respectively.

The total number of water-level-measurement pairs used to construct the water-level change maps was 307 for 2015–16, 259 for 2011–16, 247 for 1990–2016, and 239 for 1977–2016 (table 2). Water-level changes for 2015–16 for wells screened in the Evangeline aquifer were determined by subtracting the measured depth to water blsd in 2016 from the measured depth to water blsd in 2015 and are depicted as stated for the Chicot aquifer above. The 1-year changes ranged from a 65-ft decline in southwestern Harris County at the border of Harris and Fort Bend Counties to a 61-ft rise in central Harris County (sheet 7). For 2011–16, water-level-altitude contours ranged from a 60-ft decline in southwestern Harris County to a 40-ft rise in south-central Montgomery County extending into north-central Harris County (sheet 8). For 1990–2016, water-level-altitude contours ranged from a 160-ft decline in south-central Montgomery County and north-central Harris County to two areas with 160-ft rises in central and southwestern Harris County (sheet 9). For 1977–2016, water-level-altitude contours ranged from a 320-ft decline in south-central Montgomery County to a 240-ft rise in southeastern Harris County (sheet 10). As a comparison to historical water-level declines, the aforementioned area with a 320-ft of decline is only 30 ft less than the area that had a maximum water-level altitude of as much as 350-ft below datum, which was documented in southeastern Harris County in 1977 (Gabrysch, 1979). The 1977–2016 water-level-change map depicts a broad area of decline through northern, northwestern, and southwestern Harris County extending into southeastern and northeastern Waller, southern Montgomery, and western Liberty Counties and into northeastern and east-central Fort Bend County (sheet 10). A broad area of rise is depicted in central, eastern, and southeastern Harris County and extending into the northernmost part of Brazoria County and the southwestern area of Liberty County (sheet 10).

Jasper Aquifer

Water-level measurements from 109 wells (table 3) were used to construct the approximate 2016 water-level-altitude map of the Jasper aquifer (sheet 11). In 2016, the water-level-altitude contours ranged from 200 ft below datum in south-central Montgomery County and extended into north-central Harris County to 250 ft above datum in northwestern Montgomery County extending into east-central Grimes County and southwestern Walker County (sheet 11). Depictions of water-level change for 2015–16, 2011–16, and 2000–16 are presented on sheets 12, 13, and 14, respectively.

The total number of water-level-measurement pairs used to construct the water-level change maps was 95 for 2015–16, 89 for 2011–16, and 90 for 2000–16 (table 3). Water-level changes for 2015–16 for wells screened in the Jasper aquifer were determined by subtracting the measured depth to water blsd in 2016 from the measured depth to water blsd in 2015 and are depicted as stated for the Chicot aquifer above. These 1-year changes ranged from a 38-ft decline in two areas in south-central Montgomery County and north-central Harris County to a 51-ft rise in northern-central Montgomery County (sheet 12). For 2011–16, water-level-altitude contours ranged from a 60-ft decline in south-central Montgomery County that extends slightly into north-central Harris County to a 40-ft rise in north-central Montgomery County (sheet 13). For 2000–16, water-level-altitude contours depict water-level declines in a broad area throughout most of Montgomery County and in parts of Waller, Grimes, and Harris Counties, ranging from a 220-ft decline in two isolated areas in south-central Montgomery County to a 20-ft decline located in extreme northwestern Montgomery extending into eastern-central Grimes County (sheet 14).

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 (sheet 15) 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. The amount of cumulative compaction for each site visit 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 December.

Graphs of cumulative compaction are presented for 1973 (or later depending on when each extensometer was activated or installed) through December 2015. The rate of compaction varied from site to site (sheet 16), and the supporting cumulative compaction data used for the creation of the graphs are presented in tables 4*A*–4*M*.

The selected depth of the extensometer (sheet 16) determines the total thickness of sediment over which compaction is measured by the extensometer. Six of the extensometers measure compaction that occurs solely in 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 the Chicot and Evangeline aquifers (Lake Houston, Northeast, Southwest, Addicks, Baytown C–2 [deep], Clear Lake [deep], and Pasadena) (sheet 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). The rate of compaction is different at each extensometer 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). 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 (sheet 16). Coincident with the curtailment of groundwater withdrawals, water levels in the aquifers began to rise and recover (Kasmarek and others, 2015, sheets 5 and 10). The decreases in groundwater withdrawals resulted in a rise in water levels in the Chicot and Evangeline aquifers of as much as 200 and 240 ft, respectively, as depicted on the two 1977–2016 water-level-change maps (sheets 5 and 10) in the areas encompassing the extensometer sites.

The cumulative compaction data discussed in this report began on the extensometer installation date, but for subsequent years, the data begin on the first site visit in January and end on the last site visit in December for any given year (sheet 16; tables 4*A*–4*M*). For 2015, cumulative compaction ranged from 0.095 ft (table 4*G*) at the Texas City-Moses Lake extensometer, which solely measures compaction of the Chicot aquifer, to 3.666 ft (table *4E*) at the Addicks extensometer, which measures compaction of the Chicot and Evangeline aquifers. The graphs of cumulative compaction data from installation in 1975 through 2015 for the Pasadena extensometer and from installation in 1973 through 2015 for the Baytown C–1 (shallow) and Baytown C–2 (deep) extensometers indicate cumulative compaction values of 0.518 (Pasadena extensometer), 0.982 (Baytown C–1 [shallow] extensometer), and 1.121 ft (Baytown C–2 [deep] extensometer) (sheet 16; tables 4*M*, 4*H*, and 4*I*, respectively).

From January through December 2015, the Northeast (table 4*B*), Southwest (table 4*C*), Addicks (table 4*E*), Johnson Space Center (table 4*F*), and Clear Lake (deep) (table 4*L*) extensometers recorded net decreases in land-surface elevation, but the Lake Houston (table 4*A*), East End (table 4*D*), Texas City-Moses Lake (table 4*G*), Baytown C–1 (shallow) (table 4*H*), Baytown C–2 (deep) (table 4*I*), Seabrook (table 4*J*), Clear Lake (shallow) (table 4*K*), and Pasadena (table 4*M*) extensometers recorded net increases in land-surface elevation.

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 (sheet 16). These asymptotic compaction-rate patterns are 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 geographic locations of the extensometers to the geographic areas of the long-term water-level changes in the Chicot and Evangeline aquifers (sheets 4–5 and 9–10, respectively) for both long-term periods, 1990–2016 and 1977–2016, the relatively large areas of water-level rises coincide with the compaction-rate decreases, with the exception of the Addicks extensometer site.

Cumulative compaction data from the Addicks extensometer (table 4*E*) indicate a consistent rate of compaction beginning from the time that the extensometer was installed in mid-1974 to about mid-2003; the rate of compaction remained steady during this period because the extensometer is located in regulatory area 3 (fig. 15) of the HGSD and, as such, was not scheduled for a 30-percent groundwater withdrawal reduction until 2011 (Harris-Galveston Subsidence District, 2013). During the period of a consistent rate of compaction from mid-1974 through mid-2003, therefore, groundwater withdrawal continued unabated in the area adjacent to the Addicks extensometer site with an associated calculated rate of compaction of about 0.1 ft per year. Additionally, the rate of compaction during August 2003–December 2003 decreased to about 0.004 ft; this decrease in the rate of compaction likely is 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. For 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 0.023 ft per year during 2009–15 on the basis of a beginning value of 3.502 ft in January 2009 and an ending value of 3.666 ft in December 2015 (sheet 16; table 4*E*).

The graph of cumulative compaction data obtained from the Seabrook extensometer (sheet 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 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 (sheet 16) (table 4). During about the first 37 years of the period of record, through about early May 2009, the cumulative compaction data recorded at the Baytown C–1 (shallow) extensometer were consistently less than the cumulative compaction data recorded at the Baytown C–2 (deep) extensometer, with a difference of 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 2015, the difference in cumulative compaction data for the two sites was within 0.139 ft (tables 4*H* and 4*I*). The cause of this recent increased rate of compaction is not certain, but in addition to the factors controlling compaction discussed previously in the section “Subsidence and Compaction Processes,” the presence of a known normal fault proximal to the Baytown site documented by Verbeek and Clanton (1978) and Shah and Lanning-Rush (2005) may be a contributing factor. Because of the recent increase in the rate of compaction at the Baytown C–1 (shallow) extensometer, the 2015 trend and difference in cumulative compaction recorded by the Baytown C–1 (shallow) extensometer and the Baytown C–2 (deep) extensometer more closely match the trend and difference in cumulative compaction of 0.024 ft recorded in December 2015 by the Clear Lake (shallow) and Clear Lake (deep) extensometers (sheet 16; tables 4*K* and 4*L*).

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, since January 1981 until December 2015, a slight rise in land-surface-elevation of approximately 0.098 ft has occurred (table 4*G*; sheet 16). The graphs of 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 (sheet 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.

Changes in Effective Stress Caused by Groundwater Withdrawals from the Chicot and Evangeline Aquifers

Two historical USGS reports presented information concerning the relation between changes in effective stress in pounds per square inch on the aquifers caused by changes in groundwater withdrawal from the Chicot and Evangeline aquifers at the 13 extensometers and associated nested piezometers (Gabrysch, 1978; Gabrysch and Coplin, 1990). Water-level data from 1978 and 1987 were discussed in the report by Gabrysch and Coplin (1990) that graphically depicted this relation. For this report, water-level data from 1988, 1998, and 2008 were selected to represent more recent decadal water-level changes in the Chicot and Evangeline aquifers. Because an extreme drought occurred from October 2010 through September 2011 (hereinafter referred to as the “2011 drought”), water-level data from 2012 were also selected, as were water-level data from the most recent year (2015). Water-level-measurement data collected during January 2012 represent the water-level stress on the aquifers caused by the extreme 2011 drought, which was the worst 1-year drought ever recorded in Texas (University of Texas

Center for Integrated Earth System Science, 2013) and which resulted in an increased demand for groundwater. During the drought, the increased demand for groundwater caused groundwater levels in the Chicot and Evangeline aquifers to decrease. The water-level data from January 1988, 1998, 2008, 2012, and 2015 were collected during site visits to the extensometers. The corresponding net compaction data are from each of the previous years (that is, 1987, 1997, 2007, 2011, and 2014, respectively).

Aquifer Stresses

In aquifer systems, effective stress is a result of the pressure applied by the combined weight of the saturated and unsaturated sediment overburden on the granular skeletal matrix of the sediments composing the aquifer system counteracted by the opposing stress of the fluid pressure within the pores of the granular skeletal matrix. Terzaghi (1925) proposed the concept of effective stress, later analyzed and discussed in detail by Skempton (1961), Scott (1963), Terzaghi and Peck (1967), and Freeze and Cherry (1979). Effective stress is described mathematically by the following equation:

$$\sigma_e = \sigma_T \; p \qquad (1)$$

where

σ_e is the effective stress supported by the granular skeletal matrix of the aquifer, in pounds per square inch,

σ_T is the total stress on the aquifer, in pounds per square inch, and

p is the fluid pressure of the interstitial water within the pore spaces of the granular skeletal matrix, in pounds per square inch (Freeze and Cherry, 1979).

Determining the exact amount of effective stress at any given elevation in the confined Chicot and Evangeline aquifers is problematic because of the complex paleodepositional processes and associated heterogeneity of the aquifer. In the upper parts of the Chicot and Evangeline aquifers, the water table generally ranges from about 10 to 30 ft below land surface and typically is deeper in areas with lower topographic relief compared to areas with higher topographic relief, but the water table is constantly fluctuating throughout a given year depending on the lack or abundance of precipitation coupled with evapotranspiration rates. Additionally, Noble and others' (1996) analysis of seismic refraction data indicated that there are numerous perched water table zones with interlayered unsaturated and saturated zones, which further complicates an accurate calculation of effective stress. Furthermore, the distribution and thickness of the perched water tables vary considerably; in the more sandy and less clayey updip recharge areas, perched water tables are less numerous and thinner compared to those in the less sandy and more clayey downdip areas (Kasmarek and Strom, 2002; Kasmarek and Robinson, 2004; Kasmarek, 2013). Because the sediments composing the Chicot and Evangeline aquifers are unlithified and are subjected to different amounts of ongoing groundwater withdrawals, the amount of stress changes as water levels in the Chicot and Evangeline aquifers change. Prior to about 1891, during the predevelopment period of the aquifers in the study area (Kasmarek, 2013), the total stress on each aquifer in the Gulf Coast aquifer system was at equilibrium with the counteracting forces of effective stress and fluid pressure; this total stress (a downward force) was sustained by the combined upward force of the granular skeletal matrix of the aquifers and fluid pressure in pounds per square inch of the interstitial water within the pore spaces of the matrix (Freeze and Cherry, 1979).

During the period from 1891 to about 1975, development of the aquifers in the study area continued with increased groundwater withdrawal by an increasing number of wells. These withdrawals caused the potentiometric surfaces of the aquifers to initially decline spatially and temporally, which caused the pore pressures in the aquifer to decrease, and correspondingly, the total stress on the aquifers began to increase (fig. 6). After the HGSD was created in 1975, groundwater withdrawals began to be slowly curtailed (mostly in HGSD regulatory areas 1 and 2 [sheet 15]). In the regulatory areas where groundwater withdrawals were curtailed, groundwater levels began to rise spatially and temporally (sheets 5 and 10), pore pressures began to increase, and the total stress on the aquifers began to decrease. The change in effective stress on each individual aquifer is approximated as follows:

$$d\sigma_e = d\sigma_T \; d_p \qquad (2)$$

where

$d\sigma_e$ is the change in effective stress, in pounds per square inch,

$d\sigma_T$ is the change in total stress on the individual aquifer, in pounds per square inch, and

d_p is the change in fluid pressure of the interstitial water within the pore space of the granular skeletal matrix, in pounds per square inch (Freeze and Cherry, 1979).

The weight density of water can be defined as follows:

$$y = \rho g \qquad (3)$$

where

y is the weight density of water, in pounds per square inch,

ρ is the fluid density of water, in pounds per cubic inch, and

g is gravity (constant) of about 386.09 inches per second squared.

A slug is the mass that accelerates by 12 inches per second squared when a force of 1 pound is exerted on it; pure water has a weight density of 1.940 slugs per cubic foot at a temperature of 4 °Celsius. Recalling that p is the fluid pressure of the interstitial water within the pore spaces of the granular skeletal matrix, in pounds per square inch, Freeze and Cheery (1979, p. 53–54) explained how changes in effective stress are governed by changes in the hydraulic head (equations 4–7):

$$p = y\psi \tag{4}$$

where

- y is the weight density of water, in pounds per cubic foot, and
- ψ is the pressure head, in inches.

The pressure head also is equal to the difference between the hydraulic head and the elevation head:

$$\psi = h - z \tag{5}$$

where

- ψ is the pressure head, in inches,
- h is the hydraulic head, in inches, and
- z is the elevation head, in inches (Freeze and Cherry, 1979).

It then follows that changes in effective stress at a point are governed by changes in the hydraulic head at that point:

$$d\sigma_e = -\,yd\psi \tag{6}$$

where

- $d\sigma_e$ is the change in effective stress, in pounds per square inch,
- y is the weight density of water, in pounds per square inch, and
- $d\psi$ is the change in pressure head, in feet (Freeze and Cherry, 1979).

Alternatively, $d\sigma_e$ can be determined as follows:

$$d\sigma_e = -\,ydh \tag{7}$$

where

- $d\sigma_e$ is the change in effective stress, in pounds per square inch,
- y is the weight density of water, in pounds per square inch, and
- dh is the change in the hydraulic head, in inches (Freeze and Cherry, 1979).

Changes in Water Levels as an Indicator of Effective Stress

Although equations 1–7 require few parameters to calculate effective stress or changes in effective stress, determining the values for these parameters is difficult. For example, accurately determining the weight of the saturated and unsaturated sediment overburden on the granular skeletal matrix of the sediments and the opposing stress of the fluid pressure within the matrix requires the collection of extensive amounts of data and is beyond the scope of this report. A less complex method is to estimate changes in effective stress by multiplying the measured water level (depth to water blsd) for each piezometer at each site by 0.4335 pounds per square inch (psi), the pressure exerted by 1 foot of standing water in a given piezometer (http://www.engineeringtoolbox.com/pressure-head-water-d_1354.html). Water-level data for 1988, 1998, 2008, 2012, and 2015 and the corresponding net compaction values recorded by the extensometers for 1987, 1997, 2007, 2011, and 2014 were used to illustrate the cause and effect relations between changes in water levels caused by groundwater withdrawals and the resulting changes in effective stress (table 5). The relations between screened depths blsd and measured depths to water blsd are presented (figs. 8–17). Each of these figures includes a different “stress scale” where the length of scale is graduated in units of psi with respect to the range of values in the x-axis (figs. 8–17). Each stress scale is incremented in whole numbers according to the amount of pressure exerted by each foot of standing water. For a given piezometer, the stress that occurred in January of each year is presented and compared to the net annual compaction (table 4) that occurred in the previous year (table 5). To determine the approximate changes in stress at any depth blsd for the individual years, the unique stress scale on each figure can be overlaid across the dashed lines of interest. For example, the “0” of the stress scale could be placed on the green dashed line of figure 8 and then the changes in stress relative to January 2008 can be determined for the years represented by the other dashed lines.

As explained in the “Borehole Extensometers” section of this report, each extensometer was designed to function also as a piezometer (fig. 7), which makes it possible to measure the depth to water blsd at each extensometer site. With the exception of the Johnson Space Center site, each extensometer site also includes from one to seven nested piezometers installed proximally to the extensometer that are screened at different depths. The corresponding water-level data for the piezometers at each site, the associated stress values produced at each site, and the associated net cumulative compaction data are presented in this report (table 5). The water-level data for each piezometer or extensometer were also archived in the USGS NWIS database (http://waterdata.usgs.gov/tx/nwis/gw).

For the piezometer within the extensometer at the Addicks site (LJ–65–12–726) (fig. 8), the approximate effective stress (hereinafter referred to as “stress”) values ranged from 143.62 to 174.86 psi (table 5). The stress values of 143.62 and 174.86 psi were produced by the water levels measured in January 2008 of 331.30 ft blsd and in January 1998 of 403.38 ft blsd (table 5), respectively. The corresponding net compaction values recorded by the extensometer at the Addicks site ranged from 0.005 ft in 2007 to 0.067 ft in 1997 (table 5). The water level of 373.42 ft blsd measured in January 2012, representative of the 2011 drought period, produced a stress value of 161.88 psi; the extensometer recorded a corresponding net compaction value of 0.073 ft in 2011. Compared to the other extensometer sites in the study area, the relatively large and sustained groundwater withdrawals in areas adjacent to the Addicks site (HGSD regulatory area 3, sheet 15) and corresponding relatively large water-level changes caused the largest net cumulative compaction (sheet 16).

For the piezometer within the extensometer at the Lake Houston site (LJ–65–07–909) (fig. 9), stress values that ranged from 66.58 to 71.64 psi were produced by water levels measured in January 1988 of 153.58 ft blsd and in January 1998 of 165.26 ft blsd; the corresponding net compaction values ranged from 0.001 ft in 2007 to 0.009 ft in 1997. A 2012 stress value of 69.33 psi was produced by a water level of 159.94 ft blsd measured in January 2012; the corresponding net compaction value was 0.032 ft in 2011. The 2012 stress value of 69.33 psi was about the same as the 2008 stress value of 68.74 psi produced by a water level of 158.56 ft blsd; the corresponding net compaction value in 2007 was 0.001 ft (table 5). The 2012 stress value was also about the same as the stress values recorded at this site for 1998 (71.64 psi) and 2015 (70.34 psi).

For the piezometer within the extensometer at the Southwest extensometer site (LJ–65–21–226) (fig. 10), stress values that ranged from 98.97 to 130.85 psi (table 5) were produced by water levels of 228.30 ft blsd (January 2012) and 301.85 ft blsd (January 1988) (table 5). The corresponding net compaction values ranged from 0.059 ft in 2011 to 0.170 ft in 1987 (table 5). The 2012 stress value at the Southwest extensometer site was smaller than the stress values from 1988, 1998, 2008, or 2015 at this site. The Southwest site is in HGSD regulatory area 2, where groundwater withdrawals were curtailed beginning in 1975, and is about 4 miles from HGSD regulatory area 3, where the curtailment of groundwater withdrawals began more recently, in 2011. During each of the 5 years, the stress value for the piezometer within the Southwest extensometer was less than the corresponding stress values for piezometers LJ–65–21–230 and LJ–65–21–227, which are screened at shallower depths compared to the piezometer within the Southwest extensometer.

For the piezometer within the extensometer at the Northeast extensometer site (LJ–65–14–746) (fig. 11), the stress values ranged from 97.11 to 146.45 psi. Stress values of 97.11 and 146.45 psi were produced by water levels measured in January 2008 of 224.01 ft blsd and in January 1988 of 337.84 ft blsd, respectively. The corresponding net compaction values ranged from +0.015 ft (a compaction value preceded by a plus sign indicates a net rise in land-surface elevation) in 2007 to 0.060 ft in 1987. The 2012 stress value of 102.21 psi was produced by a measured water level of 235.77 ft blsd, with a corresponding net compaction value of 0.075 ft in 2011. The 2012 stress value was larger than the 97.11 psi stress value for 2008, less than the 1988 (146.45 psi) and 1998 (132.79 psi) stress values, and about the same as the 2015 stress value (103.14 psi). The 1998 and 2015 stress values were produced by measured water levels of 306.33 ft and 237.92 ft blsd, respectively, with corresponding net compaction values of 0.007 ft in 1997 and 0.027 ft in 2014.

For the piezometer within the extensometer at the Baytown C–1 (shallow) extensometer site (LJ–65–16–930) (fig. 12), the stress values ranged from 44.36 to 61.83 psi (table 5). The stress values of 44.36 and 61.83 psi were produced by water levels measured in January 2008 (102.33 ft blsd) and in January 1988 (142.63 ft blsd) (table 5), respectively. The corresponding net compaction values ranged from 0.010 ft in 2007 to 0.009 ft in 1987 (table 5). The 46.42 psi stress value for 2012 differed only slightly from the 2008 and 2015 stress values (44.36 and 46.00 psi, respectively) but was less than the 1988 (61.83 psi) and 1998 (50.40 psi) stress values. The screened interval of piezometer LJ–65–16–932 is deeper than the screened interval of the Baytown C–1 (shallow) extensometer site (LJ–65–16–930) and shallower than the Baytown C–2 (deep) extensometer site (LJ–65–16–931). The 2012 stress value (58.41 psi) for piezometer LJ–65–16–932 was similar to the 2008 (54.59 psi) and the 2015 (57.32 psi) stress values measured at this site but considerably less than the 1988 (88.42 psi) and 1998 (70.56 psi) stress values for this site. Additionally, the stress values measured at piezometer LJ–65–16–932 for the selected 5 years consistently exceeded the stress values at the Baytown C–1 (shallow) extensometer site (LJ–65–16–930) (fig. 12).

For the piezometer within the extensometer at the Baytown C–2 (deep) extensometer site (LJ–65–16–931) (fig. 12), stress values ranged from 44.64 to 70.48 psi (table 5). The stress values of 44.64 and 70.48 psi were produced by water levels measured in January 2008 of 102.98 ft blsd and January 1988 of 162.58 ft blsd (table 5), respectively, with corresponding net compaction values of 0.001 ft in 2007 and 0.012 ft in 1987 (table 5). The 2012 stress value of 46.03 psi was produced by a measured water level of 106.18 ft blsd. The 2012 stress value was about the same as the 2015 stress value of 45.03 produced by a measured water level of 103.87 ft blsd, but the net compaction of 0.115 ft in 2011 corresponding to the 2012 stress value was appreciably larger than the net compaction value of 0.005 ft in 2014 corresponding to the 2015 stress value. The 1998 stress value of 59.69 psi produced by a measured water level of 137.70 ft blsd was larger than the 2012 stress value, but in contrast to the net compaction of 0.115 ft in 2011, the net compaction value of +0.012 ft in 1997 indicated a net rise in land-surface elevation corresponding to the 1998 stress value.

Piezometer LJ–65–16–932 has a deeper screened interval compared to the Baytown C–1 (shallow) extensometer site (LJ–65–16–930) and a shallower screened interval compared to the Baytown C–2 (deep) extensometer site (LJ–65–16–931). During each of the 5 years (1988, 1998, 2008, 2012, and 2015), the stress value at piezometer LJ–65–16–932 exceeded the stress values observed at both the shallow and deep Baytown extensometer sites.

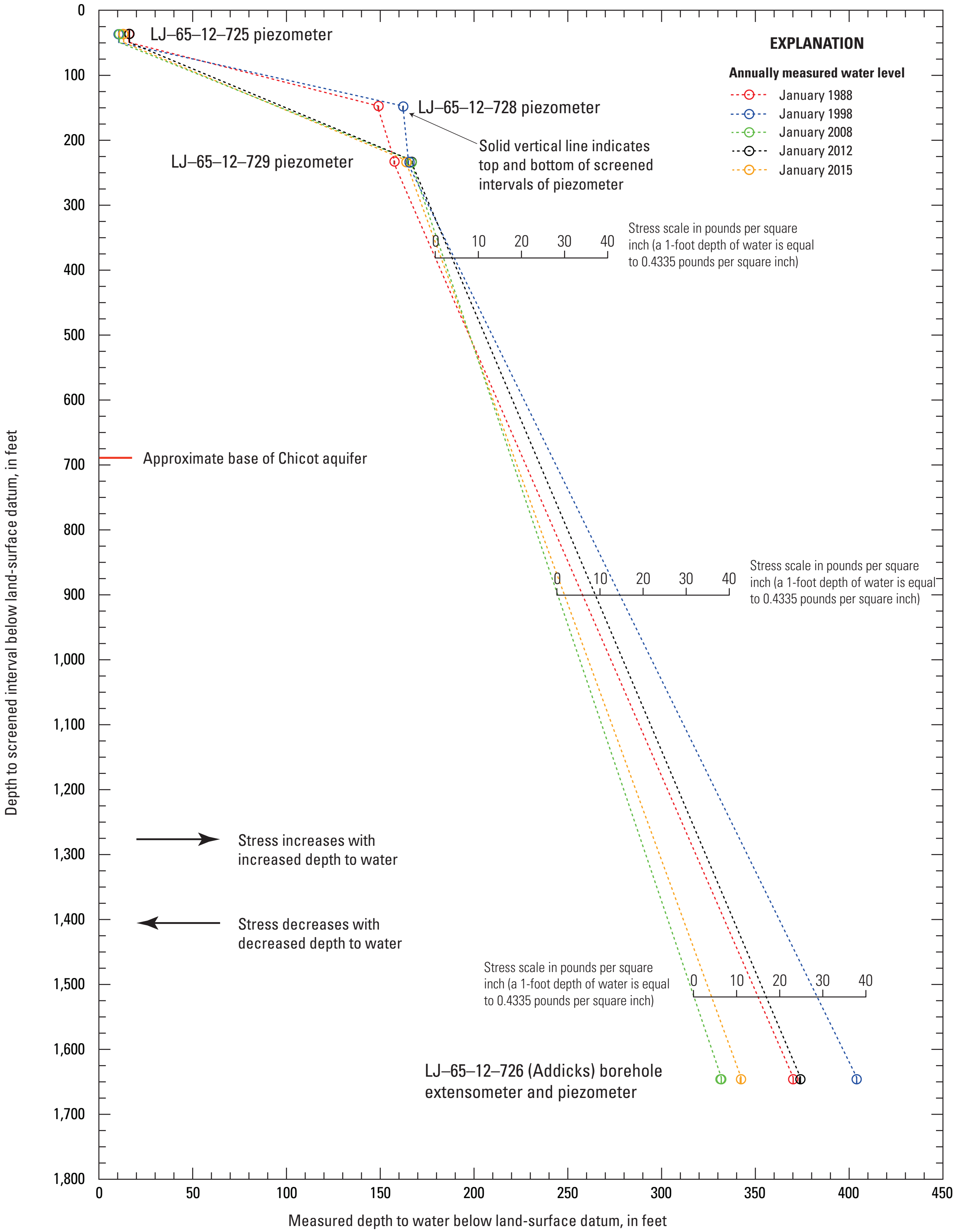

Figure 8. Depth to water below land-surface datum measured in piezometers screened at different intervals at the Addicks borehole-extensometer site in Harris County, Texas, during January 1988, 1998, 2008, 2012, and 2015; a stress scale in pounds per square inch corresponding to the measured depth to water below land-surface datum is included.

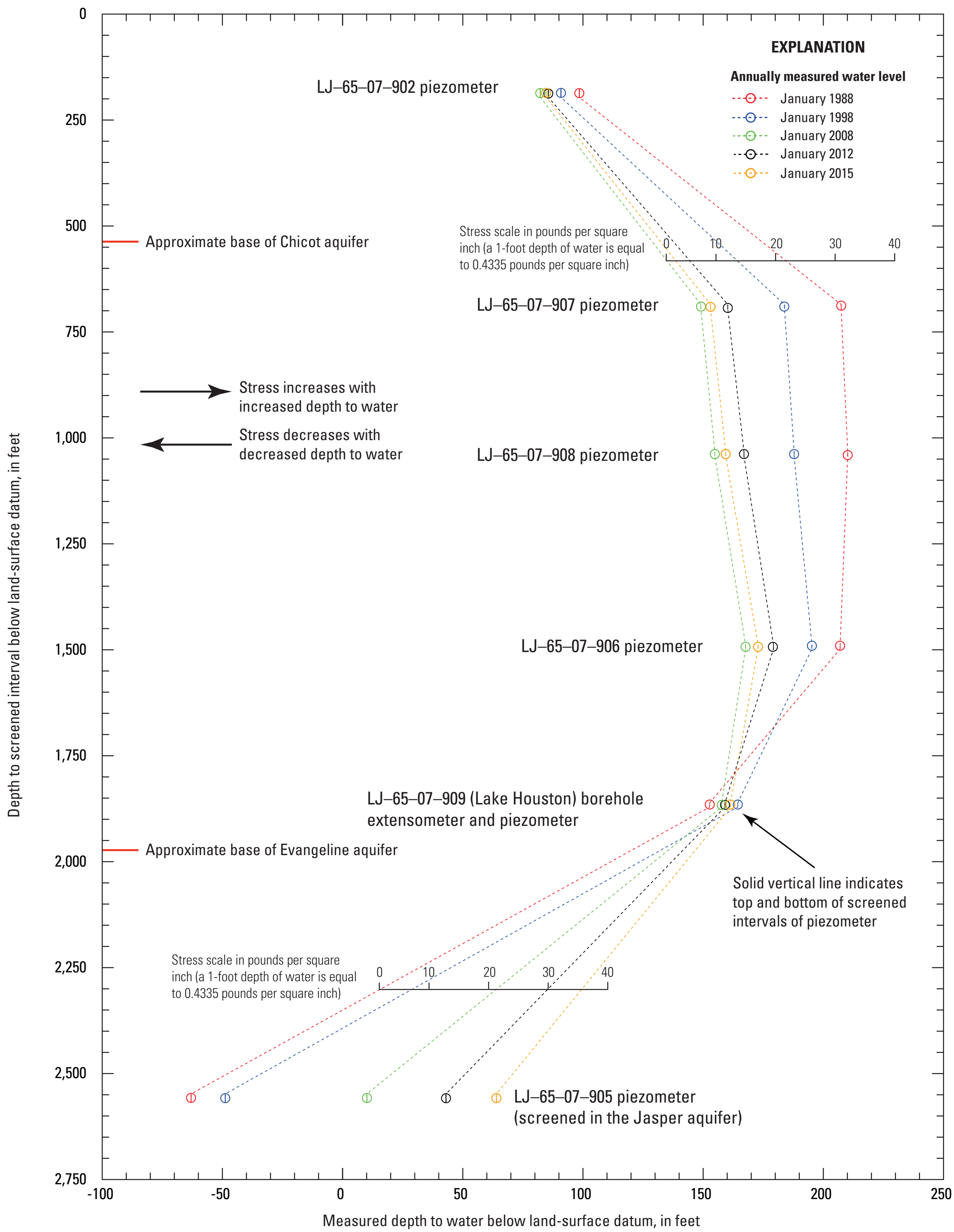

Figure 9. Depth to water below land-surface datum measured in piezometers screened at different intervals at the Lake Houston borehole-extensometer site in Harris County, Texas, during January 1988, 1998, 2008, 2012, and 2015; a stress scale in pounds per square inch corresponding to the measured depth to water below land-surface datum is included.

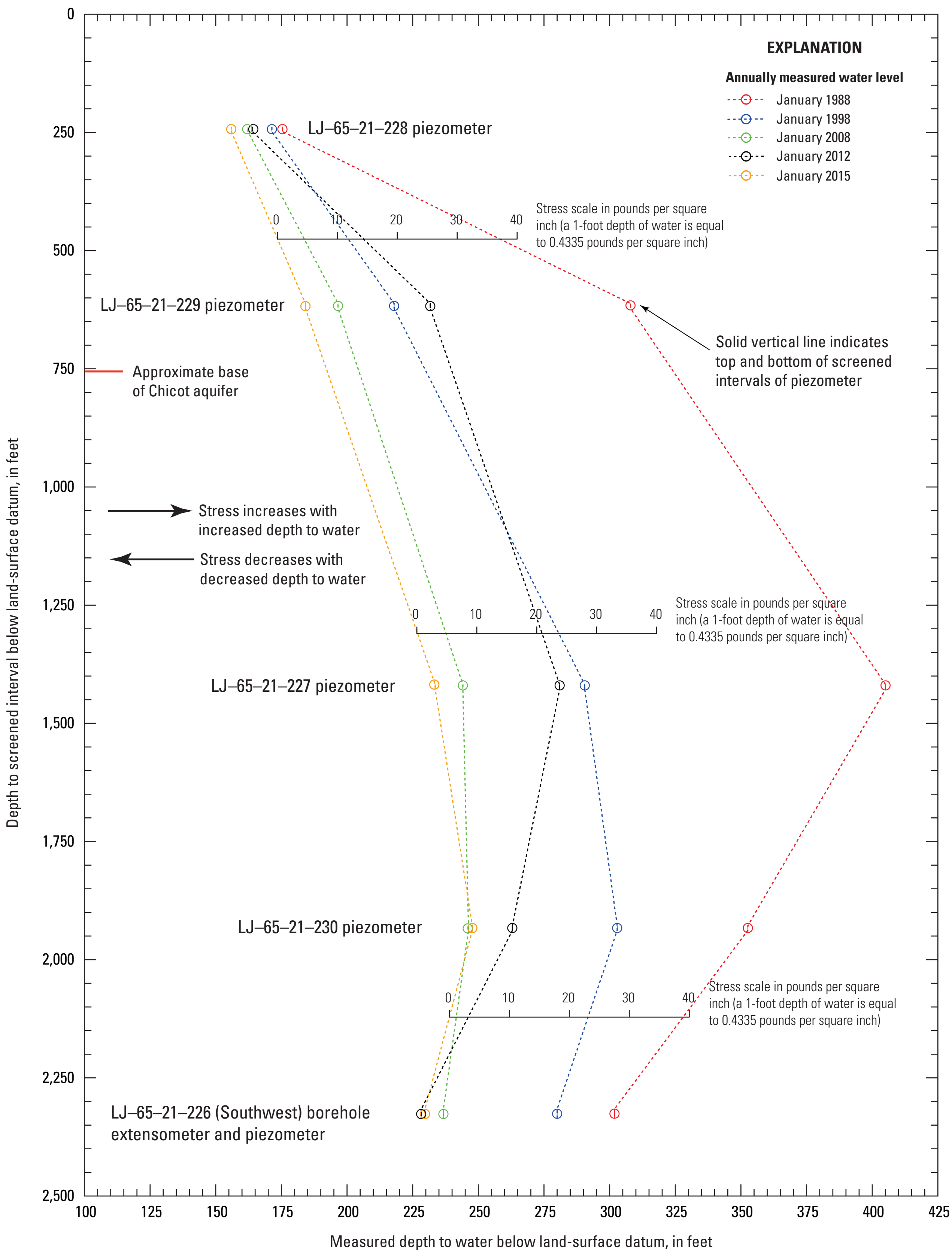

Figure 10. Depth to water below land-surface datum measured in piezometers screened at different intervals at the Southwest borehole-extensometer site in Harris County, Texas, during January 1988, 1998, 2008, 2012, and 2015; a stress scale in pounds per square inch corresponding to the measured depth to water below land-surface datum is included.

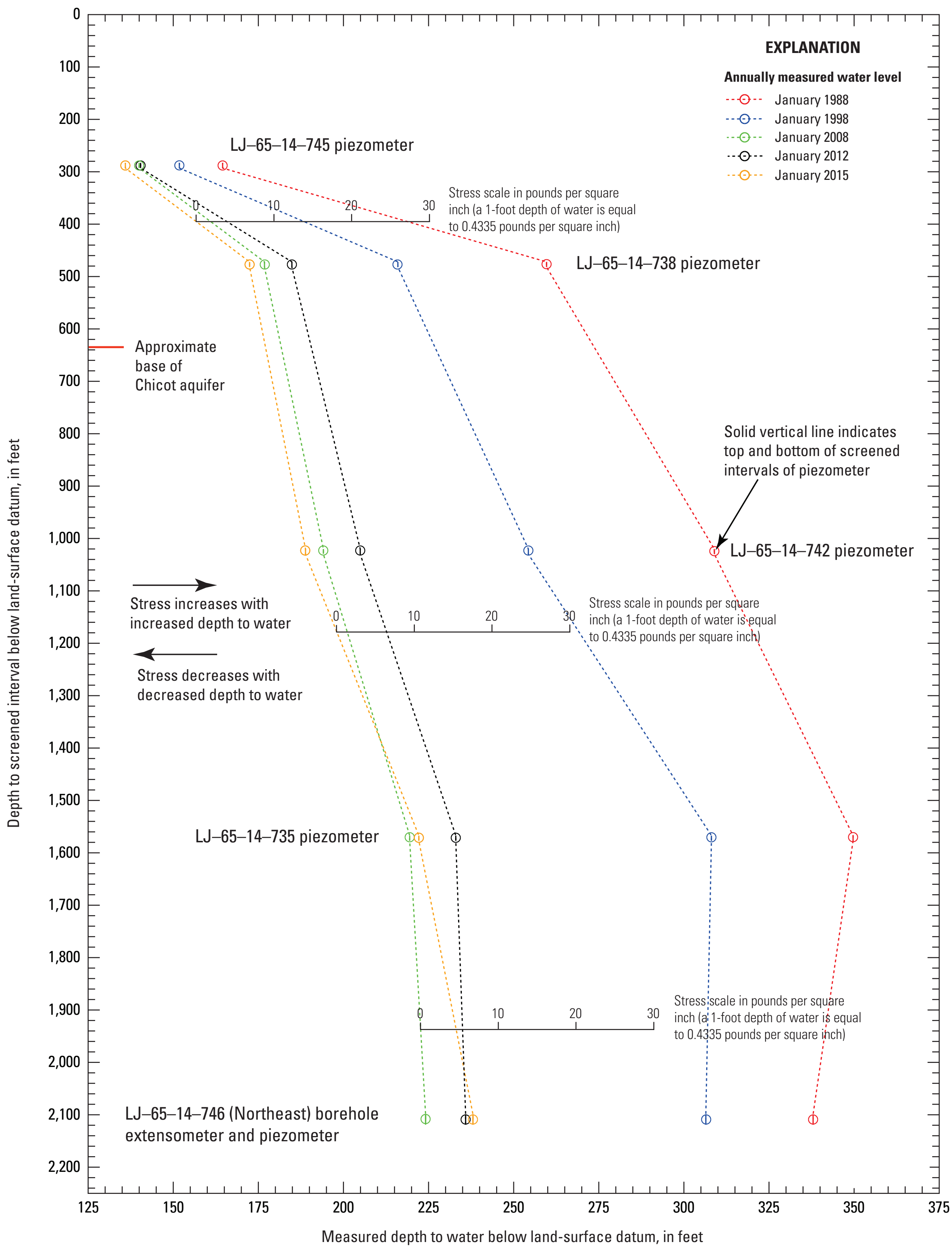

Figure 11. Depth to water below land-surface datum measured in piezometers screened at different intervals at the Northeast borehole-extensometer site in Harris County, Texas, during January 1988, 1998, 2008, 2012, and 2015; a stress scale in pounds per square inch corresponding to the measured depth to water below land-surface datum is included.

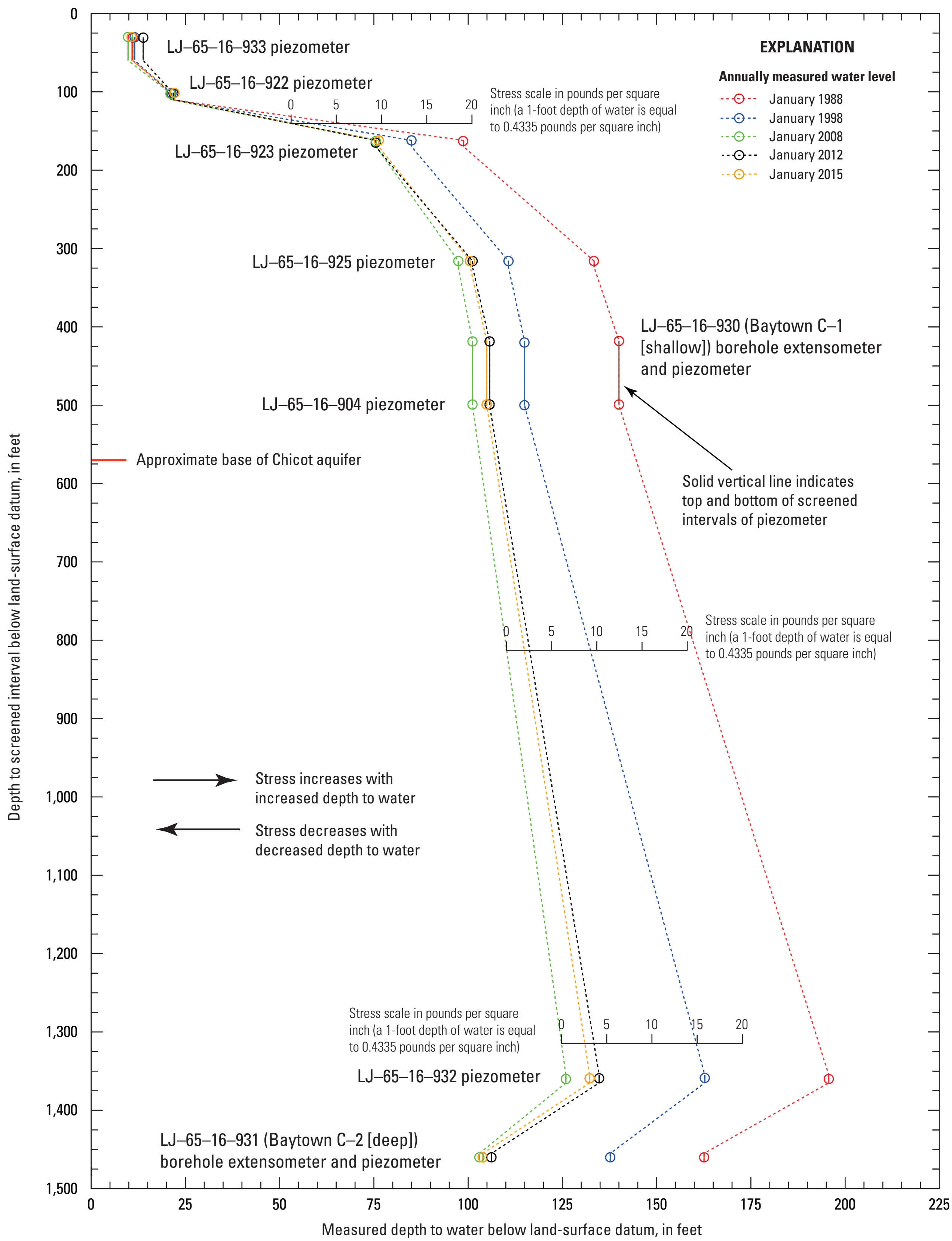

Figure 12. Depth to water below land-surface datum measured in piezometers screened at different intervals at the Baytown C–1 (shallow) and Baytown C–2 (deep) borehole-extensometer site in Harris County, Texas, during January 1988, 1998, 2008, 2012, and 2015; a stress scale in pounds per square inch corresponding to the measured depth to water below land-surface datum is included.

For the piezometer within the extensometer at the Pasadena extensometer site (LJ–65–23–322) (fig. 13), the stress values ranged from 41.84 to 59.48 psi (table 5). The stress values of 41.84 and 59.84 psi were produced by water levels measured in January 2012 of 96.51 ft blsd and January 1988 of 137.22 ft blsd (table 5), respectively, with corresponding net compaction values that ranged from 0.192 ft in 2011 to 0.034 ft in 1987 (table 5). The 2012 stress value of 41.84 psi produced by a measured water level of 96.51 ft blsd, with a corresponding net compaction value of 0.192 ft in 2011, was less than the stress recorded during each of the other 4 years when the stress values ranged from 43.81 to 59.48 psi. The relatively small stress value recorded at the Pasadena extensometer site in January 2012 was likely a result of the relatively small groundwater withdrawals in the predominantly industrial area adjacent to this site during the 2011 drought.

For the piezometer within the extensometer at the East End extensometer site (LJ–65–22–622) (fig. 14), stress values that ranged from 74.26 to 124.42 psi (table 5) were produced by the water levels measured in January 2015 of 171.31 ft blsd and January 1988 of 287.01 ft blsd (table 5), respectively, with corresponding net compaction values that ranged from 0.003 ft in 2014 to 0.070 ft in 1987 (table 5). The 2012 stress value of 79.49 psi produced by a measured water level of 183.36 ft blsd, with a corresponding net compaction value of 0.013 ft in 2011, was less than the stress values recorded in 1988 (124.42 psi) and 1998 (92.65 psi) but greater than the stress values recorded in 2008 (76.34 psi) and 2015 (74.26 psi). The small stress value recorded at the extensometer site in 2012 was likely caused by a relative lack of groundwater withdrawals during the 2011 drought in the area adjacent to the location of the extensometer compared to the amount of groundwater withdrawals in the adjacent area during the other 4 years, particularly during 1988 and 1998.

For the piezometer within the extensometer at the Texas City-Moses Lake extensometer site (KH–64–33–920) (fig. 15), stress values that ranged from 20.12 to 26.48 psi (table 5) were produced by water levels measured in January 2008 of 46.42 ft blsd and January 1988 of 61.09 ft blsd, respectively (table 5), with corresponding net compaction values that ranged from 0.001 ft in 2007 to 0.011 ft in 1987 (table 5). The 2012 stress value of 20.48 psi produced by a measured water level of 47.25 ft blsd, with a corresponding net compaction value of 0.002 ft in 2011, was about the same as the 2008 (20.12 psi) and 2015 (20.64 psi) stress values and less than the stress values of 26.48 and 22.76 psi recorded in 1988 and 1998, respectively. Piezometer KH–64–33–919 has the deepest screened interval at the Texas City-Moses Lake extensometer site, and its stress values are similar to the stress values recorded by the piezometer within the extensometer at the Texas City-Moses Lake extensometer site (KH–64–33–920) (table 5). Compared to the other extensometer sites in the study area, the relatively small groundwater withdrawals in areas adjacent to the Texas City-Moses Lake site (HGSD regulatory area 1, sheet 15) and corresponding relatively small water-level changes caused the smallest compaction rate and smallest total net cumulative compaction (sheet 16).

For the piezometer within the extensometer at the Clear Lake (shallow) extensometer site (LJ–65–32–424) (fig. 16), stress values that ranged from 59.88 to 82.57 psi (table 5) were produced by water levels measured in January 2015 of 138.13 and January 1988 of 190.47 ft blsd (table 5), respectively, with corresponding net compaction values that ranged from +0.001 ft in 2014 to 0.030 ft in 1987 (table 5). The 2012 stress value of 60.90 psi (produced by a measured water level of 140.49 ft blsd, with a corresponding net compaction value of 0.018 ft in 2011) was about the same as the 2008 and 2015 stress values of 60.03 and 59.88 psi, respectively, and less than 1988 and 1998 stress values of 82.57 and 67.61 psi, respectively.

The stress values at the Clear Lake (shallow) extensometer site were more variable compared to the stress values at the Clear Lake (deep) extensometer site. For the piezometer within the extensometer at the Clear Lake (deep) extensometer (LJ–65–32–428) (fig. 16), the stress values ranged from 50.74 to 57.03 psi (table 5). The stress values of 50.74 and 57.03 psi were produced by water levels measured in January 1988 of 117.05 ft blsd and January 2015 of 131.56 ft blsd, respectively (table 5), with corresponding net compaction values that ranged from 0.026 ft in 1987 to 0.002 ft in 2014 (table 5). The 2012 stress value of 54.32 psi produced by a measured water level of 125.31 ft blsd, with a corresponding net compaction value of 0.010 ft in 2011, was slightly greater than the 1988 and 2008 stress values of 50.74 and 51.38 psi, respectively, and slightly less than the 1998 and 2015 stress values of 56.32 and 57.03 psi, respectively.

For the piezometer within the extensometer at the Johnson Space Center extensometer site (LJ–65–32–401) (fig. 16), stress values that ranged from 47.60 to 67.63 psi (table 5) were produced by water levels measured in January 2008 of 109.81 ft blsd and January 1988 of 156.00 ft blsd (table 5), respectively, with corresponding net compaction values that ranged from 0.029 ft in 2007 to 0.028 ft in 1987 (table 5). The 2012 stress value of 49.45 psi produced by a measured water level of 114.08 ft blsd, with a corresponding net compaction value of 0.066 ft in 2011, was smaller than the 1988 and 1998 stress values of 67.63 and 54.36 psi, respectively, and only slightly larger than the 2008 and 2015 stress values of 47.60 and 48.08 psi, respectively. Comparing the stress values for the Clear Lake (shallow) extensometer (LJ–65–32–424), which has a screened interval from 1,071 ft blsd to 1,721 ft blsd, with the stress values for the Clear Lake (deep) extensometer (LJ–65–32–428), which has a screened interval from 3,010 blsd to 3,028 ft blsd, the stress values for the Clear Lake (shallow) extensometer are larger than the Clear Lake (deep) extensometer during each of the 5 years (1988, 1998, 2008, 2012, and 2015). Groundwater withdrawals from adjacent wells that are similarly screened as the Clear Lake (shallow) extensometer likely account for the differences in stress values between the shallow and deep Clear Lake extensometer sites. Similarly, for all 5 years, the stresses at the Clear Lake (shallow) extensometer were greater than the stresses at the Johnson Space Center extensometer site (fig. 16).

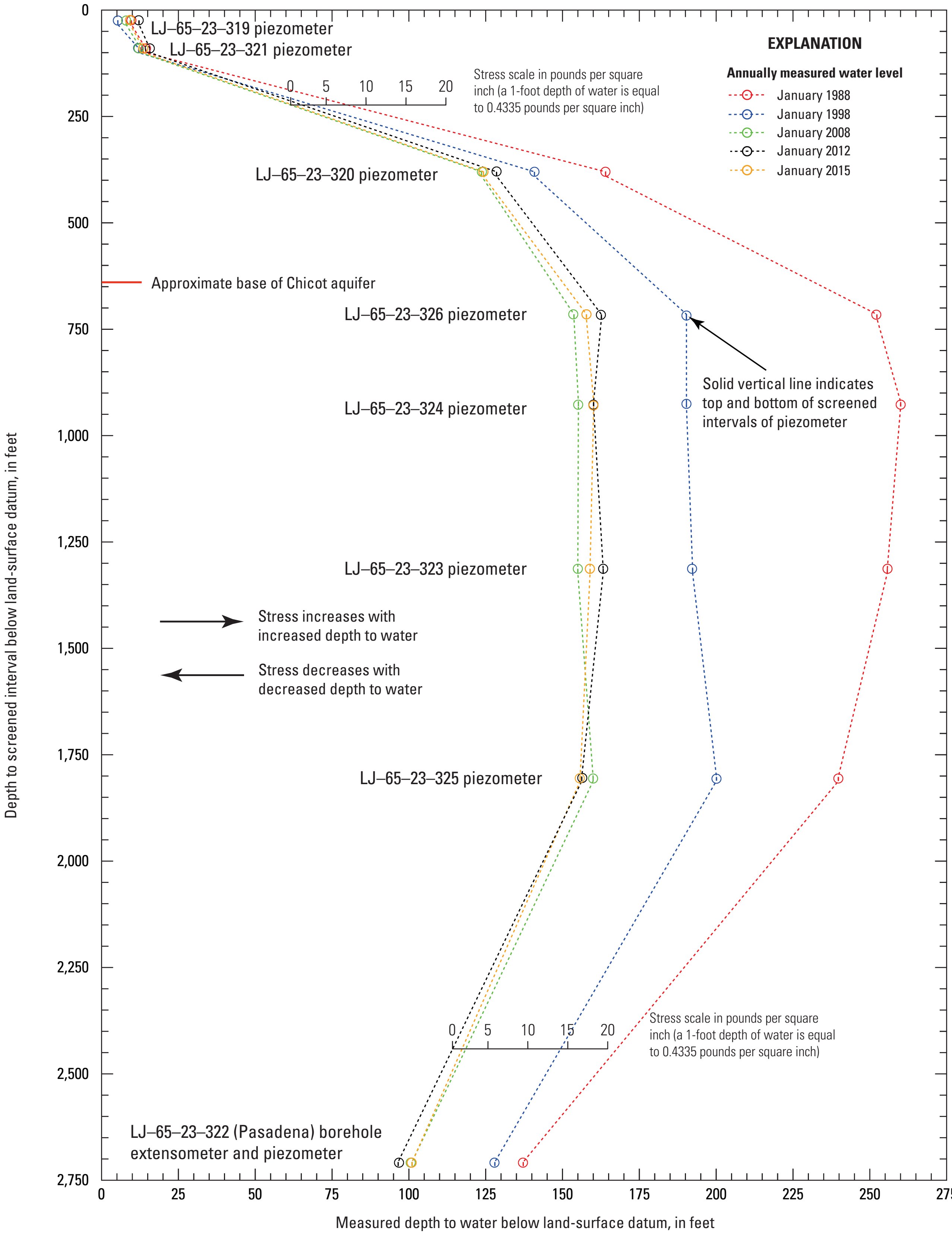

Figure 13. Depth to water below land-surface datum measured in piezometers screened at different intervals at the Pasadena borehole-extensometer site in Harris County, Texas, during January 1988, 1998, 2008, 2012, and 2015; a stress scale in pounds per square inch corresponding to the measured depth to water below land-surface datum is included.

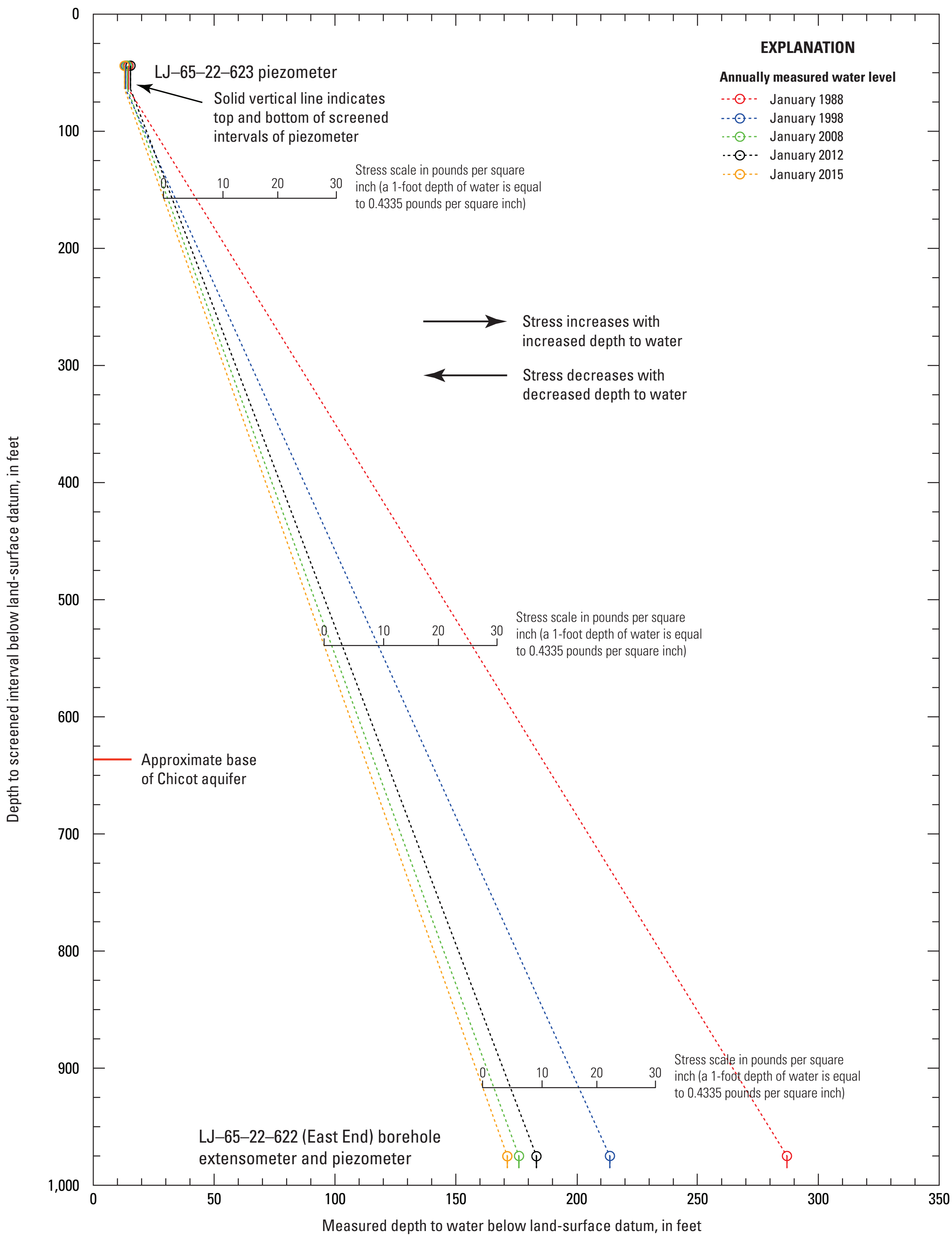

Figure 14. Depth to water below land-surface datum measured in piezometers screened at different intervals at the East End borehole-extensometer site in Harris County, Texas, during January 1988, 1998, 2008, 2012, and 2015; a stress scale in pounds per square inch corresponding to the measured depth to water below land-surface datum is included.

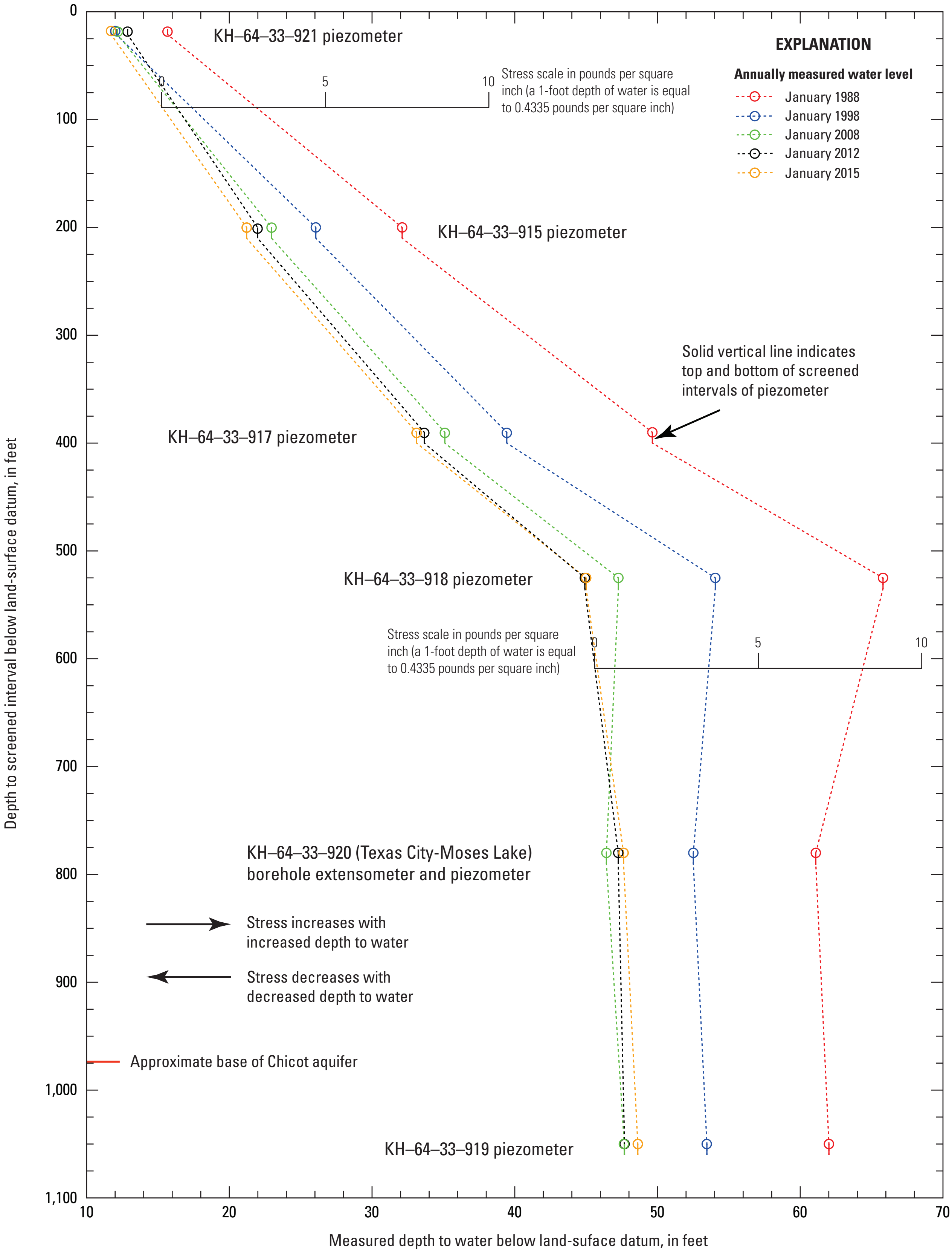

Figure 15. Depth to water below land-surface datum measured in piezometers screened at different intervals at the Texas City-Moses Lake borehole-extensometer site in Harris County, Texas, during January 1988, 1998, 2008, 2012, and 2015; a stress scale in pounds per square inch corresponding to the measured depth to water below land-surface datum is included.

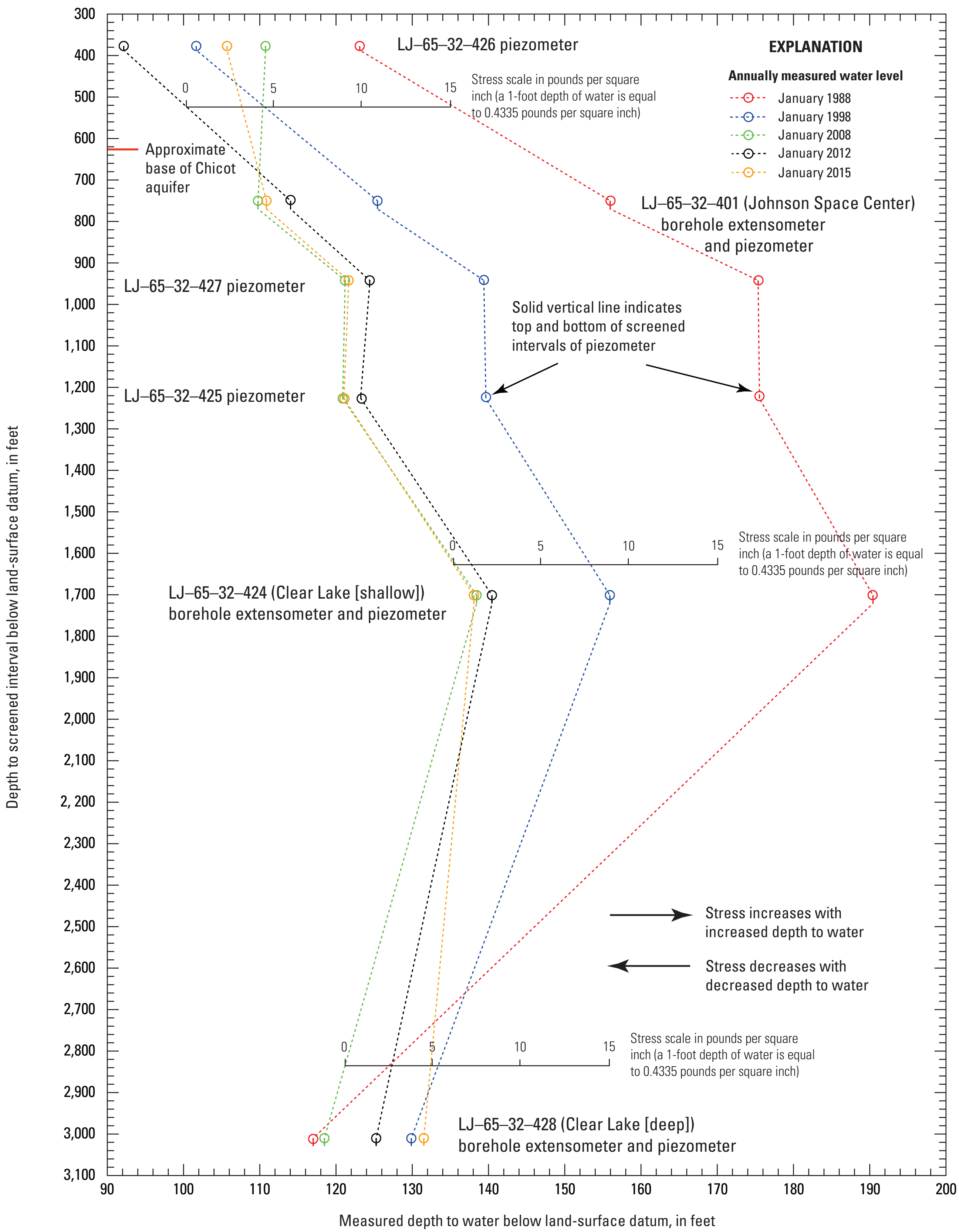

Figure 16. Depth to water below land-surface datum measured in piezometers screened at different intervals at the Clear Lake and Johnson Space Center borehole-extensometer sites in Harris County, Texas, during January 1988, 1998, 2008, 2012, and 2015; a stress scale in pounds per square inch corresponding to the measured depth to water below land-surface datum is included.

For the piezometer within the extensometer at the Seabrook extensometer site (LJ–65–32–625) (fig. 17), stress values ranged from 42.36 psi in 2015 to 62.90 psi in 1988 (table 5). The stress values of 42.36 and 62.90 psi were produced by water levels measured in January 2015 of 97.71 ft blsd and January 1988 of 145.10 ft blsd (table 5), respectively, with corresponding net compaction values that ranged from 0.001 ft in 2014 to 0.059 ft in 1987 (table 5). The 2012 stress value of 43.22 psi was less than the 1988 and 1998 (49.80 psi) stress values and similar to the 2008 and 2015 the stress values of 42.50 and 42.36 psi, respectively. Piezometer LJ–64–32–627 has a shallower screened interval compared to the piezometer within Seabrook extensometer (LJ–65–32–625), whereas piezometer LJ–64–32–626 has a deeper screened interval compared to the piezometer within Seabrook extensometer (LJ–65–32–625). During each of the 5 years (1988, 1998, 2008, 2012, and 2015), similar water levels and thus similar stress values were measured by the piezometer within the extensometer at the Seabrook extensometer (LJ–65–32–625) and by piezometers LJ–64–32–627 and LJ–65–32–626. For the 5 years, stress values at piezometer LJ–64–32–627 ranged from 41.42 to 62.94 psi; at piezometer LJ–64–32–626, stress values ranged from 42.21 to 64.29 psi.

For the 13 extensometers during the selected 5 years, the Texas City-Moses Lake extensometer recorded the smallest stress value of 20.12 psi, produced by a measured water level of 46.42 ft blsd in 2008, with a corresponding net compaction value of 0.001 ft in 2007. The Addicks extensometer recorded the largest stress value of 174.86 psi produced by a measured water level of 403.38 ft blsd in 1998, with a corresponding net compaction value of 0.067 ft in 1997. During the 2011 drought, all 13 extensometers recorded varying amounts of compaction that ranged from a net compaction value of 0.002 ft recorded by the Texas City-Moses Lake extensometer to a net compaction value of 0.192 ft recorded by the Pasadena extensometer. The 10 figures depicting the relation between the depth to the screened interval and measured depth to water blsd for the piezometers installed at extensometer sites (figs. 8–17) provide insight into how the aquifers are affected by water-level changes in the aquifers caused by groundwater withdrawals, into the cause and effect relation controlling aquifer stress in combination with the equilibration of residual excess pore pressures, and hence into the changes in land-surface elevations caused by the compaction process of the fine-grained sediments composing the Chicot and Evangeline aquifers. It is worth noting that the largest stress value for a given year at a given extensometer site was not always associated with the largest net annual compaction (table 5).

Data Limitations

Before 2016, most land-surface elevations at wells used during this study were derived from USGS 1:24,000-scale 7.5-minute topographic quadrangle maps, which are accurate to plus or minus 2.5 ft. Land-surface elevations at wells installed in Harris County were derived from a DEM 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). These altitudes 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 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.

This year (2016), all values of vertical coordinate information (land-surface elevations) were updated by using USGS National Geospatial Program three-dimensional elevation values referenced to NAVD 88 (http://nationalmap.gov/3DEP/index.html). These updated values were used to update the NWIS database for all sites in the study area and enhance the accuracy of the maps depicting water-level altitudes and the subsequent calculations used to create the point values that are used as control data during the creation of the water-level-altitude maps and water-level-altitude-change maps. For the 1-year maps of water-level change, however, values were calculated by subtracting the water-level measurement of depth to water blsd for the current year (2016) from the water-level measurement of depth to water blsd from the historical year. This approach eliminates all water-level-change data affected by changing the land-surface-datum values that could be misleading and inaccurate. Additionally for all sites, the values of horizontal coordinate information (latitude and longitude) were updated to the North American Datum of 1983 (NAD 83) and used to update the NWIS database.

Changes in land-surface elevations were not included 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. It is important, therefore, that the effects of changes in land-surface elevation used on the maps of water-level change must be considered and accounted for if the maps of water-level change are to accurately reflect differences between current year and historical year 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

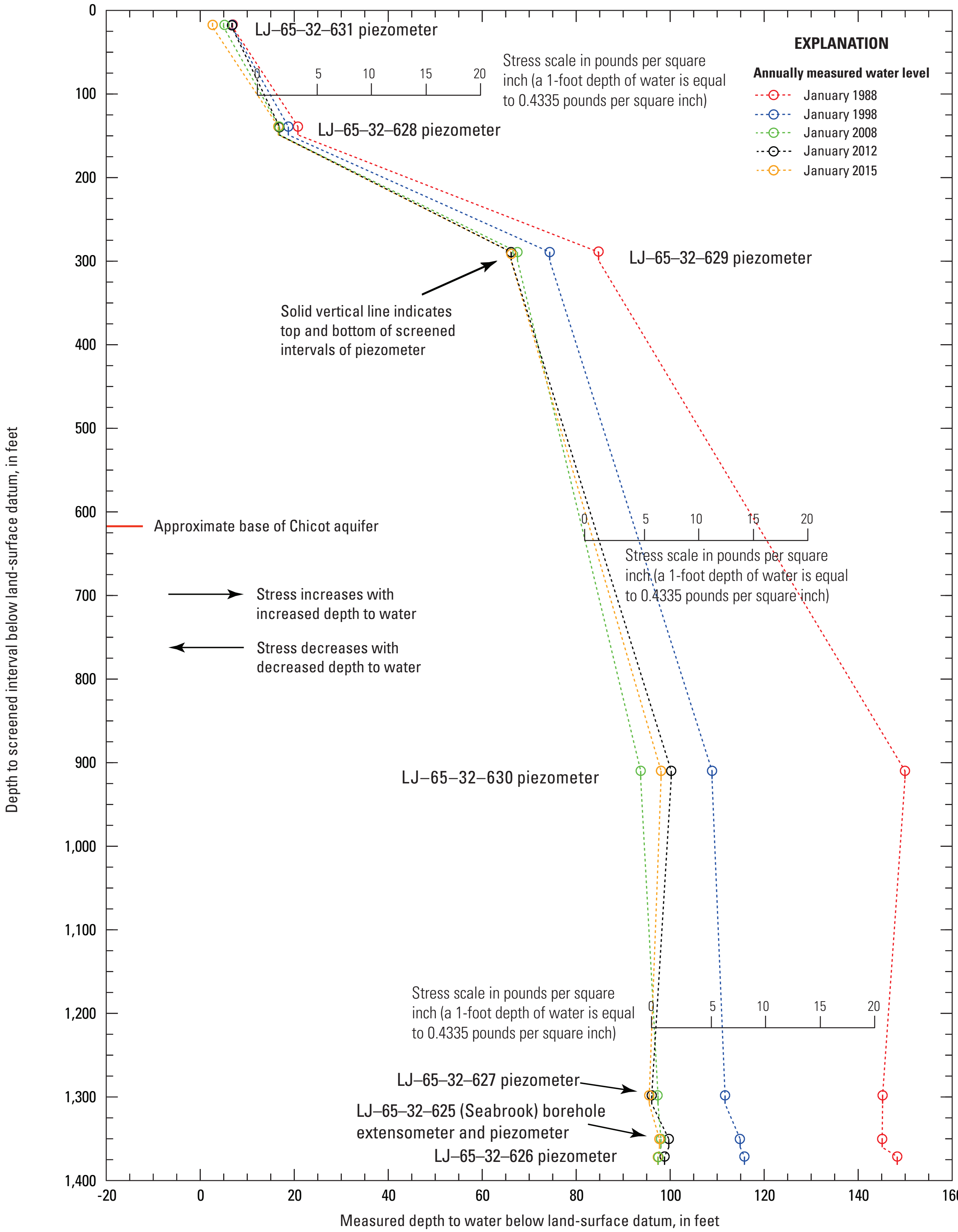

Figure 17. Depth to water below land-surface datum measured in piezometers screened at different intervals at the Seabrook borehole-extensometer site in Harris County, Texas, during January 1988, 1998, 2008, 2012, and 2015; a stress scale in pounds per square inch corresponding to the measured depth to water below land-surface datum is included.

a mathematical approximation that could vary as much as plus or minus 0.5 ft in addition to accuracies associated with the 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.

Long-term cumulative compaction data recorded at each extensometer site (sheet 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 results 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 solely the sediments of 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 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.

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, 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 2015–March 2016 (water levels usually are higher during these months compared to the rest of the year).

This report contains regional-scale maps depicting approximate 2016 water-level altitudes for the Chicot, Evangeline, and Jasper aquifers; maps depicting 1-year (2015–16) water-level changes for each aquifer; maps depicting approximate contoured 5-year (2011–16) water-level changes for each aquifer; maps depicting approximate contoured long-term (1977–2016 and 1990–2016) water-level changes for the Chicot and Evangeline aquifers; a map depicting approximate contoured long-term (2000–16) water-level changes for the Jasper aquifer; a map depicting locations of borehole-extensometer (hereinafter referred to as "extensometer") sites; 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 December 2015; and graphs depicting the relation between the depth to the screened interval below land-surface datum and the depth to water below land-surface datum caused by changes in groundwater withdrawals from the Chicot and Evangeline aquifers at the 13 extensometers and associated nested piezometers. Tables listing the water-level data used to construct each of the 14 sheets and the measured cumulative compaction data for each extensometer site are included, as are graphs of the cumulative compaction data.

Water-level measurements from 177 wells were used to construct the approximate 2016 water-level-altitude map of the Chicot aquifer, and water-level-altitude contours ranged from 200 ft below the vertical datum (North American Vertical Datum of 1988; hereinafter, datum) in a localized area in northwestern Harris County to 200 ft above datum in west-central Montgomery County. Water-level changes in the Chicot aquifer during 2015–16 ranged from a 39-ft decline in southwestern Harris County to a 26-ft rise in northern Brazoria County. Contoured 5-year and long-term changes in water-level altitudes in the Chicot aquifer ranged from a 30-ft decline to a 20-ft rise (2011–16), from a 140-ft decline to a

160-ft rise (1990–2016), and from a 120-ft decline to a 200-ft rise (1977–2016). The 1977–2016 water-level-change map for the Chicot aquifer depicts broad areas of water-level decline in northern, northwestern, and southwestern Harris County and across parts of north-central, eastern, and southeastern Fort Bend County and extending into southeastern Waller County. Water-level declines extend from Fort Bend County into northwestern and northeastern Brazoria County. Additionally, a broad area of water-level rise is depicted in central, eastern, and southeastern Harris County, all of Galveston County, the eastern and northernmost parts of Brazoria County, and part of northeastern Fort Bend County.

Water-level measurements from 320 wells were used to construct the approximate 2016 water-level-altitude map of the Evangeline aquifer, and water-level-altitudes contours ranged from 250 ft below datum in three separate areas located in south-central Montgomery County extending into north-central Harris County, in western-central Harris County, and in southwestern Harris County to 200 ft above datum in southeastern Grimes and northwestern Montgomery Counties. Water-level changes during 2015–16 ranged from a 65-ft decline to a 61-ft rise. Contoured 5-year and long-term changes in water-level altitudes ranged from a 60-ft decline to a 40-ft rise (2011–16), from a 160-ft decline to a 160-ft rise (1990–2016), and from a 320-ft decline to a 240-ft rise (1977–2016). The 1977–2016 water-level-change map depicts a broad area of decline through northern, northwestern, and southwestern Harris County extending into southeastern and northeastern Waller, southern Montgomery, and western Liberty Counties and into the northeastern and east-central Fort Bend County. A broad area of rise is depicted in central, eastern, and southeastern Harris County and extending into the northernmost part of Brazoria County and the southwestern area of Liberty County.

Water-level measurements from 109 wells were used to construct the approximate 2016 water-level-altitude map of the Jasper aquifer, and water-level-altitude contours ranged from 200 ft below datum in south-central Montgomery County and extending into north-central Harris County to 250 ft above datum in northwestern Montgomery County extending into east-central Grimes County and southwestern Walker County. Water-level changes in the Jasper aquifer ranged from a 38-ft decline to a 51-ft rise (2015–16), and the contoured 5-year long-term water-level changes ranged from a 60-ft decline to a 40-ft rise (2011–16). Contours of water-level-altitude changes declined in a broad area throughout most of Montgomery County and in parts of Waller, Grimes, and Harris Counties and ranged from a 220-ft decline in two isolated areas in south-central Montgomery County to a 20-ft decline located in extreme northwestern Montgomery extending into eastern-central Grimes County (2000–16).

Compaction of subsurface sediments (mostly in the fine-grained silt and clay layers) in the Chicot and Evangeline aquifers was recorded continuously at the 13 extensometers at 11 sites since the extensometers 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. Water levels in the Chicot and Evangeline aquifers have risen as much as 200 and 240 ft, respectively, as depicted on the two long-term (1977–2016) water-level-change maps in the areas encompassing the extensometer sites. For the period of record beginning in 1973 (or later depending on activation or installation date) and ending in December 2015, measured cumulative compaction at the 13 extensometers ranged from 0.095 ft at the Texas City-Moses Lake extensometer that measures compaction solely in the Chicot aquifer to 3.666 ft at the Addicks extensometer that measures compaction in the Chicot and Evangeline aquifers. From January through December 2015, the Northeast, Southwest, Addicks, Johnson Space Center, and Clear Lake (deep) extensometers recorded net decreases of land-surface elevation, but the Lake Houston, East End, Texas City-Moses Lake, Baytown C–1 (shallow), Baytown C–2 (deep), Seabrook, Clear Lake (shallow), and Pasadena extensometers recorded net increases of land-surface elevation.

Graphs of the relation between the depth to the screened interval and the measured depth to water for the piezometers at each extensometer site were created to illustrate how changes in water levels caused by changes in groundwater withdrawal from the Chicot and Evangeline aquifers affect the approximate effective stress values (hereinafter referred to as “stress values”) at the 11 extensometer sites and associated nested piezometers. These 10 graphs provide insight into how the aquifers are affected by water-level changes in the aquifers caused by groundwater withdrawals, into the cause and effect relation controlling aquifer stress in combination with the equilibration of residual excess pore pressures, and hence into the changes in land-surface elevations caused by the compaction process of the fine-grained sediments composing the Chicot and Evangeline aquifers. For the 11 extensometer sites during the selected years 1988, 1998, 2008, 2012, and 2015, the Texas City-Moses Lake extensometer had the smallest stress value of 20.12 pounds per square inch (psi) produced by a measured water level of 46.42 ft below land-surface datum (blsd) in 2008 with a corresponding net compaction value of 0.001 ft. The Addicks extensometerhad the largest stress value of 174.86 psi produced by a measured water level of 403.38 ft blsd in 1998 with a corresponding net compaction value of 0.067 ft in 1997. During the 2011 drought, all 13 extensometers recorded varying amounts of compaction that ranged from a net compaction value of 0.002 ft recorded by the Texas City-Moses Lake extensometer to a net compaction value of 0.192 ft recorded by the Pasadena extensometer. The largest stress value for a given year at a given extensometer site was not always associated with the largest net annual compaction.

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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