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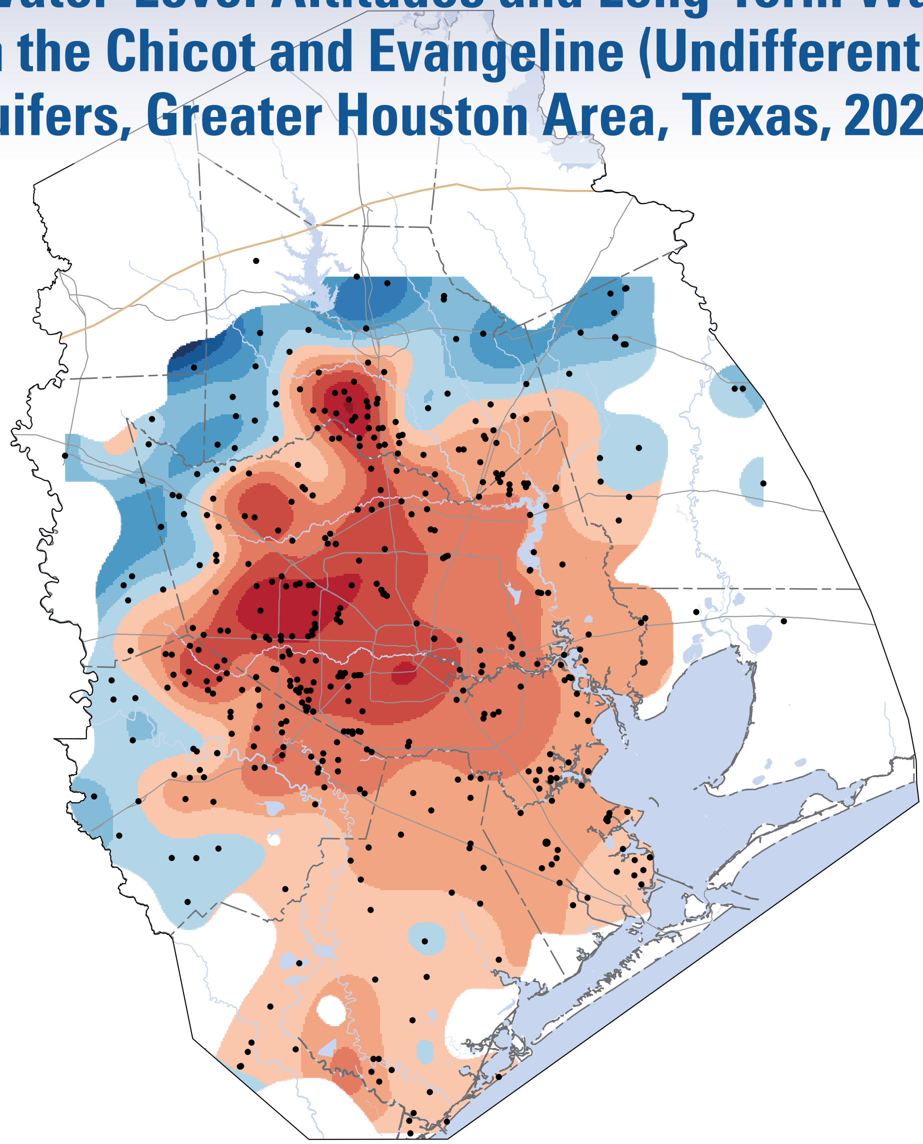
Prepared in cooperation with the Harris-Galveston Subsidence District, City of Houston, Fort Bend Subsidence District, Lone Star Groundwater Conservation District, and Brazoria County Groundwater Conservation District

Status of Water-Level Altitudes and Long-Term Water-Level Changes in the Chicot and Evangeline (Undifferentiated) and Jasper Aquifers, Greater Houston Area, Texas, 2021



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

Status of Water-Level Altitudes and Long-Term Water-Level Changes in the Chicot and Evangeline (Undifferentiated) and Jasper Aquifers, Greater Houston Area, Texas, 2021

By Christopher L. Braun and Jason K. Ramage

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	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
	Length	
meter (m)	3.281	foot (ft)
meter (m)	1.094	yard (yd)

Datum

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

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

Abbreviations

>	greater than
BCGCD	Brazoria County Groundwater Conservation District
DEM	digital elevation model
FBSD	Fort Bend Subsidence District
HGSD	Harris-Galveston Subsidence District
LSGCD	Lone Star Groundwater Conservation District
NAVD 88	North American Vertical Datum of 1988
NWIS	National Water Information System
USGS	U.S. Geological Survey

Status of Water-Level Altitudes and Long-Term Water-Level Changes in the Chicot and Evangeline (Undifferentiated) and Jasper Aquifers, Greater Houston Area, Texas, 2021

By Christopher L. Braun and Jason K. Ramage

Abstract

Since the early 1900s, groundwater withdrawn from the primary aquifers that compose the Gulf Coast aquifer system—the Chicot and Evangeline (undifferentiated) and Jasper aquifers—has been the primary source of water in the greater Houston area, Texas. 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 the status of water-level altitudes and water-level changes in aquifers in the greater Houston area.

In contrast to previous reports, the Chicot and Evangeline aquifers are treated as a single hydrogeologic unit in this report. In 2021, shaded depictions of water-level altitudes for the Chicot and Evangeline aquifers (undifferentiated) ranged from 300 feet (ft) below the North American Vertical Datum of 1988 (NAVD 88) to 300 ft above NAVD 88. The largest decline in water-level altitudes indicated by the 1977–2021 long-term water-level-change map for the Chicot and Evangeline aquifers (undifferentiated) was in the north-central part of The Woodlands, Tex., whereas the 1990–2021 long-term water-level-change map for the Chicot and Evangeline aquifers (undifferentiated) depicts a large area of decline in water-level altitudes in northwestern Harris County, northwest of Jersey Village, Tex. The largest rise in water-level altitudes in the Chicot and Evangeline aquifers (undifferentiated) was observed in a relatively large area in southeastern Harris County for 1977–2021, whereas the largest rise in water-level altitudes for 1990–2021 was in a relatively large area in central Harris County.

In 2021, shaded depictions of water-level altitudes for the Jasper aquifer ranged from 250 ft below NAVD 88 to 300 ft above NAVD 88. The 2000–21 long-term water-level-change map for the Jasper aquifer depicts water-level declines throughout most of the study area where water-level-altitude data from the Jasper aquifer were collected, with the largest decline in northern Harris County southwest of The Woodlands.

Introduction

The greater Houston area in Texas includes approximately 11,000 square miles and encompasses all or part of 11 counties (Harris, Galveston, Fort Bend, Montgomery, Brazoria, Chambers, Grimes, Liberty, San Jacinto, Walker, and Waller). The study area was referred to as the "Houston-Galveston region" in previous reports in the annual series of reports depicting the status of water-level altitudes and long-term water-level changes in aquifers in the greater Houston area (for example, Braun and others, 2019; Braun and Ramage, 2020); referring to it as the "greater Houston area" better describes the current (2021) extent of the study area. Groundwater withdrawn from the three primary aquifers that compose the Gulf Coast aquifer system—the Chicot, Evangeline, and Jasper aquifers—has been the primary source of water for municipal supply, commercial and industrial use, and irrigation in the greater Houston area 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-level altitudes in the aquifers were declining annually, resulting in land-surface subsidence in the greater Houston area (Coplin and Galloway, 1999). By 1977, the withdrawals had resulted in water-level declines in southeastern Harris County of 300 and 350 feet (ft) below the North American Vertical Datum of 1988 (NAVD 88) in the Chicot and Evangeline aquifers, respectively (Gabrysch, 1979).

To regulate and reduce groundwater withdrawals in Harris and Galveston Counties, the 64th Texas State Legislature authorized the establishment of the Harris-Galveston Subsidence District (HGSD) in 1975 (Harris-Galveston Subsidence District, 2021). After establishing the HGSD, the Texas State Legislature established an additional subsidence district (Fort Bend Subsidence District

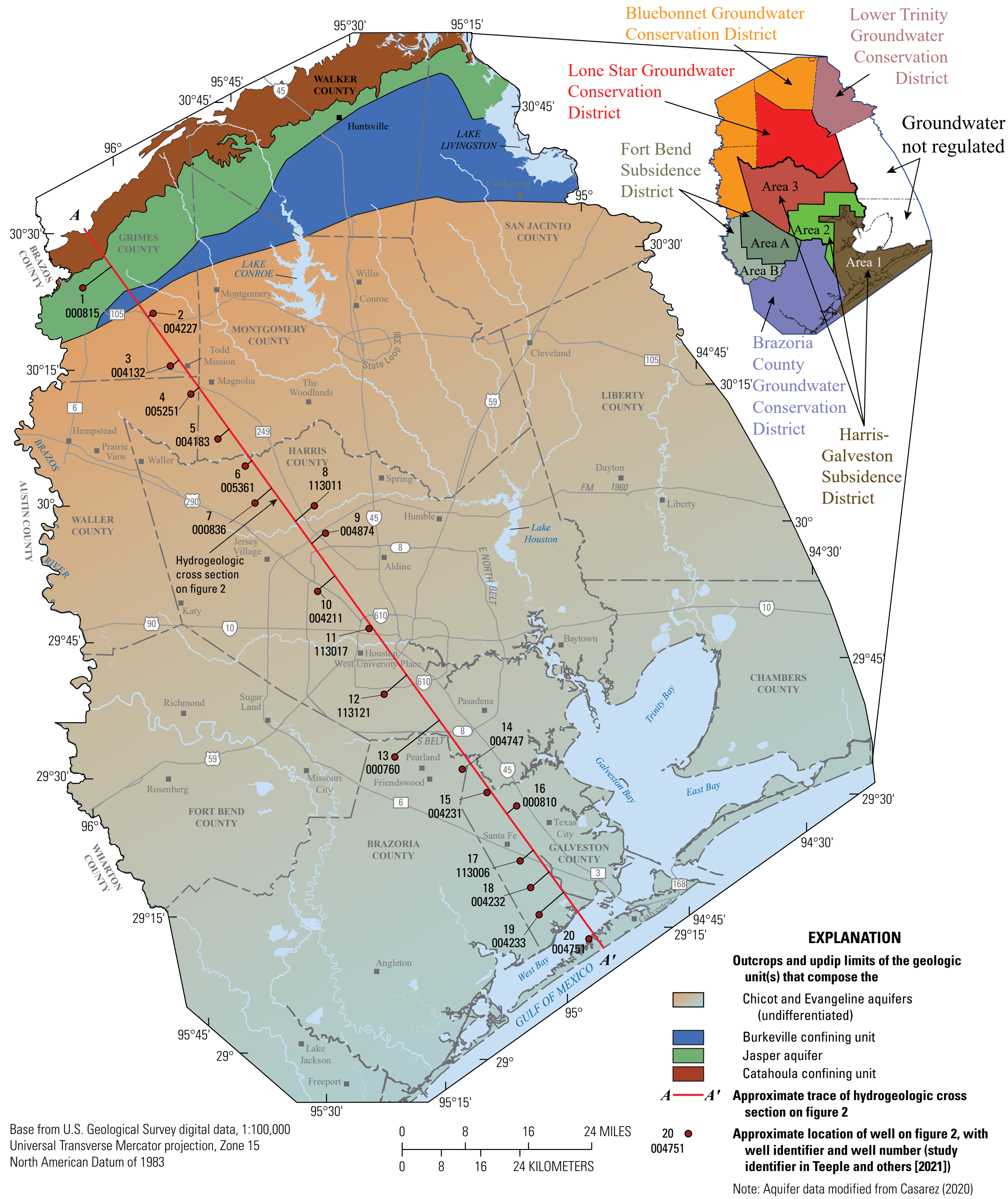


Figure 1. Locations of groundwater regulatory districts; approximate trace of hydrogeologic cross section *A–A′*; and outcrops and updip limits of the hydrogeologic units in the Gulf Coast aquifer system in the greater Houston area, Texas.

[FBSD]) and four groundwater conservation districts (Lone Star Groundwater Conservation District [LSGCD], Brazoria County Groundwater Conservation District [BCGCD], Bluebonnet Groundwater Conservation District, and Lower Trinity Groundwater Conservation District) in the greater Houston area (fig. 1) to enable the regulation of groundwater withdrawals within their respective jurisdictions. The FBSD was established by the 71st Texas State Legislature in 1989 (Fort Bend Subsidence District, 2021), the LSGCD and Bluebonnet Groundwater Conservation District were established by the 77th Texas State Legislature in 2001 (Bluebonnet Groundwater Conservation District, 2021; Lone Star Groundwater Conservation District, 2021), the BCGCD was established by the 78th Texas State Legislature in 2003 (Brazoria County Groundwater Conservation District, 2021), and the Lower Trinity Groundwater Conservation District was established by the 79th Texas State Legislature in 2005 (Lower Trinity Groundwater Conservation District, 2021). Regulatory plans to gradually decrease groundwater withdrawals (in conjunction with increased use of alternative surface-water supplies) are currently (2021) being phased in throughout most of the study area (fig. 1). The current groundwater management plans of each district are available on their respective websites (Fort Bend Subsidence District, 2013; Harris-Galveston Subsidence District, 2013; Brazoria County Groundwater Conservation District, 2017; Bluebonnet Groundwater Conservation District, 2018; Lower Trinity Groundwater Conservation District, 2019; Lone Star Groundwater Conservation District, 2020). Groundwater withdrawals are currently (2021) not regulated by a groundwater conservation district in two counties in the greater Houston area (Liberty and Chambers Counties; fig. 1).

Since the 1970s, the U.S. Geological Survey (USGS), in cooperation with the HGSD, has monitored water-level altitudes and published reports on the status of water-level altitudes and long-term water-level changes in the greater Houston area; following their establishment by the Texas State Legislature, the FBSD, LSGCD, and BCGCD became cooperative participants in the study as well. An extensive network of groundwater-monitoring wells was first established by the USGS in 1977, which led to the first published water-level-altitude maps of the Chicot and Evangeline aquifers in 1979 for the greater Houston area (Gabrysch, 1979). A comprehensive report for the Chicot and Evangeline aquifers depicting 1990 water-level altitudes was first published by the USGS in 1991 (Barbie and others, 1991). The USGS also first published a water-level-altitude map of the Jasper aquifer in 2001 for the greater Houston area (Coplin, 2001). Additional information on the history of water-level-altitude monitoring and of the USGS reports published to document water-level altitudes and water-level changes in the greater Houston area is provided in Kasmarek and Ramage (2017).

This report assesses water-level altitudes and water-level changes differently than did the previous USGS reports in the annual series of reports depicting the status of water-level altitudes and long-term water-level changes in aquifers in the greater Houston area; the nature and reasoning behind these changes are described in greater detail in Ramage and others (2022). For instance, the Chicot and Evangeline aquifers are treated as a single hydrogeologic unit, hereinafter referred to as the “Chicot and Evangeline aquifers (undifferentiated),” in this report (figs. 2 and 3), as opposed to being treated as distinct aquifers as was done in the previous USGS water-level-altitude reports related to the greater Houston area (for example, Braun and others, 2019; Braun and Ramage, 2020). The decision to treat the Chicot and Evangeline aquifers as a single hydrogeologic unit was made in response to one of the findings from two reports, a report by Young and others (2017) on the delineation of fresh, brackish, and saline groundwater resources based on interpretation of geophysical logs and a report by Young and Draper (2020), which updated the delineation of the Burkeville confining unit and the base of the Chicot aquifer defined by Young and others (2017). The findings from Young and others (2017) and Young and Draper (2020) led to hydrogeologic unit reclassification for a large proportion of the wells in the groundwater-monitoring network used to collect long-term groundwater levels for the annual series of reports. Because the hydrogeologic units associated with such a large proportion of the wells in the groundwater-monitoring network required reclassification, the basis for comparison to the maps published in the previous USGS reports depicting water-level altitudes and water-level changes in the greater Houston area (for example, Braun and others, 2019; Braun and Ramage, 2020) would no longer be valid. Water-level-altitude and water-level-change maps from previous reports in the annual series of reports, while not directly comparable to current (2021) maps, still have value for identifying areas where groundwater demands are highest and where water-level changes over time are most pronounced.

Other changes to this report relative to recent (since 2016) USGS reports related to groundwater levels in the greater Houston area (for example, Braun and others, 2019; Braun and Ramage, 2020) include (1) the addition of 1-year and 5-year change maps for the Chicot and Evangeline (undifferentiated) and Jasper aquifers and an additional long-term change map (1990–2021) for the Chicot and Evangeline aquifers (undifferentiated) and (2) a transition from depicting water-level altitudes and water-level changes as interpretive contours (generated by methods described in Braun and Ramage [2020]) to producing grids by using a geostatistical interpolative technique (kriging) (Shi, 2014) to represent water-level altitudes and long-term water-level changes in the greater Houston area.

Purpose and Scope

The purpose of this report, prepared by the USGS in cooperation with the HGSD, City of Houston, FBSD, LSGCD, and BCGCD, is to depict water-level altitudes and long-term water-level changes in the Chicot and Evangeline (undifferentiated) and Jasper aquifers in the greater Houston area,

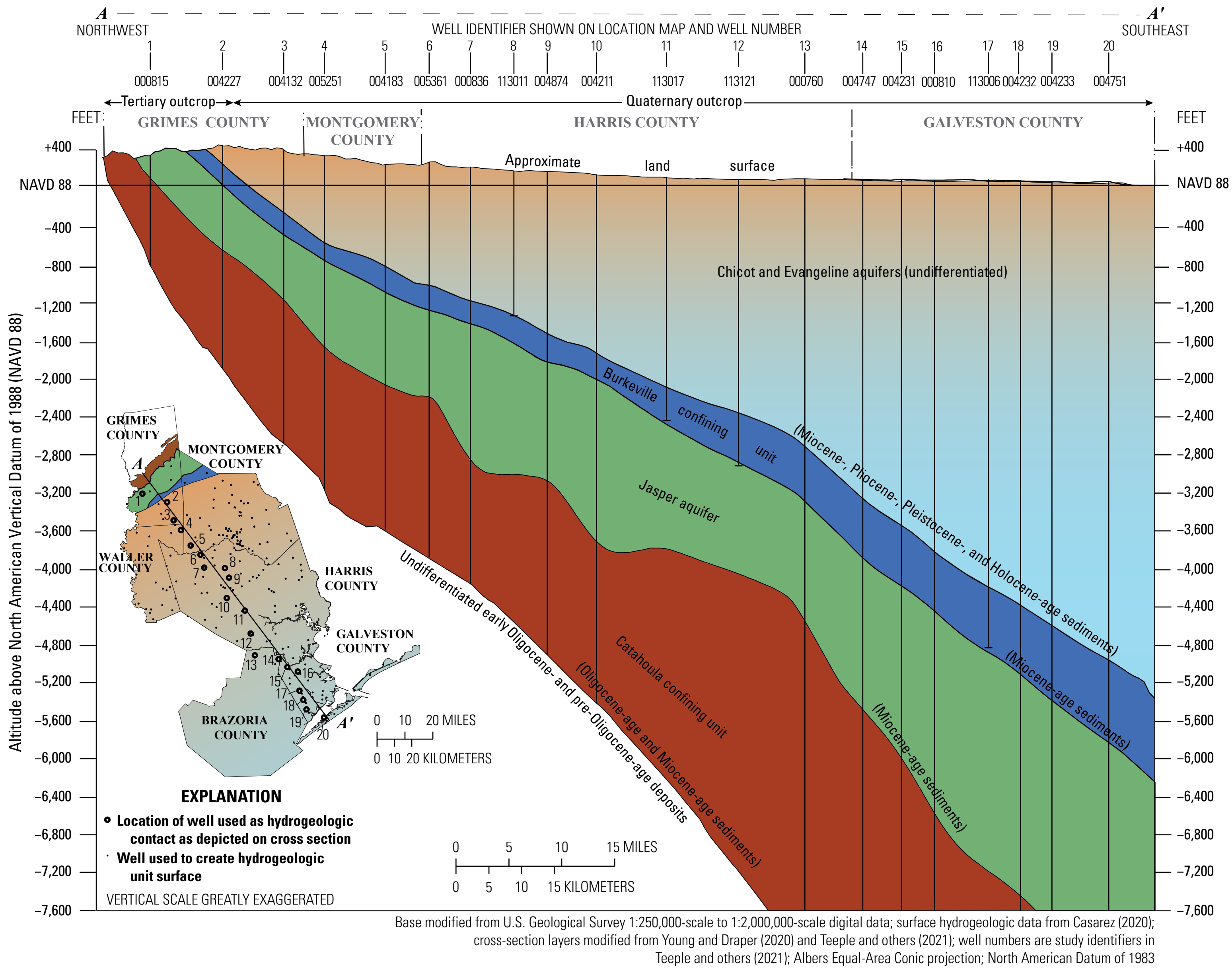
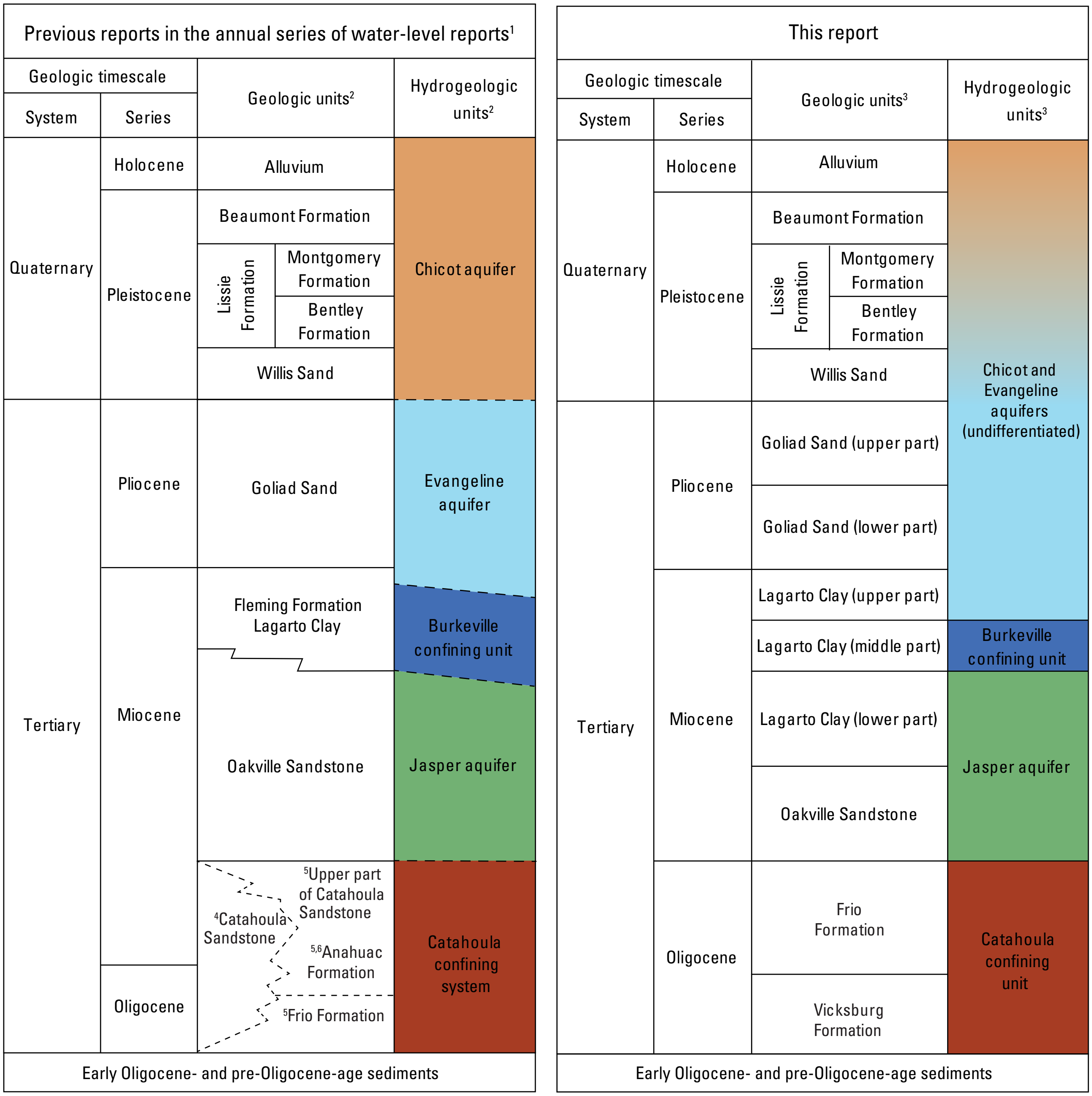


Figure 2. Hydrogeologic cross section *A–A′* of the Gulf Coast aquifer system in Grimes, Waller, Montgomery, Harris, Brazoria, and Galveston Counties, Texas.



[1]For example, Braun and others (2019) and Braun and Ramage (2020).
[2]Modified from Sellards and others (1932), Baker (1979), and Meyer and Carr (1979).
[3]Modified from Young and others (2012, 2014) and Young and Draper (2020).
[4]Located in the outcrop.
[5]Located in the subcrop.
[6]"Anahuac Formation" is not an approved U.S. Geological Survey unit name but has been referred to previously in a U.S. Geological Survey report by Swanson and others (2013).

Note: Dashed lines shown between hydrogeologic units in previous reports in the annual series indicate that the geologic units shown as containing the hydrogeologic units in question are not absolute.

Figure 3. Traditional and updated depictions of the geologic and hydrogeologic units of the Gulf Coast aquifer system in the greater Houston area, Texas.

Texas. An overview of the hydrogeology of the study area is provided, and regional-scale maps depicting approximate water-level altitudes for 2021 (represented by measurements made during November 2020 through March 2021), long-term water-level changes in the Chicot and Evangeline aquifers (undifferentiated) (1977–2021 and 1990–2021) and the Jasper aquifer (2000–21), and short-term water-level changes (2016–21 and 2020–21) for the Chicot and Evangeline (undifferentiated) and Jasper aquifers are featured.

Hydrogeology of the Study Area

The following overview of the hydrogeology of the study area is summarized from Kasmarek and Ramage (2017). From land surface down, the hydrogeologic units in the study area include the Chicot and Evangeline aquifers (undifferentiated), Burkeville confining unit, Jasper aquifer, and Catahoula confining unit (fig. 3). The three primary aquifers in the Gulf Coast aquifer system in the greater Houston area (the Chicot, Evangeline, and Jasper aquifers) are composed of laterally discontinuous deposits of gravel, sand, silt, and clay (Baker, 1979). The percentage of clay and other fine-grained, clastic material generally increases downdip (Baker, 1979). The uppermost Chicot and Evangeline aquifers (undifferentiated) are contained in Holocene- and Pleistocene-age (Quaternary-age) sediments and Pliocene- and Miocene-age (Tertiary-age) sediments (Baker, 1979, 1986) (fig. 2). The more deeply buried Jasper aquifer is contained in Miocene-age sediments (Baker, 1979, 1986) (fig. 2). The stratigraphic relations between these hydrogeologic units are shown on hydrogeologic cross section *A–A′* (figs. 1 and 2) of the Gulf Coast aquifer system, which extends through the greater Houston area from northwestern Grimes County southeastward through Waller, Montgomery, Harris, and Brazoria Counties before terminating at the coast in Galveston County.

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); these sediments, which compose the Gulf Coast aquifer system, were deposited by fluvial-deltaic processes and subsequently were eroded and redeposited by worldwide episodic changes in sea level 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 hydrogeologic units representing the aquifers and confining units thus crop out in bands inland from, and approximately parallel to, the coast and become progressively more deeply buried and confined toward the coast (fig. 2) (Kasmarek and others, 2013). The aquifers receive recharge where the hydrogeologic units composing the aquifers crop out (Kasmarek and Robinson, 2004) (fig. 2). The Burkeville confining unit is stratigraphically positioned between the Chicot and Evangeline (undifferentiated) and Jasper aquifers (fig. 2), thereby restricting groundwater flow between the Chicot and Evangeline (undifferentiated) and Jasper aquifers. The rationale for not differentiating the Chicot from the Evangeline aquifer includes the absence of a confining unit between the Chicot and Evangeline aquifers (fig. 2). Previous investigators have noted that the absence of a confining unit between the Chicot and Evangeline aquifers implies that the two aquifers are hydraulically connected, allowing groundwater to flow between them (Liu and others, 2019). Because of this hydraulic connection, water-level changes that occur in one aquifer can affect groundwater levels in the adjoining aquifer (Kasmarek and others, 2010). Supporting evidence of the interaction of groundwater flow between the Chicot and Evangeline aquifers includes the similarities between long-term water-level-change maps for each aquifer (for example, figs. 5 and 7 in Braun and Ramage [2019] and figs. 5 and 7 in Braun and others [2020]), which indicate that the areas where groundwater levels have risen or declined are approximately spatially coincident. Additional evidence of the hydraulic connection between the Chicot and Evangeline aquifers was provided by Borrok and Broussard (2016, p. 330); their geochemical evaluation of the Chicot aquifer system from 1993 to 2015 in Louisiana indicated that in some years (1998, 2008, and 2011) certain wells screened in the Chicot aquifer "appeared to be tapping water with a geochemistry (temperature, salinity, alkalinity, [and so forth]) matching the underlying Evangeline aquifer."

Hydraulic properties of the Chicot aquifer do not differ appreciably from those of 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. Proceeding updip and inland of the Quaternary- and Tertiary-age sediments containing the Chicot and Evangeline aquifers (undifferentiated), the older geologic units (containing the Burkeville confining unit, the Jasper aquifer, and the Catahoula confining unit) sequentially outcrop (figs. 1 and 2). In the updip areas of the Jasper aquifer, the aquifer can be differentiated from the Chicot and Evangeline aquifers (undifferentiated) on the basis of the depths to water below land-surface datum, which are shallower (closer to land surface) in the Jasper aquifer compared to those in the Chicot and Evangeline aquifers (undifferentiated). 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 altitude of the Burkeville confining unit (figs. 2 and 3). When considered together, the various lines of evidence that suggest a hydraulic connection between the Chicot and Evangeline aquifers provide sufficient justification for treating the Chicot and Evangeline aquifers as a single hydrogeologic unit.

Precipitation falling on the land surface overlying these aquifers returns to the atmosphere as evapotranspiration, becomes surface runoff until it reaches streams, or infiltrates as groundwater recharge to the unconfined updip sediments composing the aquifers (Williamson and others, 1990; Healy, 2010). The infiltrating water moves downgradient toward the coast, reaching the intermediate and deep zones of the aquifers southeastward of the outcrop areas, 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 from the confined downdip areas of the aquifer system (Kasmarek and Robinson, 2004).

Previous Studies

An extensive network of groundwater-monitoring wells was established by the USGS in 1977, and groundwater-level data collected during springs of 1977 and 1978 were used to create the first published water-level-altitude maps of the Chicot and Evangeline aquifers in the greater Houston area in 1979 (Gabrysch, 1979). In cooperation with the FBSD, which adopted its groundwater management plan in 1990 (Fort Bend Subsidence District, 2013), 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 depicting water-level altitudes for 1990 was published by the USGS in 1991 (Barbie and others, 1991) and was revised in 1997 when updated well data became available (Kasmarek, 1997). Similarly, after the establishment of the LSGCD in 2001, the USGS began publishing water-level-altitude maps of the Jasper aquifer in the greater Houston area (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). Since 2007, 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 greater Houston area (Kasmarek and Houston, 2008; Kasmarek and others, 2009, 2010, 2012, 2013, 2014, 2015, 2016; Johnson and others, 2011; Kasmarek and Ramage, 2017; Shah and others, 2018; Braun and others, 2019; Braun and Ramage, 2020).

Methods

This section describes the methods used to (1) collect and process water-level data used in this report, (2) determine water-level altitudes, and (3) depict long-term and short-term water-level changes in the study area. The data collection and processing methods are similar to those described in previous reports by Gabrysch (1979), Kasmarek and Houston (2007), and Kasmarek and Ramage (2017). Kriging processes used to depict water-level altitudes and water-level-change maps are described briefly herein and in detail in Ramage and others (2022).

Water-Level Measurements

Water-level measurements were obtained from 590 observation wells in the study area by USGS personnel during November 2020 through March 2021. At each well, a measuring point was established (if one had not already been previously established) to determine the depth to water. The height above land surface of the measuring point at each well was measured with an engineering ruler. The depth to water below land-surface datum was then calculated by subtracting out the height (or depth if the measuring point is below land surface, in which case the sign associated with the measuring point would be negative) of the measuring point at each well to represent the 2021 water-level altitudes of the Chicot and Evangeline (undifferentiated) and Jasper aquifers (Ramage, 2022). These 590 measurements were made by using a calibrated steel tape, airline, or electric groundwater-level tape in accordance with methods described in Cunningham and Schalk (2011). Each well was measured during the November 2020 through March 2021 time period to provide a "snapshot" of water-level altitudes in the aquifers associated with individual wells.

In 2021, seven additional water-level measurements representing less than 2 percent of the total number of water-level measurements were provided by municipal utility districts, industrial entities, and powerplants. Municipal utility districts supply water to the businesses and residents of the greater Houston area (Municipal District Services, 2022). Water is used by oil and gas industrial entities during hydrocarbon processing (Allison and Mandler, 2018) and by powerplants to generate electrical power (Torcellini and others, 2003). The provided water levels were typically measured by using air pressure to determine the saturated thickness above the pump intake, and multiple pressure measurements were usually collected as a quality-control measure. Air pressure measurements tend to provide less precision than do measurements made with either a steel tape or electric tape; therefore, all measurements provided by other entities were rounded to the nearest foot. Groundwater levels that were provided by municipal utility districts, industrial entities, or powerplants are identified as such in the "source" field in Ramage (2022); additional information about these wells can be obtained from the USGS National Water Information System (NWIS) (U.S. Geological Survey, 2022b).

Most of the measured wells were being pumped at least once daily (and some more frequently) during the study period. Therefore, well pumps were turned off for at least 1 hour before the water-level measurements were made in order to obtain a water-level measurement that approximated the static conditions within the aquifer. Antecedent withdrawal rates and pumping status of nearby wells were not always known and, in such instances, could have affected the representativeness of the water-level data that were collected. To ensure that the recorded water-level measurement was accurate, at least two water-level measurements were made at each well while the well was not being pumped. After the water-level-measurement data were collected, they were thoroughly evaluated and incorporated into a geographic information system as point-data layers and subsequently used for the construction of water-level-altitude and water-level-change maps. The water-level measurements collected or provided for this study were carefully reviewed by USGS personnel and were compiled in Ramage (2022). All collected water-level measurements were uploaded into NWIS (U.S. Geological Survey, 2022b); provided water-level measurements were not uploaded into NWIS. All collected and provided water-level altitudes measured at each well for the Chicot and Evangeline (undifferentiated) and Jasper aquifers and associated metadata are published in a companion data release (Ramage, 2022).

Kriging

This section is modified from the “Kriging” section of Ramage and others (2022). Kriging was used to grid water-level-altitude data from 2021 and to grid long-term water-level changes for each hydrogeologic unit in question. Kriging has long been recognized as an effective method for interpolating hydrologic data, particularly water-level data, as an alternative to contouring methods (Varouchakis and others, 2012) and is a well-established geostatistical method (Matheron, 1963; Paramasivam and Venkatramanan, 2019) that provides an optimized unbiased linear prediction with a minimum mean estimation error. Kriging, like other interpolation methods, uses a weighted average of all measured values to predict values at unmeasured locations. The weights assigned to measured values are spatially dependent. The spatial dependency is quantified by the spatial correlation of the measured locations and is assumed to be more similar in spatial proximity and diverge as spatial distance increases. Correlation between measured locations and their spatial distance relative to one another is defined by the experimental semivariogram and the best-fit model that attempts to minimize the estimation error (Olea, 1975, 2009). Kriging methods for depicting water-level altitudes and water-level changes provide several advantages compared to manual contouring methods described in Kasmarek and Ramage (2017). One of the advantages of kriging over traditional, manual contouring methods is that kriging provides estimated values of the variable of interest at unmeasured locations. Kriging also provides a means of quantifying the estimation uncertainty (standard deviation or square root of the provided variance), allowing for evaluation of the estimation reliability (Todini, 2001). This estimation uncertainty can be useful for determining the spatial variability of the data and allowing for possible optimization of the network of groundwater-monitoring wells. Additional details related to the kriging processes used to depict shaded gridded representations of water-level altitudes in the Chicot and Evangeline (undifferentiated), and Jasper aquifers are described in Ramage and others (2022).

Determination of Water-Level Altitudes

The 2021 regional-scale depictions of water-level altitudes presented in this report were derived from water-level-measurement data collected throughout the 11-county study area from November 2020 through March 2021 (water levels usually are higher because groundwater use is at its lowest during these months compared to the rest of the year). Water-level altitudes were calculated by subtracting the water-level measurement from the land-surface elevation at each well referenced to NAVD 88 (National Ocean Service, 2021). Prior to 2016, water-level altitudes published in this annual series of USGS reports were referenced to either the National Geodetic Vertical Datum of 1929 or NAVD 88, whereas all water-level altitudes published in 2016 and after are referenced to NAVD 88.

The accuracy of land-surface-elevation data at wells used in the annual series of reports has gradually improved over time as digital elevation models (DEMs) progressively replaced traditional methods of determining land-surface elevations from topographic maps. The most accurate land-surface-elevation data available were used by the USGS for each historical annual depiction of water-level altitudes in the study area. To determine land-surface elevations for 2021, a corresponding land-surface datum was obtained for each well by using a USGS National Geospatial Program 1-meter DEM that provides three-dimensional elevation values referenced to NAVD 88 (Arundel and others, 2015; U.S. Geological Survey, 2022a, b). In 1977, land-surface-elevation data were extracted from USGS 1:24,000-scale 7.5-minute topographic quadrangle maps for the Gulf of Mexico coastal area, which have a 5-ft contour as described in Gabrysch (1979) and thereby provide an accuracy of approximately 2.5 ft. The DEM used to determine land-surface elevations in 2021 provides an accuracy of 0.5 ft.

Color-shaded gridded representations (shaded grids) of the 2021 water-level altitudes measured in wells completed in the Chicot and Evangeline (undifferentiated) and Jasper aquifers were prepared; each color shade represents a 50-ft increment in water-level altitudes to match the contour interval commonly used in previous reports in the annual series of reports depicting the status of water-level altitudes in aquifers in the greater Houston area. The shaded grids are published in a companion data release (Ramage and Braun, 2022). The water-level-altitude grids are approximate, regional-scale depictions of the water-level altitudes in wells in the Chicot and Evangeline (undifferentiated) and Jasper aquifers, and the areal extents and locations of the shaded areas represented by these grids represent the combined effects of total groundwater withdrawals from all groundwater wells screened in the Gulf Coast aquifer system within the shaded area.

Depicting Long-Term Water-Level Changes

Maps depicting long-term changes in water-level altitudes in the Chicot and Evangeline (undifferentiated) and Jasper aquifers were constructed for the period of record available for each of the aquifers; data are from 1977 to 2021 for the Chicot and Evangeline aquifers (undifferentiated) and from 2000 to 2021 for the Jasper aquifer. A long-term change map for the period from 1990 to 2021 for the Chicot and Evangeline aquifers (undifferentiated) was also created to serve as a benchmark date to highlight changes in groundwater levels that may have occurred since the establishment of the FBSD in 1989 and the subsequent increase in the number of wells that were inventoried by the USGS in Fort Bend, Harris, Brazoria, and Waller Counties in 1989 and 1990. Long-term water-level-change maps were constructed from gridded water-level-altitude data from the current year (2021) and from each respective beginning year for the period of record (1977 and 1990, respectively, for the Chicot and Evangeline aquifers [undifferentiated] and 2000 for the Jasper aquifer).

A mask was applied to the gridded 2021 water-level altitudes to retain only those grid cells with variance values less than or equal to the mean variance of the 2021 grid (as a whole) as a means of either removing potential outliers or hiding grid cells with insufficient data density. Water-level-altitude data from wells measured in the historical year (1977, 1990, or 2000) were gridded using the same methods that were used to generate the 2021 water-level-altitude grids, and a mask was applied to the gridded historical altitudes to retain only those grid cells with variance values less than or equal to the mean variance of the historical grid (as a whole). The resulting grids derived from water-level-altitude data from 2021 and either 1977, 1990, or 2000 were then cropped to a common geospatial extent before subtracting the historical grid from the 2021 grid. The reason the grids needed to be cropped to a common geospatial extent is because the network of wells where groundwater levels were measured in each aquifer changed over time as wells began actively pumping in response to expansion of the Houston metropolitan area or were taken out of service in certain parts of the study area as surface-water usage increased and groundwater usage decreased (among other reasons). The area of water-level change shown on the maps is based primarily on the availability of groundwater-level data in both 2021 and the historical landmark year of interest. Another factor when determining the area of mapped water-level change is the computed variance associated with each estimated water-level altitude at each grid cell for both the current year (2021) water-level altitude and historical year altitude gridded surface. If the computed variance at any given grid cell is equal to or smaller than the overall mean variance for each respective gridded surface for the current and historical year, the data are deemed valid for inclusion in the mapped area depicting water-level-altitude change (Ramage and others, 2022). The datasets of water-level-change values (difference between 2021 and historical year water-level-altitude values) are available in Ramage (2022); the grids and their associated variance distribution maps that were produced from the water-level data collected from the network of groundwater-monitoring wells (along with a description of the processes by which these datasets were produced) are included in Ramage and Braun (2022).

Depicting Short-Term Water-Level Changes

Maps depicting short-term changes in water-level altitudes in the Chicot and Evangeline (undifferentiated) and Jasper aquifers were constructed to represent changes during the past 5 years (2016–21) and during the past year (2020–21). Because these change maps represent a much shorter time period than do the long-term change maps, changes at the local scale (individual wells or small group of proximal wells) can be more pronounced in them than in long-term change maps, which are more representative of long-term regional-scale variations in groundwater levels. As a result, using a shaded grid to represent these short-term changes tends to lead to pronounced concentric patterns (bullseyes) in the short-term change maps. Therefore, short-term water-level changes were instead depicted by shading a circular symbol at each of the wells measured during both years representing the short-term interval in question, where the shading represents water-level rises or declines at 10-ft intervals. Kriging was not used to depict the short-term water-level changes. Instead, direct subtraction of water levels at each well measured at both the beginning and ending of the periods of interest (2016–21 and 2020–21) is represented by the shading at each well in the short-term change maps.

Water-Level Altitudes and Long-Term and Short-Term Water-Level Changes

Maps of water-level altitudes and long-term and short-term water-level changes were constructed for the Chicot and Evangeline (undifferentiated) and Jasper aquifers in the study area (figs. 4–12). The maps in this report depict approximate water-level altitudes for 2021 (figs. 4 and 9) and long-term (1977–2021 and 1990–2021) changes in the Chicot and Evangeline aquifers (undifferentiated) (figs. 5 and 6) by using shaded grids where each shade represents a 40-ft interval. To approximate long-term (2000–21) changes in water-level altitudes for the Jasper aquifer, shaded grids representing 20-ft intervals were used (fig. 10). All long-term water-level changes depicted in this report are considered approximate.

Locations of wells used to construct the 2021 water-level-altitude maps for the Chicot and Evangeline (undifferentiated) and Jasper aquifers are presented in Ramage (2022) and Ramage and Braun (2022). Certain water-level-altitude measurements collected during November 2020 through March 2021 were not used to construct the water-level maps presented in this report for the Chicot and Evangeline (undifferentiated) and Jasper aquifers. The vast majority of the wells that were excluded from consideration when constructing the water-level maps were colocated wells in nests. It is not possible to establish a variance-distance relation between observations made at the same location during the kriging process, so prior to the kriging process, colocated wells must be "declustered." When two or more wells were colocated, data from the well where the water level was deepest were retained. The reason that the data from the well with the deepest water level were retained at colocated well sites is because that well was expected to have a water level that was most analogous to nearby production wells, which tend to be deeper and have deeper water levels than do domestic wells or piezometers. Production wells make up the majority of the wells in the groundwater-monitoring network, particularly in Harris County, where most of the colocated wells are located. A much smaller proportion of the wells were excluded from consideration when constructing the water-level maps because they were not consistent with water-level altitudes obtained from nearby wells screened in the same aquifer for one of the following reasons: (1) the water-level altitude at the well in question differed appreciably from the water levels measured in other wells in the surrounding area and was deemed to be erroneous or (2) water had been withdrawn recently from the well in question and the water-level altitude at this well was still rising. The companion data release by Ramage and Braun (2022) identifies the water-level-altitude measurements that were used to construct maps of water-level altitudes and water-level changes by using kriging methods for each aquifer. Of the 590 observation wells where water-level measurements were made in the study area, measurements from 527 wells were used in the creation of water-level-altitude maps. Individual water-level altitudes measured at each well for the Chicot and Evangeline (undifferentiated) and Jasper aquifers and associated metadata are provided in companion data releases (Ramage, 2022; Ramage and Braun, 2022).

Chicot and Evangeline Aquifers (Undifferentiated)

Groundwater-level-measurement data from 434 wells (Ramage, 2022) were used to depict the 2021 water-level altitudes for the Chicot and Evangeline aquifers (undifferentiated) (fig. 4). In 2021, observed water-level altitudes for the Chicot and Evangeline aquifers (undifferentiated) were lowest (250–300 ft below NAVD 88, which corresponds to the interval from −300 to −250 ft in fig. 4) in a relatively small area in the north-central part of The Woodlands, Tex. The highest observed water-level altitudes (250–300 ft above NAVD 88, which corresponds to the interval from greater than [>] 250 to 300 ft in fig. 4) for the Chicot and Evangeline aquifers (undifferentiated) in 2021 were in an area northwest of Todd Mission, Tex.

The largest decline in water-level altitudes (360–400 ft, which corresponds to the interval from −400 to −360 ft in fig. 5) indicated by the 1977–2021 long-term water-level-change map for the Chicot and Evangeline aquifers (undifferentiated) was in the north-central part of The Woodlands (fig. 5), whereas the 1990–2021 long-term water-level-change map for the Chicot and Evangeline aquifers (undifferentiated) depicts a large area of decline in water-level altitudes (240–280 ft, which corresponds to the interval from −280 to −240 ft in fig. 6) in northwestern Harris County, northwest of Jersey Village, Tex. (fig. 6). The largest rise in water-level altitudes in the Chicot and Evangeline aquifers (undifferentiated) (200–240 ft, which corresponds to the interval from >200 to 240 ft in fig. 5) was observed in a relatively large area in southeastern Harris County for 1977–2021, whereas the largest rise in water-level altitudes for 1990–2021 (160–200 ft, which corresponds to the interval from >160 to 200 ft in fig. 6) was observed in a relatively large area in central Harris County.

The 5-year (2016–21) short-term water-level-change map for the Chicot and Evangeline aquifers (undifferentiated) depicts the largest declines (50 ft or more) at two wells in northern Fort Bend County and the largest rises (more than 40 ft) at three wells in southwestern Harris County and at one well in northern Harris County south of The Woodlands (fig. 7). The 1-year (2020–21) short-term water-level-change map for the Chicot and Evangeline aquifers (undifferentiated) depicts the largest decline (40 ft or more) at a well in northern Fort Bend County and the largest rise (more than 30 ft) at a well in Waller, Tex., near the boundary between Waller and Harris Counties (fig. 8).

Jasper Aquifer

Water-level-measurement data from 93 wells (Ramage, 2022) were used to depict the approximate 2021 water-level altitudes for the Jasper aquifer (fig. 9). In 2021, water-level altitudes for the Jasper aquifer were lowest (200–250 ft below NAVD 88, which corresponds to the interval from −250 to −200 ft in fig. 9) at a location in the central part of The Woodlands in northern Harris and southern Montgomery Counties, whereas water-level altitudes for the Jasper aquifer were highest (250–300 ft above NAVD 88, which corresponds to the interval from >250 to 300 ft in fig. 9) in eastern Grimes and northwestern Montgomery Counties (fig. 9).

Annual water-level-altitude data have been collected from wells completed in the Chicot and Evangeline aquifers (undifferentiated) since 1977, whereas annual water-level-altitude data have been collected from wells completed in the Jasper aquifer since only 2000. The 2000–21 long-term water-level-change map for the Jasper aquifer (fig. 10) depicts

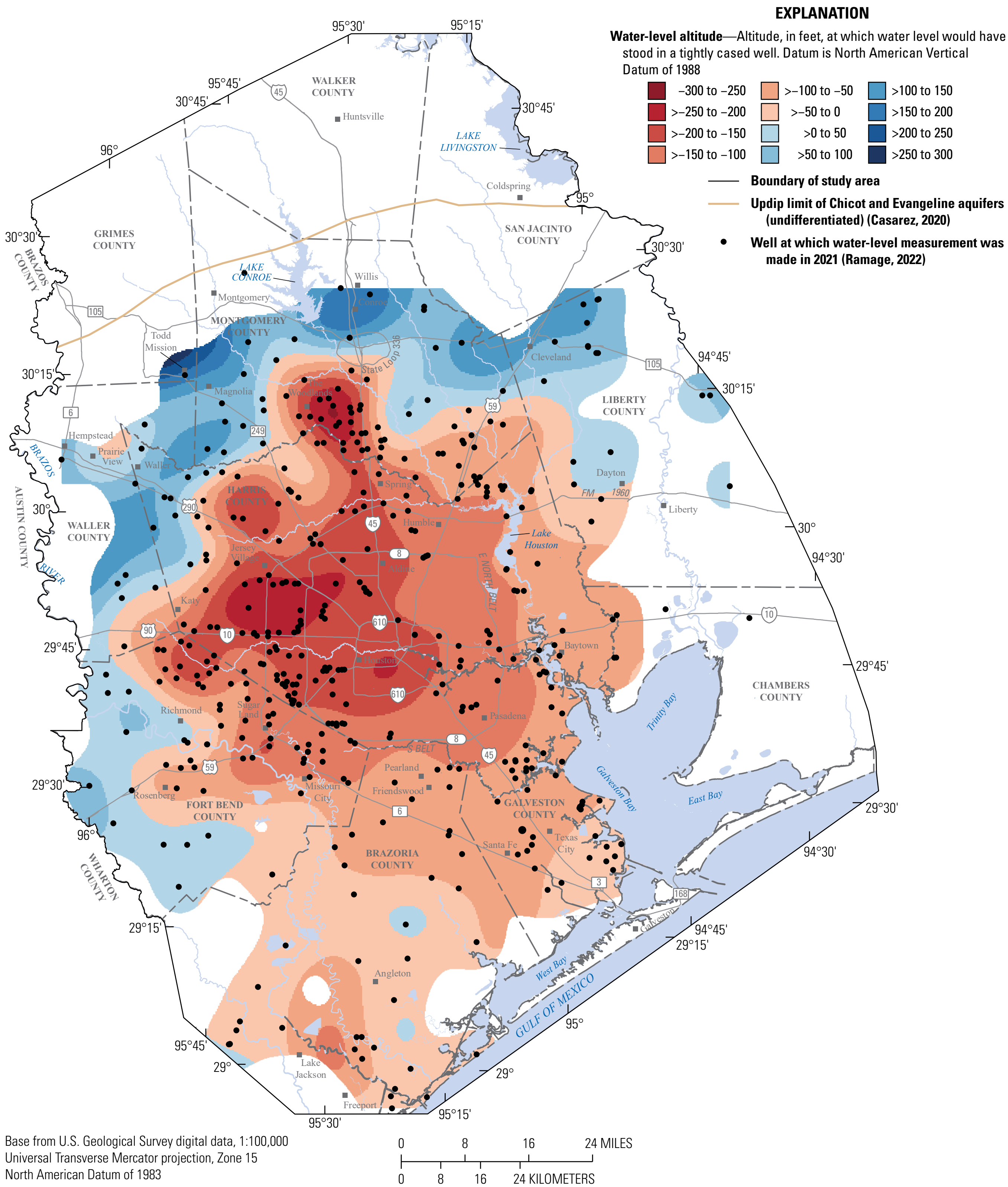


Figure 4. Approximate 2021 water-level altitudes of the Chicot and Evangeline aquifers (undifferentiated), greater Houston area, Texas (water-level-measurement data collected during November 2020 through March 2021).

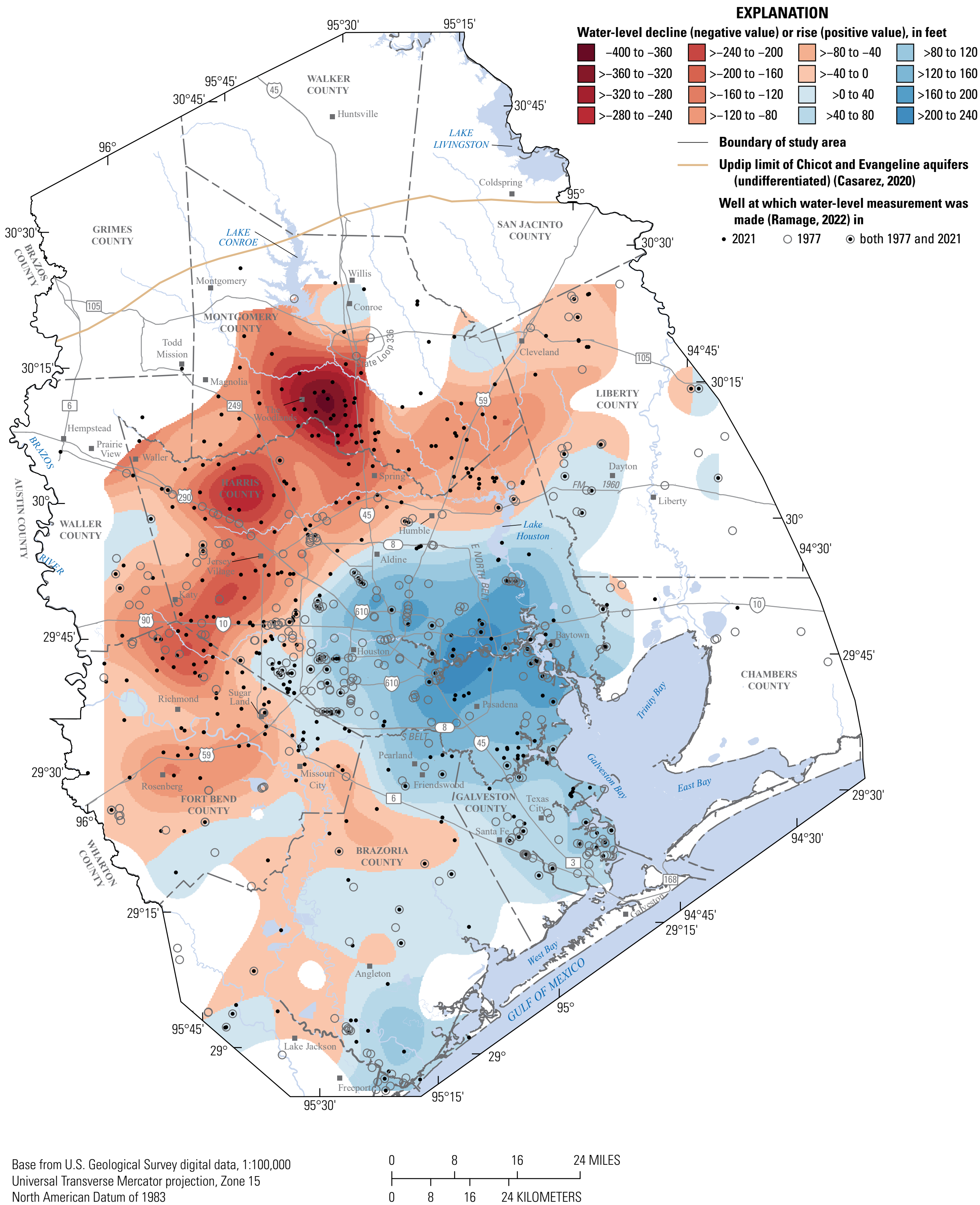
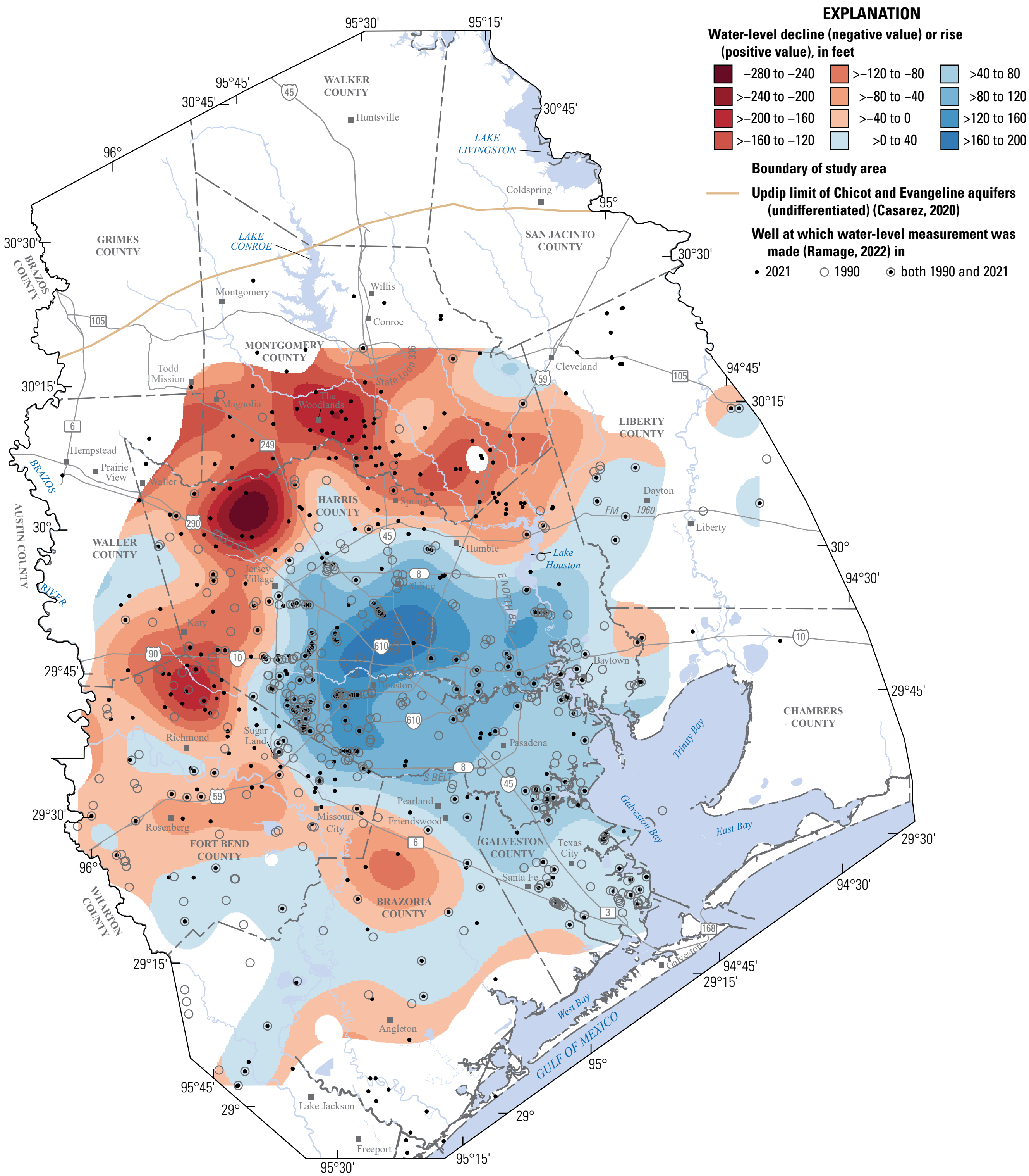


Figure 5. Approximate 1977–2021 water-level changes in the Chicot and Evangeline aquifers (undifferentiated), greater Houston area, Texas.



Base from U.S. Geological Survey digital data, 1:100,000
Universal Transverse Mercator projection, Zone 15
North American Datum of 1983

0 8 16 24 MILES
0 8 16 24 KILOMETERS

Figure 6. Approximate 1990–2021 water-level changes in the Chicot and Evangeline aquifers (undifferentiated), greater Houston area, Texas.

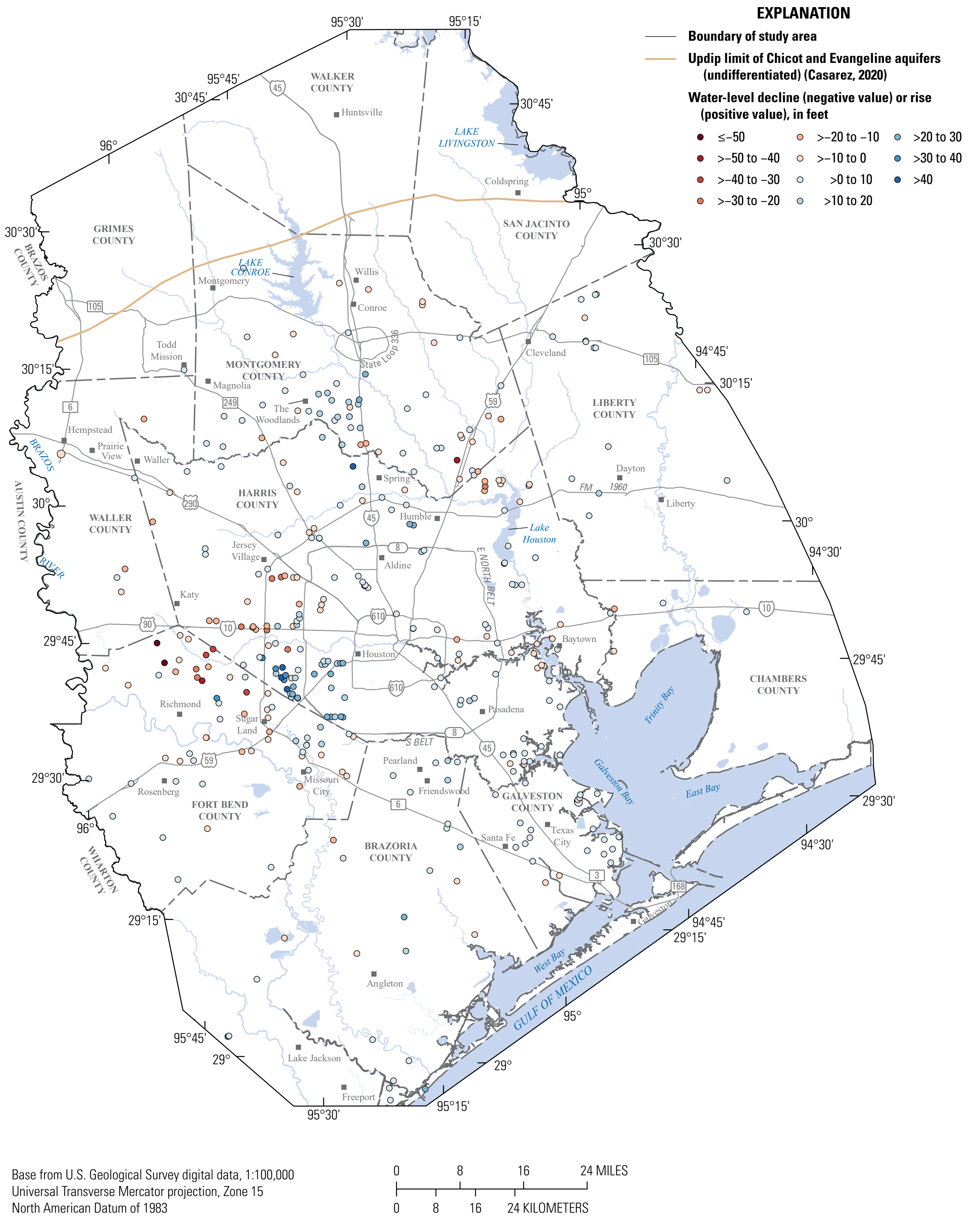


Figure 7. Approximate 2016–21 water-level changes at wells screened in the Chicot and Evangeline aquifers (undifferentiated), greater Houston area, Texas.

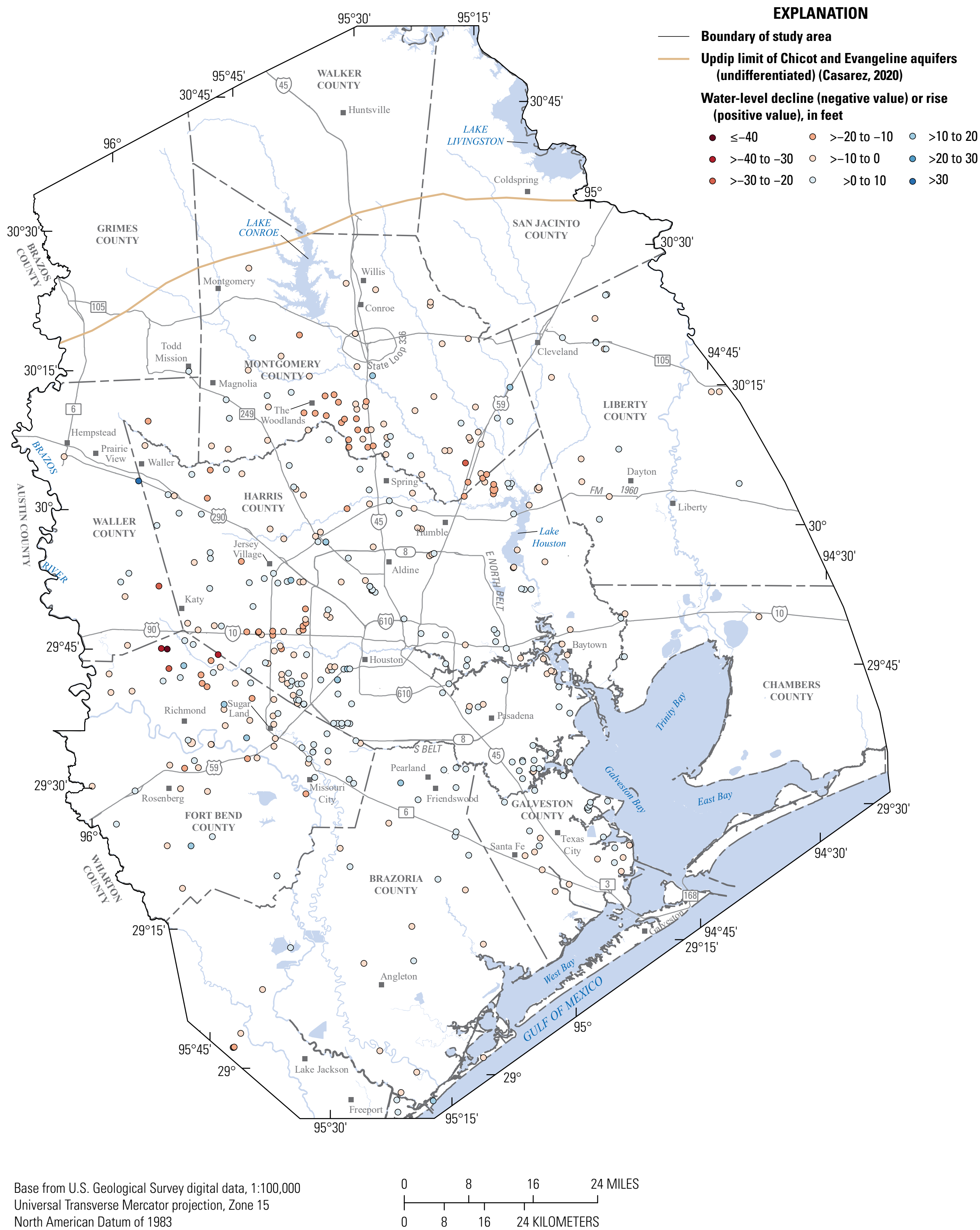


Figure 8. Approximate 2020–21 water-level changes at wells screened in the Chicot and Evangeline aquifers (undifferentiated), greater Houston area, Texas.

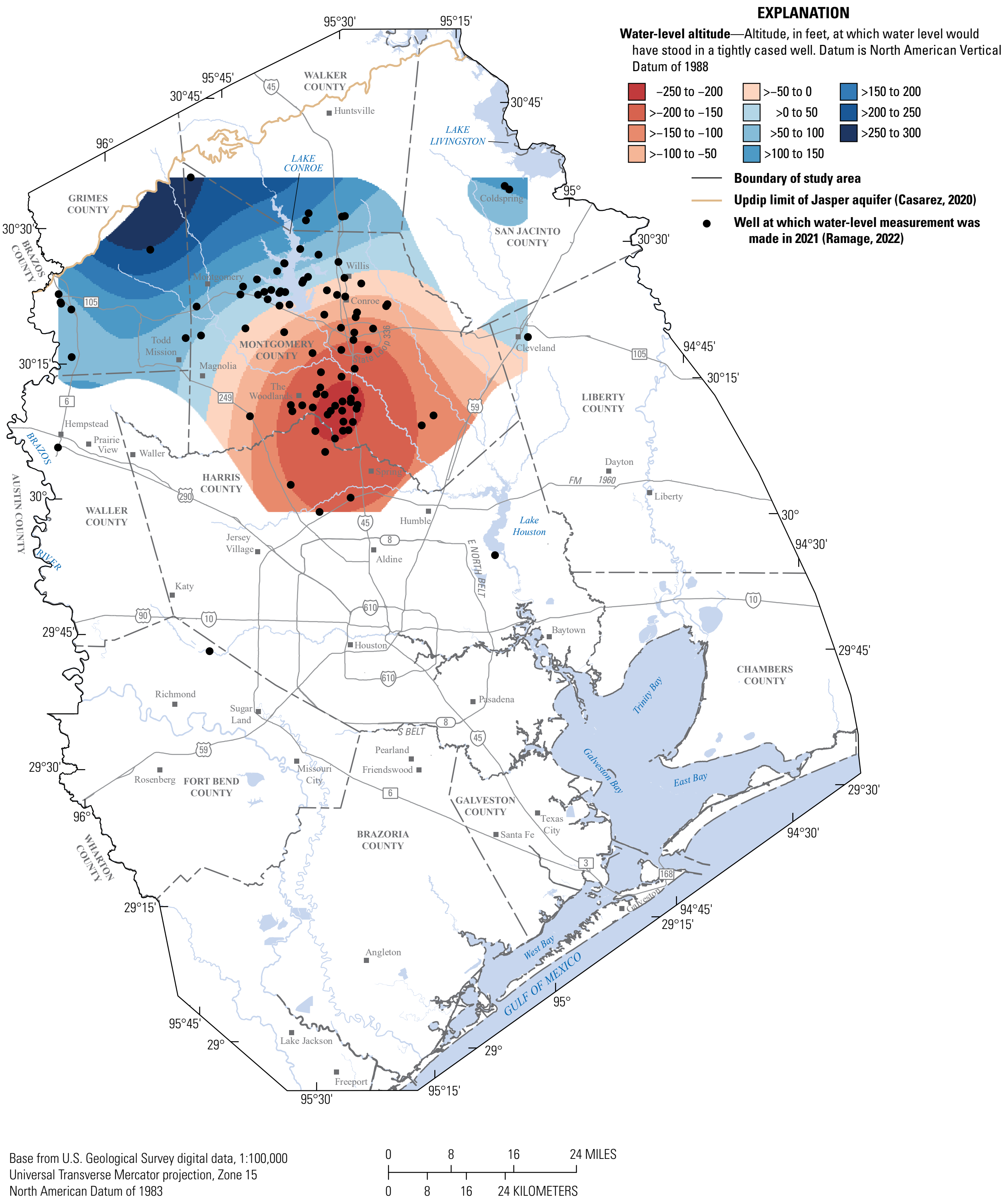


Figure 9. Approximate 2021 water-level altitudes in the Jasper aquifer, greater Houston area, Texas (water-level-measurement data collected during November 2020 through March 2021).

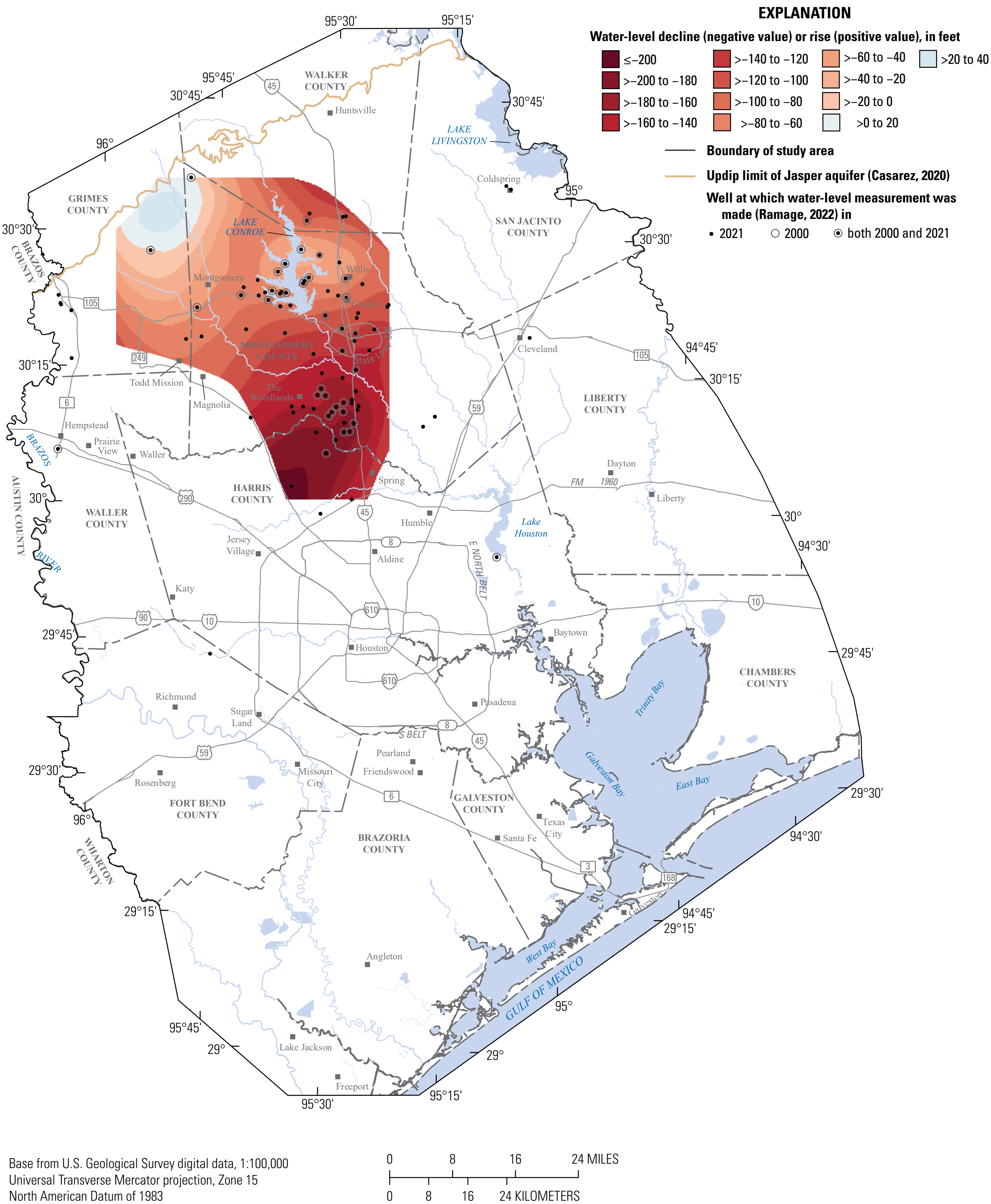


Figure 10. Approximate 2000–21 water-level changes in the Jasper aquifer, greater Houston area, Texas.

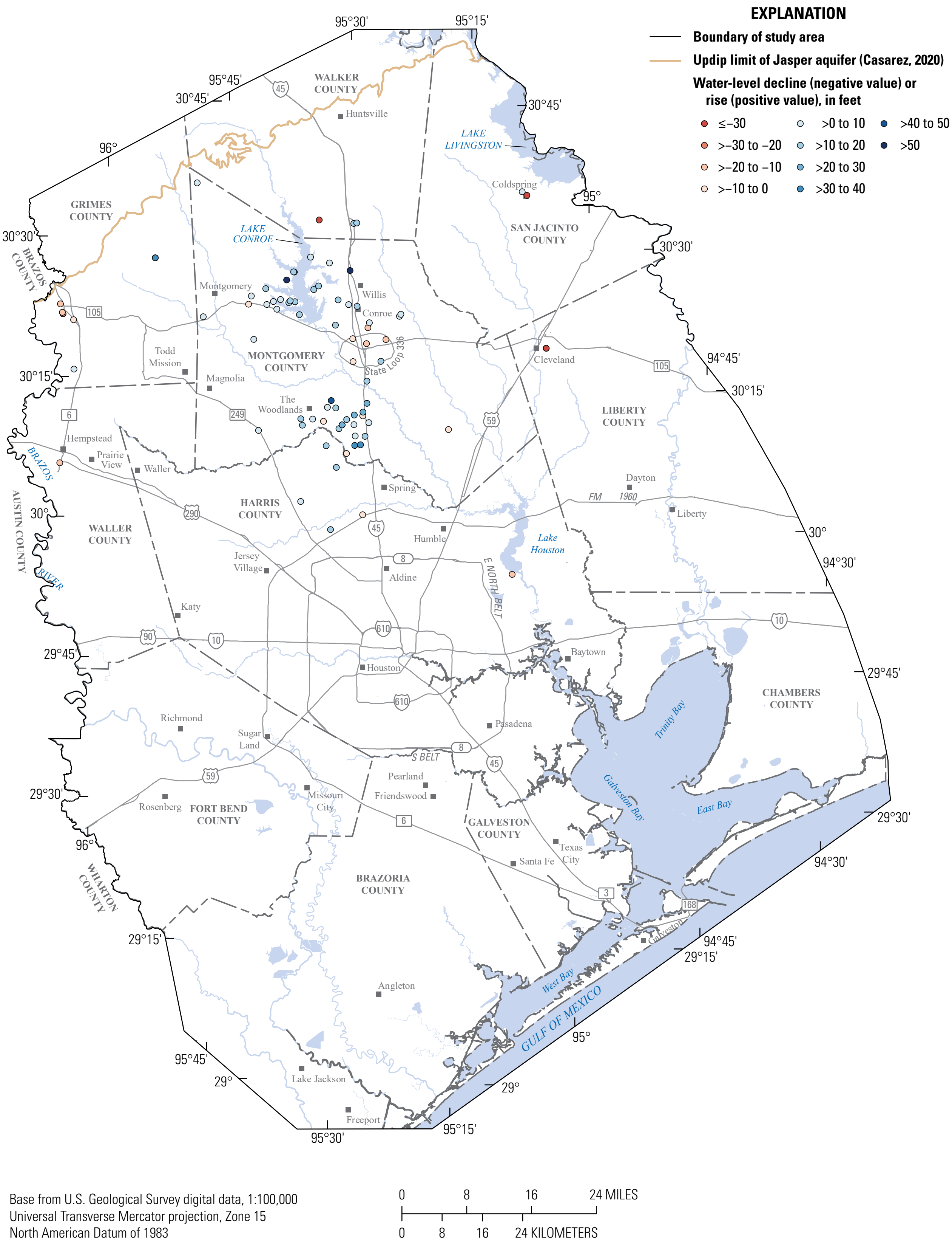


Figure 11. Approximate 2016–21 water-level changes at wells screened in the Jasper aquifer, greater Houston area, Texas.

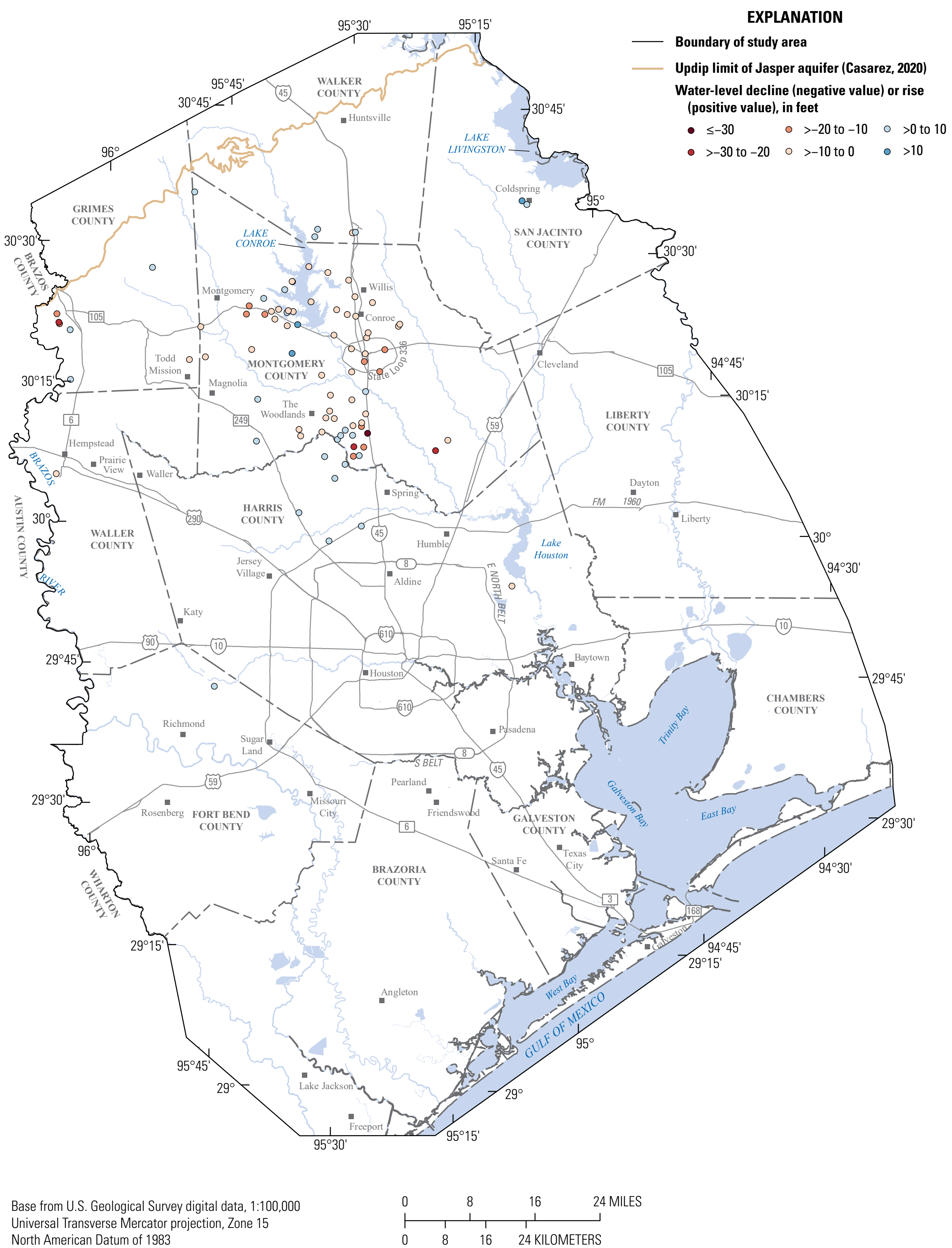


Figure 12. Approximate 2020–21 water-level changes at wells screened in the Jasper aquifer, greater Houston area, Texas.

water-level declines throughout most of the study area where water-level-altitude data from the Jasper aquifer were collected, with the largest decline (200 ft or more, which corresponds to the interval less than or equal to −200 ft in fig. 10) in northern Harris County southwest of The Woodlands.

The 5-year (2016–21) short-term water-level-change map for the Jasper aquifer depicts the largest declines (30 ft or more) at wells in Coldspring, Tex., and Cleveland, Tex., and at a well in southern Walker County and the largest rises (more than 50 ft) at two wells in northern Montgomery County (fig. 11). The 1-year (2020–21) short-term water-level-change map for the Jasper aquifer depicts the largest decline (30 ft or more) at a well in southern Montgomery County near the eastern part of The Woodlands and the largest rises (more than 10 ft) at two wells southeast of Montgomery, Tex. (fig. 12).

Data Limitations

As described in the “Methods” section, the accuracy of the land-surface-elevation data has gradually improved over time. Any changes in land-surface elevations, such as inaccuracies associated with the DEM source data, could affect the accuracy of the long-term water-level-change maps depicting the differences between the current year (2021) and the historical year (1977, 1990, or 2000) altitudes (Kasmarek and Ramage, 2017).

Shaded representations of water-level altitudes and water-level changes should be viewed in a regional context because water-level altitudes in the Chicot and Evangeline aquifers (undifferentiated) and in the Jasper aquifer are dynamic and can change rapidly in individual wells and spatially over larger areas encompassing many wells as a result of changes in local and regional groundwater withdrawals and different antecedent conditions prior to when groundwater-level measurements were made. Although the shaded gridded surfaces provide more information than did the previously used contours and are based on geostatistical interpolation, the resulting data between groundwater-level measurements are estimated data. Users should be aware that water-level changes may have occurred since the water levels were determined for the report. Inherent uncertainties exist in these data such as antecedent withdrawal rates and the pumping status of nearby wells. When evaluating the gridded depictions of water-level altitudes and water-level changes (figs. 4–6, 9, and 10), users should exercise discretion and know the limitations of these data when drawing conclusions or making policy decisions. These data should not be used for engineering applications.

Summary

The greater Houston area, Texas, consists of Harris, Galveston, Fort Bend, Montgomery, Brazoria, Chambers, Grimes, Liberty, San Jacinto, Walker, and Waller Counties. Since the early 1900s, groundwater withdrawn from the primary aquifers that compose the Gulf Coast aquifer system—the Chicot and Evangeline (undifferentiated) and Jasper aquifers—has been the primary source of water for municipal supply, commercial and industrial use, and irrigation in the greater Houston area. 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 the status of water-level altitudes and water-level changes in aquifers in the greater Houston area. Groundwater levels in wells screened in these aquifers were measured during November 2020 through March 2021 (water-level altitudes usually are higher during these months compared to the rest of the year).

This report presents water-level altitudes and water-level changes differently than did the previous U.S. Geological Survey reports in the annual series; differences include (1) treatment of the Chicot and Evangeline aquifers as a single hydrogeologic unit as opposed to distinct aquifers, (2) the addition of 1-year and 5-year change maps for the Chicot and Evangeline (undifferentiated) and Jasper aquifers and an additional long-term change map (1990–2021) for the Chicot and Evangeline aquifers (undifferentiated), and (3) a transition from depicting water-level altitudes and water-level changes as interpretive contours to producing grids by using a geostatistical interpolative technique (kriging) to represent water-level altitudes and long-term water-level changes in the greater Houston area.

This report contains regional-scale maps depicting approximate 2021 water-level altitudes and both short-term (1-year and 5-year) and long-term water-level changes in the Chicot and Evangeline (undifferentiated) and Jasper aquifers. Water-level measurements from 434 and 93 wells were used to depict the approximate 2021 water-level altitudes for the Chicot and Evangeline (undifferentiated) and Jasper aquifers, respectively.

In 2021, shaded depictions of water-level altitudes for the Chicot and Evangeline aquifers (undifferentiated) ranged from 300 feet (ft) below the North American Vertical Datum of 1988 (NAVD 88) to 300 ft above NAVD 88. The largest decline in water-level altitudes (360–400 ft) indicated by the 1977–2021 long-term water-level-change map for the Chicot and Evangeline aquifers (undifferentiated) was in the north-central part of The Woodlands, Tex., whereas the 1990–2021 long-term water-level-change map for the Chicot and Evangeline aquifers (undifferentiated) depicts a large area of decline in water-level altitudes (240–280 ft) in northwestern Harris County, northwest of Jersey Village, Tex. The largest rise in water-level altitudes in the Chicot and Evangeline aquifers (undifferentiated) (200–240 ft) was observed in a relatively large area in southeastern Harris County for 1977–2021, whereas the largest rise in water-level altitudes for 1990–2021 (160–200 ft) was observed in a relatively large area in central Harris County. The 5-year (2016–21) water-level-change

map for the Chicot and Evangeline aquifers (undifferentiated) depicts the largest declines (50 ft or more) at two wells in northern Fort Bend County and the largest rises (more than 40 ft) at three wells in southwestern Harris County and at one well in northern Harris County south of The Woodlands. The 1-year (2020–21) short-term water-level-change map for the Chicot and Evangeline aquifers (undifferentiated) depicts the largest decline (40 ft or more) at a well in northern Fort Bend County and the largest rise (more than 30 ft) at a well in Waller, Tex., near the boundary between Waller and Harris Counties.

In 2021, shaded depictions of water-level altitudes for the Jasper aquifer ranged from 250 ft below NAVD 88 to 300 ft above NAVD 88. The 2000–21 long-term water-level-change map for the Jasper aquifer depicts water-level declines throughout most of the study area where water-level-altitude data from the Jasper aquifer were collected, with the largest decline (200 ft or more) in northern Harris County southwest of The Woodlands. The 5-year (2016–21) water-level-change map for the Jasper aquifer depicts the largest declines (30 ft or more) at wells in Coldspring, Tex., and Cleveland, Tex., and at a well in southern Walker County. The largest rises (more than 50 ft) were indicated at two wells in northern Montgomery County. The 1-year (2020–21) short-term water-level-change map for the Jasper aquifer depicts the largest decline (30 ft or more) at a well in southern Montgomery County near the eastern part of The Woodlands and the largest rises (more than 10 ft) at two wells southeast of Montgomery, Tex.

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