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Impacts of Groundwater Withdrawal Regulation on Subsidence in Harris and Galveston Counties, Texas, 1978–2020

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ABSTRACT

Land subsidence has affected the greater Houston-Galveston region for over a century. Land subsidence in this region is caused by aquifer compaction due to groundwater withdrawal. Previous research has shown significant subsidence occurred from 1906 to 1978 with measured subsidence around 10 feet in the Houston Ship Channel. The Harris-Galveston Subsidence District (Subsidence District) was established in 1975 to regulate groundwater withdrawals in order to prevent subsidence in Harris and Galveston counties. After the creation of the Subsidence District, groundwater withdrawal was first regulated in Galveston County and southeast Harris County. This regulation resulted in less than one-tenth of one foot of subsidence recorded around the Houston Ship Channel from 1977 to 1985. More recently, the Subsidence District performed a wholistic analysis on historical measured subsidence using data from published reports and the subsidence monitoring network that were used as input parameters to model subsidence in the region. This analysis produced two key results that both show how the regulation of groundwater withdrawal can effectively lessen and even eliminate subsidence. The first outcome of this analysis involved the subtraction of the 1906–2000 estimated subsidence contour map from the 1906–1978 measured subsidence contour map to create an estimated subsidence map from 1978 to 2000. The second outcome used global positioning system (GPS) data from permanent GPS stations in the subsidence monitoring network to estimate subsidence from 2000 through 2020 that were modeled to create a 2000–2020 estimated subsidence map. Both subsidence maps will be presented to highlight the impact of groundwater regulation during the conversion to alternative water within Regulatory Areas One and Two. These Regulatory Areas, which

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include the Houston Ship Channel, that experienced significant subsidence prior to 1978 show essentially no additional subsidence post-conversion.

INTRODUCTION

Land subsidence in the greater Houston-Galveston region was first identified at Goose Creek Oil Field in Baytown, Texas, as evident in submerged platforms, surficial faulting, and measured three feet of subsidence over eight years beginning in 1918 (Pratt and Johnson, 1926). Although land subsidence at Goose Creek was caused by hydrocarbon extraction, the same phenomenon applies for groundwater extraction due to the geology and hydrogeology in this region. The Gulf Coast aquifer system is an accretionary wedge of unconsolidated sediments and contains three primary hydrogeologic units that are feasible for groundwater withdrawal. Baker (1979) classified these units based on facies associations, geophysical logs, and fauna. From youngest to oldest, these units are the Chicot aquifer, the Evangeline aquifer, and the Jasper aquifer (Fig. 1). The Chicot and Evangeline aquifers are hydrologically connected and comprise the shallow system. The Jasper aquifer is separated from the shallow system by the Burkeville Confining Unit (Baker 1979).

As the Houston-Galveston region experienced population growth and increased industrialization in the 1940s through 1970s, groundwater was the primary source water to meet water

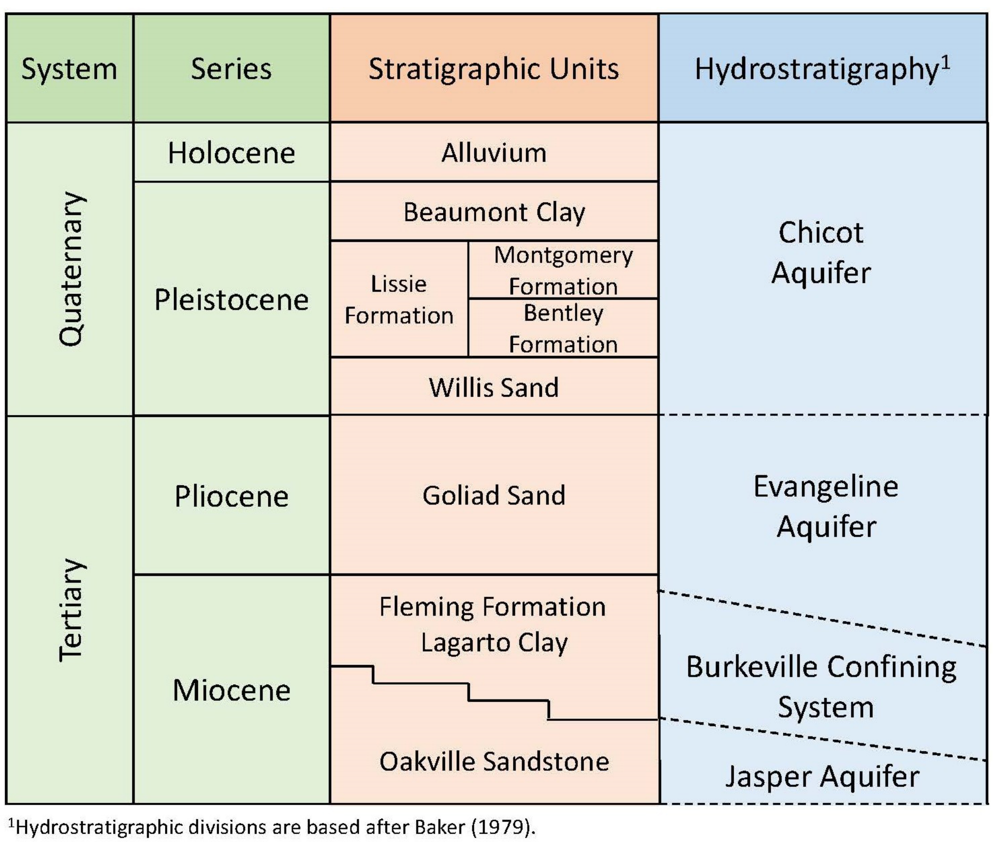


Figure 1. Stratigraphic column of the primary hydrostratigraphic units used for groundwater withdrawal in the Houston-Galveston region (modified after Baker, 1979).

demands. The majority of groundwater was sourced from the Chicot and Evangeline aquifers for municipal, agricultural, and industrial use (Michel, 2006). From 1943 through 1977, water level declines experienced a maximum of 250 feet in the Chicot aquifer in Clear Lake and 300 feet in the Evangeline aquifer in Houston (Gabrysch, 1982). The significant groundwater withdrawals produced aquifer compaction resulting in as much as nine feet of subsidence as measured in the Pasadena area.

The drastic declines in aquifer water levels and associated subsidence lead to the creation of the Harris Galveston Coastal Subsidence District in 1975, renamed in 2005 to Harris-Galveston Subsidence District (Subsidence District), with the purpose to regulate groundwater withdrawal in Harris and Galveston counties in order to prevent subsidence. The 1999 Regulatory Plan divided the Subsidence District into three (3) regulatory areas (Fig. 2) that each have a particular percentage of water demand sourced from groundwater (Harris-Galveston Subsidence District, 1999). Regulatory Areas One and Two are fully converted such that only 10 percent and 20 percent, respectively, of the total water demand can be sourced from groundwater. Regulatory Area Three is currently undergoing conversion as this area completed the first conversion in 2010 to 70 percent of total water demand sourced from groundwater. Future conversion deadlines will occur within Regulatory Area Three in 2025 and 2035 to 40 percent and 20 percent groundwater, respectively.

METHODS

Land-surface elevation data has been recorded in the Houston-Galveston region since 1906. A series of releveling surveys have been conducted over the years including 1943, 1973, 1978, 1987, 1995, 2000, and 2007. As elevation data prior to 1943 is sparse for the Houston-Galveston region, this study relied on published measured subsidence contour maps as the primary data source for subsidence from 1906 through 1978 (Fig. 3) (Gabrysch, 1982). This historical data incorporated first-order elevations of benchmarks from a large releveling survey conducted in a cooperation between the Subsidence District and the National Geodetic Survey in 1978. Another large first-order surveying campaign occurred in 2000 which aided in creation of the 1906 through 2000 measured subsidence contour map (Fig. 4) (Gabrysch and Neighbors, 2005).

Both the 1906–1978 and the 1906–2000 subsidence contour maps depict total estimated subsidence over the specified time period. This study utilized geographic information system (GIS) techniques to transform the contour lines from the published maps into raster grids. Then a raster subtraction was performed between the 1906–1978 grid from the 1906–2000 grid. This time period of 1978 through 2000 was selected as it includes the conversion of the Subsidence District's Regulatory Areas One and Two from groundwater to alternative water sources.

Global positioning system (GPS) data were selected as the input parameters to create an estimated subsidence contour map from 2000 to 2020. The methods for deriving subsidence from GPS data are addressed in (Wang et al., 2015) and (Agudelo et al., 2020). GPS data collected from 225 GPS stations within the subsidence monitoring network across eight counties were used to calculate the total subsidence from 2000 to 2020.

The 2000 to 2020 estimated subsidence contours were calculated by assigning a constant rate, or linear regression, for a five year interval based on period of monitoring for GPS stations that did not monitor the full-time interval and applying those rates over the specified time to estimate the total vertical displacement. For example, GPS station P041 began monitoring in 2007 so the starting 5 year rate extended from 2007 to 2011. This starting rate was used as the constant rate from 2000 to 2006 in order to estimate the rate of change prior to monitoring and adequately represent the full-time interval. For GPS stations that either began or continued monitoring in 2000, such as P001, the total vertical displacement observed in the period of record (i.e., 2000 to 2020) was used instead of applying a constant rate (Fig. 5).

GPS stations that began monitoring in 2015 through 2018 and were surrounded by GPS stations whose period of record included the entire time period between 2000 and 2020 were excluded due to a bias observed in the modeling algorithm. Such stations skewed the results from the majority of GPS stations located in northern Harris and southern Montgomery counties and

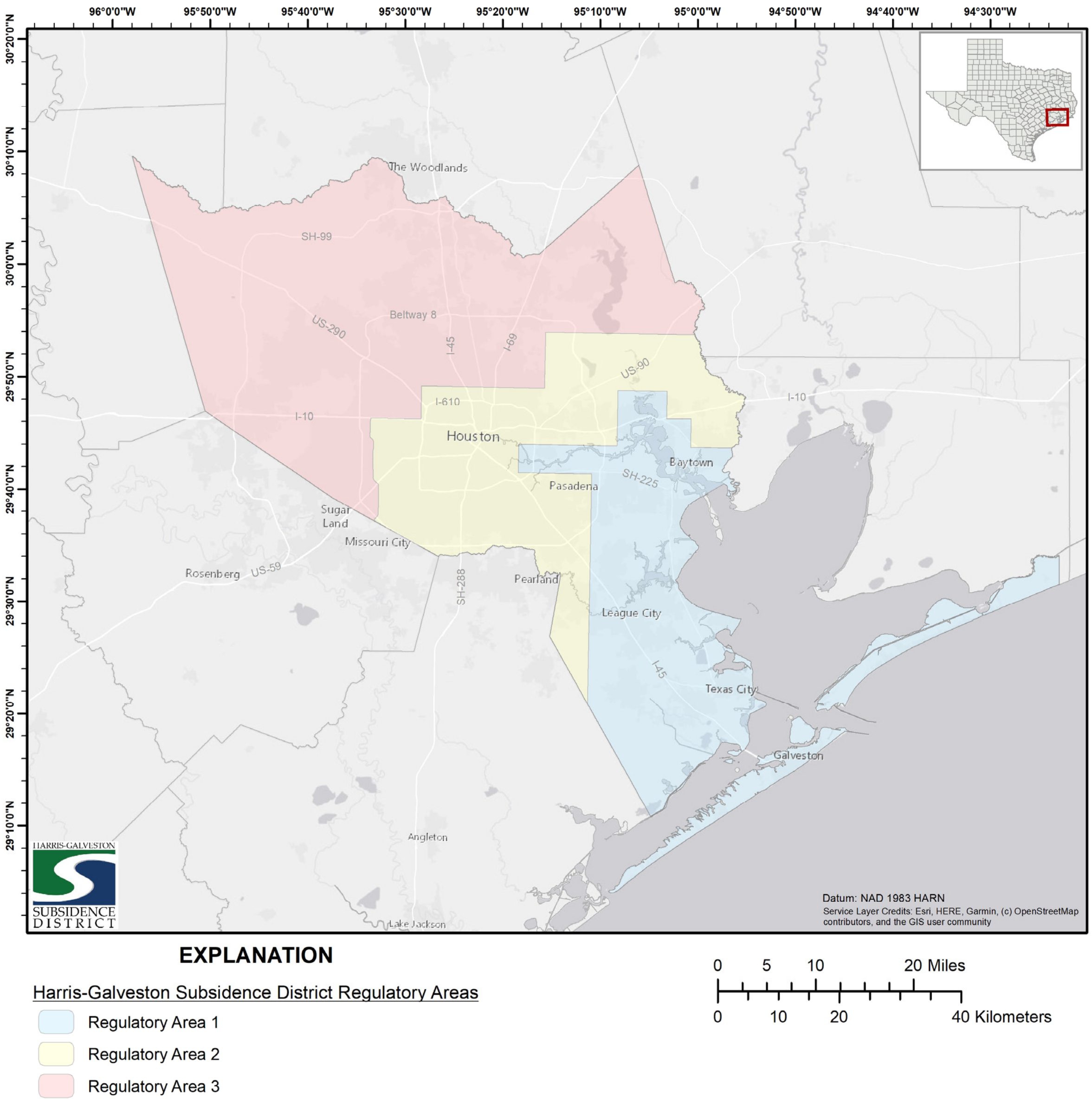


Figure 2. Delineation of the Harris-Galveston Subsidence District's Regulatory Areas as stated in the 1999 Regulatory Plan (Harris-Galveston Subsidence District, 1999).

produced impractical contours from a technical perspective. The estimated total subsidence from approximately eight excluded stations were between 0.3 and 0.9 feet of subsidence. Furthermore, the excluded stations began monitoring after groundwater conversions in these areas and the subsidence values did not agree with the local trend observed from GPS stations with the full period of record from 2000 to 2020.

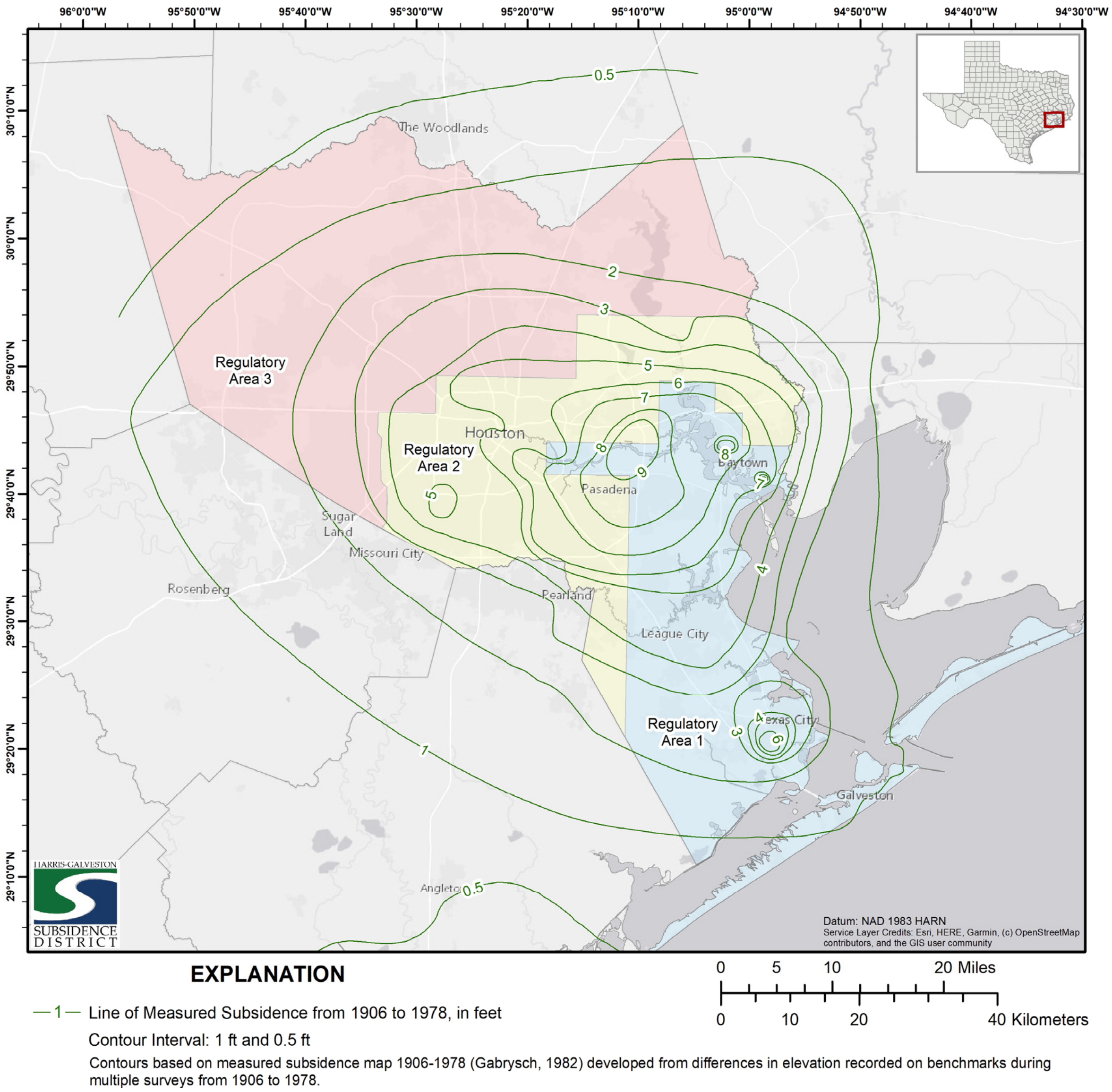


Figure 3. Total subsidence from 1906 to 1978, in feet, measured from differences in elevations at benchmarks surveyed from 1906 to 1978 (modified after Gabrysch, 1982).

RESULTS

The 1978–2000 subsidence map (Fig. 6) highlights the impact of groundwater regulation during the conversion to alternative water within Regulatory Areas One and Two as areas like Houston Ship Channel that experienced significant subsidence (over 10 feet) prior to 1978 show very little subsidence post conversion. Areas within Regulatory Area Three were still experiencing subsidence as no regulation on groundwater withdrawal was enforced during that time.

The 2000–2020 estimated subsidence map (Fig. 7) shows essentially no subsidence in Regulatory Areas One and Two as the conversion milestones were already achieved prior to this

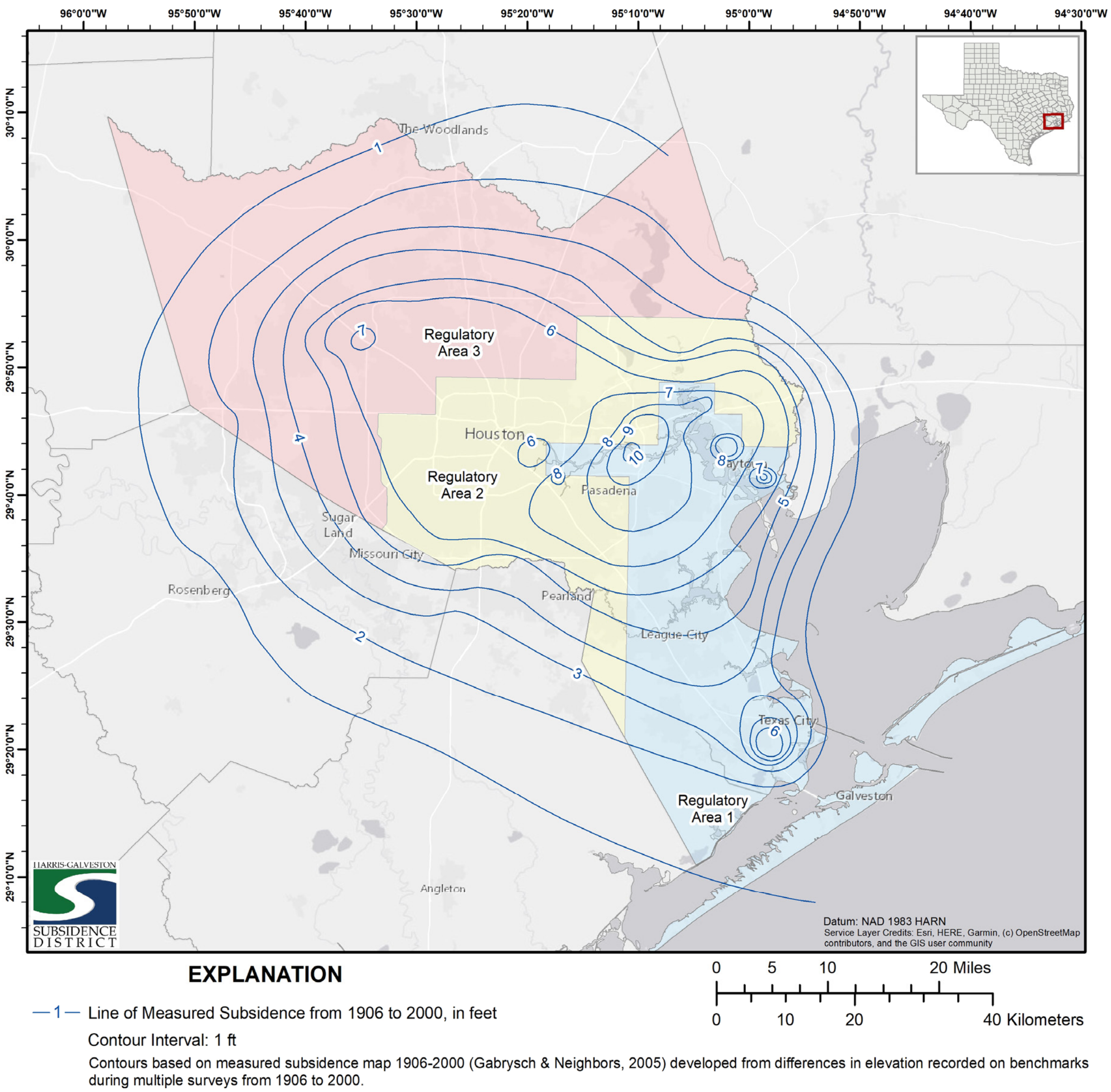


Figure 4. Total subsidence from 1906 to 2000, in feet, measured from differences in elevations at benchmarks surveyed from 1906 to 2000 (modified after Gabrysch and Neighbors, 2005).

time interval. Some isolated areas, such as Katy, The Woodlands, Spring, and Cypress, within Regulatory Area Three show over one foot of subsidence with a maximum of two feet over 20 years as these areas are still undergoing conversion to alternative water sources.

SUMMARY AND CONCLUSIONS

The areas like Pasadena and the Houston Ship Channel in the greater Houston-Galveston region experienced up to ten feet of subsidence due to aquifer compaction from significant

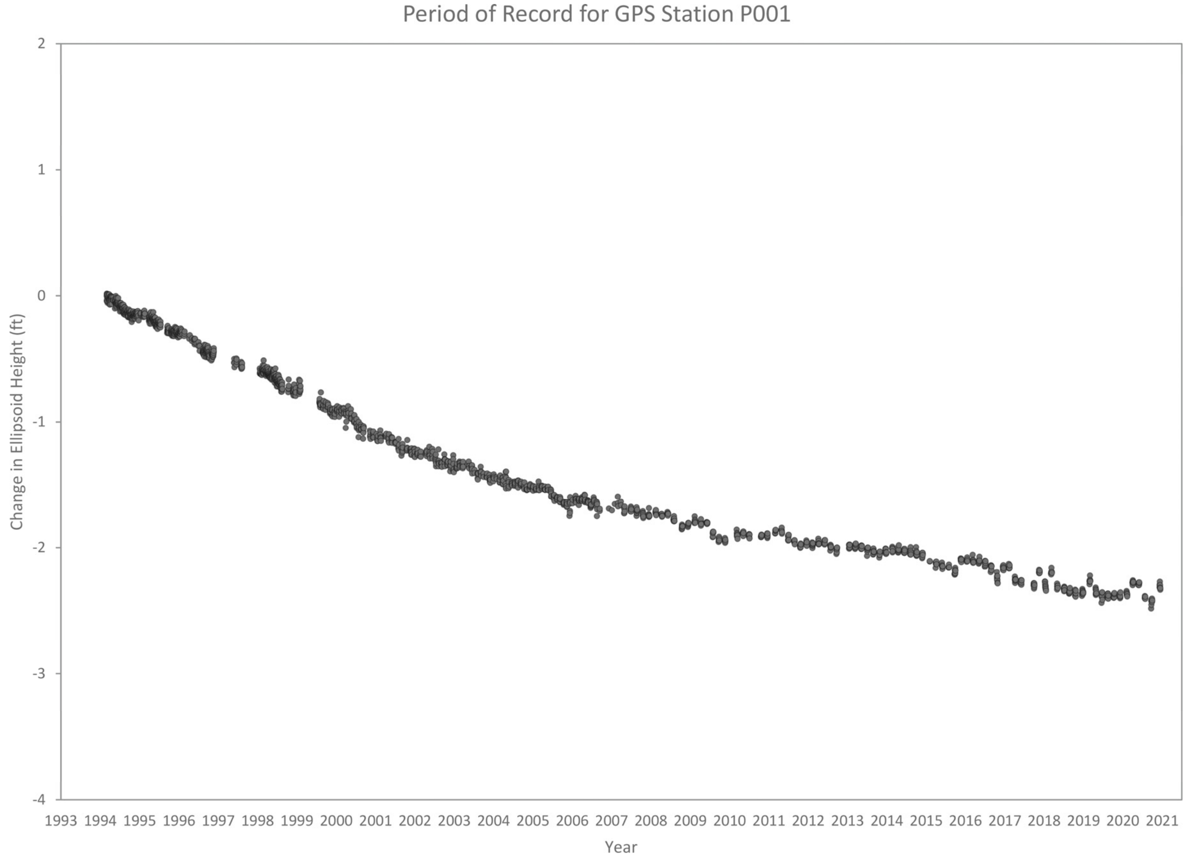
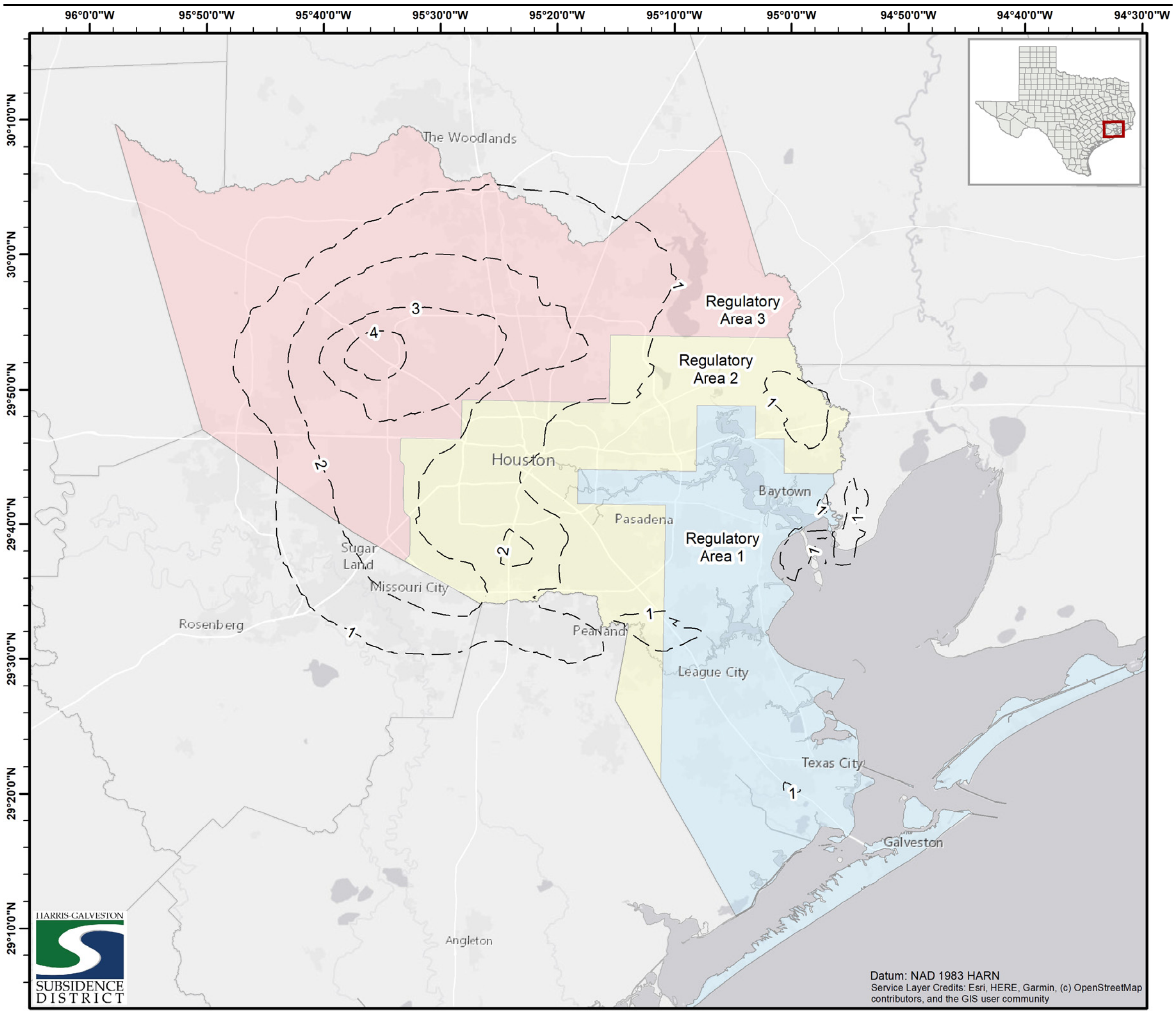


Figure 5. Period of record GPS–derived time series plot for GPS station P001, located in Jersey Village, Texas. The vertical displacement, as shown in the change in ellipsoidal height, from 2000 through 2020 was used to estimate the subsidence experienced at P001. This value was used as input to model the estimated subsidence contours from 2000 to 2020.

groundwater withdrawal from 1906 to 1978. The Subsidence District was established in 1975 by the Texas Legislature with the purpose of regulating groundwater withdrawal to prevent subsidence. From data collection ranging from large scale first-order surveys to GPS monitoring as well as detailed and informed regulatory planning, the Subsidence District has continued to use innovative techniques to monitor subsidence in this region.

Land surface elevation data acquired from leveling surveys and GPS data over the past 40 years has been critical to understand the changes in subsidence rates in the greater Houston-Galveston region. The impact of the Subsidence District's regulation of groundwater withdrawal within fully converted regulatory areas is further demonstrated as water level altitudes in the Chicot and Evangeline aquifers have increased up to 240 feet from 1977 to 2021 in the Pasadena area (Greuter and Petersen, 2021).

Galveston County and portions of southeast Harris County began the conversion to alternative water in the 1980s and culminated in the mid-1990s. As a result of this conversion, subsidence was greatly reduced in these areas. Within the past 20 years, practically no subsidence has occurred in fully converted regulatory areas (Fig. 7). Future conversion milestones will aid in the lessening of subsidence in portions of northwest Harris County and continued regulatory planning founded in high-quality and best available science will help achieve the Subsidence District's mission to prevent subsidence.



EXPLANATION

—1— Line of Estimated Subsidence from 1978 to 2000, in feet

Contour Interval: 1 ft

0 5 10 20 Miles

0 10 20 40 Kilometers

Contours based on GIS grid subtraction of measured subsidence maps from 1906 to 2000 (Source: Gabrysch, 1982 and Gabrysch & Neighbors, 2005).

Figure 6. Total estimated subsidence from 1978 to 2000, in feet, utilizing GIS grid subtraction of measured subsidence from 1906 to 1978 (Gabrysch, 1982) and measured subsidence from 1906 to 2000 (Gabrysch and Neighbors, 2005).

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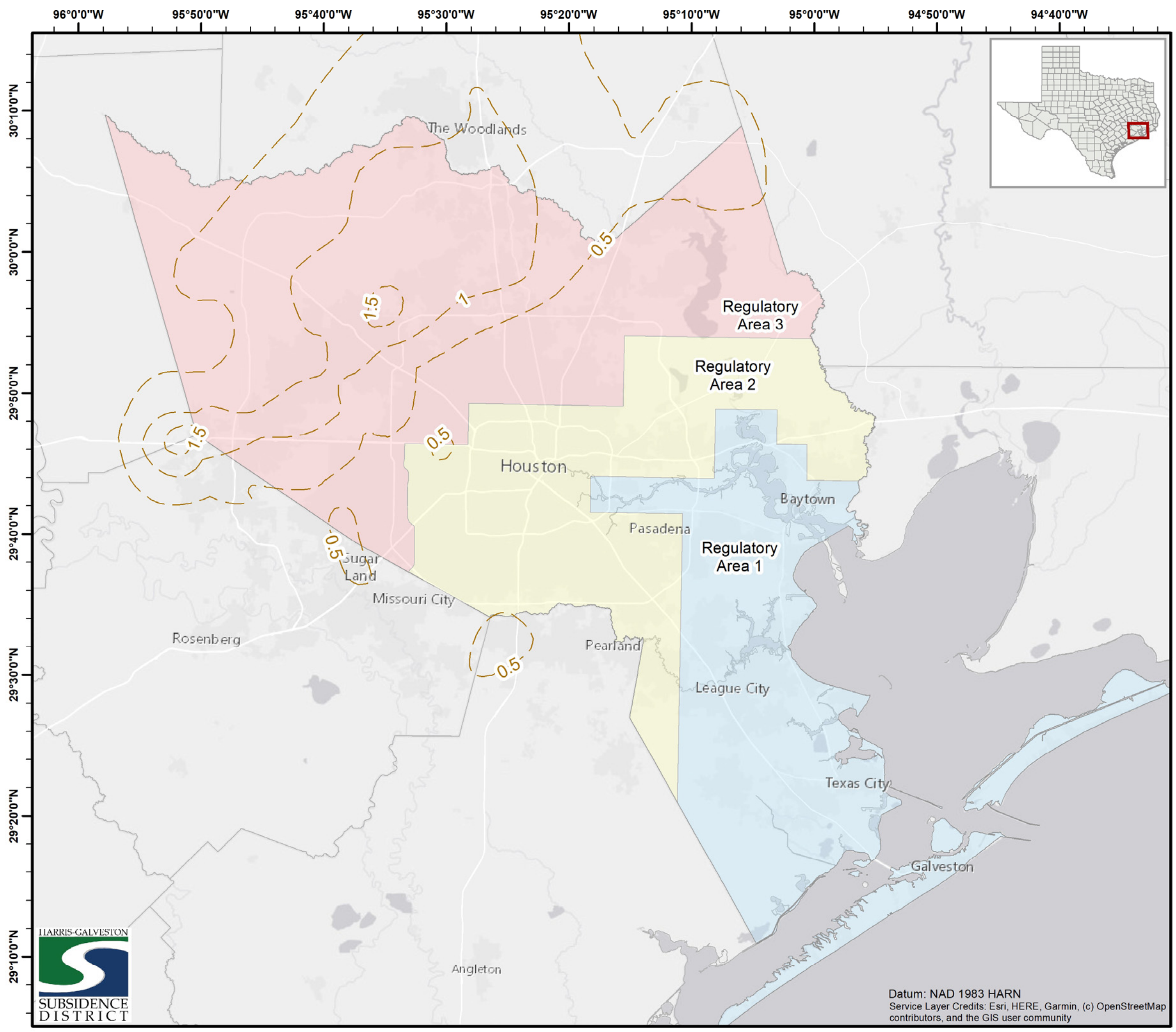

EXPLANATION

—1— Line of Estimated Subsidence from 2000 to 2020, in feet

Contour Interval: 0.5 ft

Contours estimated from GPS data processed from GPS stations with more than three years of data and referenced to stable Houston reference frame, Houston20 (GPS data source: Greuter and Petersen, 2021).

0 4 8 16 Miles

0 5 10 20 Kilometers

Figure 7. Total estimated subsidence from 2000 to 2020, in feet, estimated from GPS data acquired from approximately 225 GPS stations, located within the subsidence monitoring network, with more than three years of data.

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