Appendix B – Subsidence Monitoring Network and Data

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Subsidence Monitoring Network

GPS Station Overview

The subsidence monitoring network comprises a collaboration of local to state to federal agencies who operate and maintain global position system (GPS) stations in the greater Houston-Galveston region. In 2021, the Harris-Galveston Subsidence District (HGSD) collected raw data from 227 GPS stations to assess and understand changes in the land-surface elevation in the region. The analysis of such data, including details on data processing and uncertainty, is provided in subsequent sections.

Fort Bend County contains a total of 32 GPS stations that were analyzed in 2021. The District currently operates and maintains 22 GPS stations with 21 stations located in Fort Bend County and one (1) station in southwestern Waller County. HGSD operates and maintains 73 GPS stations in Harris, Galveston, Brazoria, Montgomery, Waller and Chambers counties. Surrounding groundwater conservation districts (GCDs) such as Brazoria County GCD and Lone Star GCD operate and maintain 14 and six (6) GPS stations, respectively. The University of Houston (UH) operates 66 GPS stations with nine (9) in Fort Bend County and the Texas Department of Transportation (TXDOT) operates 39 GPS stations with two (2) located in Fort Bend County. **Figure 1** includes the location and operators of GPS stations that were analyzed in the subsidence monitoring network.

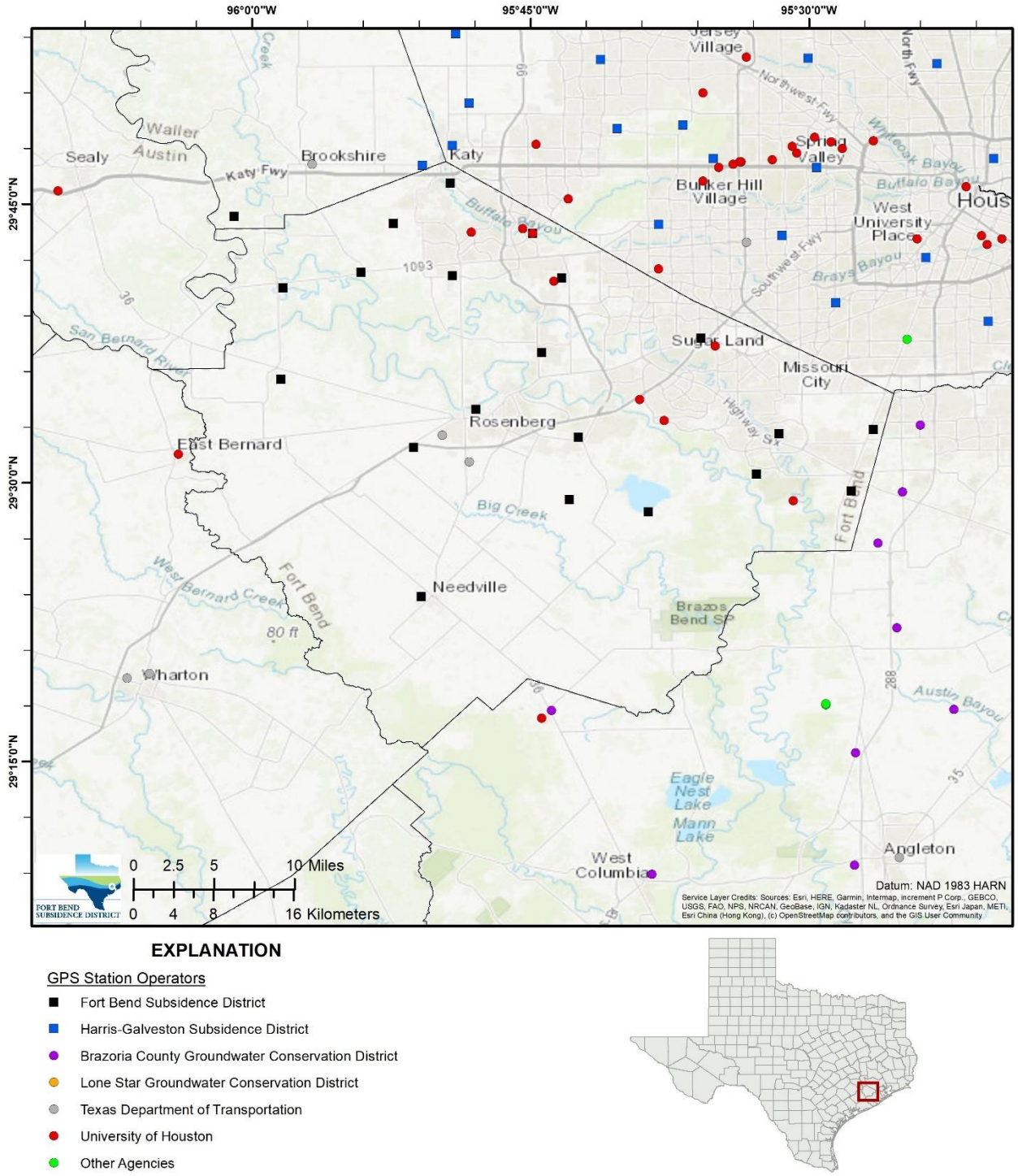

Figure 1: Location of GPS stations designated by operator in Fort Bend and surrounding counties.

The GPS stations are constructed in different ways based on when they were installed and operator preferences. The main design for permanent GPS stations utilized by the District is a periodically measured (PAM) GPS station. Other types of permanent GPS station include a building mount, which is primarily used by UH, and an extensometer.

The District designed a permanent GPS station in the mid-1990s to apply a consistent measurement method across multiple counties. This design is known as a PAM and is named after the original port-a-measure method utilized by the District in the early 1990s when the GPS station was not a permanent structure and each location collected data periodically. The PAM design consists of two-inch galvanized pipe drilled approximately 34 feet below ground surface and extends eight feet above the ground surface. The pipe is anchored in a concrete plug at the base and enclosed by centering bands and PVC pipe near the surface to reduce movement. The exposed pipe (i.e., the section of pipe that extends eight-feet above the ground surface) is mounted with an antenna adapter to secure the global navigation satellite system (GNSS) antenna. A separate two-inch pipe is installed within a few feet from the antenna pipe in order to hold an enclosure box, which stores a battery and GNSS receiver, and a mounted solar panel. Both pipes are surrounded by four bollards and encased in a concrete slab for protection. **Figure 2** depicts a schematic of the District's PAM design.

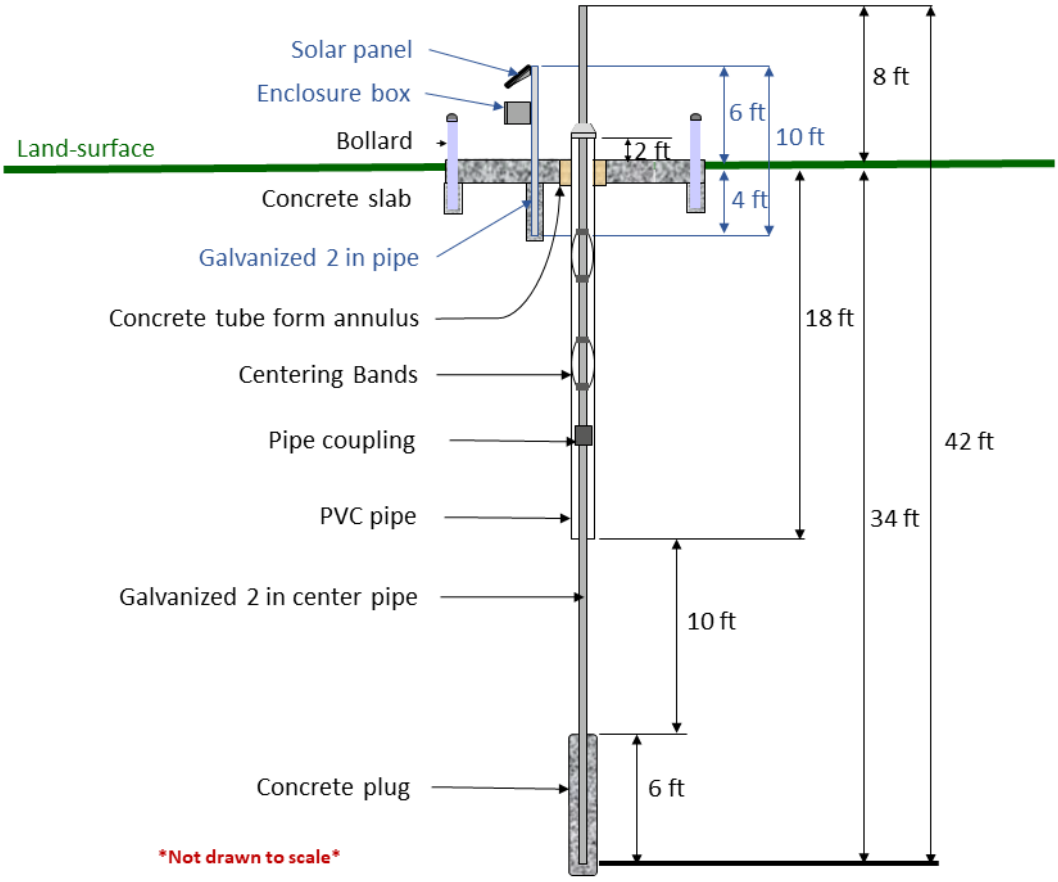

Figure 2: Schematic of the District's PAM design for a permanent GPS station. Note the schematic is not drawn to scale and is intended for visual purposes only. All numbers are provided in US standard measurement.

The USGS operates and maintains 14 borehole extensometers, which are wells drilled to various depths (650 to 3,300 feet below ground surface) and anchored with a concrete plug in order to measure compaction within different aquifers (Kasmarek, et al., 2015). **Figure 3** illustrates the extensometer design that includes an outer casing equipped with slip-joints to maintain well integrity by preventing damage from subsidence and the inner pipe attached to a concrete plug at the bottom of the borehole.

Such extensometers use digital recorders, which are connected to the inner pipe, to continuously measure the change between the inner pipe and the land-surface elevation. The UH operates one GPS station (i.e., UHKD) that has a GNSS antenna mounted on the extended inner pipe.

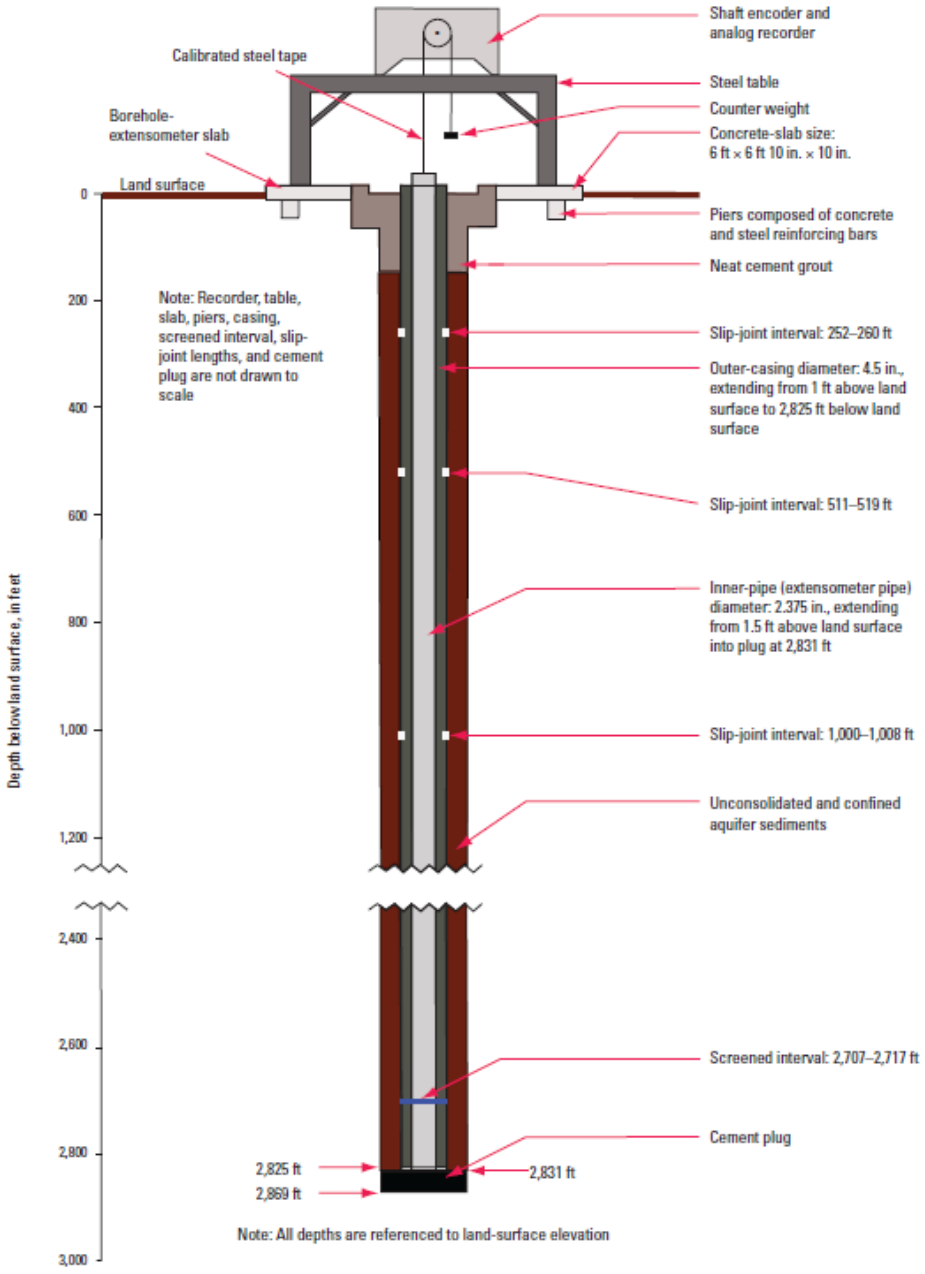

Figure 3: Cross-sectional view of an extensometer adapted from (Kasmarek, et al., 2016).

The building mount is another design for a GPS station. Building mounts have a GNSS antenna mounted on or near the building's roof. Buildings with deep foundation as well as clear sky views are selected as optimal locations to measure land-surface elevation change and limit interference. The building mount design is used by UH throughout the greater Katy and Sugar Land areas.

Subsidence Monitoring Types

GPS data are collected at each of the GPS stations every thirty seconds during the duration of monitoring, which varies from periodic to continuous. The District operates both periodic and continuous monitoring GPS stations. Other operators, such as UH and TXDOT, operate continuous monitoring stations.

Periodic monitoring stations collect GPS data for approximately seven days every two months at the GPS station. These stations are constructed in the PAM design and use a Trimble GNSS antenna and receiver to gather land-surface data.

Continuous monitoring stations collect GPS data every day of the year and some are designated as continuously operating reference stations (CORS). CORS are designed in two ways: 1) the PAM design or 2) mounted on preexisting structures. The District operates one (1) CORS (i.e., P096) that is constructed in the PAM design. Other operators like the UH typically mount the GPS antenna on the roof of suitable buildings.

Subsidence Data

As of 2021, the District uses GPS data from 227 GPS stations spread across 20 counties in southeast Texas. The District uses GPS data from other agencies like HGSD, BCGCD, LSGCD, and TXDOT as well as the UH to understand local to regional subsidence trends. **Figure 4** depicts the subsidence monitoring network with a map identification number for each GPS station and two map insets to provide greater detail in the denser areas. Additional information for each map identification number is included as a table within **Appendix C.**

The GPS data collected by the District measure the land-surface as a three-component displacement time series involving the horizontal (East-West), vertical (North-South), and the ellipsoidal height (up-down) components. GPS data are processed and converted to the Stable Houston Reference Frame 2020 (Houston20). Additional methods of GPS data processing include identification of outliers and estimations of site velocities and associated uncertainties.

Outliers are identified through a series of steps that include applying a locally weighted scatterplot smoothing (LOWESS) algorithm to obtain a time-series trend with two (2) iterations, removing the residual time-series trend, and estimating the median of absolute deviations (MAD) of the residual time-series (Wang, et al., 2022). The subsidence rate of a GPS station is estimated using the linear regression of the most recent five-year ellipsoidal height data (i.e., 2017-2021), at stations that have a minimum of three years of data. The root mean square (RMS) accuracy of the GPS data provided in this report is approximately 5-8 millimeters for the vertical direction or ellipsoidal height (Wang, et al., 2022).

The entire GPS dataset from all contributors are reprocessed every few years as improvements in positioning software, updates to global to regional reference frames, and other data processing analysis tools, such as orbital clock updates, are disseminated to users. Caution should be applied when attempting to mix or compare old GPS datasets with newer versions as GPS data processing is both a complex and a dynamic procedure.

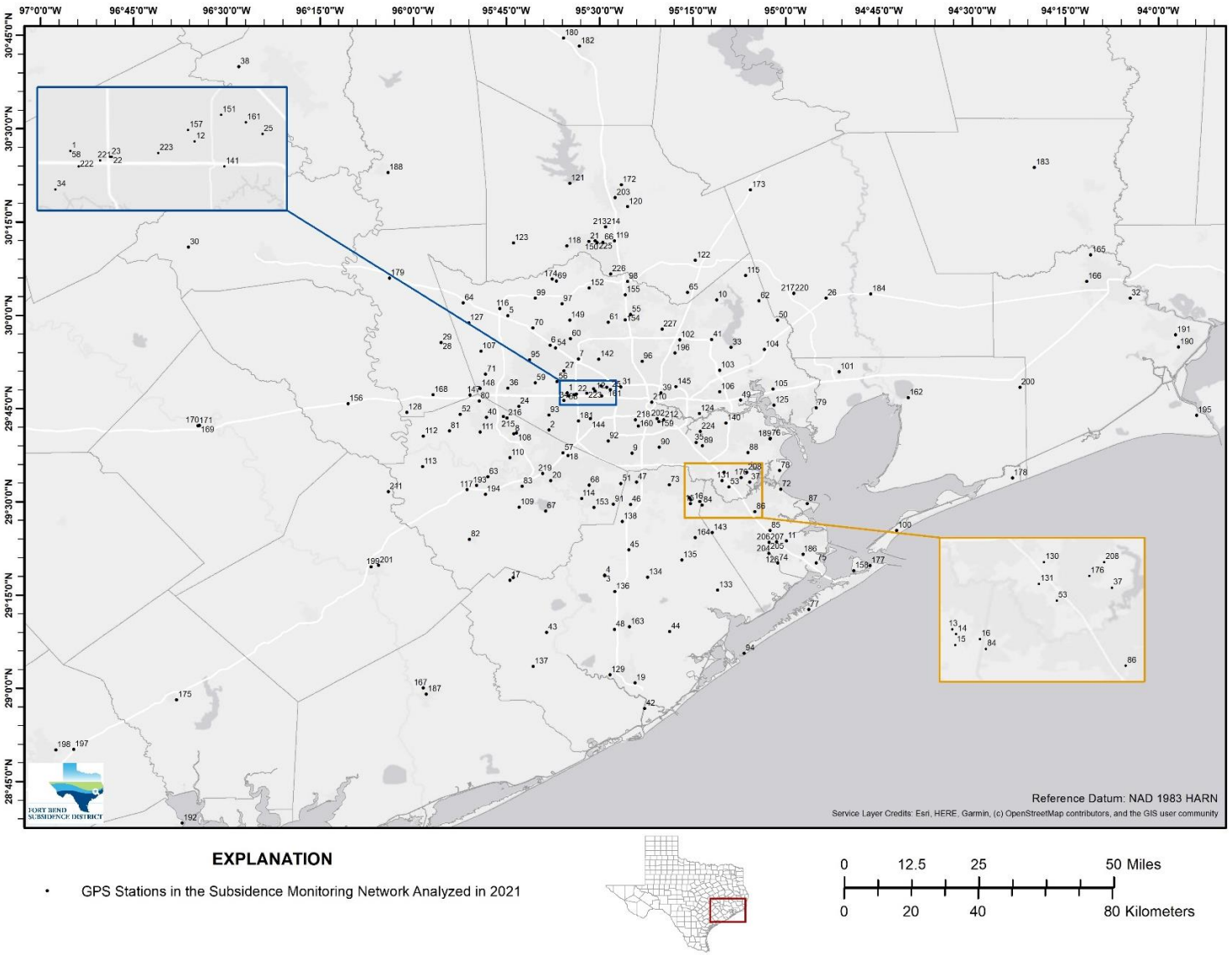

Figure 4: Location and map identification number of GPS stations that monitor periodically or continuously within Fort Bend and surrounding counties, Texas, 2021.

Regulatory Area A

GPS stations have been operating since 1994 within Regulatory Area A to measure subsidence. Regulatory Area A has 29 GPS stations with a maximum subsidence rate of 2.19 cm per year measured in the Katy area. **Figure 5** displays the GPS stations in Regulatory Area A with labels identifying the name of each station.

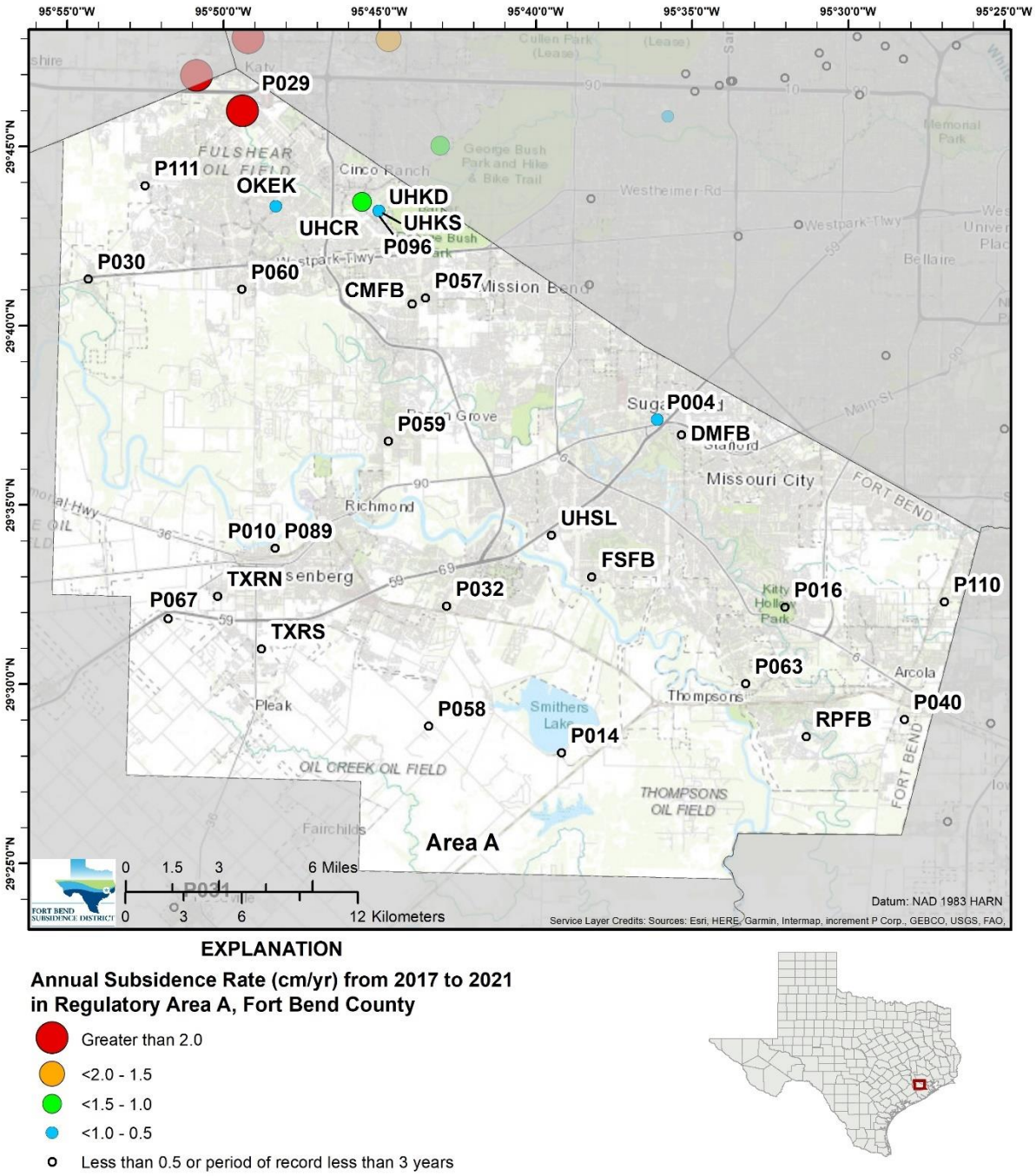

Figure 5: Annual subsidence rate in cm per year estimated from periodic and continuous GPS data measured from GPS stations with three or more years monitoring within Regulatory Area A in Fort Bend County, Texas, 2017-2021.

The majority of the higher subsidence rates are located in northern Fort Bend County. GPS station P029, located in Katy, shows the greatest subsidence rate at 2.19 cm per year (**Figure 6**). P029 has measured approximately 23.8 cm (9.3 inches) of subsidence since 2007.

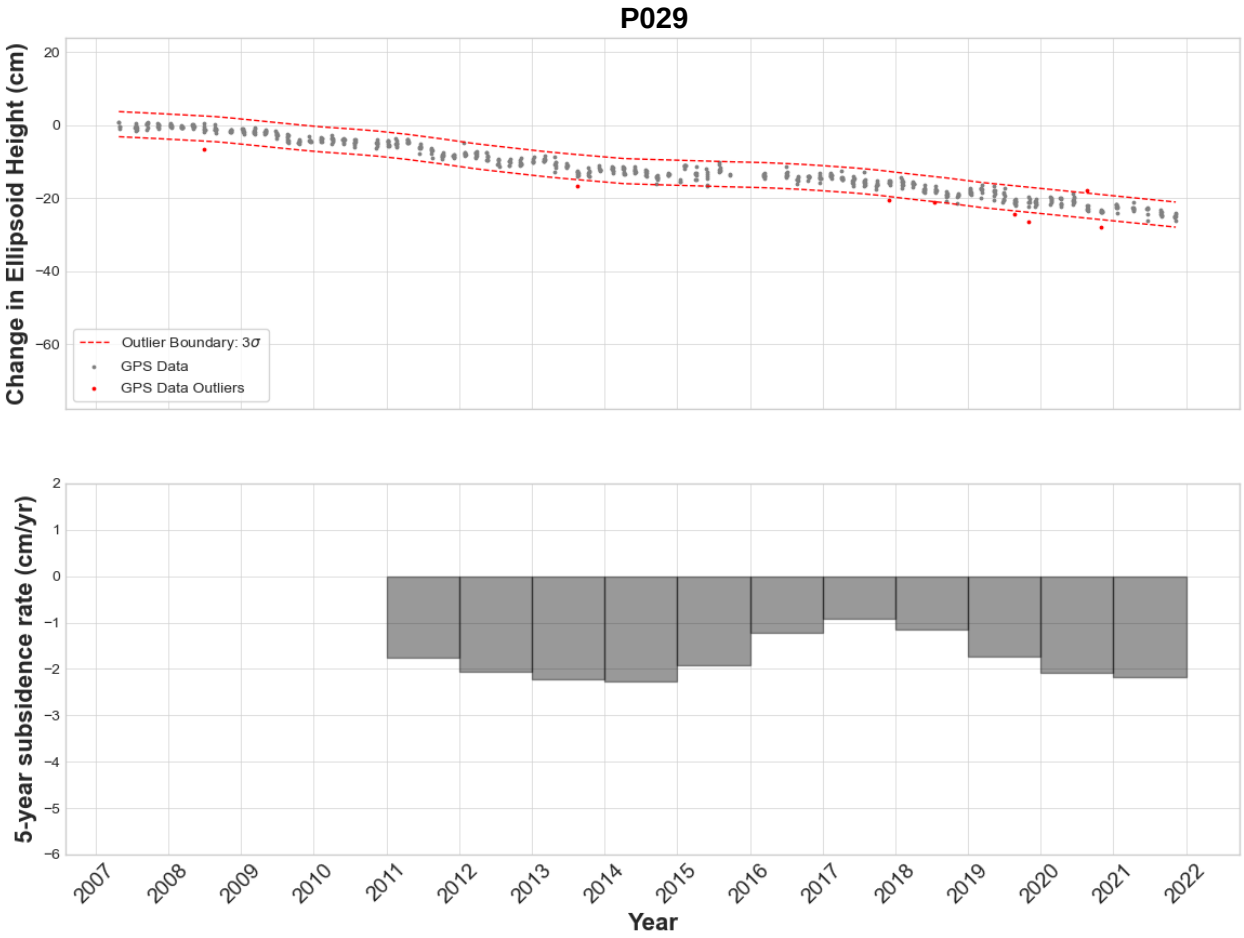

Figure 6: Period of record plot for P029 located in Katy, Texas, 2007 to 2021. This site measured 23.8 cm of subsidence over 14 years and the annual subsidence rate is 2.19 cm per year. Processed data (grey circles) located inside the outlier boundary (red dashed lines) are used when calculating subsidence rates. Processed GPS data identified as outliers (red circles) are excluded from subsidence rate calculations and are shown for informational purposes only.

The greatest total cumulative subsidence observed in Fort Bend County is 27.3 cm (10.7 inches) measured at GPS station P004, located in Sugar Land, over 27 years (**Figure 7**). P004 has an average subsidence rate estimated at 0.58 cm per year from 2017 through 2021.

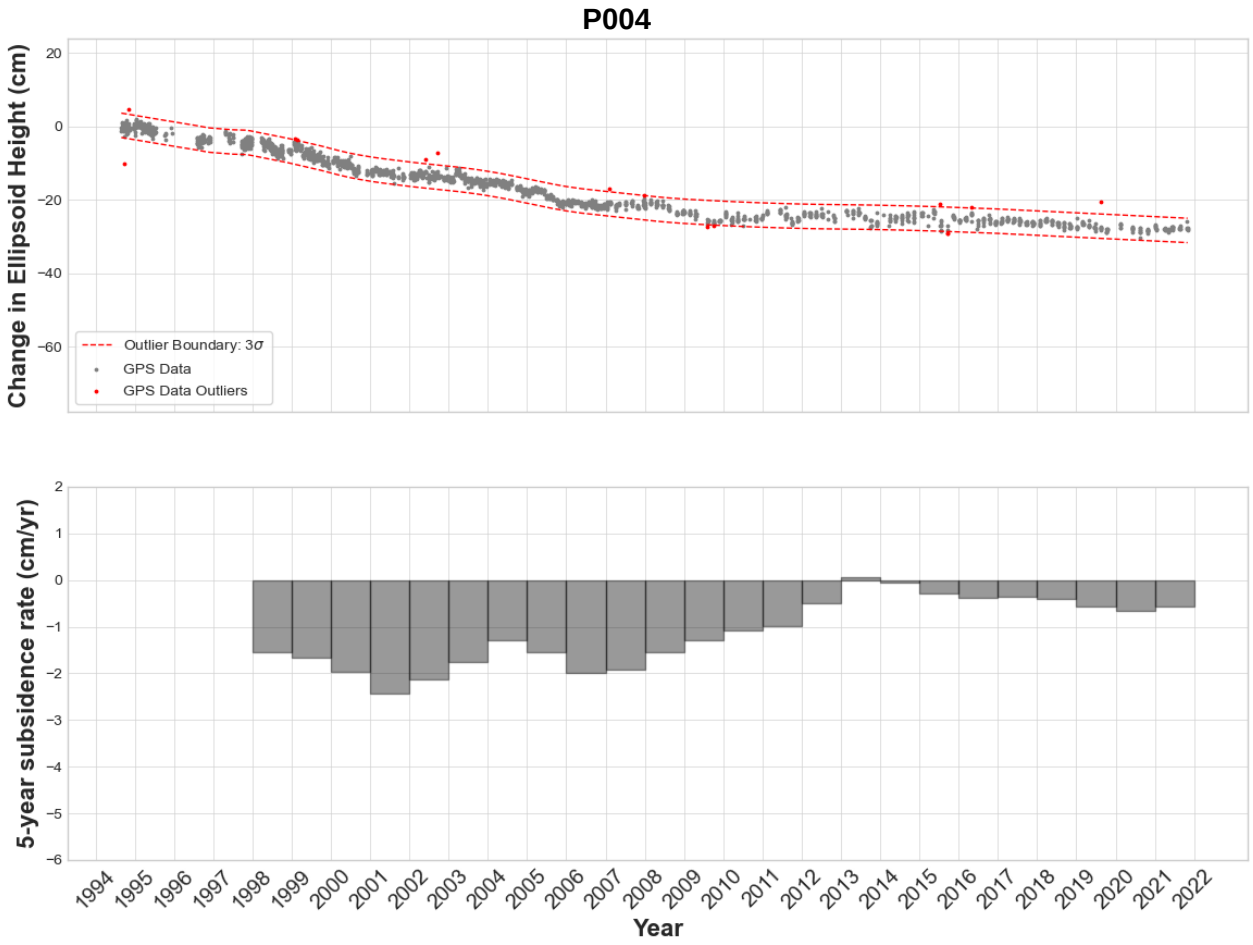

Figure 7: Period of record plot for P004 located in Sugar Land, Texas, 1994 to 2021. This site measured 27.3 cm of subsidence over 27 years and the annual subsidence rate is 0.58 cm per year. Processed data (grey circles) located inside the outlier boundary (red dashed lines) are used when calculating subsidence rates. Processed GPS data identified as outliers (red circles) are excluded from subsidence rate calculations and are shown for informational purposes only.

Regulatory Area B

Regulatory Area B has no groundwater withdrawal restrictions. GPS stations have been operating since 2007 within this area to measure subsidence. Regulatory Area B contains three (3) GPS stations, all of which have a subsidence rate less than half a centimeter per year. **Figure 8** displays the GPS stations in Regulatory Area B with labels identifying the name of each station.

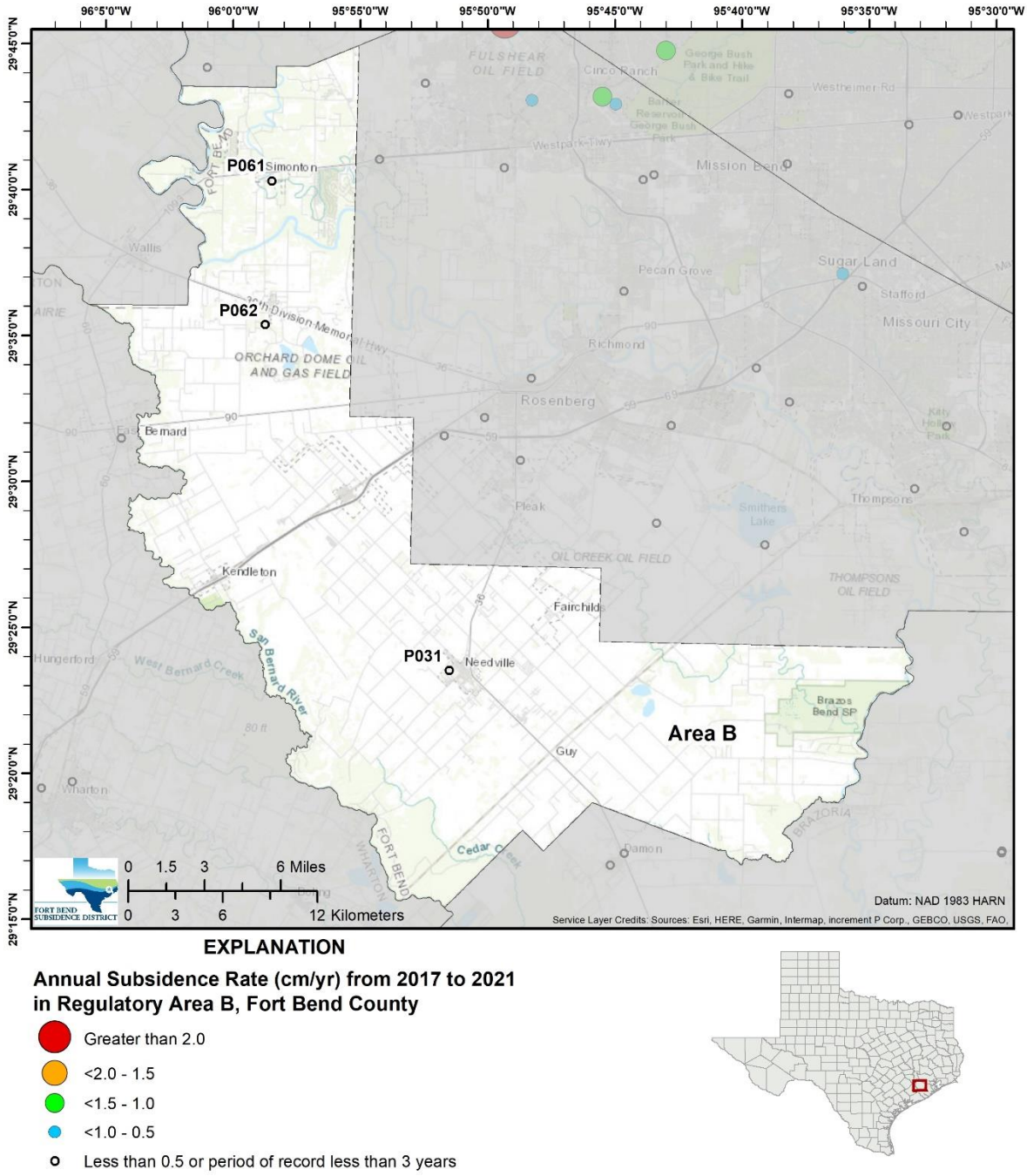

Figure 8: Annual subsidence rate in cm per year estimated from periodic and continuous GPS data measured from GPS stations with three or more years monitoring within Regulatory Area B in Fort Bend County, Texas, 2017-2021.

All three GPS stations in Regulatory Area B have remained relatively stable. GPS station P031, located in Needville within southern Fort Bend County, shows minor seasonal variations since monitoring began in 2007 and is generally stable (**Figure 9**). The annual subsidence rate for P031 is 0.31 cm per year.

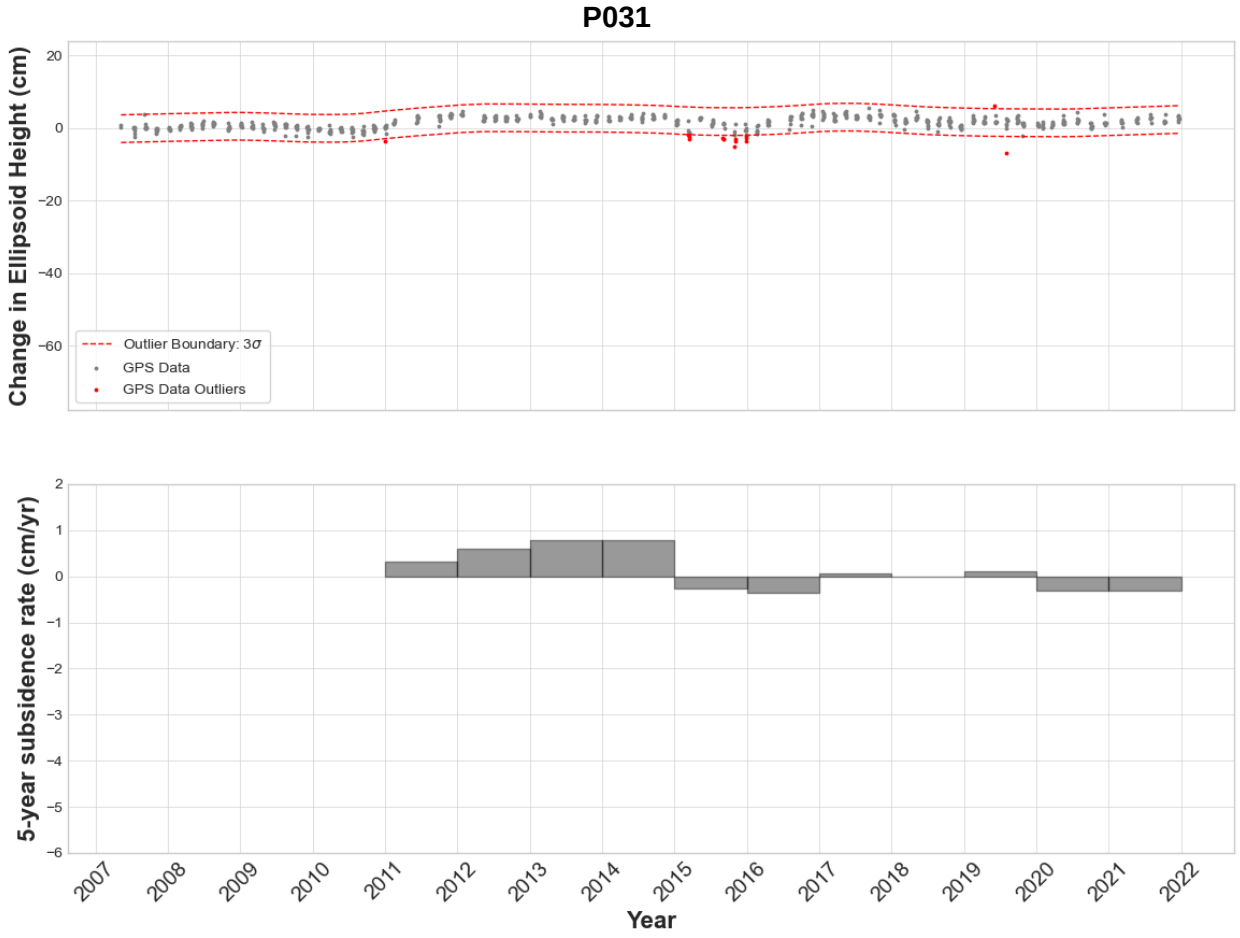

Figure 9: Period of record plot for P031 located in Needville, Texas, 2007 to 2021. This station measured 2.6 cm of uplift over 14 years and the annual subsidence rate is 0.31 cm per year. Processed data (grey circles) located inside the outlier boundary (red dashed lines) are used when calculating subsidence rates. Processed GPS data identified as outliers (red circles) are excluded from subsidence rate calculations and are shown for informational purposes only.

References

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