

## Appendix B – Subsidence Monitoring Data

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## Measurement Methodology

The GPS data collected by the District for use in measuring land-surface elevation include a three-component displacement time series involving the horizontal (East-West), vertical (North-South), and the ellipsoidal height (i.e., elevation above or below the reference ellipsoid) components. GPS data are processed and converted to the Stable Houston Reference Frame 2020 (Houston20). The subsidence rate of a GPS monitoring site is estimated using the linear regression of the most recent five-year GPS observation data (i.e., 2015-2019), at sites that have a minimum of three years of data.

The District collects GPS data at 215 sites across the region. Most of these sites collect data periodically, while a few stations collect data continuously. GPS data are collected at each of the GPS monitoring sites every thirty seconds during the duration of monitoring, which varies from periodic to continuous. The GPS monitoring sites are constructed in different ways based on the duration of monitoring and the operator. The District operates both periodic and continuous monitoring sites. Other operators, such as UH, operate continuous monitoring sites. The construction and design of each type of site are described below.

The periodic monitoring sites collect GPS data for approximately seven days every two months at the periodically measured sites (previously called port-a-measure sites or PAM sites). These sites are designed as a 2.5-in pipe drilled approximately 20 to 40 feet below ground surface with an 8 ft extension pipe above the ground. The extension pipe is mounted with an antenna. A separate pipe, which holds a box for a battery and receiver, is installed within a few feet from the antenna pipe. The antenna and receiver are kept at each PAM station for approximately one week every two months to collect GPS data.

The continuous monitoring sites collect GPS data every day of the year at the continuously operating reference stations (CORS). CORS are designed in two ways: 1) the same manner as the PAM previously described or 2) mounted on preexisting structures. The District operates six CORS (P024, P034, P049, P080, and P081) that are constructed in the same manner as the PAM sites previously described.

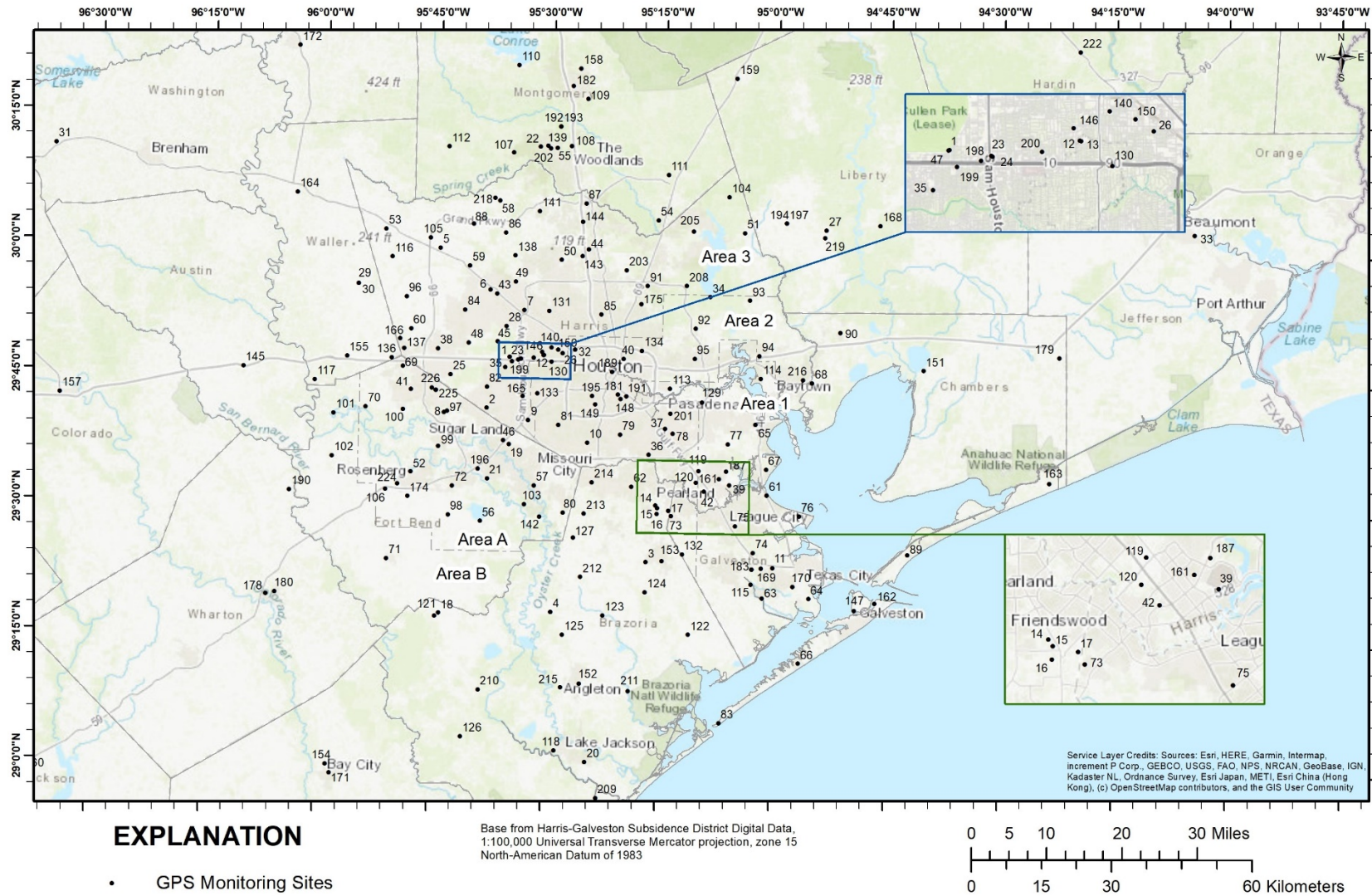
The preexisting structures include buildings and extensometers. GPS antennas are mounted to concrete buildings with deep foundations as well as good sky views in order to accurately measure land surface elevation change and limit interference. This CORS design is used by UH throughout the greater Houston area.

Within the Houston-Galveston area, 14 borehole extensometers, which are operated and maintained by the USGS, were constructed as wells drilled to various depths (650 to 3,300 feet below ground surface) and anchored in stable strata with a concrete plug in order to measure compaction within different aquifers (Kasmarek, et al., 2015). The outer casing is equipped with slip-joints to maintain well integrity by preventing damage from subsidence and the inner pipe is attached to a concrete plug at the bottom of the borehole. Such extensometers use analog recorders, which are connected to the inner pipe, to continuously measure the change between the inner pipe and the land surface elevation. The District operates five CORS (ADKS, LKHU, NETP, TXEX, and P096) installed on the extensometers.

## GPS Monitoring Network

The collaboration between the District, UH, FBSD, BCGCD, and LSGCD creates a GPS monitoring network in the Harris-Galveston area. **Figure 1** depicts the GPS monitoring network with a map identification number for each GPS monitoring site 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**.

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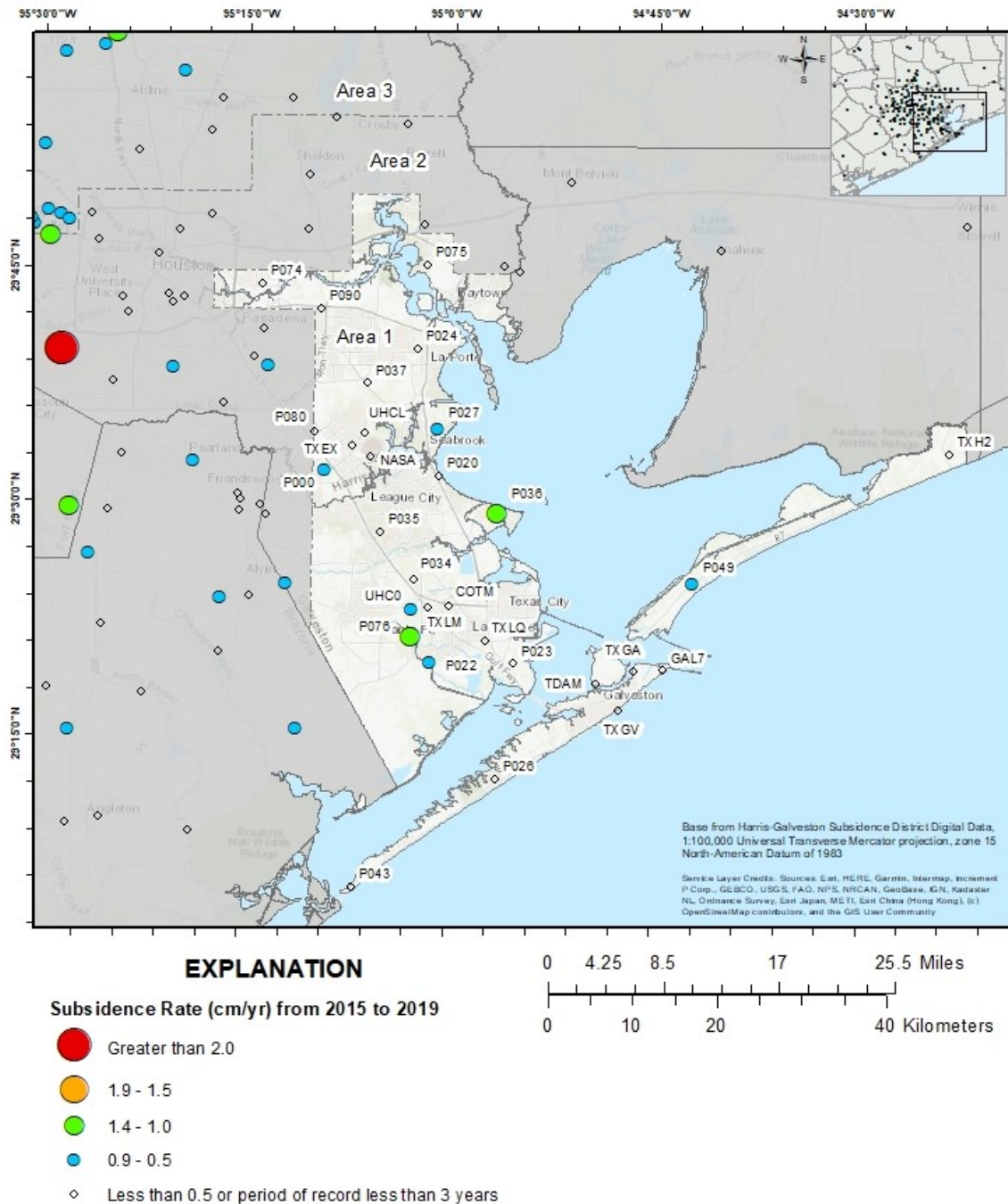


**Figure 1:** Location and map identification number of GPS monitoring sites that record periodic or continuous GPS data within Harris and surrounding Counties, Texas, 2015-2019. The map insets show the map identification number of the higher density areas with a smaller scale to provide greater detail.



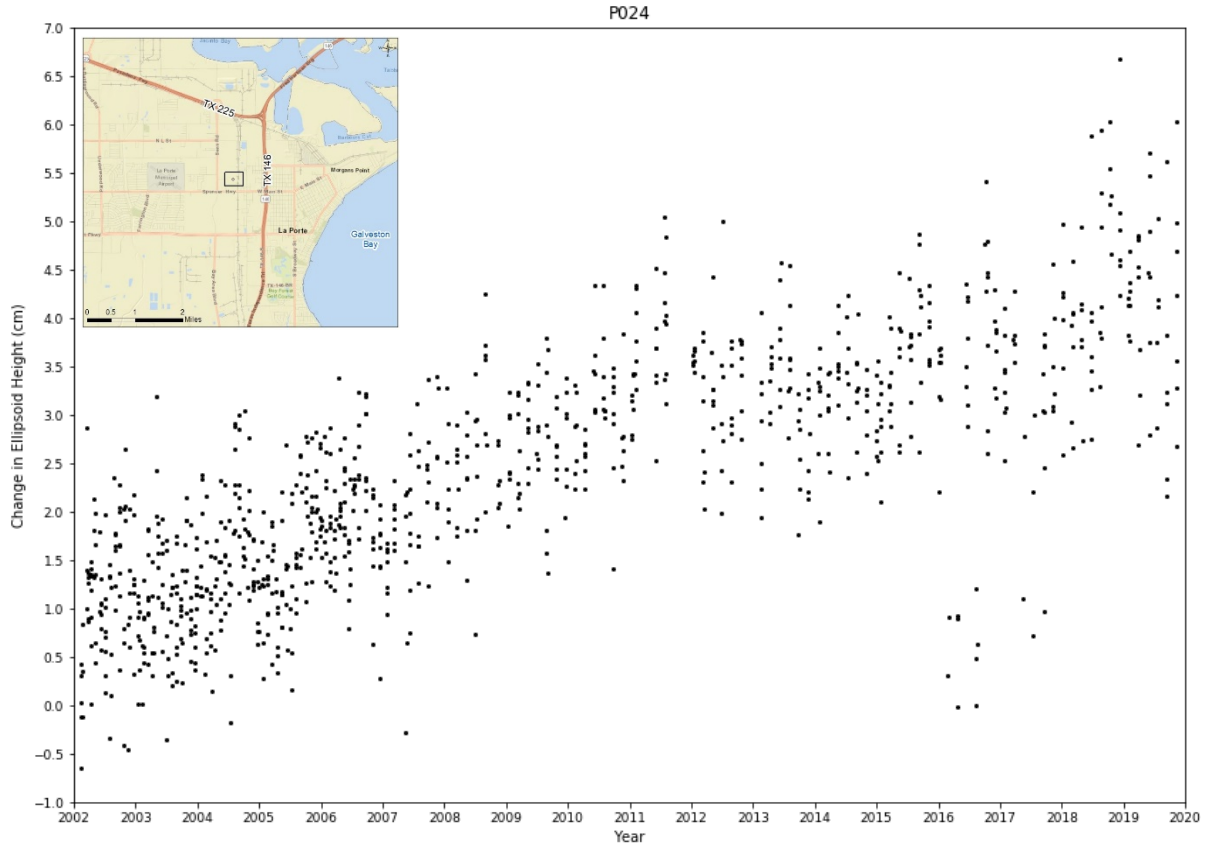
### Regulatory Area One

Regulatory Area One achieved full regulatory level conversion in the 1990s. GPS monitoring sites have been operating since 1996 within this area to measure subsidence. The annual subsidence rate averaged for the 32 GPS monitoring sites in Regulatory Area One is 0.23 cm per year. **Figure 3** displays the GPS monitoring sites in Regulatory Area One with labels identifying the name of each site.



**Figure 3:** Annual subsidence rate in cm per year estimated from periodic and continuous GPS data measured from GPS monitoring sites within Regulatory Area One in Harris and Galveston Counties, Texas, 2015-2019.

Approximately 78 percent of GPS monitoring sites in Regulatory Area One have experienced uplift or remained stable based upon the annual subsidence rate. GPS monitoring site P024, which is located in LaPorte, shows a rise in land surface elevation (**Figure 4**). P024 has measured approximately 3 cm of uplift since 2002.

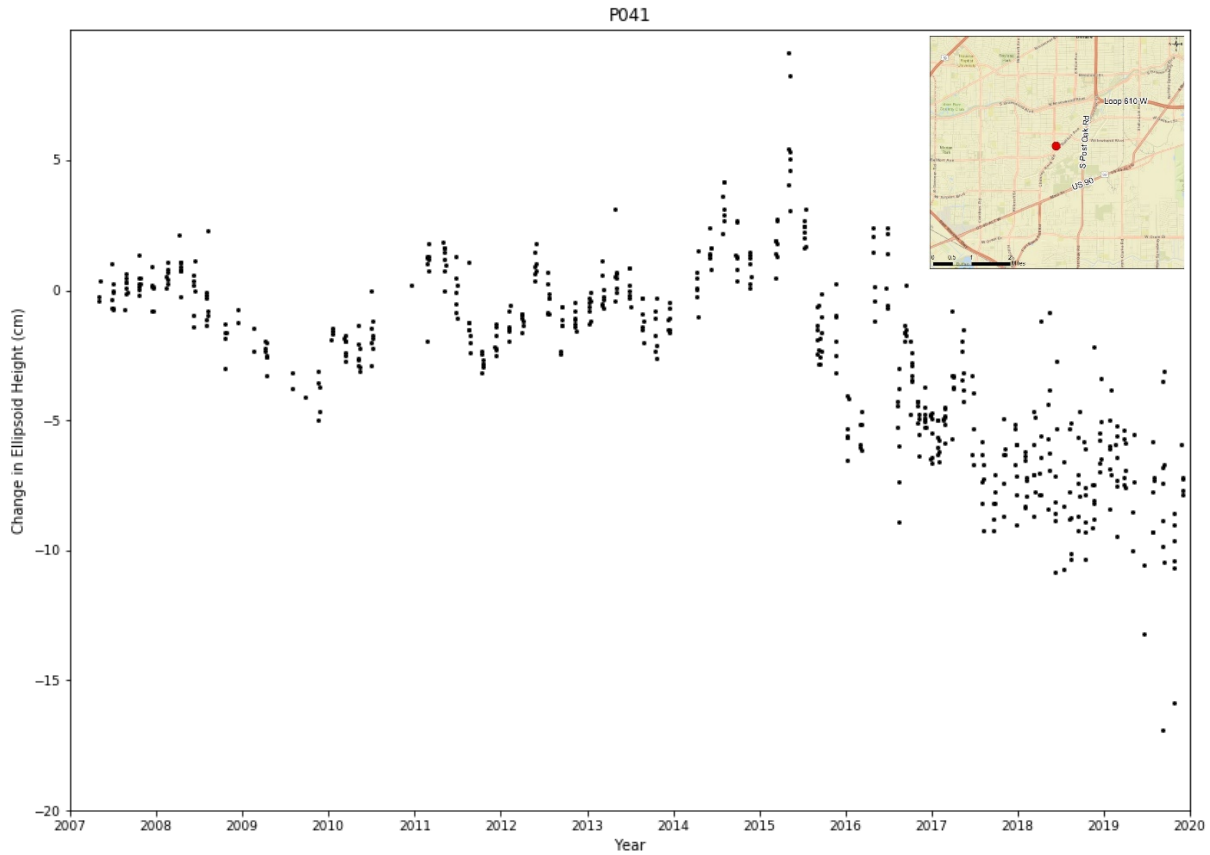


**Figure 4:** Period of record data for GPS monitoring site P024 located in LaPorte, Texas. Inset map shows the location of P024, which is the circle in the black box, southwest of the intersection between TX-225 and TX-146.





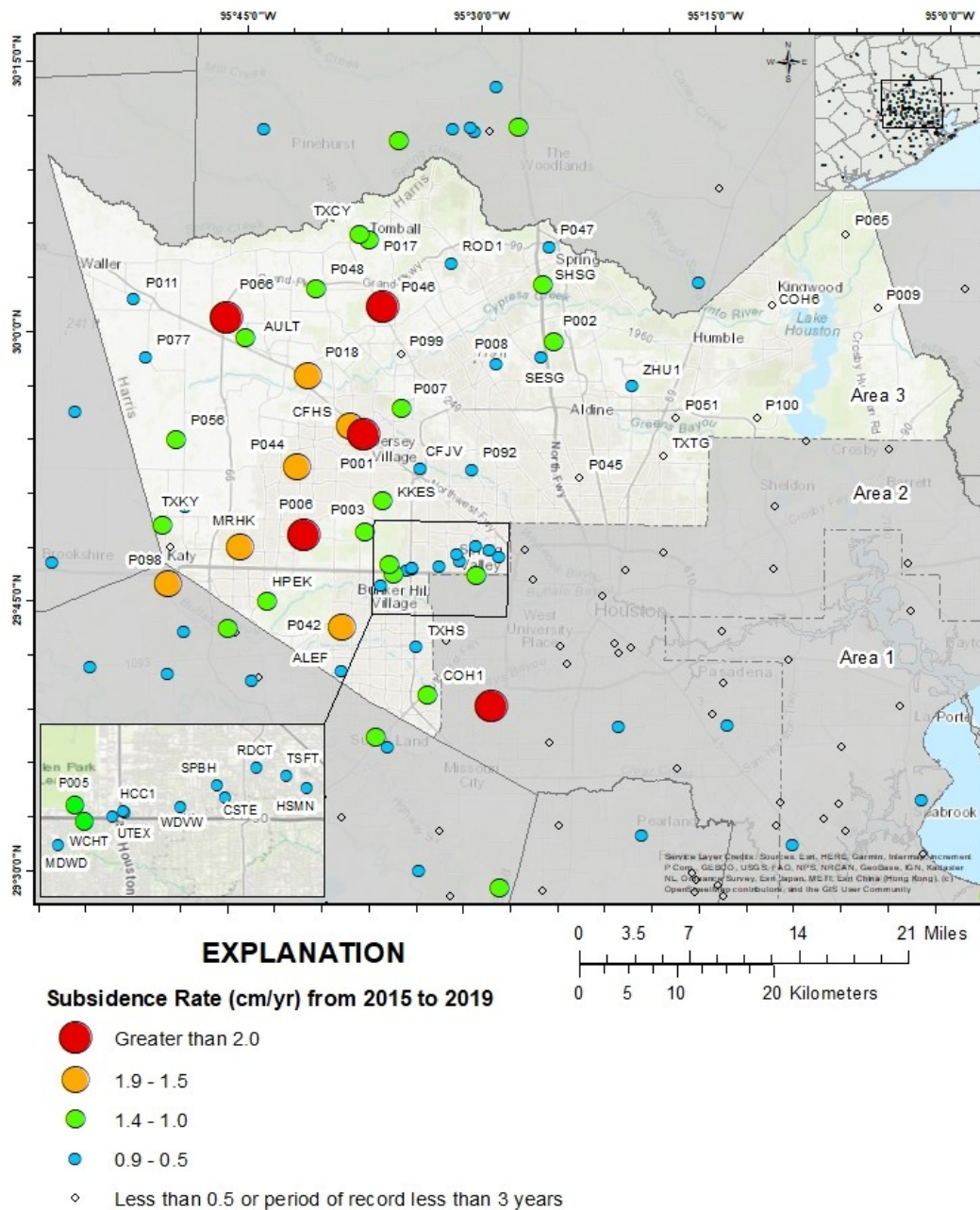
Approximately 82 percent of GPS monitoring sites in Regulatory Area Two have remained relatively stable or experienced minor uplift based upon the annual subsidence rate. GPS monitoring site P041 located in the Westbury neighborhood (Brays Oak district in Southwest Houston) shows a relatively stable rate from 2007 to 2015 then a decline beginning in 2016 (**Figure 6**). P041 has measured approximately 9 cm of subsidence since 2007 with an annual subsidence rate of 2.08 cm per year.



**Figure 6:** Period of record data for GPS monitoring site P041 located in the Westbury neighborhood (Brays Oak district in Southwest Houston) from 2007 to 2019. P041 measured 9.07 cm of subsidence since 2007 with an annual subsidence rate of 2.08 cm/yr.

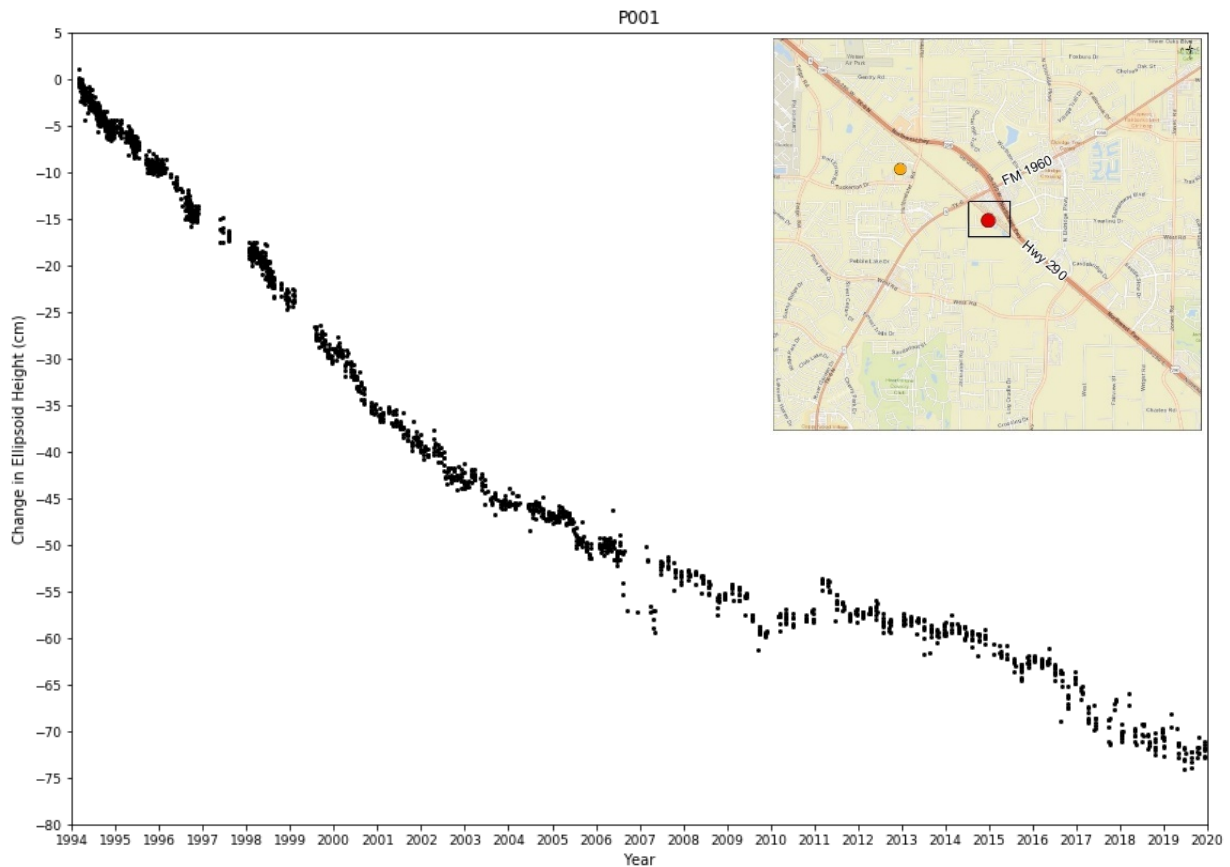
### Regulatory Area Three

Regulatory Area Three has not been fully converted; although some entities such as the City of Houston and Regional Water Authorities have been transitioning to alternative water sources since 2010. GPS monitoring sites have been operating since 1993 within this area to track subsidence. The annual subsidence rate averaged for the 57 GPS monitoring sites in Regulatory Area Three is 0.94 cm per year. **Figure 7** displays the GPS monitoring sites in Regulatory Area Three with labels identifying the name of each site.



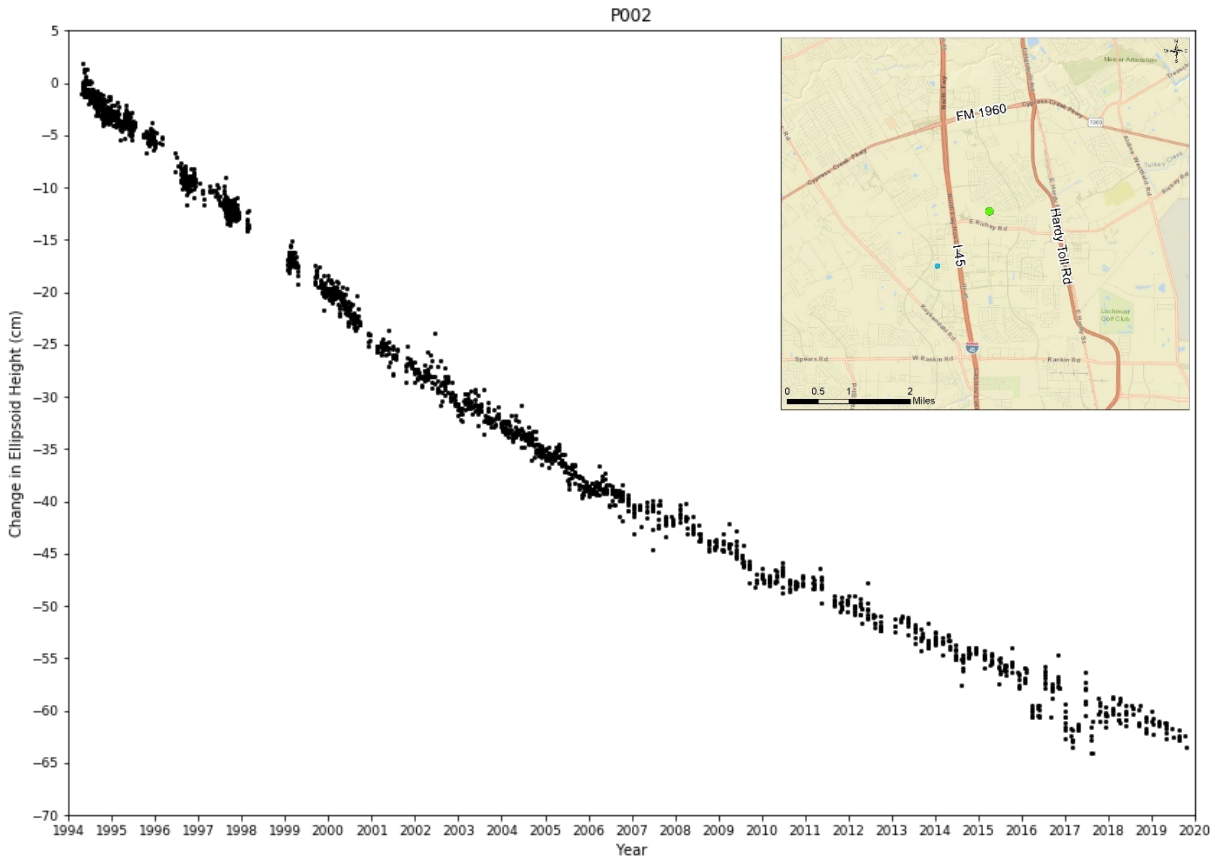
**Figure 7:** Annual subsidence rate in cm per year estimated from periodic and continuous GPS data measured from GPS monitoring sites within Regulatory Area Three in Harris and Galveston Counties, Texas, 2015-2019.

Approximately 79 percent of GPS monitoring sites in Regulatory Area Three have measured subsidence greater than 0.5 cm per year. GPS monitoring site P001, which is located in Jersey Village, has measured the highest subsidence rate at 2.54 cm per year in Regulatory Area Three. Since monitoring began in 1994, P001 has recorded 71.8 cm of subsidence over the 25 years in operation. As displayed in **Figure 8**, the GPS data for P001 show a generally consistent, declining trend.



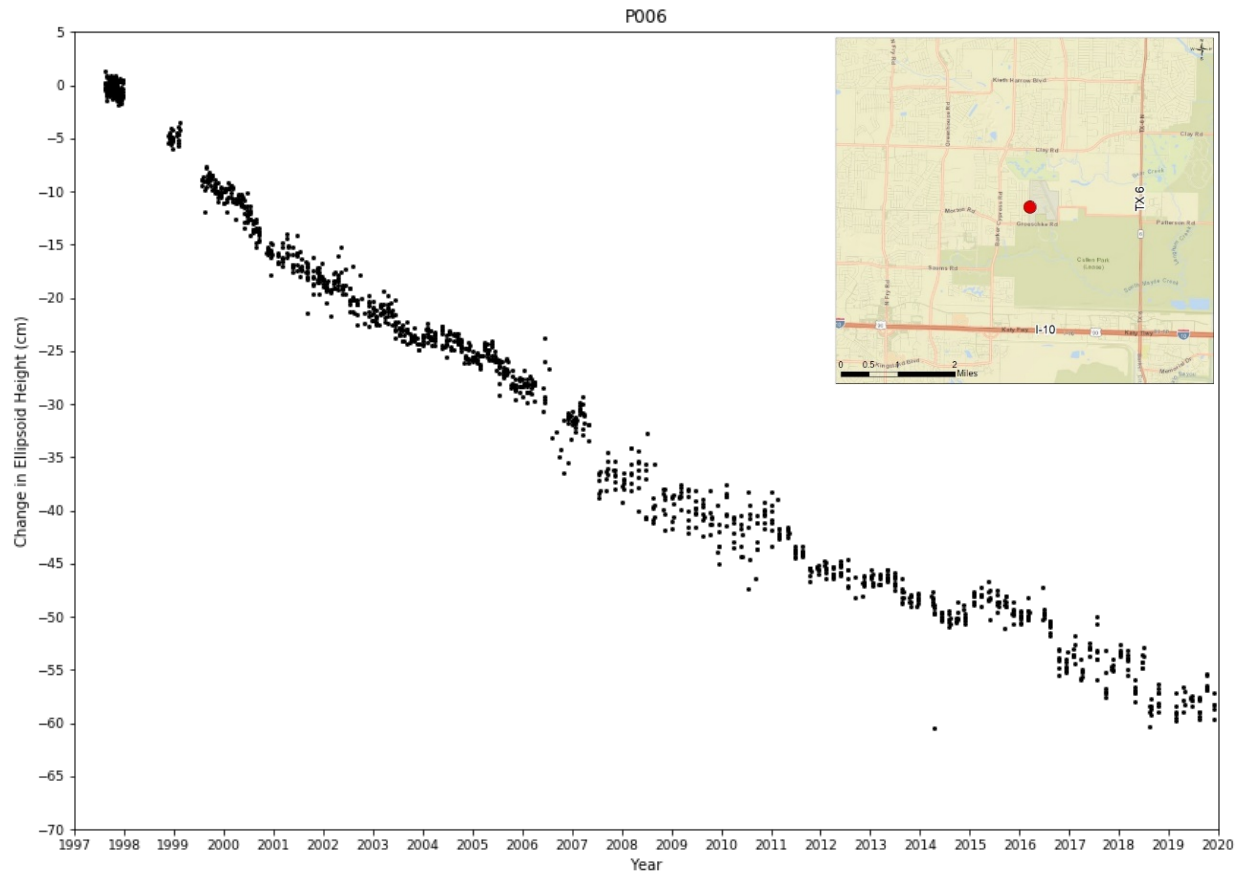
**Figure 8:** Period of record plot for GPS monitoring site P001 located in Jersey Village, Texas, 1994-2019. This site measured 71.8 cm of subsidence over 25 years and the annual subsidence rate is 2.54 cm per year. The inset map shows the location of P001, southwest of the intersection between FM-1960 and Hwy 290.

Another site that has been in operation since 1994 is P002 located in Spring. P002 has measured 62.29 cm of subsidence over 25 years and has a subsidence rate of 1.28 cm per year. **Figure 9** contains the period of record plot for P002 and similarly shows a declining trend.



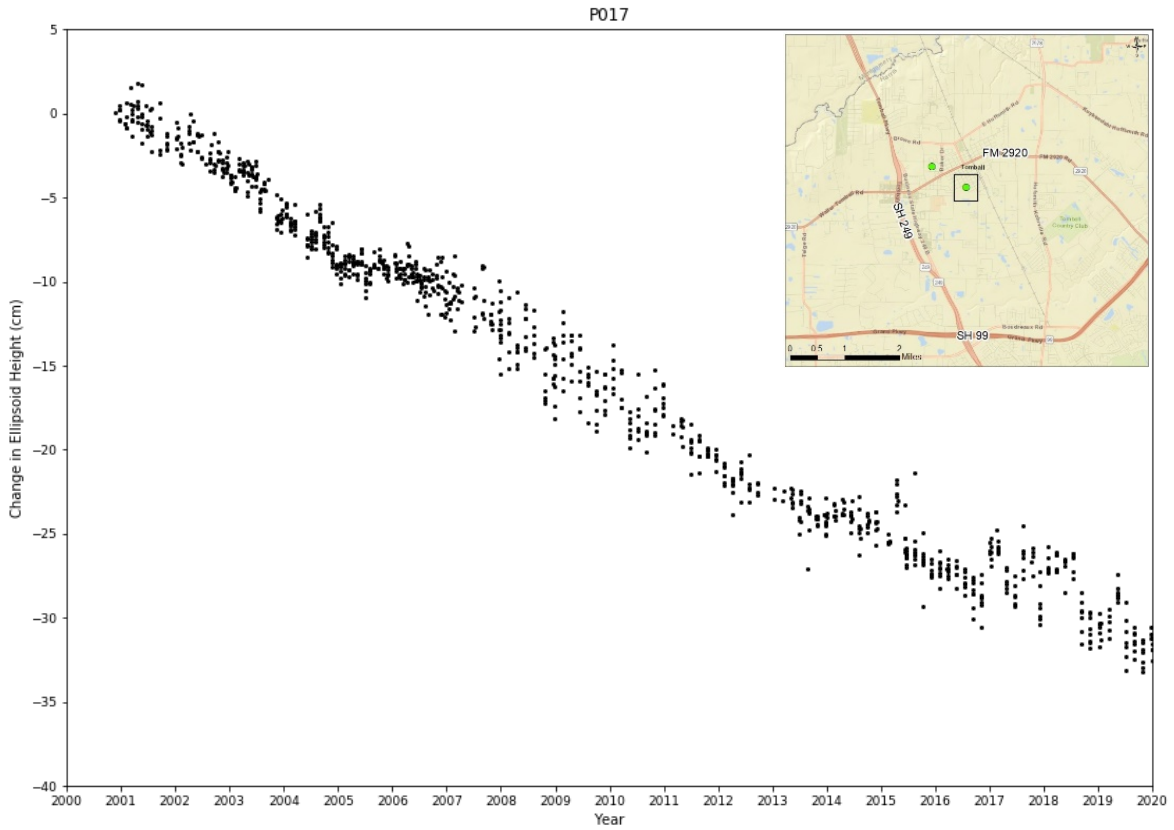
**Figure 9:** Period of record plot for GPS monitoring site P002 located in Spring, Texas, 1994-2019. This site measured 62.29 cm of subsidence over 25 years and the annual subsidence rate is 1.28 cm per year. The inset map shows the location of P002, the green circle southeast of the intersection between FM 1960 and I-45.

GPS monitoring site P006 located in the West Houston Airport, northwest of the intersection between I-10 and TX-6, also recorded high subsidence rate of 2.34 cm per year and a total of 57.3 cm of subsidence over 22 years. **Figure 10** includes the period of record data for P006 and shows a declining trend since monitoring began in 1997.

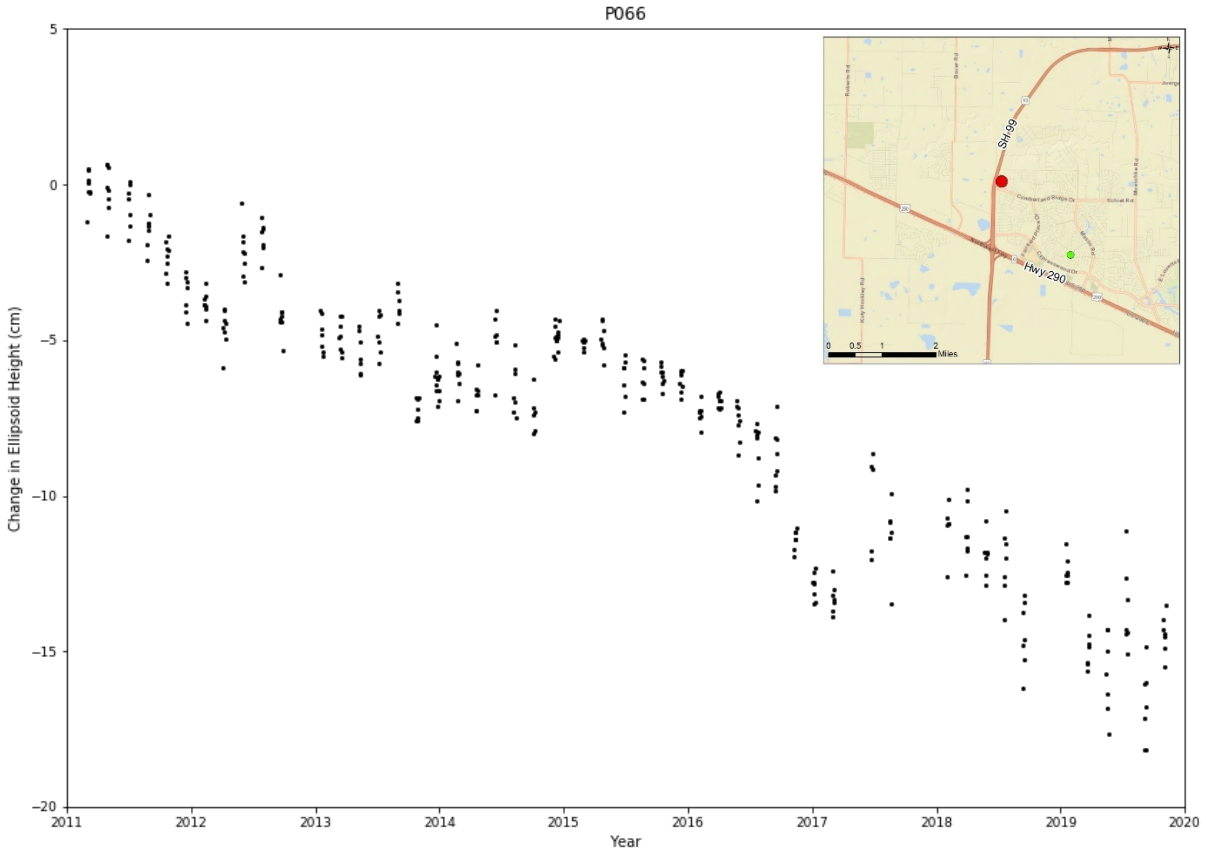


**Figure 10:** Period of record plot for GPS monitoring site P006 located in Houston, Texas, 1997-2019. This site measured 57.31 cm of subsidence over 22 years and the annual subsidence rate is 2.34 cm per year. The inset map shows the location of P006, the red circle northwest of the intersection between I-10 and TX-6.

GPS monitoring sites P017 and P066 are located in areas of expanding residential communities in Tomball and Cypress, respectively. Since 2000, P017 has shown a consistent decline in land surface elevation with a total of 31.34 cm of subsidence over 19 years (**Figure 11**). Similarly, GPS data for P066 show a constant decline since 2011 with 15.1 cm of subsidence over 8 years (**Figure 12**).



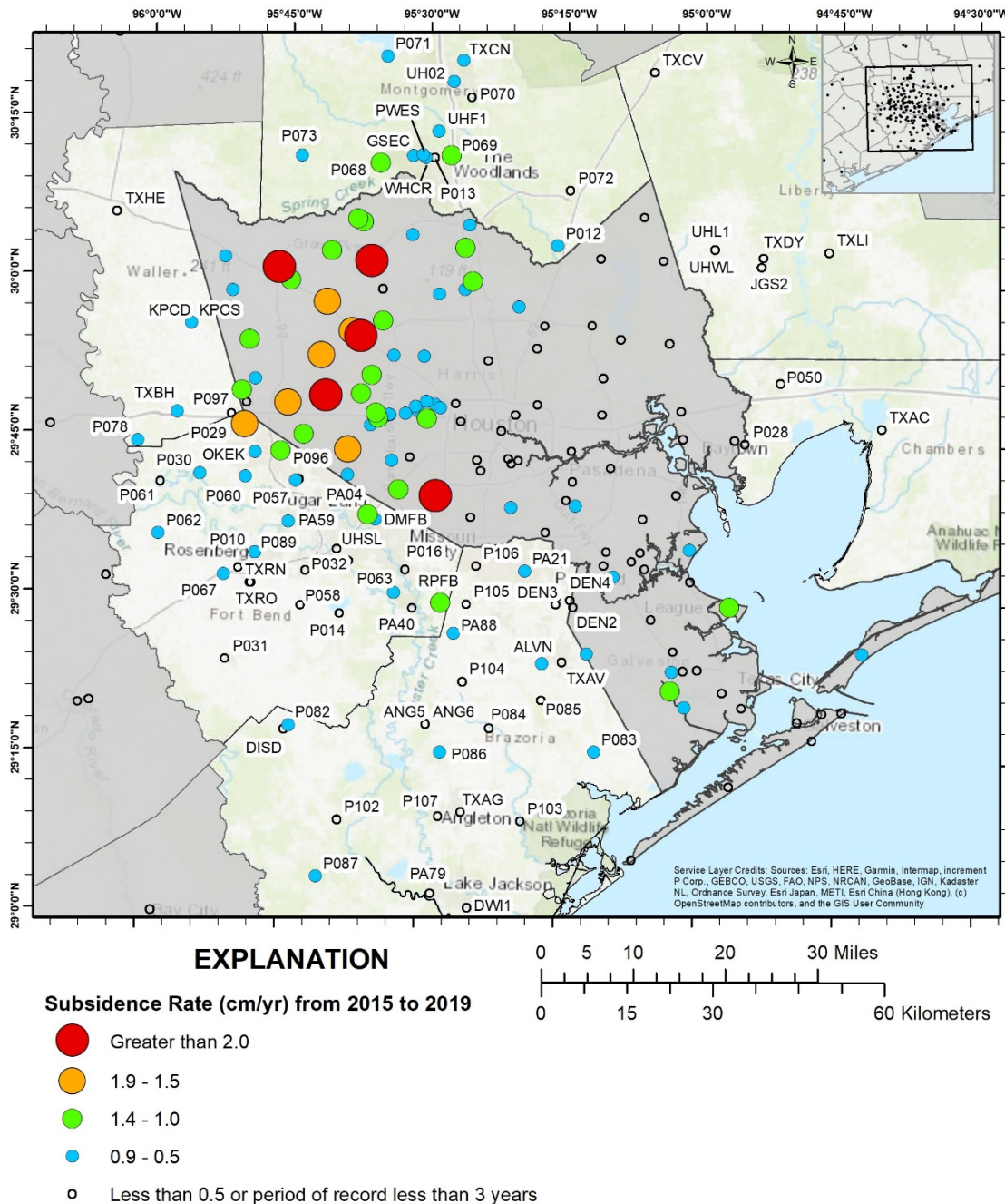
**Figure 11:** Period of record plot for GPS monitoring site P017 located in Tomball, Texas, 2000–2019. This site measured 31.34 cm of subsidence over 19 years and the annual subsidence rate is 1.14 cm per year. The inset map shows the location of P017, the green circle in the black box northeast of the intersection between SH-249 and FM-2920.



**Figure 12:** Period of record plot for GPS monitoring site P066 located in Cypress, Texas, 2011-2019. P066 measured 15.1 cm of subsidence over 8 years and the annual subsidence rate is 2.22 cm per year. The inset map shows the location of P066, the red circle northeast of the intersection between SH-99 and Hwy 290.

### Surrounding Counties

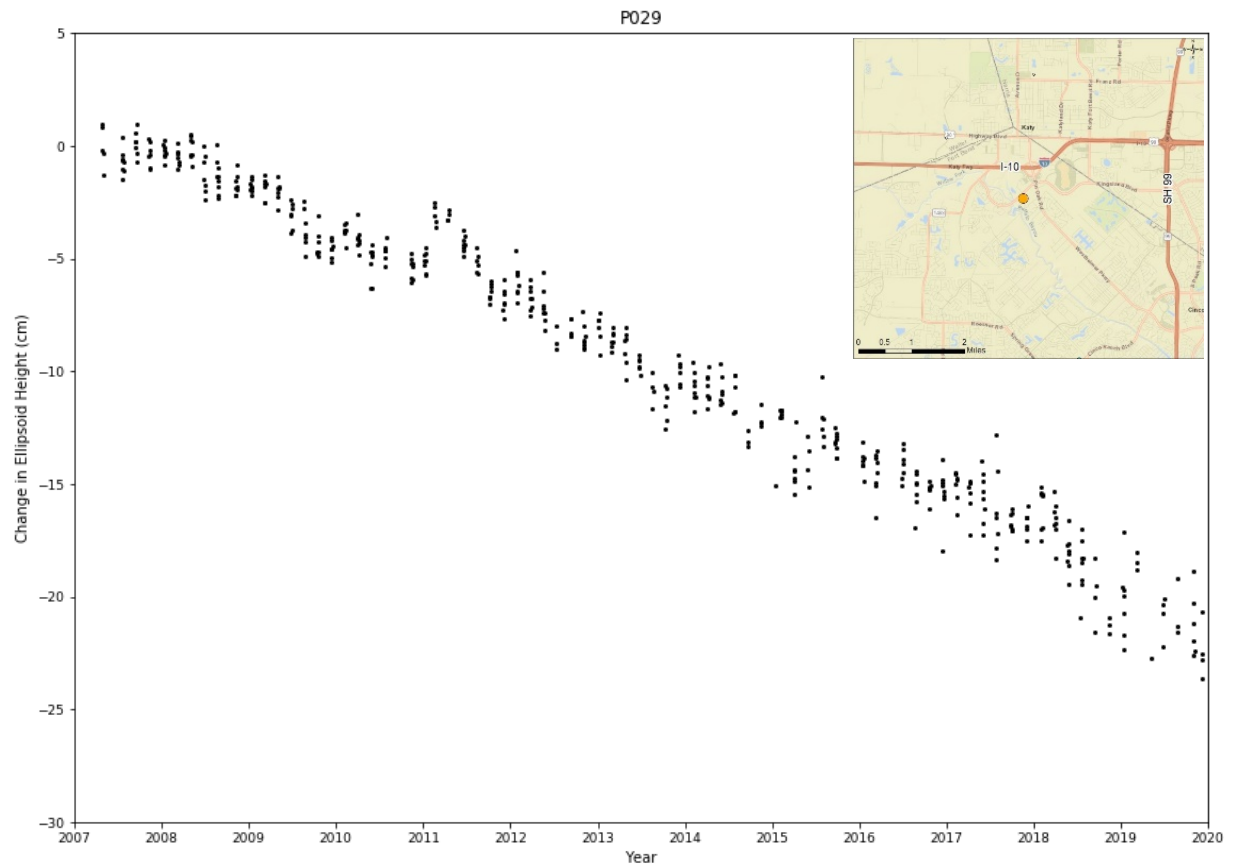
Counties that surround the District include Brazoria, Fort Bend, Waller, Montgomery, Liberty, and Chambers. The majority of GPS monitoring sites in these counties are operated by other subsidence and groundwater conservation districts and their GPS data are included in the GPS network. **Figure 13** displays the GPS monitoring sites located in the surrounding counties.



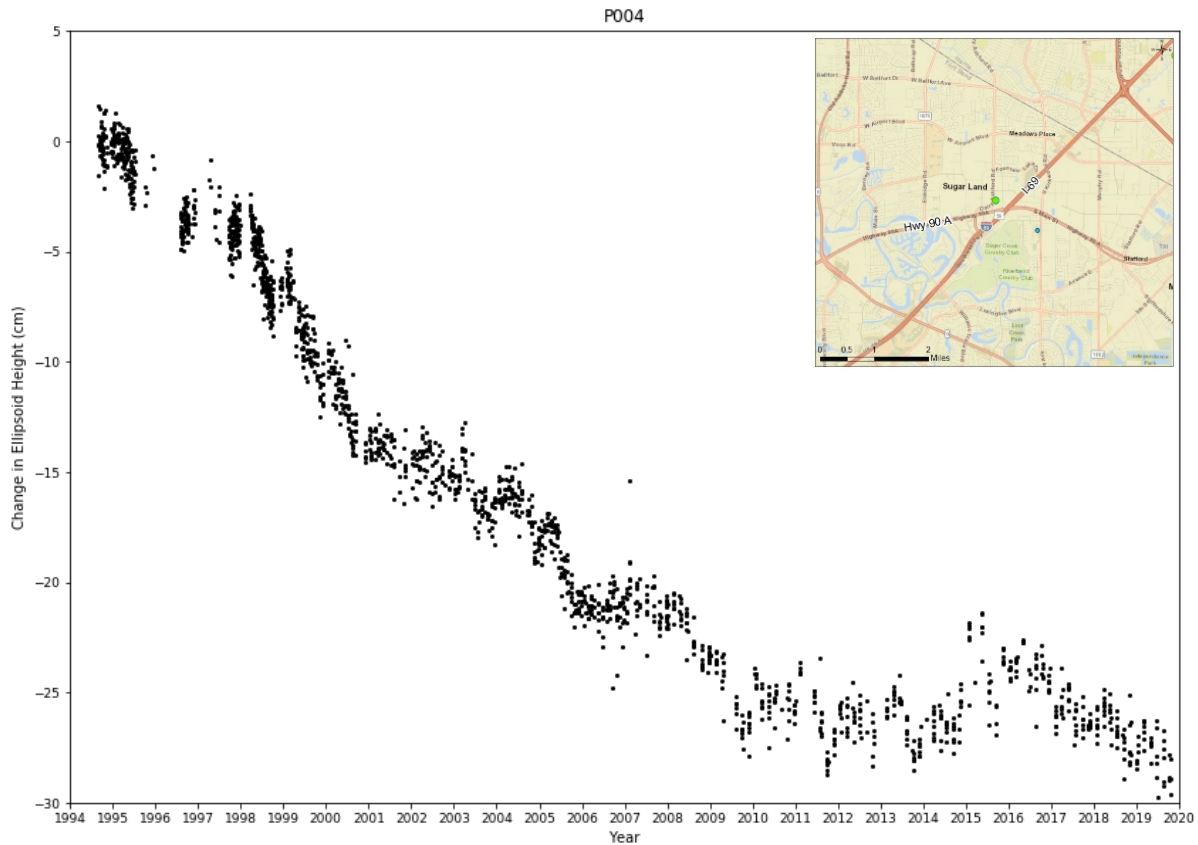
**Figure 13:** Annual subsidence rate in cm per year estimated from periodic and continuous GPS data measured from GPS monitoring sites within Brazoria, Fort Bend, Waller, Montgomery, Liberty, and Chambers Counties, Texas, 2015-2019.



Fort Bend County contains 31 GPS monitoring sites operated by Fort Bend Subsidence District and UH. The average of the annual subsidence rate for 31 sites in Fort Bend County is 0.51 cm per year and approximately 48 percent of these sites have measured subsidence greater than 0.5 cm per year. GPS monitoring site P029, located in Katy, has the highest subsidence rate at 1.95 cm per year in Fort Bend County. Since monitoring began in 2007, P029 has measured 21.52 cm of subsidence (**Figure 14**). Another site with a high subsidence rate (1.24 cm per year) is P004, located in Sugar Land. GPS monitoring site P004 has recorded 28.41 cm of subsidence over 25 years (**Figure 15**).

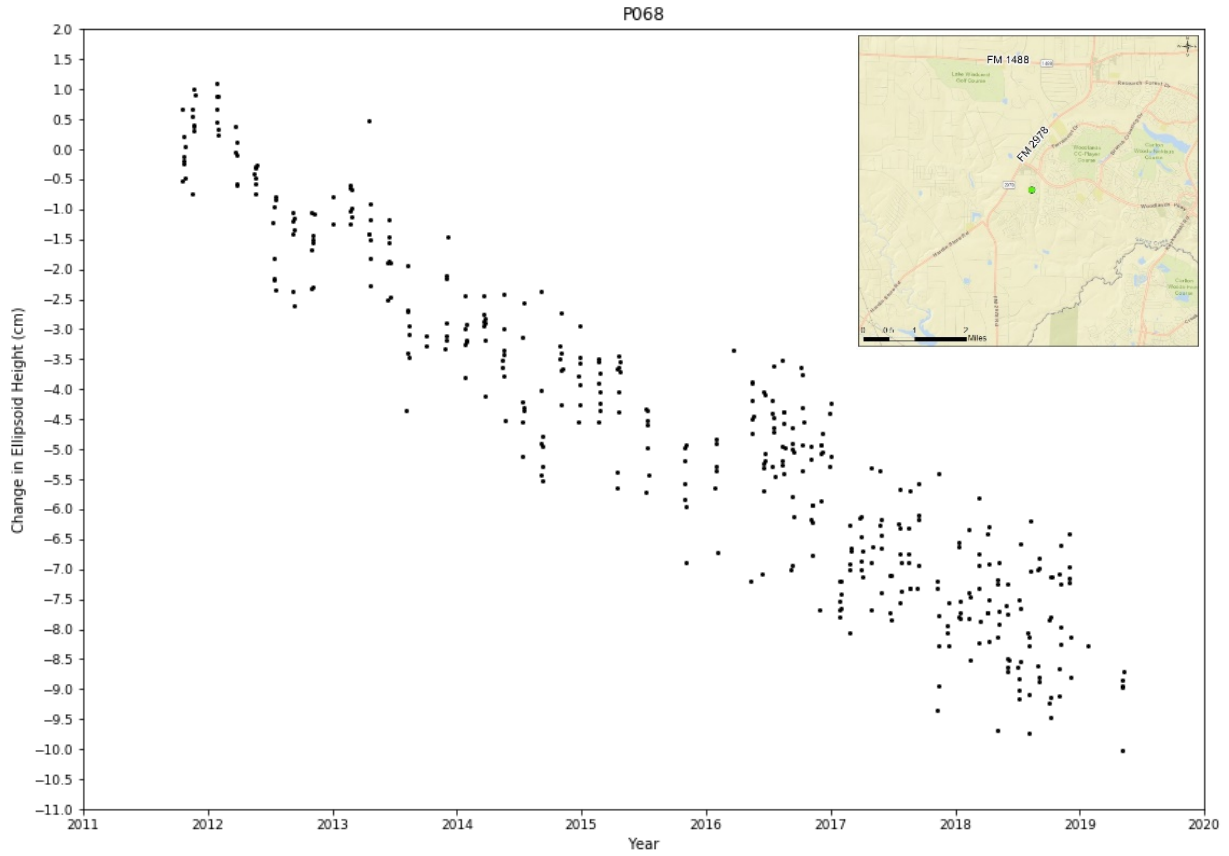


**Figure 14:** Period of record plot for P029 located in Katy, Texas, 2007 to 2019. This site measured 21.52 cm of subsidence over 12 years and the annual subsidence rate is 1.95 cm per year. The inset map shows the location of P029, the orange circle southwest of the intersection between I-10 and SH-99.



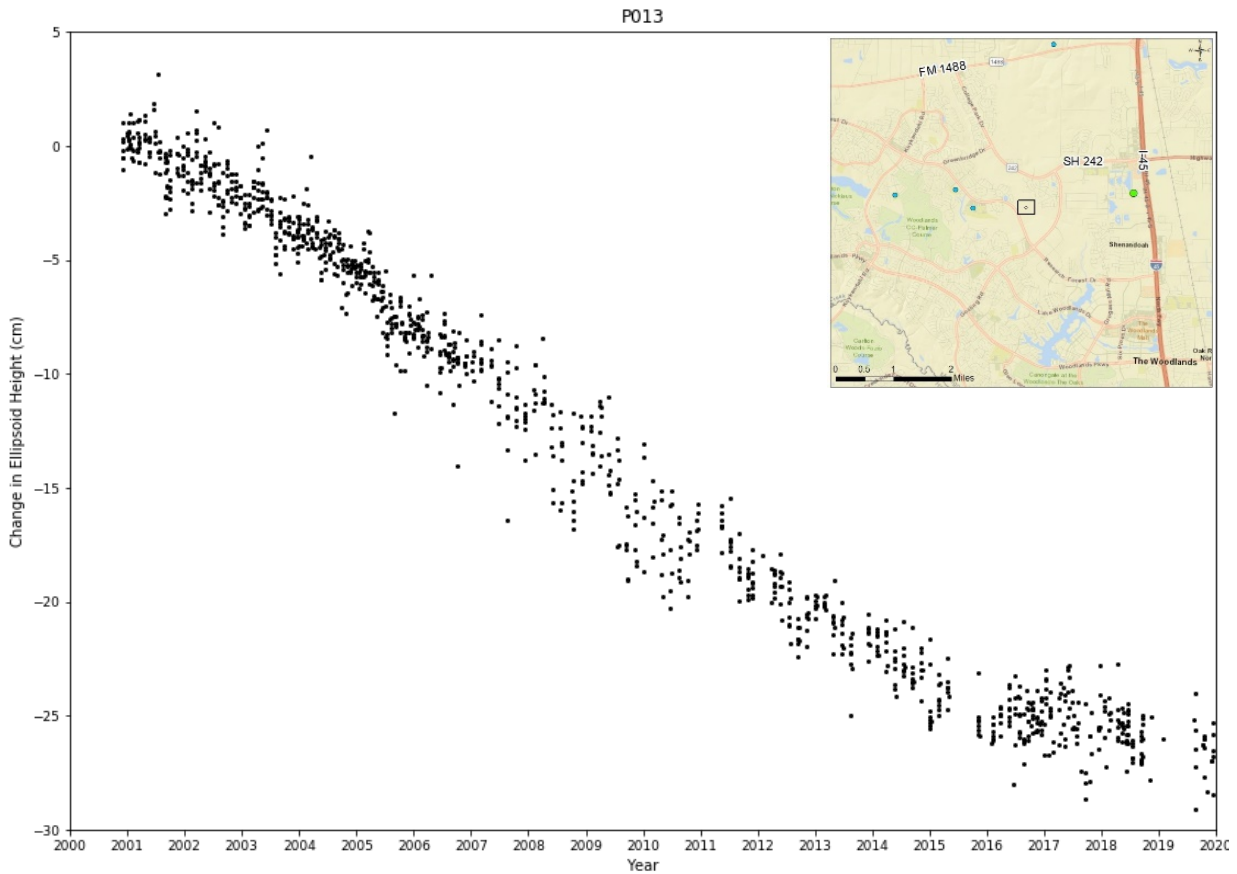
**Figure 15:** Period of record plot for P004 located in Sugar Land, Texas, 1994 to 2019. This site measured 28.41 cm of subsidence over 12 years and the annual subsidence rate is 1.24 cm per year. The inset map shows the location of P004, the green circle northwest of the intersection between I-69 and Highway 90A.

Montgomery County contains 15 GPS monitoring sites operated by Lone Star Groundwater Conservation District and UH. The average of the annual subsidence rate for 15 sites in Montgomery County is 0.59 cm per year and roughly 73 percent of these sites have experienced subsidence greater than 0.5 cm per year. GPS monitoring site P068, located in The Woodlands, has the highest subsidence rate at 1.13 cm per year in Montgomery County. Since monitoring began in 2011, P068 has measured 8.21 cm of subsidence (**Figure 16**).



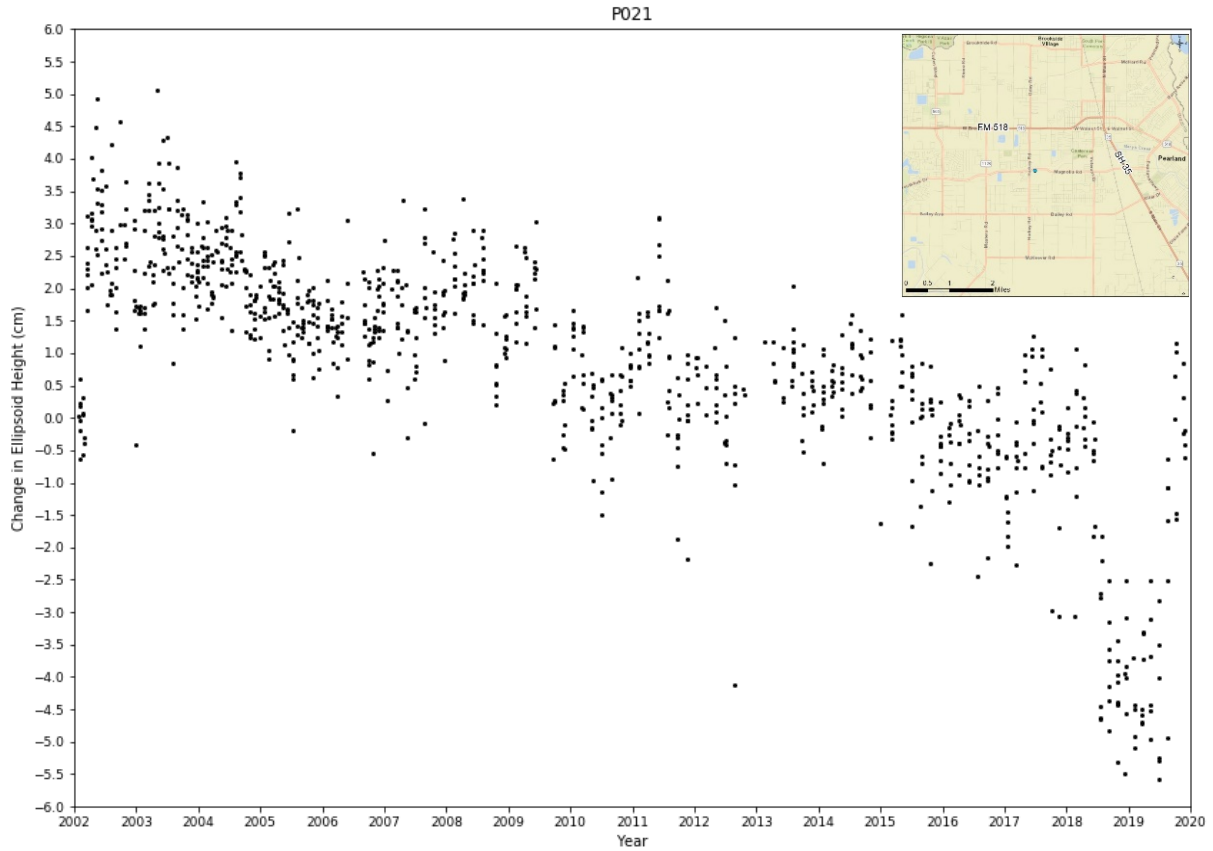
**Figure 16:** Period of record plot for P068 located in The Woodlands, Texas, 2011-2019. This site measured 8.21 cm of subsidence over 8 years and the annual subsidence rate is 1.13 cm per year. The inset map shows the location of P068, the green circle southeast of the intersection between Woodlands Parkway and FM 2978.

Another site in The Woodlands that has the greatest subsidence (26.77 cm over 19 years) in Montgomery County is P013. GPS monitoring site P013 showed a change in the rate in 2015 from a decline to relatively flat trend (**Figure 17**). Alternative water supply began in 2015 in this area of The Woodlands and as such the subsidence trend has remained flat from 2015 to 2019.

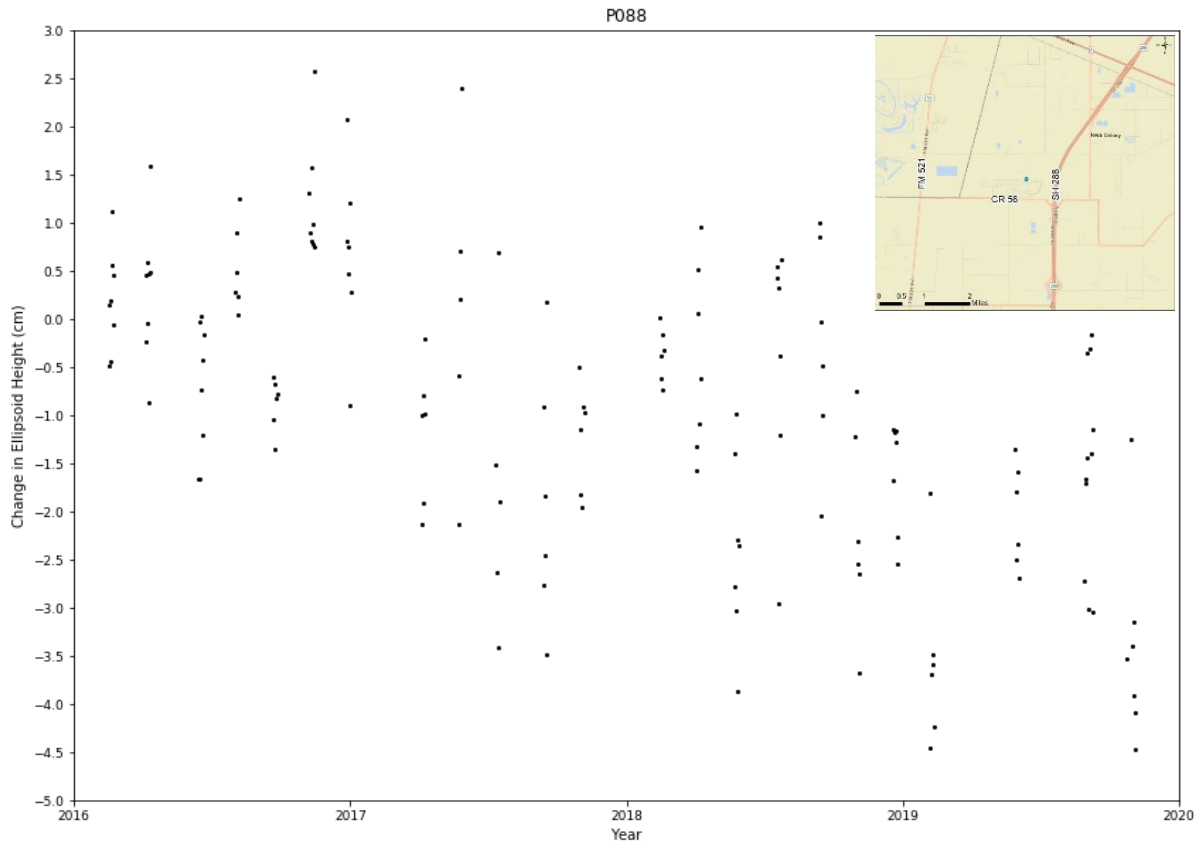


**Figure 17:** Period of record plot for P013 located in The Woodlands, Texas, 2000-2019. This site measured 26.77 cm of subsidence over 19 years and the annual subsidence rate is 0.41 cm per year. The inset map shows the location of P013, the circle in the black box southwest of the intersection between SH-242 and I-45.

Brazoria County contains 27 GPS monitoring sites operated by Brazoria County Groundwater Conservation District, UH, and the District. The majority of GPS monitoring sites in Brazoria County are relatively young (i.e., less than 5 years in operation). The average of the annual subsidence rate for 27 sites in Brazoria County is 0.23 cm per year. Approximately 74 percent of these sites have remained relatively stable with an annual subsidence rate under 0.5 cm per year. GPS monitoring site P021, located in Pearland, has the highest subsidence rate at 0.84 cm per year in Brazoria County. Since monitoring began in 2002, P021 has measured 2.44 cm of subsidence, which is very low over 18 years (**Figure 18**). Another site in Brazoria County that has higher subsidence rate (0.74 cm per year) is P088. GPS monitoring site P088 has measured 2.68 cm of subsidence since 2016 and shows a relatively constant trend (**Figure 19**).



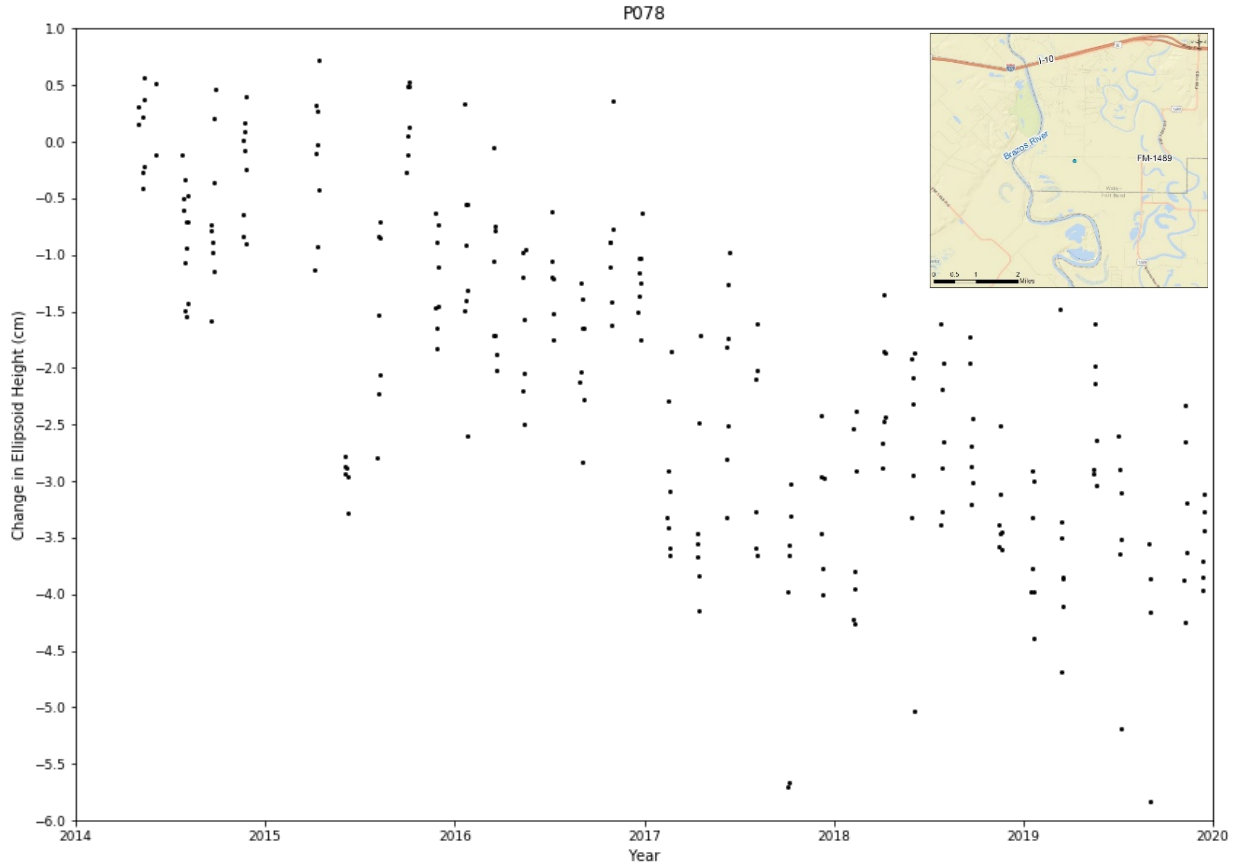
**Figure 18:** Period of record plot for P021, located in Pearland, Texas 2002-2019. This site measured 2.44 cm of subsidence over 18 years and the annual subsidence rate is 0.84 cm per year. The inset map shows the location of P021, the blue circle southwest of the intersection between SH-35 and FM-518.



**Figure 19:** Period of record plot for P088 located in Rosharon, Texas, 2016-2019. P088 measured 2.68 cm of subsidence over 4 years and the annual subsidence rate is 0.74 cm per year. The inset map shows the location of P088, the blue circle northwest of the intersection between CR-56 and SH-288.

Other surrounding counties, which include Waller, Liberty and Chambers, show very little subsidence, with observed rates of less than 0.5 cm per year. Waller and Liberty counties each contain six GPS monitoring sites operated by UH, TxDOT, and the District. In Waller County, the average of the annual subsidence rate for all six sites is 0.39 cm per year and roughly 50 percent of these sites have measured subsidence rates under 0.5 cm per year. The average of the annual subsidence rate for all six sites in Liberty County is 0.07 cm per year. Chambers County has four GPS monitoring sites operated by the District and TxDOT. The average of the annual subsidence rate for Chambers County GPS monitoring sites is very low at 0.002 cm per year. In Liberty and Chambers counties, 100 percent of the GPS monitoring sites have experienced very little subsidence with rates below 0.5 cm per year.

GPS monitoring site P078, located in Brookshire, has measured the highest subsidence rate at 0.6 cm per year in Waller County. Monitoring at P078 began in 2014 and has shown 3.51 cm of subsidence over six years (**Figure 20**).



**Figure 20:** Period of record data for P078, located in Brookshire, Texas 2014-2019. This site measured 3.51 cm of subsidence over 6 years and the annual subsidence rate is 0.60 cm per year. The inset map shows the location of P078, the blue circle southwest of the intersection between SH-35 and FM-518 and east of the Brazos River.