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## Appendix B – Subsidence Monitoring Data

## Table of Contents

Appendix B – Subsidence Monitoring Data .....	i
Measurement Methodology.....	4
GPS Monitoring Network.....	5
Regulatory Area A.....	8
Regulatory Area B .....	11
Other Counties.....	14

## List of Figures

<b>Figure 1:</b> Location and map identification number of GPS monitoring sites that record periodic or continuous GPS data within Fort Bend 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. ....	6
<b>Figure 2:</b> Location of GPS monitoring sites designated by operator in Fort Bend and surrounding Counties, Texas, 2019. ....	7
<b>Figure 3:</b> Annual subsidence rate in cm per year estimated from periodic and continuous GPS data measured from GPS monitoring sites within Regulatory Area A in Fort Bend County, Texas, 2015-2019. ....	8
<b>Figure 4:</b> 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. ....	9
<b>Figure 5:</b> Period of record plot for P004 located in Sugar Land, Texas, 1994 to 2019. This site measured 28.41 cm of subsidence over 25 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.....	10
<b>Figure 6:</b> Annual subsidence rate in cm per year estimated from periodic and continuous GPS data measured from GPS monitoring sites within Regulatory Area B in Fort Bend County, Texas, 2015-2019.....	11
<b>Figure 7:</b> Period of record plot for P062 located in Orchard, Texas, 2011 to 2019. This site measured 5.07 cm of subsidence over eight years and the annual subsidence rate is 0.62 cm per year. The inset map shows the location of P062, the blue circle southeast of the intersection between FM-1489 and SH-36. ....	12
<b>Figure 8:</b> Period of record plot for P031 located in Needville, Texas, 2007 to 2019. This site measured 1.5 cm of uplift over 12 years and the annual subsidence rate is 0.13 cm per year. The inset map shows the location of P031, the circle in the black box west of the intersection between FM-360 and FM-1236. ....	13
<b>Figure 9:</b> Annual subsidence rate in cm per year estimated from periodic and continuous GPS data measured from GPS monitoring sites within Harris, Galveston, Brazoria, Waller, Montgomery, Liberty, and Chambers Counties, Texas, 2015-2019. ....	14
<b>Figure 10:</b> 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.....	15
<b>Figure 11:</b> 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. ....	16

**Figure 12:** 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. ....17

**Figure 13:** 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. ....18

**Figure 14:** 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. ....19

## 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.

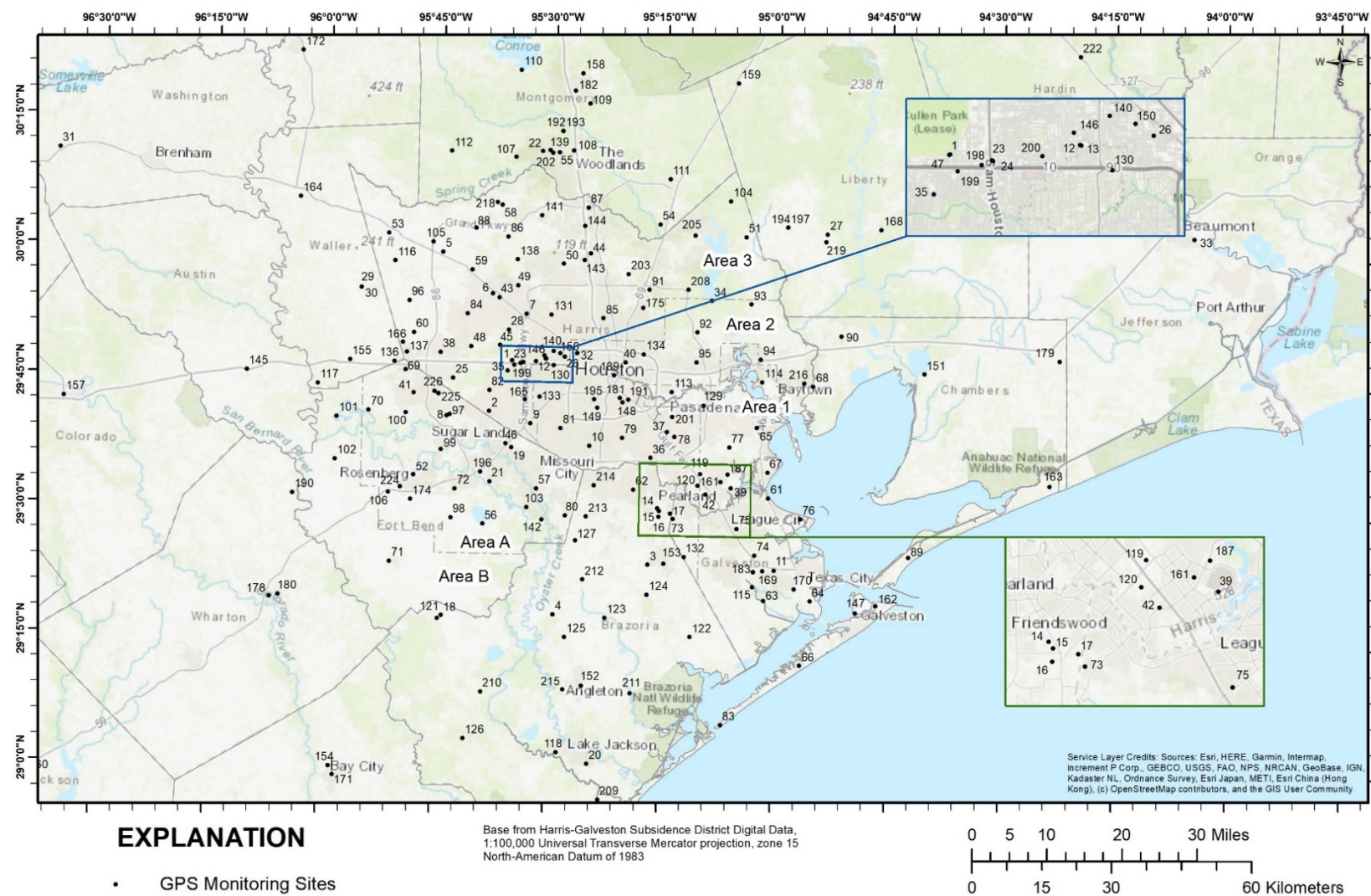
The preexisting structures include buildings and extensometers. GPS antennas are mounted to concrete buildings with deep foundations as well as good sky views in order to accurately measure land surface elevation change and limit interference. This CORS design is used by UH throughout the greater Houston 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 two Districts operate five CORS (ADKS, LKHU, NETP, TXEX, and P096-Cinco MUD) installed on the extensometers.

## GPS Monitoring Network

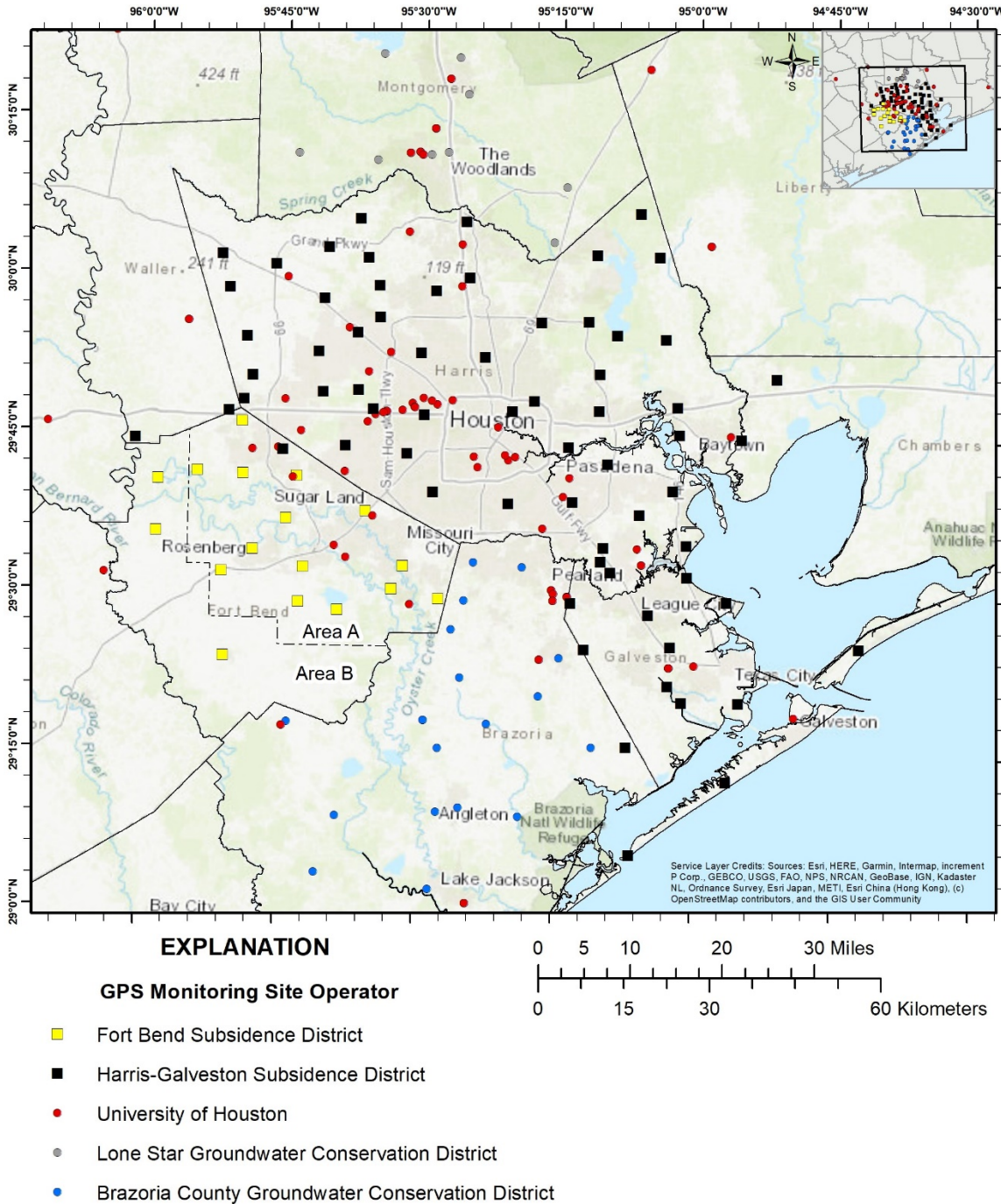
The collaboration between the District, HGSD, UH, BCGCD, and LSGCD creates a GPS monitoring network in the Houston-Galveston area. **Figure 1** depicts the GPS monitoring network with a map identification number for each GPS monitoring site and two map insets to provide greater detail in the denser areas. Additional information for each map identification number is included as a table within **Appendix C**.

Appendix B – Subsidence Monitoring Data



**Figure 1:** Location and map identification number of GPS monitoring sites that record periodic or continuous GPS data within Fort Bend 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.

The District operates 31 GPS monitoring sites and collects data from the GPS monitoring sites operated by HGSD, LSGCD, BCGCD, and UH. The UH operates 75 GPS monitoring sites within Harris and surrounding counties. **Figure 2** includes the location and operators of GPS monitoring sites within the greater Houston-Galveston area.

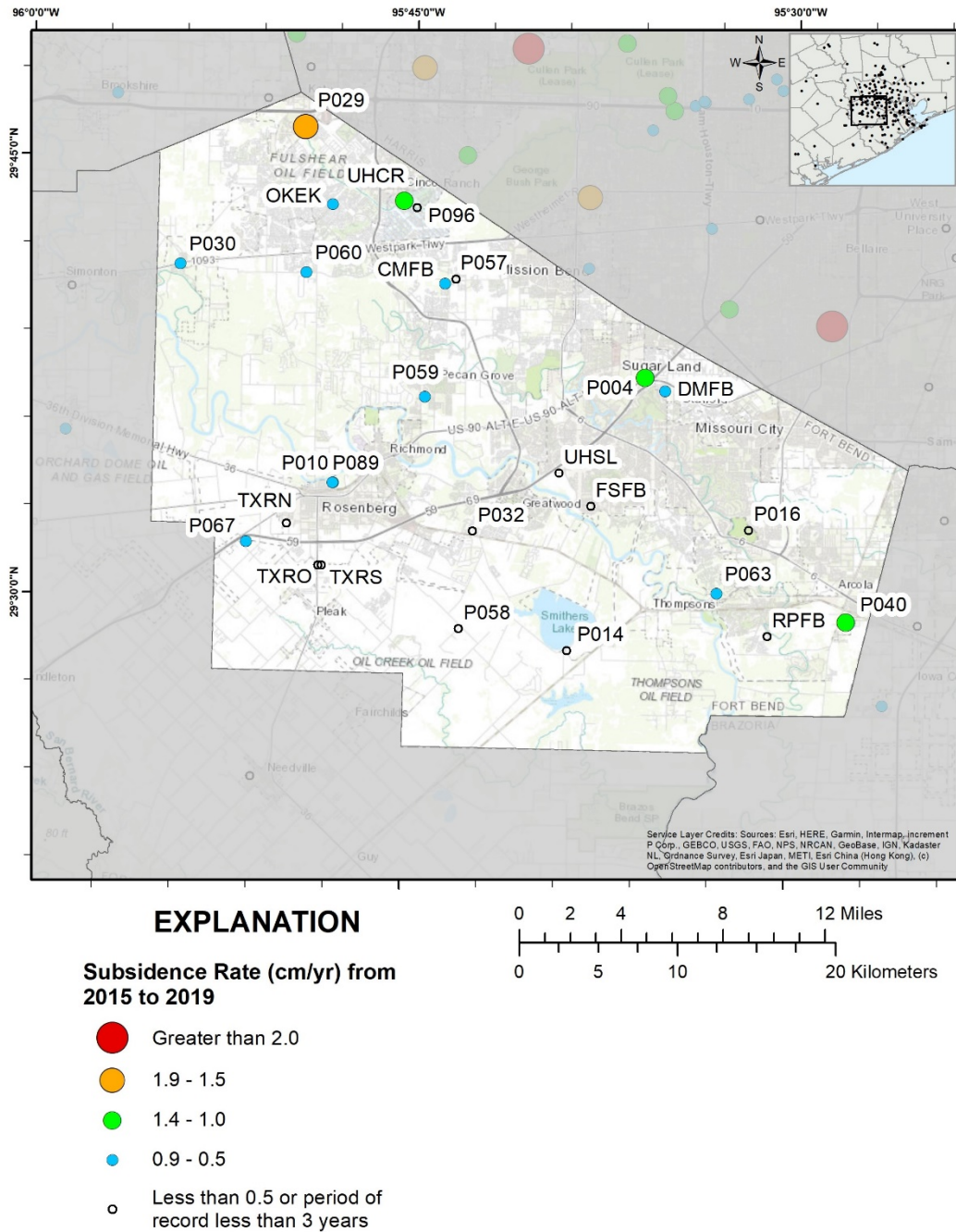


**Figure 2:** Location of GPS monitoring sites designated by operator in Fort Bend and surrounding Counties, Texas, 2019.

### Regulatory Area A

Regulatory Area A is undergoing regulatory level conversion to alternative water since 2013. GPS monitoring sites have been operating since 1994 within this area to measure subsidence. The annual subsidence rate averaged for the 28 GPS monitoring sites in Regulatory Area A is 0.52 cm per year.

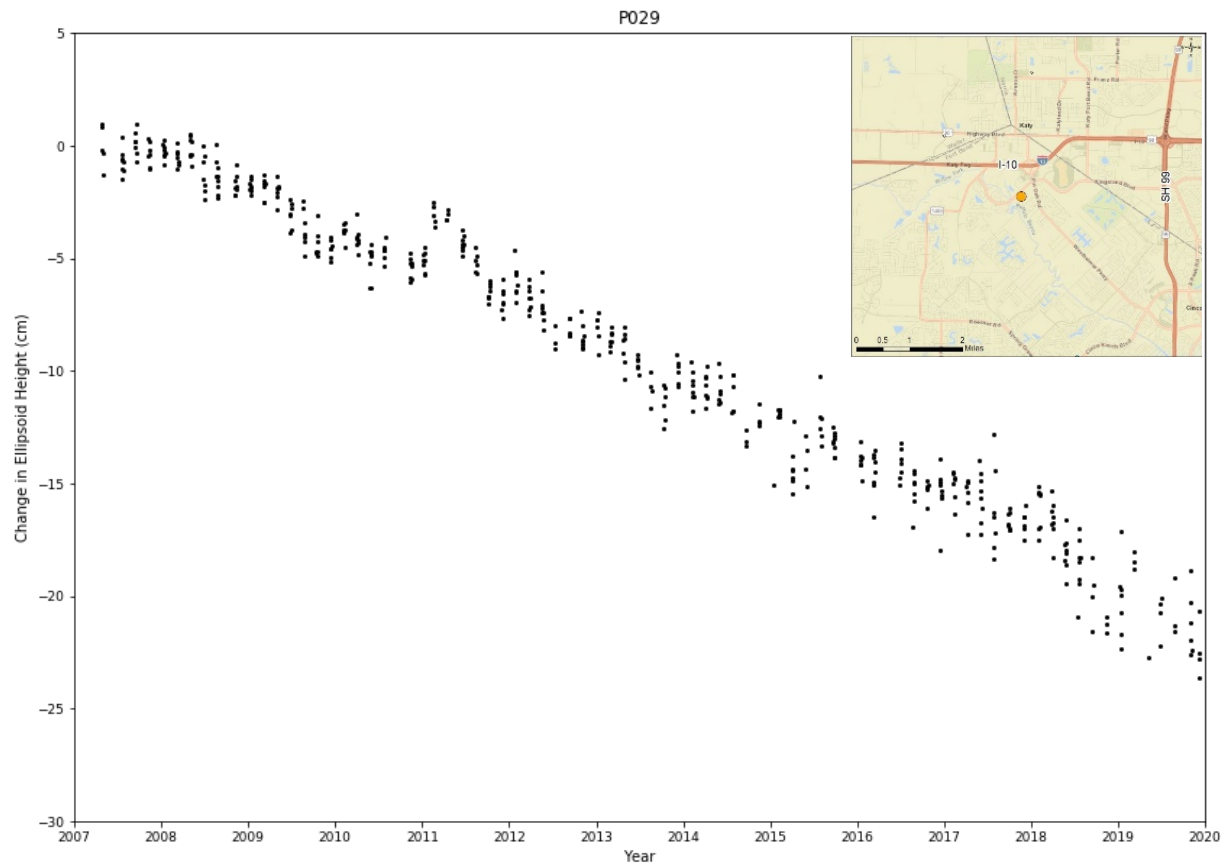
**Figure 3** displays the GPS monitoring sites in Regulatory Area A with labels identifying the name of each site.



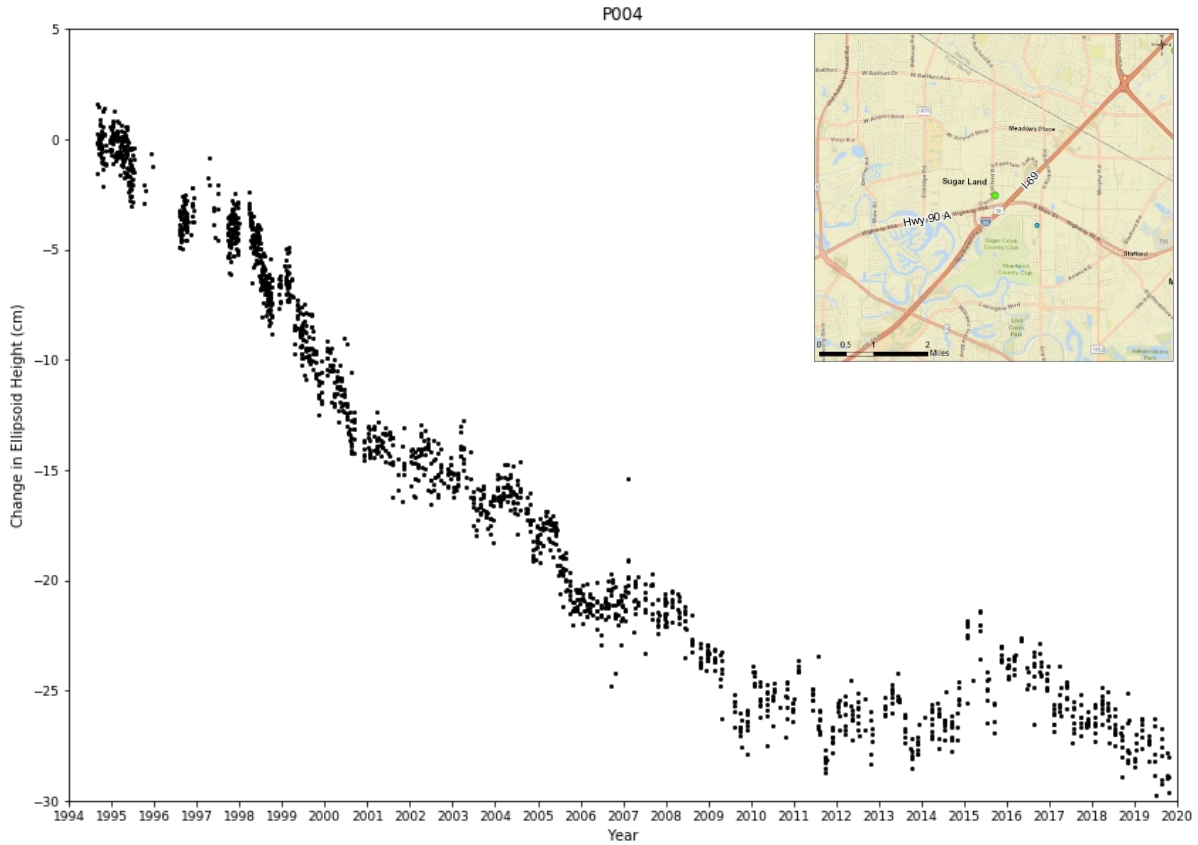
**Figure 3:** Annual subsidence rate in cm per year estimated from periodic and continuous GPS data measured from GPS monitoring sites within Regulatory Area A in Fort Bend County, Texas, 2015-2019.



Approximately 50 percent of GPS monitoring sites in Regulatory Area A have experienced subsidence with rates greater than 0.5 cm per year. The majority of the higher rates are located in the north and western sections of Fort Bend County. GPS monitoring site P029, which is located in Katy, shows the greatest subsidence rate at 1.95 cm per year (**Figure 4**). P029 has measured approximately 21.5 cm of subsidence since 2007. The highest subsidence observed in Fort Bend County is 28.4 cm measured at GPS monitoring site P004, located in Sugar Land, over 25 years (**Figure 5**). P004 also has a high subsidence rate estimated at 1.24 cm per year.



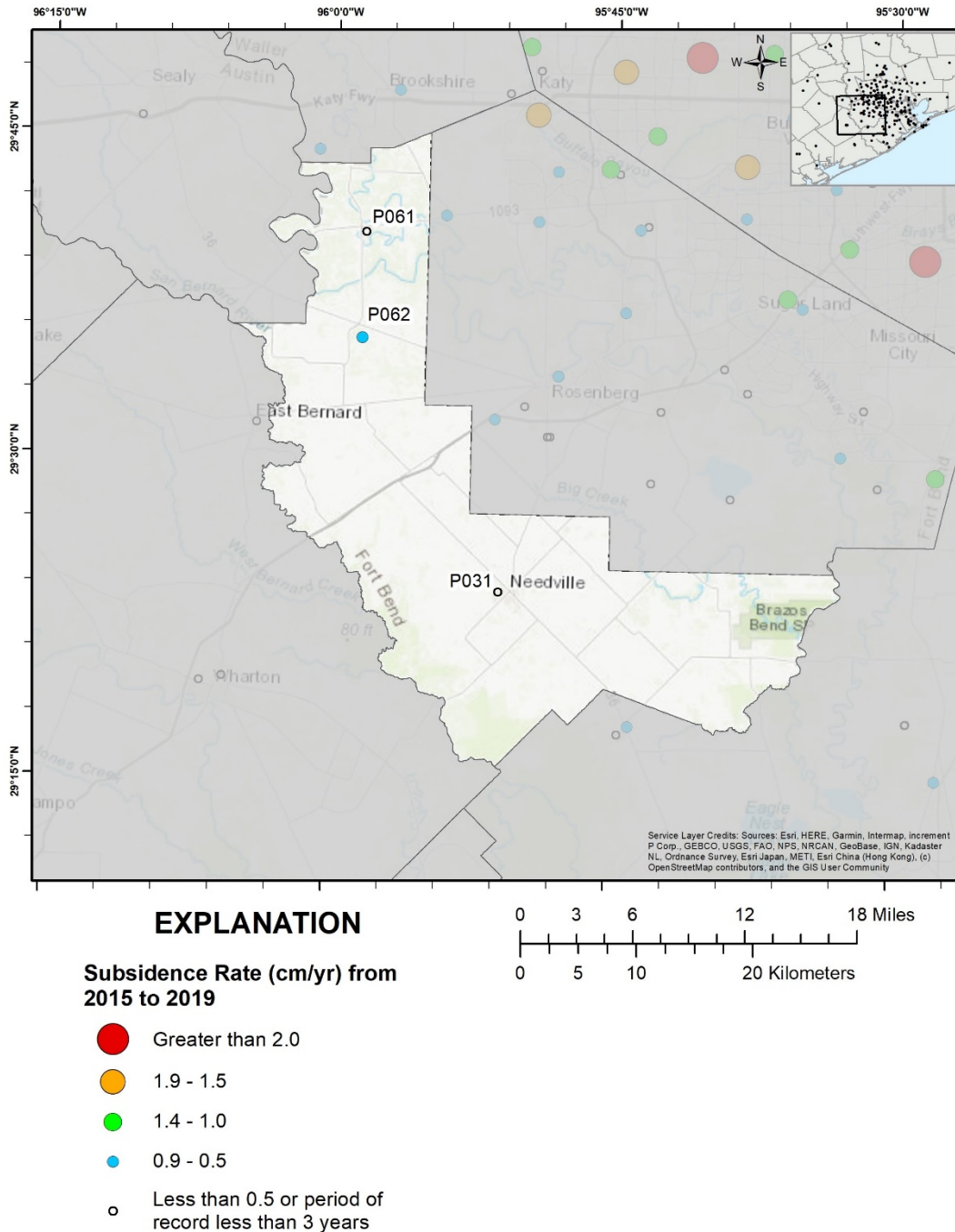
**Figure 4:** Period of record plot for P029 located in Katy, Texas, 2007 to 2019. This site measured 21.52 cm of subsidence over 12 years and the annual subsidence rate is 1.95 cm per year. The inset map shows the location of P029, the orange circle southwest of the intersection between I-10 and SH-99.



**Figure 5:** Period of record plot for P004 located in Sugar Land, Texas, 1994 to 2019. This site measured 28.41 cm of subsidence over 25 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.

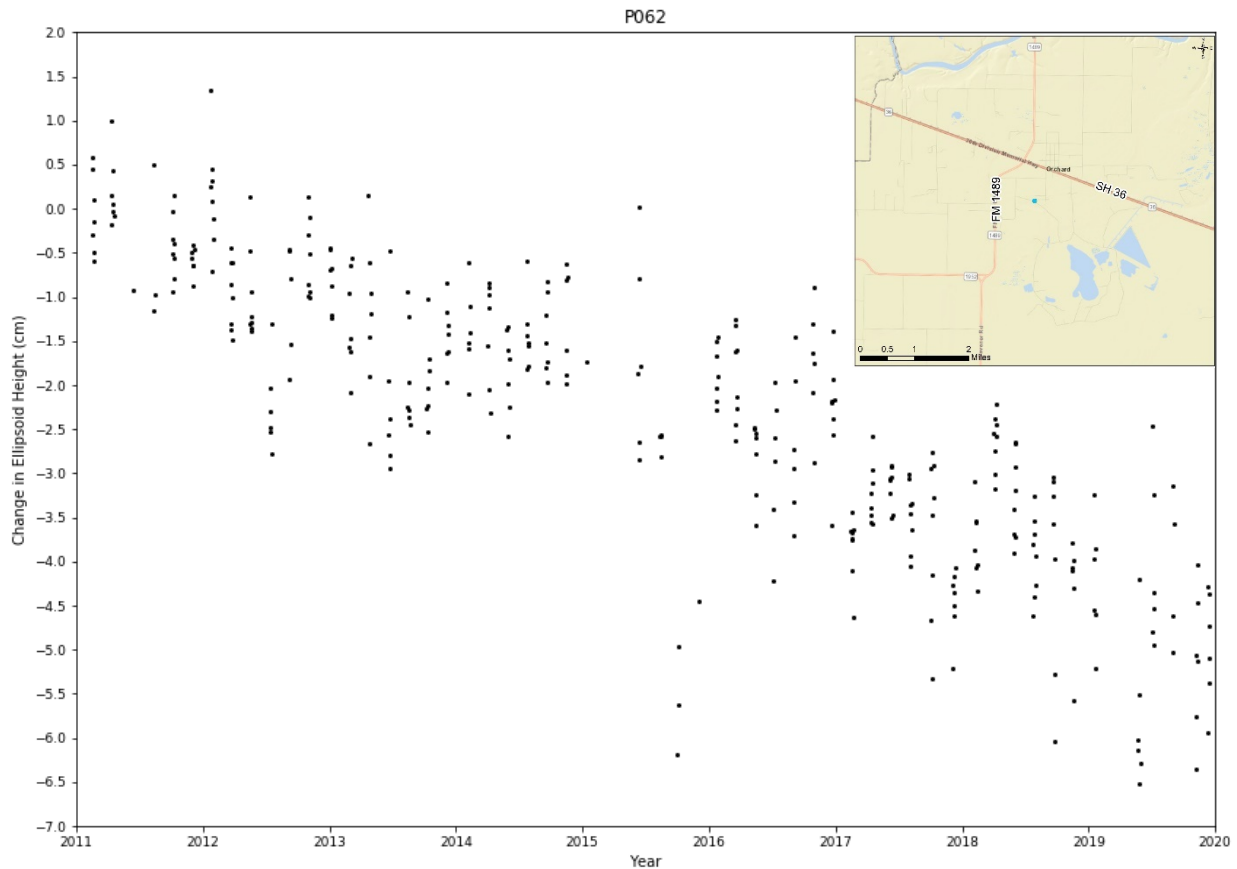
### Regulatory Area B

Regulatory Area B has no groundwater withdrawal restrictions. GPS monitoring sites have been operating since 2007 within this area to measure subsidence. The annual subsidence rate averaged across the three GPS monitoring sites in Regulatory Area B is 0.38 cm per year. **Figure 6** displays the GPS monitoring sites in Regulatory Area B with labels identifying the name of each site.

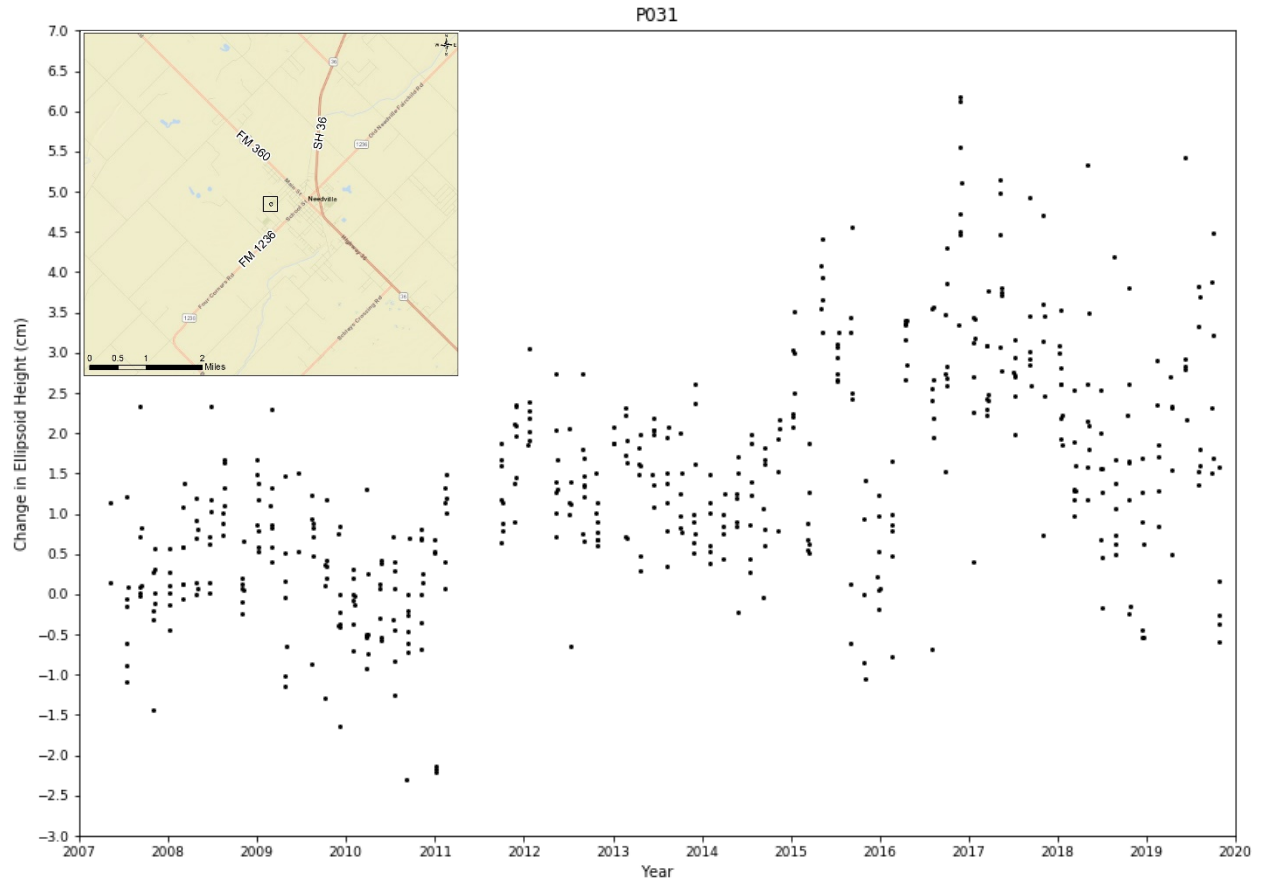


**Figure 6:** Annual subsidence rate in cm per year estimated from periodic and continuous GPS data measured from GPS monitoring sites within Regulatory Area B in Fort Bend County, Texas, 2015-2019.

Two of GPS monitoring sites in Regulatory Area B have remained relatively stable. GPS monitoring site P062 located in the Orchard shows a subsidence rate of 0.62 cm per year with total subsidence measuring at 5.07 cm over eight years (**Figure 7**). P041 has measured approximately 9 cm of subsidence since 2007 with an annual subsidence rate of 2.08 cm per year. GPS monitoring site P031, located in Needville within southern Fort Bend County, shows minor (1.5 cm) uplift since monitoring began in 2007 (**Figure 8**). The annual subsidence rate for P031 is 0.13 cm per year.



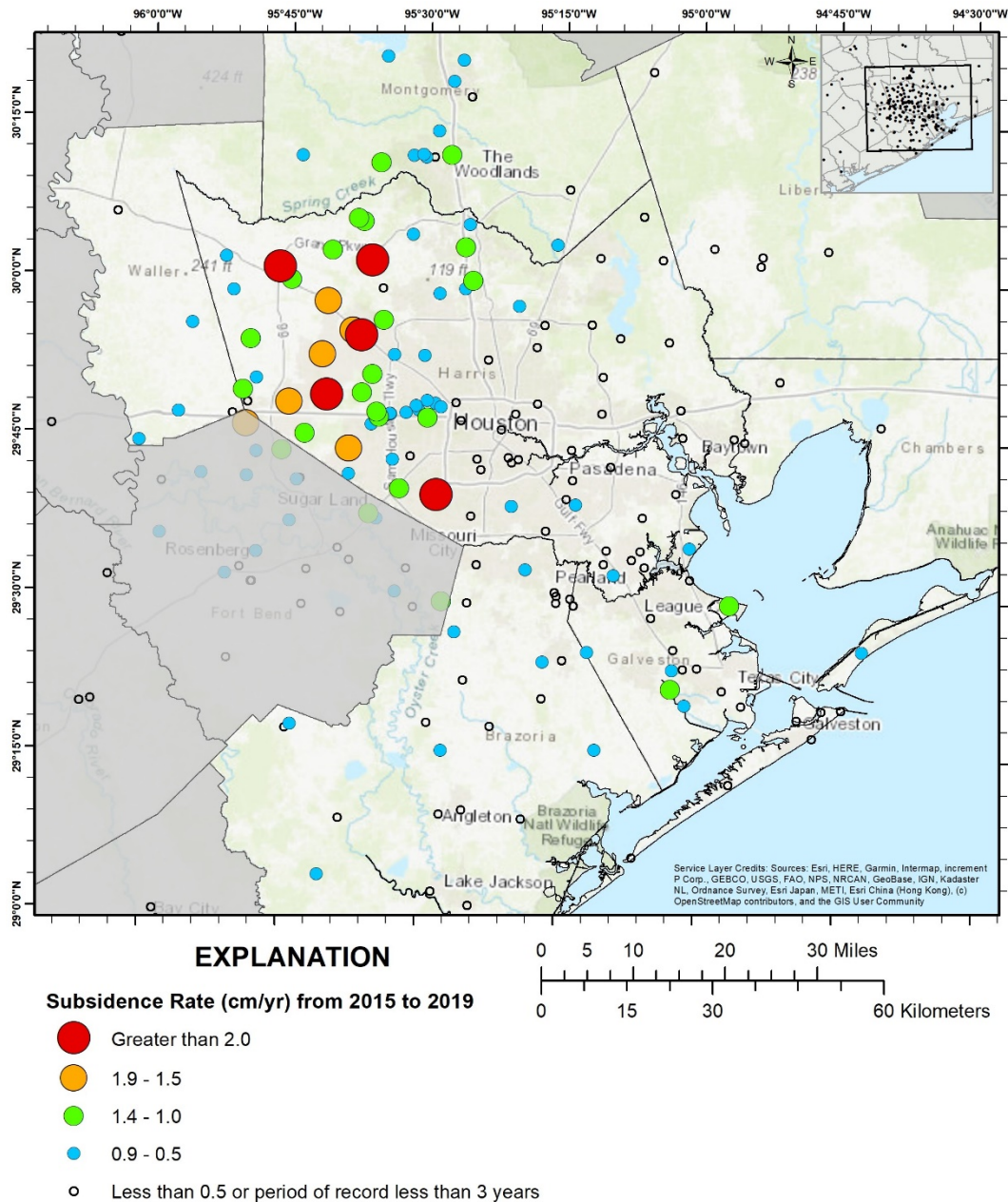
**Figure 7:** Period of record plot for P062 located in Orchard, Texas, 2011 to 2019. This site measured 5.07 cm of subsidence over eight years and the annual subsidence rate is 0.62 cm per year. The inset map shows the location of P062, the blue circle southeast of the intersection between FM-1489 and SH-36.



**Figure 8:** Period of record plot for P031 located in Needville, Texas, 2007 to 2019. This site measured 1.5 cm of uplift over 12 years and the annual subsidence rate is 0.13 cm per year. The inset map shows the location of P031, the circle in the black box west of the intersection between FM-360 and FM-1236.

### Other Counties

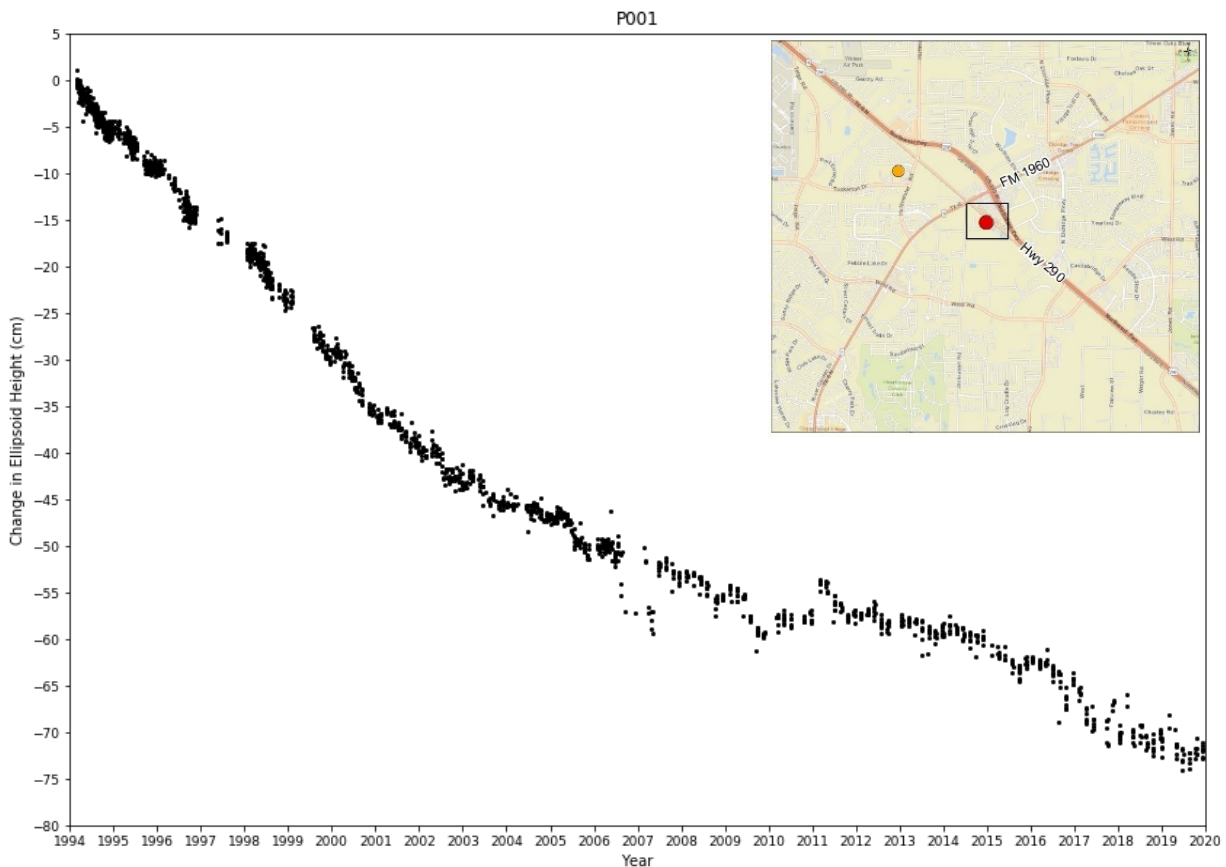
Other counties included in the GPS monitoring network include Harris, Galveston, Brazoria, Waller, Montgomery, Liberty, and Chambers. The majority of GPS monitoring sites in these counties are operated by other subsidence districts, groundwater conservation districts, and UH. Their GPS data are included in the GPS network. **Figure 9** displays the GPS monitoring sites located in the other counties within the network.



**Figure 9:** Annual subsidence rate in cm per year estimated from periodic and continuous GPS data measured from GPS monitoring sites within Harris, Galveston, Brazoria, Waller, Montgomery, Liberty, and Chambers Counties, Texas, 2015-2019.

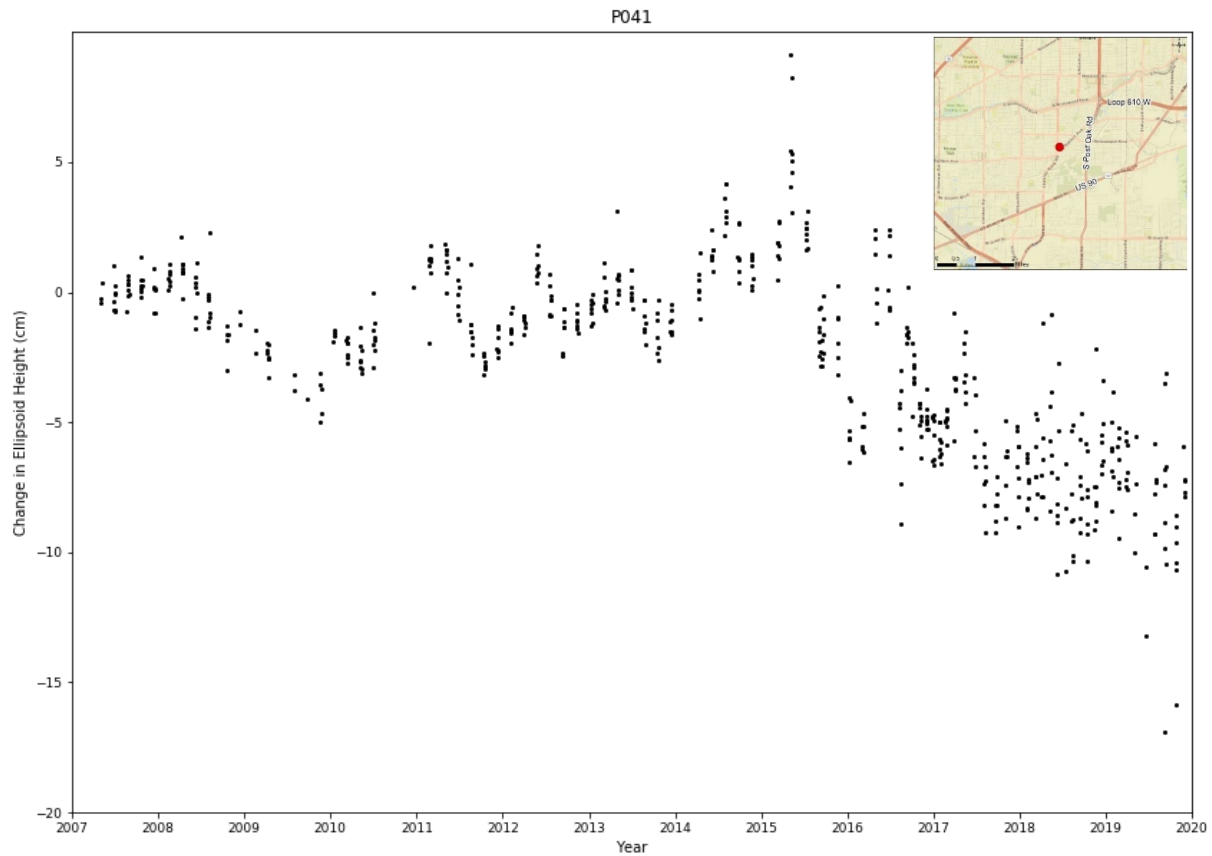
Harris County has the highest subsidence rates (greater than 2.0 cm per year) in the western portion along State Highways 99, 290, 6, and 249. This area is located in HGSD Regulatory Area Three, which has not been fully converted to alternative water sources; although some entities, such as the City of Houston and Regional Water Authorities, have been transitioning to alternative water sources since before 2010. The annual subsidence rate averaged for the 94 GPS monitoring sites within Harris County is 0.63 cm per year. Approximately 55 percent of the GPS monitoring sites in Harris County have subsidence rates greater than 0.5 cm per year.

GPS monitoring site P001, located in Jersey Village, has measured the highest subsidence rate at 2.54 cm per year and has recorded 71.8 cm of subsidence over 25 years in operation (**Figure 10**).



**Figure 10:** 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.

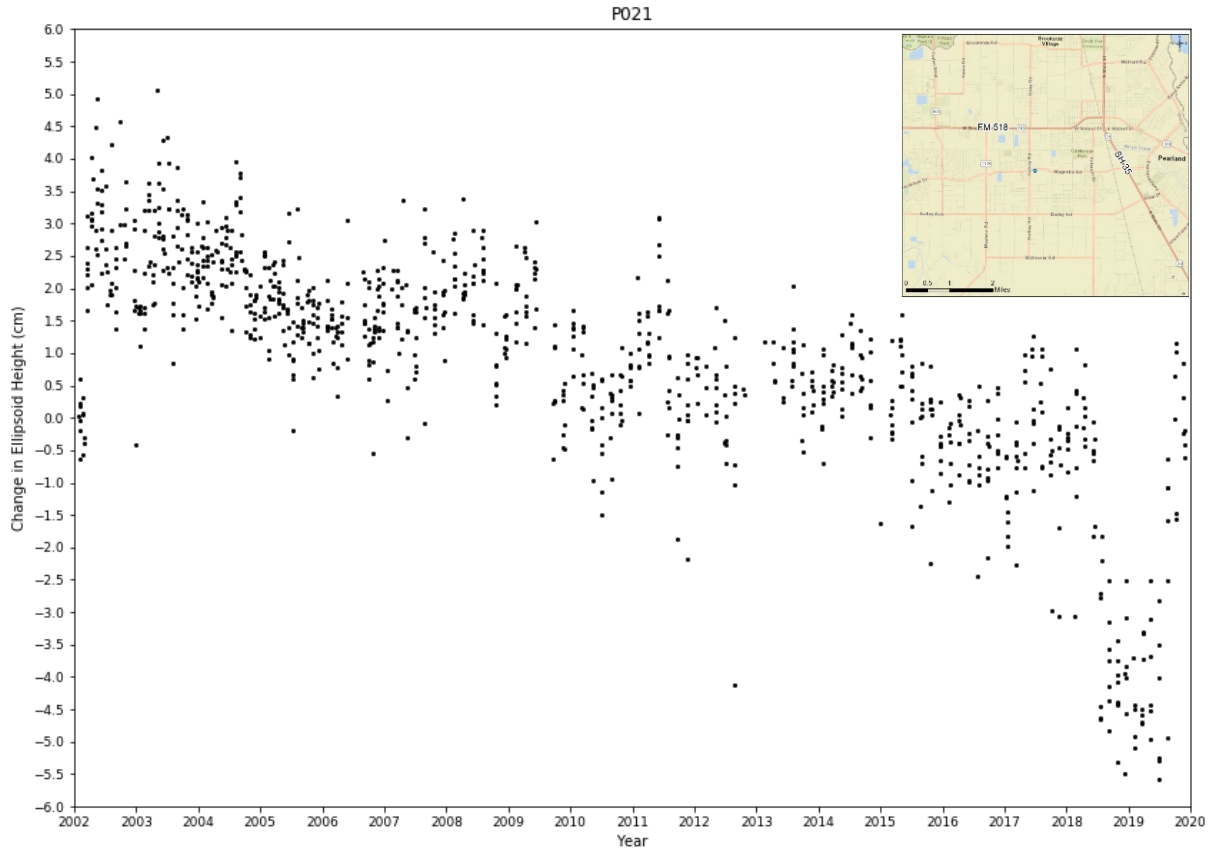
GPS monitoring site P041 located in the Westbury neighborhood (Brays Oak district in Southwest Houston) shows a relatively stable rate from 2007 to 2015 then a decline beginning in 2016 (**Figure 11**). P041 has measured approximately 9 cm of subsidence since 2007 with an annual subsidence rate of 2.08 cm per year.



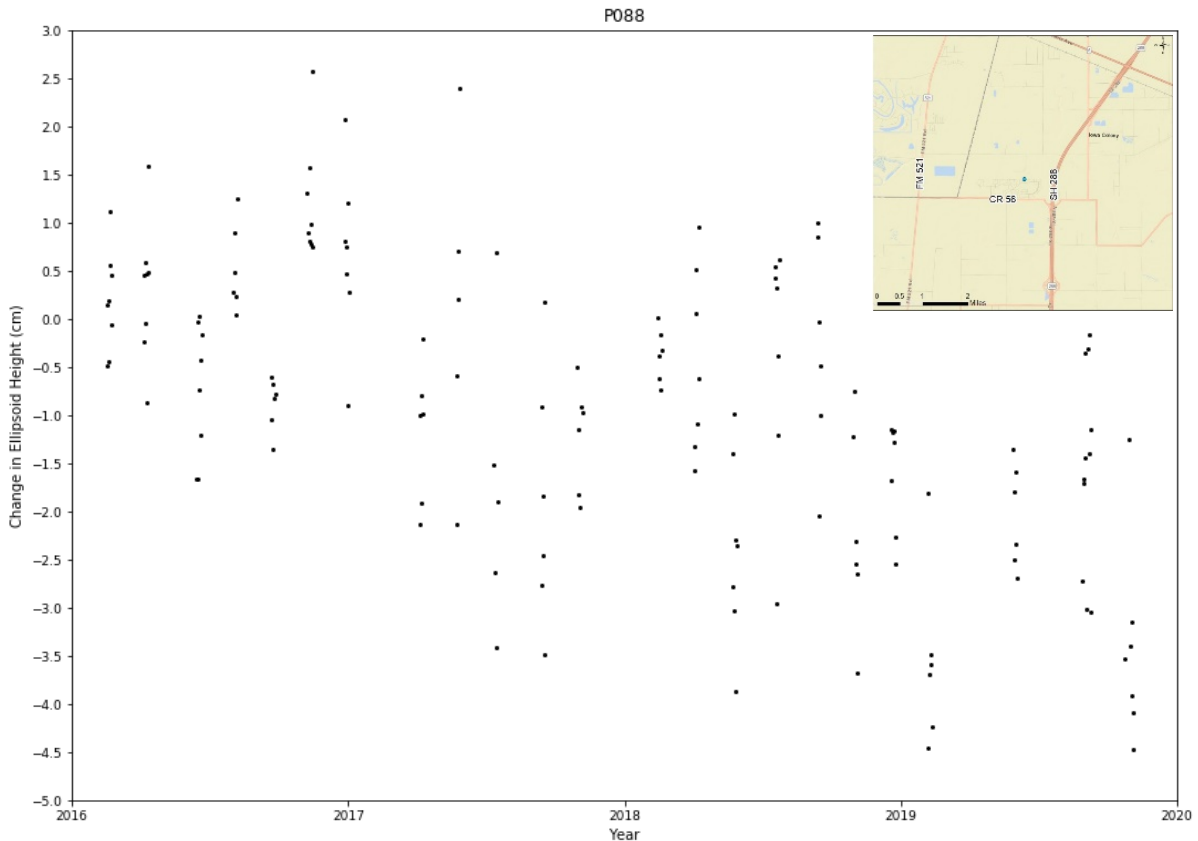
**Figure 11:** Period of record data for GPS monitoring site P041 located in the Westbury neighborhood (Brays Oak district in Southwest Houston) from 2007 to 2019. P041 measured 9.07 cm of subsidence since 2007 with an annual subsidence rate of 2.08 cm/yr.

Brazoria County contains 27 GPS monitoring sites operated by Brazoria County Groundwater Conservation District, UH, and the HGSD. 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 12**). 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 13**).





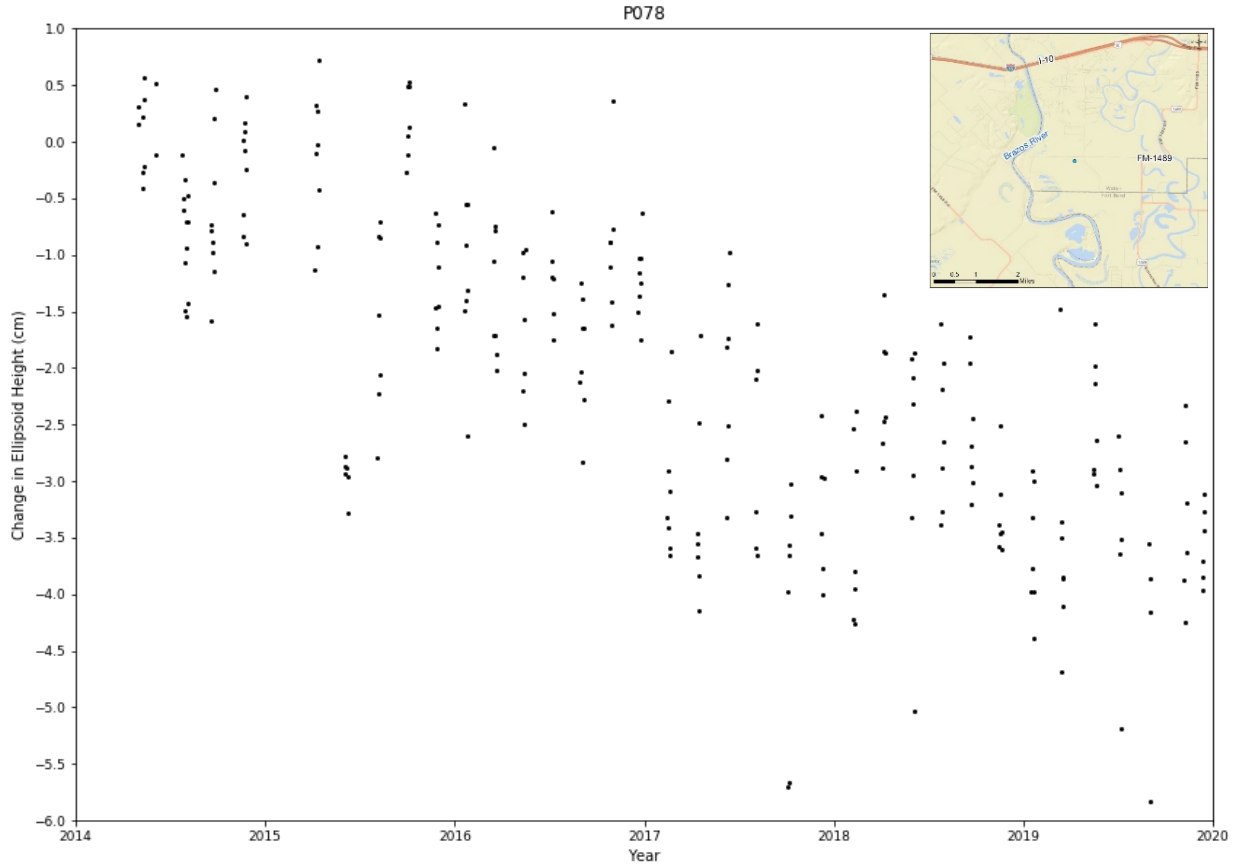
**Figure 122:** Period of record plot for P021, located in Pearland, Texas 2002-2019. This site measured 2.44 cm of subsidence over 18 years and the annual subsidence rate is 0.84 cm per year. The inset map shows the location of P021, the blue circle southwest of the intersection between SH-35 and FM-518.



**Figure 133:** 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 counties, including 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 HGSD. 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 HGSD 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 14**).



**Figure 144:** 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.