LONE STAR
GROUNDWATER CONSERVATION DISTRICT

June 18, 2020

MINUTES OF SPECIAL BOARD MEETING

The Board of Directors of the Lone Star Groundwater Conservation District ("District") met in special session, open to the public, in the Lone Star GCD – James B. "Jim" Wesley Board Room located at 655 Conroe Park North Drive, Conroe, Texas and also held via a publicly accessible webinar/telephone conference call, within the boundaries of the District on June 18, 2020.

CALL TO ORDER:

President Hardman presided and called to order the regular Board of Directors meeting at 6:02 PM, announcing that it was open to the public.

ROLL CALL:

The roll was called of the members of the Board of Directors, to wit:

Jon Paul Bouché
Harry Hardman
Jonathan Prykryl
Larry A. Rogers
Jim Spigener
Stuart Traylor

All members of the Board were present, thus constituting a quorum of the Board of Directors. Also, in attendance at said meeting were Samantha Reiter, General Manager; Stacey V. Reese, District Counsel; District staff; and members of the public. *Copies of the public sign-in sheets and comment cards received are attached hereto as Exhibit "A".*

PRAYER AND PLEDGES OF ALLEGIANCE:

President Hardman called on Director Bouché for the opening prayer and Director Larry A. Rogers to lead the Pledge of Allegiance and the Pledge of Allegiance to the state flag.

PUBLIC COMMENTS:

No public comments.

EXECUTIVE SESSION:

No executive session.

RECONVENE IN OPEN SESSION:

None needed.

RECEIVE PRESENTATION ON THE SUBSIDENCE STUDY PHASE I DRAFT REPORT:

Ms. Reiter explained that both technical consultants, Mike Thornhill and Mike Keester were online and making their reports via webinar.

a) Discussion, consideration, and possible action regarding approval of the Subsidence Study Phase I Draft Report for publication in preparation for Stakeholder Meeting.

Mr. Mike Thornhill, District technical consultant, outlined Phase I topics of the study being: hydrogeology and subsidence, existing studies and data, preliminary modeling, regulation and management, Phase I conclusions and Phase 2 scope of work.

Mike Keester discussed hydrostratigraphy for the county. He reviewed the subsidence process and displayed a contour map showing subsidence in Montgomery County and noting that over a 5-year period there is generally an average subsidence rate of 0.5 inches per year. In his assessment, he cited the three primary factors affecting the potential subsidence as clay with distribution thickness; water level change and the historical water level. A change in stress on the formation is what causes compaction. He mentioned that the HGSD estimated that Montgomery County has experienced 3-feet of subsidence since 1906.

Mr. Mike Thornhill noted the importance of using the existing studies and data throughout Phase I. One such study he cited was the Gabrysch and Bonnet Land-Surface Subsidence Study where core samples were gathered from the Chicot and Evangeline aquifers. He also discussed the 12 extensometers in the area for the Chicot and Evangeline. Presently, there are no extensometers in Montgomery County. Director Spigener made point that since no extensometers exist in Jasper aquifer, then the know the source of the subsidence remains inconclusive.

The next topic examined was remote sensing made up of two types called LiDAR and InSAR. The Chicot water levels have shown very little decline. Mike Keester explained the hydrographs for the Evangeline indicate more pronounced water level decline during the period of 1988-2009, and subsequently there was a slight rise in water level during 2018-2019 as compared to 2009. The Jasper aquifer water levels have increased levels over the past thirty years.

Mr. Thornhill concluded the Phase 1 Study with the following: subsidence has and will continue to occur in the Gulf Coast Area; much of the subsidence in Montgomery

County was evident prior to substantial pumping within the county; growth fault movement may be due to several factors; compaction susceptibility varies with age, depth character, and thickness; and developed comprehensive background data and understanding for Phase 2 investigations. *A copy of the DRAFT Subsidence Investigations Phase 1 Study is attached hereto as Exhibit "B".*

Director Spigener motioned to approve the Phase I Subsidence Study report and Director Larry A. Rogers seconded. Motion passed.

RECEIVE PRESENTATION FROM DISTRICT'S TECHNICAL CONSULTANT REGARDING PHASE 2 OF SUBSIDENCE STUDY AND/OR DISCUSSION REGARDING THE SAME:

Mr. Mike Keester exhibited an overview of the Phase 2 scope of work and reviewed the tasks which include: the technical evaluations of existing data and recent studies, drainage and flooding, subsidence modeling, potential impacts to drainage and flooding, reporting, recommendations and presentations.

NEW BUSINESS:

There was no new business.

ADJOURN:

There being no further business Director Traylor motioned to adjourn the meeting and Director Spigener seconded. The meeting was adjourned at 6:59 PM.

PASSED, APPROVED, AND ADOPTED THIS 14th DAY OF JULY 2020.

/s/ Larry A. Rogers

Larry A. Rogers, Board Secretary

SIGN IN SHEET

June 18, 2020
Special Board Meeting

Do you wish to speak on an agenda item?	NAME	CITY, STATE, ZIP	E-Mail	Would you like to receive LSGCD updates & information?
N	TINA FELKAI	CONROE TX	ON FILE	

Exhibit "A"

June 18, 2020 Special BOD Meeting

In-Person Participants

President Harry Hardman

Vice President Stuart Traylor

Secretary Larry Rogers

Treasurer Jim Spigener

Director Jon Bouche

General Manager Samantha Reiter

Education & Conservation Jennifer Thayer

Zoom Participants/Panelists

General Counsel Stacey Reese

Director Jonathan Prykryl

Consultant Mike Keester

Consultant James Beach

Consultant Mike Thornhill

Zoom Attendees

936-271-9203

936-488-6169

Betty Daughtry

Douglas Miller

Gregory Ellis

Jennifer Rank

John Yoars

Jordan Furmans

Laura Norton

Mark Smith

Mike Turco

Neil Gaynor

Peggy Bradshaw

Ron Kelling

Ronda Trow

Scott Custer

Sheila Faxel

Suellen Myers

Exhibit "B"

SUBSIDENCE INVESTIGATIONS – PHASE 1
ASSESSMENT OF PAST AND CURRENT INVESTIGATIONS

1.0 INTRODUCTION

Numerous studies have been conducted and reports written over the last 50 years addressing land-surface subsidence and growth-fault movement in what has been historically called the “Houston-Galveston region of Texas” which, as associated with subsidence studies, has consistently included all of Harris County and “parts of” Brazoria, Chambers, Fort Bend, Galveston, Liberty, Montgomery and Waller counties. With rapid population growth and expansion outward from central Harris County, water demand and pumping distributions have changed relatively rapidly. Additionally, the previous regulatory plan for Lone Star Groundwater Conservation District (LSGCD) has been declared not valid. Therefore, the are more concerns today regarding subsidence in the outskirts of Harris County and neighboring counties. LSGCD has cooperated and participated with the United States Geological Survey (USGS), Harris-Galveston Subsidence District (HGSD) and Fort Bend Subsidence District (FBSD) in installing new global positioning system (GPS) monitoring sites, supporting programs to monitor aquifer water levels, and in modeling efforts that include subsidence simulations. However, LSGCD had not conducted its own independent investigations to study subsidence. Therefore, LSGCD approved the Phase 1 scope of work for the subsidence study. This report provides a summary of the work conducted and descriptions of the data and information compiled.

1.1 Background

Subsidence has been a concern in the Gulf Coast Region for almost a century, particularly in the coastal areas and large portions of Harris and Galveston counties where relatively large amounts of land surface elevation changes have been documented and correlated to artesian pressure changes in the Chicot and Evangeline aquifers. Additionally, intensive historical pumping in Harris County for municipal water use and large irrigation pumping operations in the “Katy Area” (i.e., Harris, Waller and Fort Bend counties) caused notable subsidence in neighboring counties, including the southern part of Montgomery County. As population has grown outward from Houston and subsidence district regulatory programs have been implemented, the distribution of pumping has changed and so has the reported occurrence of subsidence. Current TWDB-approved modeling results indicate that, while subsidence has been arrested in the areas where the most severe compaction occurred, some areas of Harris, Fort Bend, Montgomery, Waller, Austin and some neighboring counties will experience additional subsidence through 2070, even with previous LSGCD and current subsidence district regulatory programs in place. Therefore, the potential occurrence, extent and ramifications of subsidence are of significant interest to many stakeholders in Groundwater Management Area 14 (GMA 14) and LSGCD. As LSGCD has expressed its intent to fulfill the statutory mandate to “control subsidence” and has recognized that effects of production respond more as a "common reservoir", the Phase 1 work falls within the purview of LSGCD and other groundwater conservation districts (GCDs) in the Joint Planning efforts of GMA 14.

1.2 Purpose and Goals

The purposes of the LSGCD subsidence study generally are to:

- Address subsidence from Montgomery County's perspective;
- Investigate and evaluate specific concerns and claims including possible causes and distributions of historical and future subsidence in Montgomery County and neighboring counties, and the occurrence and potential causes of activation or movement of growth local faults;
- Develop a basis for understanding potential short-term and long-term impacts and ramifications associated with subsidence and the cost-benefit of pumping groundwater; and,
- Prepare for proper subsidence (and other) considerations regarding joint-planning processes with other districts and stakeholders in GMA 14.

The primary goals of Phase 1 are:

- Developing a working understanding of historical information and reporting, including modeling with the TWDB-approved Houston Area Groundwater Model (HAGM) to ensure that subsidence is properly considered by GMA 14 in deriving desired future conditions (DFCs) for the various common reservoirs;
- Estimating the amount and distribution of subsidence within the LSGCD boundaries from pre-development periods through 2000, immediately prior to the formation of the district;
- Correlating estimates of compaction and subsidence with spatial and temporal distributions of groundwater pumping and artesian pressure changes in each layer of the Gulf Coast Aquifer system – the Chicot, Evangeline, and Jasper aquifers; and,
- Predicting using the HAGM possible compaction with various projected future pumping distributions.

1.3 Work Conducted

Phase 1 of the LSGCD subsidence study was intended to comprehensively collect and compile information and data sets, to become better educated and develop a functional overview and "working knowledge" of subsidence information, to conduct preliminary modeling utilizing the approved groundwater availability model (GAM), known as the Houston Area Groundwater Model (HAGM), in order to be prepared for the on-going GMA 14 process, and to develop detailed scope of services and costs for Phase 2 of the study. There are few conclusions in this report as Phase 1 was intended to develop a primer on subsidence information and a roadmap for moving forward with a more comprehensive study. Phase 2 will include detailed data processing and analysis, critiques and conclusions to fulfill the objectives and goals of the project. The work conducted for Phase 1 included:

Task 1.1 – Background Data Compilation and Workup – subsidence studies in the Houston area began prior to the 1970s, but detailed studies began in the mid-1970s and numerous reports of laboratory testing of core samples, monitoring results and additional studies have since been published. This task involved acquiring and compiling data from available previous studies and databases including the TWDB, the USGS, the HGSD, FBSD, LSGCD, the University of Texas Bureau of Economic Geology (BEG), the University of Houston (UH), Rice University (Rice), Texas A&M University (TAMU), other institutions, consultant reports, peer-reviewed journals and in-house libraries and files. Work products for Task 1.1 include:

- Datasets in *ArcGIS™* formats that can be utilized for sorting and analyzing data and for creating subsequent work products. Datasets include historical water level monitoring, subsidence monitoring, and groundwater pumping; and,
- Maps, cross sections, tabulations, charts, hydrographs and diagrams to illustrate the data and information, to describe the local hydrogeological and hydraulic conditions. Task 1 work provided the basis for subsequent tasks.

Task 1.2 – Synopsis of Past Studies and Information – the consultant team compiled a comprehensive digital library of subsidence studies and has provided herein key information from selected reports, including recently released reports specific to subsidence and growth fault concerns in Montgomery County. Pertinent illustrations from previous reports have been incorporated into reporting for Phase 1, and some original maps and illustrations created from the acquired datasets, including illustrating through geologic maps and cross sections variations across LSGCD and the Houston area regarding depths, structure, sand thickness, aquifer productivity, clay layers, artesian pressures and other properties associated with compaction and subsidence. This task also included building and evaluating datasets and developing illustrations regarding sequential mapping in order to illustrate historical spatial and temporal distributions of groundwater pumping and artesian pressure changes in all layers of the Gulf Coast Aquifer system, and to correlate pumping and pressure changes to compaction in the various layers and cumulative subsidence.

Task 1.3 – HAGM Modeling – this task included utilizing the current TWDB-accepted GAM known as the HAGM to assess the model predictions with respect to reported historical conditions and projected future conditions. Specifically, this task included estimating subsidence amounts and distributions in Montgomery County for time periods prior to the formation of LSGCD (and/or prior to land-surface elevation monitoring at PAM sites, etc.). Modeling efforts allowed for estimating total current compaction and corresponding subsidence in each layer of the Gulf Coast Aquifer system, and projecting future compaction in each layer and corresponding total subsidence based on various distributions of groundwater pumping.

Task 1.4 – Overview of Regulatory and Management Frameworks – this task included reviewing Chapter 36 of the Texas Water Code (TWC), the LSGCD's Management Plan, subsidence districts' regulatory plans, and historical and projected pumping schedules for Harris, Fort Bend and Galveston counties based on information presented by the subsidence districts. As groundwater owners in Harris County and Fort Bend County pump more water than owners in other counties and subsidence within and outside of those counties has already been attributed to pumping in those counties, it was important to develop future pumping distributions based on the regulatory plans and water demand projections.

Task 1.5 – Meetings with Cooperators and Stakeholders – due to COVID-19, all meetings were postponed. The LSGCD General Manager, Samantha Reiter, is in the process of scheduling one (1) meeting with potential cooperators, stakeholders and the public. The meeting will include a presentation of Phase 1 work and discussions of the scope of services prepared for Phase 2 work.

Task 1.6 – Develop Scope of Work and Costs for Subsequent Phases – this task included developing a detailed scope of services, associated specific costs, and timeline with benchmarks for deliverables for each task of Phase 2 of the subsidence study.

Task 1.7 – Summary Report and Presentation to Board – this task included providing a presentation to the board prior to the final Phase 1 report being written. This task also included preparing a written report with illustrations and supporting documentation.

2.0 HYDROGEOLOGY AND SUBSIDENCE

The Texas Water Development Board delineates the Gulf Coast Aquifer System ("GCAS") as a band of relatively young geologic formations that parallel the Gulf of Mexico coastline from the southern Texas border with Mexico to the east Texas border with Louisiana (George and others, 2011). For groundwater production, the sand units of the GCAS are the targets for well completion. For subsidence considerations, the thickness and type of clay present within the aquifers is of interest because as wells draw water from the sand units the water in the clays may leak into the sand units causing the clays to compact. The following provides a brief description of the hydrogeologic conditions with an emphasis on the conditions that may affect land surface subsidence.

2.1 Hydrostratigraphy

The hydrostratigraphy of the aquifer refers to the subsurface delineations of the geology where groundwater primarily flows. The hydrostratigraphic units of an aquifer may not be the same as the lithostratigraphic units which are delineated by the type of rock or sediment that make up the geologic units. In this section we will focus on the hydrostratigraphy of the GCAS and how the lithology correlates to the hydrostratigraphic units.

2.1.1 Lithology

Commonly, the hydrostratigraphic units which make up the GCAS in and around Montgomery County are, from shallowest to deepest, the Chicot Aquifer, the Evangeline Aquifer, the Burkeville confining unit, and the Jasper Aquifer (Young and others, 2012). Underlying the Jasper, parts of the Catahoula Formation form the Catahoula Confining System (Young and others, 2012) while the sandstone units of the formation are important sources of groundwater to some users within the LSGCD (Seifert, Jr., 2015). Young and others (2012) subdivided the hydrostratigraphic units based on identifiable age markers in the geologic units that comprise the larger units. Table 1 summarizes the local hydrostratigraphic and geologic units within Montgomery County.

The lithologic characteristics of the geologic units are controlled by the depositional system for each unit. The Fleming Group comprises the basal geologic units of the GCAS and is characterized as a fluvial-deltaic depositional system. The lowermost Oakville Formation is generally sand-rich while the overlying Lagarto typically contains more clay (Young and others, 2012). Following the classification of Young and others (2012), the Lower Lagarto and the Oakville form the Jasper Aquifer, while the Middle Lagarto correlates to the Burkville and can be identified as having a lower sand content than either the upper or lower sections of the formation.

The Goliad Formation along with the Upper Lagarto form the Evangeline Aquifer. The top of the dominant clays of the Middle Lagarto formation mark the base of the Evangeline. The Goliad Formation is a massive fluvial sandstone in the Montgomery County area. (Young and others, 2012). Generally, the sandstones in the Lower Goliad are thicker and more conglomeritic than the sandstones of the Upper Goliad (Hoel, 1982; Morton and others, 1988; Young and others, 2012).

Formations above the Goliad comprise the Chicot Aquifer. Recent alluvial deposits are considered separate from the Chicot, though for practical purposes the shallow alluvial deposits may be considered part of the Chicot aquifer as they would typically be hydraulically connected to the older formations. In the study area, the Willis Formation was deposited in a nonmarine, fluvial depositional system and is typically characterized as having gravelly coarse sands. Glacial-interglacial cycles influenced the deposition of the Lissie Formation resulting in fine-grained sand and sandy clay layers. The uppermost Beaumont Formation is clay-rich with sandy fluvial and deltaic-distributary channels.

2.1.2 Aquifer and Clay Thickness

The geologic units of the GCAS dip toward the Gulf of Mexico. As the units dip, they typically also become thicker creating a wedge shape. The total thickness of the aquifer is more than 4,000 feet in southern Montgomery County (Young and others, 2012). However, 95 percent of registered wells have a depth of 520 feet or less with groundwater production from the upper portions of the GCAS.

As previously mentioned, for groundwater production wells will be completed in the sand units of the aquifers. As water is drawn from the sands, groundwater will move from the clay layers into the sands. In areas with higher clay thicknesses the potential for subsidence is higher than for areas with thinner clays. The following provides a brief description of the sand and clay thicknesses of the formations that make up the GCAS.

The Beaumont Formation does not extend into Montgomery County. However, the Lissie and Willis formations of the Chicot Aquifer are present. The Lissie and Willis are both up to 500 thick within Montgomery County and each averages about 250 feet thick. Typically, the units are about 60 percent sand. Within Montgomery County, the clay thickness of the Lissie and Willis formations is greatest in the southeast. The estimated clay thickness of the Lissie Formation is 250 feet near Porter, TX (see Figure 2) and for the Willis Formation the estimated clay thickness is about 250 feet near The Woodlands, TX (see Figure 3). In geologic terms, these formations are relatively young with the Lissie Formation being less than 1.8 million years and the Willis Formation forming during the Miocene Epoch and being less than 5.3 million years.

For the Evangeline Aquifer, the Upper Goliad is generally not present within Montgomery County, but the Lower Goliad and the Upper Lagarto are present within most of the county. The Lower Goliad is reportedly more the 1,000 feet thick within the county and the Upper Lagarto exceeds 700 feet thick. Both units are primarily sand, but Young and others (2012) report the Upper Lagarto has a higher sand content than the Lower Goliad. However, there are some areas with very high clay thicknesses within the Lower Goliad. For example, clay thickness of up to 500 feet is found near Porter, TX in the Lower Goliad (Figure 5). In the Upper Lagarto, the clay thickness is generally greatest in a band extending from Magnolia, TX through Conroe, TX where the clay thickness is greater than 150 feet (see Figure 6). Like the formations that comprise the Chicot Aquifer, the clays within the formations that comprise the Evangeline are relatively young at less than 16 million years.

The Middle Lagarto (equivalent to the Burkeville) averages about 450 feet thick in Montgomery County with a maximum thickness of nearly 800 feet. While the Middle Lagarto is generally considered to be clay rich, sand percentage estimates from Young and others (2012) indicate the sand content is comparable to the other formations making up the GCAS. While the datasets show a relatively high sand content, the size of the sand grains may be small compared to other formations of the GCAS making it less capable of providing water to wells. The dataset from Young and others (2012) for the Middle Lagarto indicates some uncertainty in the clay thickness along a northeast trending band through Montgomery, TX. In the area updip (northwest) of the band, the clay thickness gradually increases to about 300 feet and then abruptly decreases to 200 feet or less through much of the rest of the county (see Figure 7). The uncertainty is likely associated with Young and others (2012) combining two or more datasets. The clay thickness contours to the southeast of the band are likely representative of the clay thickness in the Middle Lagarto as the estimates are based on analysis of geophysical logs in the area.

The Lower Lagarto and Oakville formations that comprise the Jasper Aquifer are found throughout nearly all of Montgomery County. These formations exceed 500 feet and 700 feet, respectively. The maximum sand percentage for these formations is slightly less than the maximum values for the other formations that comprise the GCAS. Clay thickness within the Lower Lagarto is generally more than 150 feet throughout most of the county with the clay thickness exceeding 350 feet northwest of Porter, TX (see Figure 8). The clay thickness of the Oakville Formation is typically more than the Lower Lagarto. In much of the county, the clay thickness of the Oakville exceeds 250 feet with the greatest thickness of the more than 500 feet found in an area southeast of Conroe, TX (see Figure 9).

2.2 Structure

As mentioned above, the formations of the GCAS dip and become thicker toward the Gulf of Mexico creating a wedge-shaped aquifer. The top of the GCAS is at land surface throughout the District. However, due to the formations dipping at a rate of about 65 feet per mile, in most of Montgomery County the top of the units that make up the Evangeline and Jasper hydrostratigraphic units is encountered below land surface.

To illustrate the structure of the local geologic and hydrostratigraphic units, we prepared five cross-sections through Montgomery County (see Figure 10). Three of the cross-sections are along the dip of the geologic units and are essentially perpendicular to the Gulf Coast(Figure 11, Figure 12 and Figure 13).Two cross-sections illustrate the configuration of the units along their strike and area essentially parallel to the coastline (Figure 14 and Figure 15). Structural cross-sections are from the files developed by Young and others (2012). The total dissolved solids ("TDS") isolines are from data sets developed by Young and others (2016).

The three cross-sections along the dip of the aquifer (Figure 11, Figure 12 and Figure 13) illustrate how the rate of dip is relatively consistent across the District. However, the dip and structure south of Montgomery County does not appear to reflect the shallow salt dome mapped along cross-section B-B' (Figure 12; Figure 16). In addition, the cross-sections do not appear to reflect the major growth fault mapped in Montgomery County. Nonetheless, the datasets presented do adequately reflect the complexity of the structure of the GCAS along with the estimated sand and clay thicknesses as they relate to potential subsidence.

2.3 General Subsidence Processes

As discussed by Furnans and others (2018), there are three primary variables that determine the magnitude, location, and timing of subsidence related to groundwater pumping, namely:

- The distribution, thickness, and compressibility of clay layers;
- The amount and timing of water-level changes; and,
- The lowest historical water level.

Compaction of the aquifer materials, and associated land surface subsidence, occurs when there is an increase in the effective stress on the geologic formations. Terzaghi (1925) developed a relationship that allows for the calculation of the changes in effective stress within the aquifer due to the changes in water level. According to Terzaghi's relation, the effective stress within aquifer may be simplified into two components, namely, geostatic stress and hydrostatic stress (Leake and Galloway, 2007):

$$\sigma' = \sigma - u$$

where

$\sigma' = effective\ stress\ (psi)$
$\sigma = geostatic\ stress\ (psi)$
$u = hydrostatic\ stress\ (psi)$

The geostatic stress is relatively constant being related to the depth of burial, depth to moist sediments, and the sediment characteristics. The hydrostatic stress changes easily and as water levels decline the hydrostatic stress decreases which causes the effective stress to increase. As the effective stress increases the geologic units compress causing a decrease in the ratio of the open space in the formation to the solids making up the formation (that is, the void ratio) based on the compression and recompression indices of the units which are directly related to the elastic and inelastic storage coefficients for the aquifer units (Leake and Galloway, 2007). These aquifer properties control the amount of elastic and inelastic compaction that occurs with inelastic compaction due to water level declines being permanent and of much greater magnitude than elastic compaction or expansion.

The void ratio within clay sediments is generally much higher than in sand sediments and may exceed 50 percent. In addition, clay minerals typically have a flat, plate-like structure while sands tend to be rounded and more irregular. When deposited, the orientation of the clay minerals is random, but as the effective stress increases the clay mineral grains reorient perpendicular to the direction of the effective stress. Figure 18 illustrates how this reorientation of the minerals is manifested in compaction of the aquifer and land surface subsidence.

In Houston and the surrounding area there are currently more than 200 subsidence monitoring locations. Most of these locations use global positioning satellite (GPS) receivers to monitor the movement of land surface though there are a handful of extensometers that are able to directly measure compaction of specific aquifer intervals. Figure 19 illustrates the location of several sites maintained by the University of Houston and the HGSD with a land surface subsidence monitoring history of more than five years (HGSD, 2020) along with contours of the total subsidence from 1906 to 2017 as reported by the HGSD. As Figure 19 illustrates, the highest rates and amounts of subsidence are south of Montgomery County. Based on the available measurements, the rate of subsidence is one-half inch per year or less throughout the county and is typically less than one-quarter inch per year.

3.0 EXISTING STUDIES AND DATA

Most historical subsidence studies for the "Houston-Galveston region" include all of Harris County and parts of Brazoria, Chambers, Fort Bend, Galveston, Liberty, Montgomery, and Waller counties. Subsidence has been recognized in the Houston-Galveston region of Texas for almost 100 years. One of the earliest reported occurrences of land-surface sinking is the 1926 relatively localized subsidence associated with the Goose Creek oil field.

Historical subsidence across the region is primarily associated with groundwater withdrawals from the Chicot and Evangeline aquifers in Harris County, with the earliest studies linking groundwater pumping to subsidence conducted in the 1940s and 1950s (Winslow and Doyel, 1954; Winslow and Wood, 1959; Gabrysch, 1967). There have been numerous subsidence studies conducted for the region, with some of the defining studies conducted in the 1970s and 1980s. Also, critical monitoring programs and continuations of previous studies are on-going. Additionally, new and expanded studies have begun or are being planned to add to the understanding of subsidence in the region.

3.1 Types of Studies and Data Available

This study focuses on a review of previous studies beginning in the 1970s that formed the critical background understanding of subsidence in the region and formed the basis for current and on-going monitoring programs and performed by the USGS and HGSD. The following provides a general synopsis of the types of studies available, data and information collected and compiled, and overviews of key findings from previous work. Brief detailed summaries for selected reference studies are included in Section 3.2.

3.1.1 Topography and Re-Leveling

The USGS has used topographic maps (with one-foot contour intervals) from 1915 through 1917 leveling efforts as a basis to estimate land-surface subsidence in the Houston area throughout the last 100 years (Kasmarek and others, 2009). Initially, all land-surface subsurface subsidence determinations in the region were made by geodetic differential leveling. A detailed discussion of the history and methodologies of control leveling is beyond the scope of this study.

The U.S. Department of Commerce National Oceanic and Atmospheric Administration (NOAA) discusses the history, instrumentation and methods in its document titled ***Control Leveling*** (Whalen, 1978). Measuring land-surface changes via leveling involves comparing surveyed elevations of official benchmarks at determined locations at specific times. Elevations are determined and obtained by conventional, but precise, leveling methods. The USGS reports, "Most of the determinations were made by the National Geodetic Survey and their predecessor agency, the U.S. Coast and Geodetic Survey. Elevations determined by private and public entities other than the National Geodetic Survey (City of Houston; Texas Department of Highways and Public Transportation; U.S. Army Corps of Engineers; and others) also have been used" (Gabrysch, 1980).

Reportedly, there are up to 2,500 benchmarks in the leveling network, with some sites dating back to 1906 (Ratzlaff, 1982). **Error! Reference source not found.** shows locations of benchmarks and subsidence d etermined by leveling from 1906 to 1973, showing maximum subsidence in southeastern Montgomery County of one foot. Due to the regional nature of subsidence most of the benchmarks have moved.

Therefore, re-leveling efforts were required (for example,1978 and 1987) to maintain consistency in reported subsidence values. Each leveling effort is labor intensive and relatively expensive.

As other technologies have become available and accessible, land-surface elevations determinations from new methods can be correlated to the most recent leveling efforts. For example, data from remote sensing methods such as Light Detection and Radar (LiDAR) and Interferometric Synthetic Aperture Radar (InSAR) can be obtained and processed to more cost-effectively compare land-surface movement over time and over larger areas, allowing for determinations of subsidence and fault movement. As an example, the USGS estimated long-term subsidence by subtracting land-surface elevations determined from 2001 LiDAR imagery from the 1915-1917 topographic maps, and showed maximum subsidence between 1915/1917 and 2001 of slightly less than three (3) feet in southeastern of Montgomery County (Kasmarek and others, 2009). Because leveling formed the initial basis of subsidence measurements and determinations, Phase 2 of the LSGCD subsidence study will include reviewing and understanding the evolution and accuracy of historical land-elevation measurements, particularly in Montgomery County.

3.1.2 Hydrogeology and Geotechnical

Subsidence and surficial expressions of hundreds of identified growth faults resulted in numerous studies beginning in the 1970s and 1980s, with most of the earlier studies focused in areas of greatest subsidence. In fact, the connections and relationships between land-surface subsidence, surficial movement along growth fault planes, and salt domes has been debated.

Subsidence

LRE reports that "…the three primary variables that determine the magnitude, location, and timing of subsidence related to groundwater pumping…" are: 1) the distribution, thickness and compressibility of clay layers; 2) the amount and timing of water-level changes (which are governed by pumping); and, 3) the lowest historical water level (Furnans and others, 2018). The USGS and TWDB published between 1974 and 1976 several initial and defining reports pertaining to Houston-area subsidence based on field geologic and geotechnical studies at sites within areas that had experienced the most subsidence, including:

- area of Burnett, Scott, and Crystal Bays near Baytown, Texas (Gabrysch and Bonnet, 1974);
- at Seabrook, Texas (Gabrysch and Bonnet, 1976); and,
- area of Moses Lake near Texas City, Texas (Gabrysch and Bonnet, 1976).

The three studies listed above included the following: drilling and obtaining core samples of clays from test holes; geophysical logging to determine sand and clay thicknesses; obtaining laboratory analyses of geologic and geotechnical parameters including mineralogy, specific gravity, plasticity, porosity, consolidation coefficient, and compressibility with depth (or loading); understanding of the local and regional distribution of pumping in the Chicot and Evangeline aquifers; and, compiling water-level measurements to derive artesian pressure declines in each aquifer. Deepest clay samples at the Baytown site were collected from a depth of 1,216 feet which is within the approximate upper one-third of the Evangeline aquifer. For the Baytown study, a clay core sample was collected from a University of Houston site, approximately 19 miles to the west, from a depth of 1,647 feet which is slightly deeper than the upper half of the Evangeline. The deepest clay sample collected at the Moses Lake site was collected from a depth of 700 feet, and all the clay samples for the site were obtained from the Chicot aquifer (Gabrysch and Bonnet, 1976). The deepest clay sample for the Seabrook study was collected from a depth of 1,340 feet below land surface, which is within approximately the upper 40 percent of the Evangeline aquifer. The USGS determined from the laboratory and field data ranges in a unit measure of compressibility, termed specific compaction (Gabrysch, 1967). In later reports based on the 1970s studies the USGS concluded, "Records of compaction at different depth intervals obtained from extensometers, subsidence based on elevation data, and laboratory testing show that most of the subsidence is due to compaction of shallow material. It is suspected that compressibility of the material is related both to the age of sediments and the depth of burial" (Gabrysch, 1984). The first extensometers were installed at each of the three study sites which allowed for correlation of past compaction and resulting subsidence to be correlated to the geologic, geotechnical, pumping and water-level data collected. Additionally, the three original extensometers and those added layer allow for ongoing direct measurements of compaction in the targeted completion intervals. Results of the field studies and correlating extensometer readings to leveling results for total subsidence were used to develop hydraulic and geotechnical parameters for modeling efforts including Predictions Relating Effective Stress to Subsidence (PRESS) models in Harris, Galveston, and Fort Bend Counties, and the initial Groundwater Availability Model (GAM) and Houston Area Groundwater Model (HAGM).

The geologic setting and pumping distribution in Montgomery County is and will be different than that found downdip (i.e., Harris County). As illustrated in Section 2.0, the total thicknesses and clay thicknesses in the Chicot and Evangeline layers are generally thinner in Montgomery County than in Harris County. The clay layers in the Upper Jasper are similar on both sides of the county boundary between Montgomery and Harris counties (Kasmarek and Robinson, 2004). However, there is more pumping from the Jasper in Montgomery County than in Harris County. INTERA utilized the results determined for Chicot and Evangeline clay layers in Harris County and made adjustments for depth to derive estimates for clay properties for the Jasper aquifer (Kelley and others, 2018). Gabrysch noted that relative compressibility of clay layers is related to both the geologic age and depth of materials. Based on information presented by Young and others (2012) and the University of Houston (Yu and others, 2014), **Error! Reference source not found.** summarizes the geologic age and depositional systems associated with the layers of the Gulf Coast Aquifer System.

Phase 2 of this subsidence study will provide critical and detailed assessments of thickness and distributions of sand and clay layers and associated hydraulic parameters for the Gulf Coast Aquifer System layers in Montgomery County, and particularly with respect to the Burkeville and Jasper units.

Growth Faults

The University of Texas Bureau of Economic Geology (BEG) reported in 1977 that there were at least 150 miles of active faults with topographic escarpments in Harris and Galveston counties (Kreitler, 1977). While the 1977 BEG study did not include Montgomery County, long southwest-to-northeast trending fault traces in northern Harris County almost certainly cross the county line. Fault traces are commonly recognizable as lineations on aerial photographs, although vegetation and land use changes can mask surficial fault expressions. Kreitler concluded that there is fault control of subsidence, although he did reference others who suggested that faulting and subsidence were unrelated (McClelland Engineers, 1966; Van Siclen, 1967). Kreitler also suggested that faulting may "compartmentalize" groundwater flow and resulting subsidence.

The University of Houston reports that more than 300 active faults intersect land surface in the Houston area (Engelkemeir and Khan, 2013), and used LiDAR to map faults. UH notes, "Most most (80%) of the faults in the Houston area occur over salt domes." The UH study noted that the Hockley-Conroe Fault System extends "well outside of Harris County". UH concludes that fault locations do not closely correlate to subsidence depressions, but instead appear to be more closely related to regional and salt-dome tectonics (Engelkemeir and Khan, 2013).

I2M Associates, LLC (I2M) and SWS Environmental Services (SWS) reported on growth faulting and subsidence (Campbell and others, 2018), noting Ground-Penetrating Radar (GPR) as an effective technology to characterize faults below roadways. I2M and SWS note that LiDAR will also help identify faults, but that surface mapping is also required. I2M and SWS point out that faulting is common atop and near salt domes, and that Mullican III (1988) concluded that 70 percent of 30 salt domes he evaluated experienced subsidence, collapse or both due to natural or anthropogenic causes (Campbell and others, 2018). I2M and SWS state note that "…the hypothesis that soft-sedimentation/growth faulting is related to subsidence and fluid withdrawal from the subsurface in some areas was once soundly discounted. The relationship of faulting to subsidence (or vice versa): and the mechanisms for the observed faulting are still being debated" (Campbell and others, 2018). They note that faulting is likely caused to varying degrees at different places by subsidence, movement of salt domes and the deeper Louann salt bed, and load-induced crustal warping at depth.

Southern Methodist University (SMU) reported concerning the use of interferometric synthetic aperture radar (InSAR) to identify and monitor growth faults (Qu and others, 2019). The SMU study focused on the Hockely-Conroe Fault System, identifying specifically the "…Hockley fault [sic] System, the Big Barn fault [sic] System and the Conroe Fault System" (Qu and others, 2019). The SMU report notes that salt domes are a major cause of local faulting and maps show at least three salt domes along the trend of the Hockley-Conroe Fault System. The SMU study concludes that "…newly discovered fault activation appears to be related to the stress associated with fluid pressure reductions caused by excessive water extraction from Montgomery County aquifers" (Qu and others, 2019). Specifically, the study states that the cause of the faulting associated with 2007 through 2011 InSAR imagery is related to "…excessive groundwater exploitation" and "…continuous mining of groundwater from the Jasper aquifer…" in Montgomery County (Qu and others, 2019). However, the only direct evidence provided correlating pumping to the faulting is general recitations of total groundwater pumping in Montgomery County in 1976, 2000 and 2010 (Qu and others, 2019) and a map showing "…the InSAR observed deformation rate from 2007 to 2011…" and contours illustrating groundwater elevation change in the Jasper aquifer from 2000 to 2011.

Damage to structures located atop faults that have recently moved has been identified by residents in The Woodlands and at the Conroe Aquatics Center. The San Jacinto River Authority (SJRA) installed safety measures and monitoring benchmarks along portions of its pipeline that cross the Big Barn and Egypt faults. The SJRA engaged consulting geologist Carl E. Norman, Ph.D., PG, to conduct a series of 10 measurements between 2016 and 2020 to monitor fault movement. Dr. Norman concluded that the slight movements at some of the measured benchmarks are too small to indicate fault activation or movement. Some area residents disagree with that finding. Data from the Continuous Operated Reference Stations (CORS) are available along the Hockley Fault System (near Woodlands High School) are available as part of HOUSTONNET.

Phase 2 will include collecting more fault documentation including additional reports, evaluating benchmark data, and processing available remote sensing imagery. The work will also involve conducting correlations to specific time periods as related pumping and water-level changes in and near Montgomery County.

3.1.3 Extensometers

Borehole extensometers provide the only means of direct measurement of compaction within a particular geologic interval. Extensometers are expensive to install and are only applicable for a specific site; however, they provide for a continuous record of compaction and preciseness. Combined with collecting geologic and geotechnical data, water-level measurements, and vertical and lateral pumping distributions, extensometer data allows for determining critical parameters for understanding and predicting subsidence. Extensometer data is quite helpful as it allows for correlation with other methods including leveling, GPS methods, and remote sensing technologies.

There are currently 12 sites with 14 borehole extensometers in Harris, Galveston, and Fort Bend counties, with paired (that is, shallow and deep) extensometers at two sites. Where extensometers are co-located they can be used to delineate between compaction in shallow versus deep zones. Extensometer readings also illustrate the variation in compaction based on depth, character, and thickness of the clay layers. There are no extensometers in Montgomery County, and the closet extensometer is the Lake Houston site. Extensometer information is important regarding LSGCD's subsidence study because the extensometer data were used to develop key correlations and modeling parameters used in the PRESS modeling and in the development of the GAM and HAGM.

3.1.4 Global Positioning System Network

Beginning in the late 1980s permanent sites were installed and land surface measured repetitively via global positioning system (GPS) technologies. Prior to 2000, 15 permanent sites were installed and currently there are more than 200 sites maintained and monitored by the HGSD and University of Houston (UH). There are two types of sites; Continuous Operating Reference Stations (CORS) and Port-A-Measure (PAM) sites. These sites allow for collecting relatively continuous data with good areal coverage in a cost-effective manner. The collected data requires post-processing to account for satellite orbit, clock information, atmospheric conditions, and other potential interferences. Reported "daily ambiguity" is six (6) to eight (8) millimeters vertically and less horizontally. Due to the small scale of reported subsidence (that is, millimeters or centimeters), it is critical that any problems associated with a CORS or PAM site or abnormalities in the processed data be carefully checked and corrected. For example, Lake Conroe Citizens Network (LCCN) provided public comments to LSGCD (and others) questioning the accuracy and validity of reported data and results for CORS-TXCN near the City of Conroe (Massey, 2015).

UH reports the average subsidence rate based on GPS data for the period from 2005 to 2014 to be between 17 and 19 millimeters per year (mm/yr), or 0.67 to 0.75 inches per year (in/yr), and only mentions pumping from the Chicot and Evangeline aquifers (Wang and others, 2015). Figure 29 is a map generated and presented by the Harris-Galveston Subsidence District (HGSD) showing the highest rates of subsidence during the period from 2014 to 2018 occurred in southwest Harris County, near Jersey Village, and in northwest Harris County near Tomball, with reported subsidence rates greater than 2 centimeters per year (cm/yr), or greater than 0.79 inches per year (in/yr). HGSD reports that the highest measured rates of subsidence in Montgomery County is between 1.0 and 1.4 cm/yr (0.4 and 0.6 in/yr) near the Woodlands, just to the north of Tomball and near Magnolia. HGSD provides charts and comments that subsidence at one site, PAM Site 13 (PA13), has reduced from about 2 cm/yr to less than 0.5 cm/yr coinciding with implementation of alternative water sources in Montgomery County (see Figure 30).

There are 15 GPS sites within Montgomery County. Such sites are the only means by which to timely and efficiently determine essentially real-time movement of land surface at sites in Montgomery County (and other counties). The sites only allow for determining the overall movement of land surface, and do not independently allow for determining the magnitude of compaction in any one layer of the Gulf Coast Aquifer system. Therefore, the GPS data must be carefully and accurately processed, compared, and correlated to historical pumping and water-level data.

3.1.5 LiDAR and InSAR (Remote Sensing)

Remote sensing techniques, particularly LiDAR and InSAR have been utilized to quantify land-surface movement over time with respect to both subsidence and movement along growth faults. Processing of imagery can provide high resolution and refined scale interpretations to identify even small amounts of land movement. It was previously mentioned in this report that the USGS utilized LiDAR to compare with historical topography to estimate long-term regional subsidence. Also, InSAR was discussed relative to studies to identify surface expressions of growth faults, and how subsequent dates of imagery can be used to quantify movement over time. LiDAR is typically utilized over smaller areas while InSAR may provide more expansive coverage and may be a cost-effective technology for studying fault movement and bolstering subsidence measurements. Comparing remote sensing data with GPS and extensometer measurements provides correlation and enhances reliability.

UH reported, "Contrary to previous studies in which the locations of subsidence appeared to be expanding toward the northwest, current results show that the area of subsidence is shrinking and migrating toward the northeast" (Khan and others, 2014). UH concluded that "(t)he digital elevation model (DEM) derived from LiDAR documented elevation changes within the salt domes relative to their surroundings" presumably for the period from 1994 to 2011 (Khan and others, 2014). The same study notes that sediment compaction due to groundwater withdrawal cannot account for all of the subsidence and uplift delineated, and states that more study of salt diapirism in the subsurface may be warranted.

The USGS conducted investigations utilizing GPS data and InSAR imagery to assess land-surface subsidence from 1993 to 2000. The USGS notes potential error considerations in processing and utilizing LiDAR including interference that may be introduced due to dense vegetation, atmospheric moisture, high humidity, and topography. While southern Montgomery County and areas south are relatively flat topographically, central and northern parts of the county exhibit significant topographic relief (Bawden and others, 2012). Figure A provides a map from the USGS that shows the rate of subsidence at PAM Site 13 near The Woodlands to be as much as 20 mm/yr, while the subsidence rate in northwest Harris County is at least double that rate – the dates for the map are unclear. Figure B provides a map that shows Evangeline aquifer water level changes from 1990 to 2003.

Effectively utilizing remote sensing imagery and deriving reliable and accurate results and conclusions requires proper correlation of the imagery intervals (that is, time) to known data such as pumping distribution (vertically and laterally) and water-level or pressure changes. Phase 2 of this subsidence study will look into acquiring and processing imagery and making detailed correlations and comparisons to aquifer data for all layers of the aquifer. Additionally, we understand that HGSD is undertaking expanded InSAR studies within the region. LSGCD should monitor progress of those studies and/or may wish to inquire as to participating in the studies as possible. Phase 2 of this subsidence study will better determine the level of participation by LSGCD.

Some studies have used remote sensing techniques to assess flood plains before, during and during flooding events. Phase 1 of this subsidence study focused on previous works in which subsidence and fault movements were detected and/or measured, not on studies addressing potential flooding resulting from such movement.

3.1.6 Analytical and Numeric Models

Because of population growth and regulation has resulted in relatively rapid changes in pumping locations and distributions away from where subsidence has historically been greatest and has been measured for many years, modeling has become necessary to be able to predict potential compaction and resulting subsidence over larger areas and with varying parameter estimates. Electric analog modeling of the Houston area aquifers was first conducted in 1965, and a second electric analog model was constructed in 1975 that allowed for inter-aquifer leakage (Carr and others, 1985). The USGS developed the first digital groundwater-flow model that also allowed for simulating and predicting compaction in the Chicot and Evangeline clay layers in 1985. Analytical modeling of subsidence was introduced in the early 1980s. The USGS developed the initial TWDB-approved GAM for the Northern Gulf Coast Aquifer in 2004, and the Northern Gulf Coast Aquifer GAM was updated to the HAGM in 2012 (modified in 2013). The HAGM is the first groundwater flow model that expressly simulates compaction in all of clay layers of the designated Gulf Coast Aquifer System in GMA 14, including the Burkeville confining layer and the underlying Jasper aquifer.

Analytical PRESS Model

The USGS reports that the first model to simulate land-surface subsidence is known as the Predictions Relating Effective Stress to Subsidence (PRESS) model, which is essentially a site-by-site analytical model (Kasmarek, 2013). Espey-Huston and Associates (1982) developed a model utilizing the PRESS. PRESS does not simulate water-level or artesian head changes. Fugro-McClelland, Inc. used the PRESS to simulate subsidence in 1997, and simulated water-level declines from an LBG-Guyton Associates model (1997) were used as input data for PRESS model runs at more than 20 sites in the Houston area (Kasmarek, 2013). PRESS model runs were conducted for 26 sites in Harris, Galveston and Fort Bend counties utilizing water levels from HAGM simulations as inputs; the subsidence simulated by the HAGM compared favorably with PRESS runs utilizing HAGM water-levels (Kasmarek, 2013). Figure C provides a map from the USGS showing the comparison of PRESS subsidence calculations as compared to results from the HAGM and actual measured values (Kasmarek, 2013). INTERA notes that PRESS model results are representative of a defined area over which the modeled parameters are considered representative (Kelley and others, 2018). PRESS models have been created for six (6) extensometer sites (Kelley and others, 2018). Therefore, it is apparent that the parameters for PRESS models are derived at least in part by calibrating the compaction/subsidence to actual measured values. PRESS can simulate one or two layers, but if two layers are modeled head values must be specified independently for each zone (Kelley and others, 2018).

Original GAM and the HAGM (Numeric Groundwater Flow Models)

The United States Geological Survey (USGS) reports that nine (9) groundwater flow models prior to the HAGM were developed covering at least parts of the HAGM study area (Kasmarek and Robinson, 2004). Kasmarek and Strom (2002) developed a groundwater flow model that simulated groundwater flow and compaction/subsidence in the area. Subsequently, Kasmarek and Robinson (2004) developed the original Northern Gulf Coast Aquifer Groundwater Availability Model (NGC GAM) which was conducted "…in cooperation with the Texas Water Development Board and the Harris-Galveston Coastal Subsidence District" and is reported in USGS Scientific Investigations Report (SIR) 2004-5102. While clay thickness maps were provided in the 2004 report, the USGS states, *"Compaction of clays in the Jasper aquifer and the Burkeville confining unit were not simulated because the sediments of those units are geologically older, more deeply buried, and therefore more consolidated relative to the sediments of the Chicot and Evangeline aquifers. Additionally, substantial potentiometric-surface declines such as have occurred in the Chicot and Evangeline aquifers in the greater Houston area have not occurred in the Jasper aquifer, and probably not in the Burkeville confining unit"* (Kasmarek and Robinson, 2004). The USGS reported in their subsequent report SIR 2005-5024 pertaining to projected water-level changes and subsidence utilizes the NGC GAM to simulate various hypothetical withdrawal scenarios. Subsidence predictions documented in the 2005 report showed large subsidence amounts in Montgomery County by the year 2000 with none of the subsidence represented by Jasper pumping (which was limited to less than 50 million gallons per day or less than 56,000 acre-feet per year throughout the model area). The USGS reported that the model runs (i.e., showing excessive drawdown and subsidence) using the hypothetical withdrawal scenarios "…indicated the need for modifications to the NGC GAM model input data…" (Kasmarek and others, 2005). The USGS made input changes and re-calibrated the model.

The USGS developed the HAGM in 2012 and revised the report in 2013 (Kasmarek, 2013) "…in cooperation with the Harris-Galveston Subsidence District, the Fort Bend Subsidence District, and the Lone Star Groundwater Conservation District". Per the USGS, the HAGM was updated and recalibrated to better reflect current (and future) groundwater withdrawals, and to be able to simulate compaction in the Chicot, Evangeline, Burkeville and Jasper layers of the Gulf Coast Aquifer system (Kasmarek, 2013). The USGS states, "Local and regional water managers can use the HAGM as a tool to simulate aquifer response (changes in water levels and clay compaction) to future estimated water demands" (Kasmarek, 2013). The USGS notes, "Because a large area of land-surface subsidence has been documented in Harris County and parts of Galveston, Fort Bend, Montgomery, Brazoria, Waller, Liberty, and Chambers counties, only these areas of the HAGM can be considered calibrated for elastic- and inelastic-storativity", noting values for all layers of the Gulf Coast Aquifer system (Kasmarek, 2013). Additionally, the USGS noted that "…good correlation exists between the PRESS and HAGM simulated values" for the PRESS model sites located in within HGSD and FBSD (Kasmarek, 2013). The point of this information is not that the HAGM is perfect or "correct" as, in fact, there are several problematic issues with the HAGM including the lack of documentation, general head boundary conditions simulating recharge, the lack of the model's ability to convert from artesian to water-table conditions, and possible calibration concerns. However, the HAGM is currently the best available science based on its acceptance by the TWDB and is based on numerous and repetitive efforts to calibrate a model that includes representative compaction parameters for all layers of the Gulf Coast Aquifer system.

Based on the reported model parameters and on numerous model runs conducted by LRE for GMA 14 purposes, the HAGM shows that the Burkeville confining layer and the Jasper aquifer are much less susceptible to compaction and resulting subsidence than the overlying Chicot and Evangeline aquifers. Figure D illustrates the inelastic-clay storativity parameter in the HAGM for the Jasper aquifer. Section 4.0 of this report includes discussions and illustrations of specific model runs utilizing the HAGM.

Brackish Jasper Aquifer Subsidence Model (INTERA)

INTERA created on behalf of the Harris-Galveston and Fort Bend subsidence districts a model to simulate compaction and resulting subsidence due to artesian-head reductions in the Jasper aquifer and published a report (Kelley and others, 2018). We have only reviewed the published report for the Jasper model, and do not yet have the model files. FigureE shows that the "Study Area" for delineated in the published report extended into the northern half of Montgomery County and Figure F illustrates that the model grid covers the entirety of Montgomery County additional to other counties. A review of the report shows that INTERA populated the entire model grid domain with hydraulic parameters; however, Figure G shows and the report states that the extent of the Jasper compaction model domain coincides with the brackish groundwater delineation from the brackish water delineation study reported in 2017 for the subsidence districts (Young and others, 2016; Kelley and others, 2018). Detailed reviews of the actual model files, model simulations and report are needed. However, based on our preliminary review, the INTERA Brackish Jasper model is generally based on the following:

- Utilizing laboratory geotechnical values from core samples collected from the Chicot and upper half of the Evangeline during the 1970s at the Seabrook, Moses Lake and Baytown study sites and adjusting the values for parameters including porosity, compressibility, specific storage, and vertical hydraulic conductivity values based on depths of burial; and,
- Simulating 500 feet of pressure decline in the Jasper aquifer centered for each nine-by-nine mile cell.

The INTERA report assesses "…the relative risk of subsidence from brackish groundwater development in the Jasper Aquifer" (Kelley and others, 2018). The report concludes, "The literature, available data and calibrated models confirm that the Jasper will compact." However, in the previous sentence INTERA states that there "…is a general lack of data regarding subsidence potential for the Jasper Aquifer." The INTERA Jasper report also states, "It is our opinion that the general relative risk to subsidence from pumping in the Jasper Aquifer is supported by available data under the <u>assumptions employed</u>. However, the absolute amount of compaction that may be predicted to occur is considered uncertain. For these reasons, the risk assessment was performed in a manner to report relative risk of subsidence so that the underlying trends in risk are presented without presenting actual compaction or subsidence amounts" (emphasis added). Therefore, contrary to some public statements, the INTERA Jasper model clearly does not definitively predict any certain amount of compaction (also note that all compaction does not translate to surface expressions of subsidence). Figure H illustrates potential compaction amounts from

INTERA's Jasper model with a range from low to high. Figure I provides a map included in the INTERA report illustrating the relative or "total normalized risk scope" for the Jasper Aquifer. Phase 2 of the LSGCD subsidence study will include a detailed review of INTERA's Jasper model and report.

3.1.7 Water-Level and Pumping Records

To assess pumping within Montgomery County we obtained reported pumping and permitted well data from the District. For wells that had not been assigned an aquifer within the District database, we used completion information along with the formation depths developed by Young and others (2012) to identify the likely aquifer from which the well was producing. For some wells, the production interval could not be identified and was simply assigned as producing from an indeterminate aquifer.

Reported production since 2009 peaked in 2011 at about 94,000 acre-feet. Since 2011 Overall pumping has generally decreased with the largest declines in pumping occurring in the Evangeline and Jasper. Evangeline pumping decreased from more than 42,000 acre-feet in 2011 to about 28,000 acre-feet in 2018 while Jasper pumping declined from about 38,000 acre-feet to 18,000 acre-feet during the same period. Figure 20 illustrates the total reported pumping in Montgomery County.

As would be expected with the pumping pattern illustrated in Figure 20 measured water levels tend to be deepest around 2011 followed by a general recovery. The largest changes in water levels have occurred in the deeper wells in southern Montgomery County. Figure 21 provides several hydrographs illustrating the reported changes in water levels. The location of each well associated with a hydrograph is shown on Figure 22.

Using the water level data from the TWDB Groundwater Database (TWDB, 2020), we also developed contours of the water level over the last 30 years. As we observe in the hydrographs for wells completed in the Chicot Aquifer, water levels have generally declined but at a relatively slow rate in that aquifer. Figure 23 illustrates the changes in water levels in the Chicot aquifer at 10-year intervals beginning in the winter 1988-89. Comparison of Figure 23(A) and Figure 23(D) reveals that the 50 foot contour has moved northwesterly on the map indicating deeper water levels in the Chicot Aquifer in the southern part of District.

Over the last 10 years, annual pumping volumes from the Chicot are less than 10,000 acre-feet and are generally less than 7,500 acre-feet. While these water level declines are in part due to pumping in LSGCD, the water level declines are also due to production in neighboring counties. **Error! Reference source not found.** illustrates the distribution of reported pumping from the Chicot Aquifer in Montgomery County that influences the water levels in the aquifer. As the series of maps in Figure 24 illustrate, the highest pumping rates from the Chicot are generally in The Woodlands area.

The water level declines in the Evangeline are more evident than those in the Chicot. Figure 25 we observe water levels decline from about -100 feet MSL to -250 feet MSL between map (A) and map (C). In map (D) we observe some rise in the Evangeline water levels in southern Montgomery County. As previously stated, pumping in the Evangeline has decreased recently which has resulted in the water level rise. As illustrated in the series of maps in Figure 26 much of the decrease in pumping also occurred in southern Montgomery County as indicated by the transition from warm colors to cool colors.

Most of the wells with recent Jasper water-level measurements are in southern Montgomery County (see Figure 27). While there are few early measurements, the available data on map (A) indicate relatively shallow water levels. More recent measurements shown on map (D) indicate water levels have declined by about 200 feet.

The recent distribution of pumping in the Jasper is illustrated in the map series in Figure 28. The water level declines observed in the Jasper in southern Montgomery County are primarily due to the pumping in that area. The map series on Figure 28 also shows the decrease in Jasper pumping that occurred in 2016. With the decrease in pumping we would anticipate water levels would rise.

3.2 Summaries of Selected References

The following provides brief detailed summaries of information presented in selected references related to subsidence.

3.2.1 Identification of the Vulnerability of the Major and Minor Aquifers of Texas to Subsidence with Regard to Groundwater Pumping

The objective of this project was to assess the subsidence risk due to groundwater pumping for every major and minor aquifer in Texas to assist Groundwater Conservation Districts in meeting their subsidence control and joint planning requirements. Subsidence is a process that is difficult to measure because it usually happens very slowly and can take decades to accumulate tens of feet of land surface decline. As it typically takes a long time to manifest, prediction of future subsidence due to groundwater pumping based on information available today is an important part of subsidence risk evaluation. Furnans and others (2018) synthesized water level decline predictions and aquifer characteristics using subsidence prediction tools and summarized these data for each of the major and minor aquifers in Texas.

In order to conduct the assessment, Furnans and others (2018) analyzed data from thousands of well logs and driller's reports. They also incorporated available subsidence observations, pumping records, and results from groundwater availability models to quantitatively assess subsidence potential. Using the data and calculation, they developed tools and techniques to evaluate the potential for subsidence based on clay thickness, clay type, aquifer lithology, pre-consolidation level, and future water level changes. Project deliverables included geodatabases of subsidence risk evaluations for each aquifer, a written report detailing the results of work associated with the project, and an Excel-based subsidence prediction tool.

The prediction tool developed was designed as a screening level assessment of the risk for subsidence based on clay thickness, clay type, and predicted water level changes at a well site. While it utilizes the equations for predicting subsidence, it was not designed to be used in place of numerical models which assess differential subsidence in a more robust manner. One key limitation of the tool is that it does not account for the delay between water level decline and compaction; rather, the tool applies the equations to calculate the total compaction relative to a change in water level.

3.2.2 Subsidence Risk Assessment and Regulatory Considerations for the Brackish Jasper Aquifer

The Harris-Galveston Subsidence District and Fort Bend Subsidence District commissioned Kelley and others (2018) for two purposes. In particular, the purposes of the project were to: 1) develop a relative risk assessment of subsidence related to brackish groundwater pumping in the Jasper Aquifer and 2) recommend a permitting and data collection process through which the brackish portion of the Jasper Aquifer could be developed while providing additional scientific data to aid management of the aquifer.

Results from the study (**Error! Reference source not found.**) are limited to the geographic area south of M ontgomery County, and suggest relatively high subsidence risk where the Jasper Aquifer is shallowest.

The report details methodologies for computing subsidence over time, and provides a detailed description of the mathematical basis for computing subsidence as included in both the PRESS model (Espey, Huston, and Associates, Inc., 1982) and MODFLOW-SUB (Hoffman and others, 2003). The authors utilized the MODFLOW-SUB package in conjunction with the Houston Area Groundwater Model (Kasmarek, 2013) rather than the PRESS model in assessing subsidence risk because such model results would be available over the entire study area domain (rather than at only selected PRESS model sites across the domain). The report also details a relative risk assessment methodology similar to that from Furnans and others (2018), yet applicable only to the Jasper Aquifer within Harris, Fort Bend, Galveston, and Brazoria Counties. The authors recognize the lack of available hydrogeologic data from the brackish portion of the Jasper Aquifer results in uncertainty in the computed subsidence values yet consider the uncertainty sufficiently uniform across the study area to allow for relative subsidence risk assessment.

3.2.3 Land Surface Subsidence in the Houston-Galveston Region, Texas

This report was completed in 1975 by the US Geological Survey under a cooperative agreement with the Texas Water Development Board and the cities of Houston and Galveston. A second report with the same title (yet focused on the period 1906-1980) was also completed and published in 1984. All material summarized in this section stems from these reports, referenced as: (Gabrysch and Bonnet, 1975) and (Gabrysch, 1984).

These reports present further data quantifying groundwater withdrawals in Harris and Galveston county, corresponding water level changes, and resulting rates of aquifer compaction and land subsidence. They demonstrate that subsidence rates were diminished after 1948 when Houston began utilizing more surface water to meet its water needs. This diminished subsidence rate continued until the 1970s when groundwater usage rates increased to levels exceeding those from the period before extensive surface water usage.

The authors demonstrate how subsidence may be lessened with decreased pumping of groundwater and how water levels can recover as a result. They used extensometers to measure compaction resulting from pumping in the Chicot and Evangeline aquifers, and concluded that most of the compaction was occurring within the shallower portion of the Chicot Aquifer. They also concluded that 80 to 85 percent of the subsidence that would occur as a result of groundwater pumping prior to 1973 had likely already occurred as of 1975. All combined, the reports provide evidence supporting the notion that limiting further groundwater usage in the Houston-Galveston region would limit any further subsidence. The authors also developed a basic method for predicting future subsidence based on clay compressibility, clay layer thickness, calculated water level declines, and specific-unit compaction quantities.

3.2.4 Land Surface Subsidence in the Texas Coastal Region

This report was completed in 1982 by the US Geological Survey under a cooperative agreement with the Texas Department of Water Resources. All material summarized in this section stems from the report, referenced as: (Ratzlaff, 1982). The purposes of the project were to: 1) quantify amounts of subsidence within the Gulf Coast Aquifer along the entire Texas Gulf Coast, and 2) qualitatively determine the cause for the subsidence. Potential causes were: 1) groundwater extraction, 2) oil and gas extraction, and 3) sulfur mining. Subsidence was quantified by comparing surveyed benchmarks as established by the National Geodetic Survey over the period from 1906 to 1973.

Counties of interest to LSGCD in this report were included within “Subregion 2” as defined in the USGS study. However, analysis was limited to the areas between (and including) Harris County to the Gulf of Mexico. Montgomery County was excluded from the analysis by Ratzlaff. As shown on Figure 32, analyses demonstrated that the majority of Subregion 2 experienced at least 0.5 feet of subsidence between 1906 and 1973 as a result of groundwater withdrawals. Portions of the Pasadena-Houston Ship Channel and surrounding area subsided by up to 9 feet over this same time period due to groundwater withdrawals. Subsidence due to oil and gas withdrawals was considered as a “local” occurrence and was reported as difficult to quantify due to a lack of accurate withdrawal information.

3.2.5 Investigation of Land Subsidence in the Houston-Galveston Region of Texas by using the Global Positioning System and Interferometric Synthetic Aperture Radar, 1993-2000

This report was undertaken by the US Geological Survey and was completed in 2012. All material summarized in this section stems from the report, referenced as: (Bawden and others, 2012). The report documents the use of Interferometric synthetic aperture radar (“InSAR”) along with long-term Global Positioning System (“GPS”) measurements from Continually Operating Reference Stations (“CORS”) to quantify subsidence within the Greater Houston area. The analysis was focused largely on Harris County with minimal analysis and description provided for adjacent counties. For the study, InSAR data were available from July 25, 1992 to December 19, 2000.

Analyses indicated good agreement between subsidence determined from relative GPS measurements and determined from InSAR data. Results suggest that the area of maximum historical subsidence (near Pasadena and the Houston Ship Channel) has stabilized, with subsidence largely decreasing or with the land surface elevation rebounding (increasing) slightly. The InSAR analysis also shows that most of the recent subsidence in the region is to the northwest of downtown Houston, including in portions of southern Montgomery County. Subsidence rates in southern Montgomery County were calculated as 20 mm/yr (approximately 0.75 in/yr).

Based on information reported by Bawden and others (2012), it appears that InSAR data are available for the majority of counties adjacent to Harris County, including the entire extent of Montgomery County. However, the analysis and results presented in the report largely focused on Harris County and the downtown Houston area, due to the availability of CORS GPS stations in these areas. It is possible that analysis of the InSAR data covering Montgomery County (not presented in this report) would provide additional insight into subsidence and land movement within the LSGCD.

4.0 PRELIMINARY MODELING

The Houston Area Groundwater Model (HAGM) is the TWDB adopted representation of the best available science for the GCAS. The HAGM was developed to simulate groundwater flow and compaction of the four hydrostratigraphic layers of the GCAS. Currently, the Harris-Galveston Subsidence District is working with the U.S. Geological Survey (USGS) to the replace the HAGM with the Gulf Coast Land Subsidence and Groundwater-Flow Model (GULF 2023). The USGS anticipates the draft of this new model will be complete by summer 2021.

The HAGM was published in 2013 (Kasmarek, 2013) and has been used for joint planning by Groundwater Management Area (GMA) 14 during the current and previous cycles. However, like the ongoing GULF 2023 model being developed, the HAGM was primarily developed as part a regulatory plan update by HGSD and its primary purpose was to assess the potential effects of management decisions by that entity. With a focus on the HGSD regulatory area, some modeling assumptions were applied that may be insignificant to the HGSD regulatory area but add uncertainty to the modeling results in Montgomery County. Examples of these limitations include (Keester, 2019):

- How it simulates recharge, evapotranspiration, and surface water interaction using a general head boundary;
- Grid discretization of one square mile; and,
- Constant transmissivity and storage properties.

While the HAGM has limitations with regard to its representation of the GCAS, groundwater flows, and subsidence predictions, it is nonetheless considered the best tool for planning and evaluation of groundwater management strategies. Results from modeling results simply must be interpreted within the model limitations. For this evaluation we reviewed several previously conducted model simulations to assess the potential impacts of various pumping scenarios. Table 3 summarizes the various scenarios reviewed and Table 4 provides the simulated pumping at the end of the predictive period in Montgomery County.

As shown on Table 4, there is a wide range in the simulated pumping rates for the GCAS. In the simulations review, pumping at the end of the predictive period ranges from about 64,000 to nearly 150,000 acre-feet per year. Figure 33 illustrates the range in the simulated pumping for each of the aquifers of the GCAS in Montgomery County. As we observe on the box-and-whisker plot, the greatest range in simulated pumping is from the Jasper Aquifer with comparatively small ranges in the Chicot and Evangeline.

As we observe during GMA 14 joint planning meetings, there are many ways to present the results from the HAGM. Examples of the various presentations include average drawdown, average subsidence, change in storage, or percent remaining available drawdown, along with many others (INTERA, 2019; Keester and others, 2020; LSGCD, 2020). These presentations of the results are simply ways to summarize the model output which is limited to water levels, aquifer compaction, and volumetric flow for each one square mile of the simulated hydrostratigraphic unit. Using these model outputs along with other data we are able to better understand and correlate model results to real-world measurements and measurement locations.

For our review and consideration of the results from the various scenarios, we focused on the evaluation of model results at active monitoring well locations. As recently presented to GMA 14 (Keester and others, 2020; LSGCD, 2020), rather than using results from the thousands of active model cells, we used the results at locations identified as monitoring wells in the TWDB groundwater database (TWDB, 2020). This method limits the evaluation to locations which historically also provide a real-world measurement. Figure 35 illustrates the location of monitoring wells utilized within the District to evaluate the model results. Table 5 and Table 6 provide the results at the end of the predictive period for the reviewed simulations for the average change in water levels and compaction of the aquifer sediments, respectively.

Like the distribution of pumping, the range in the average water-level decline (that is, drawdown) in the Jasper Aquifer is much larger than the Chicot or Evangeline. As shown on **Error! Reference source not found.**, the average drawdown in the Jasper ranges from nearly zero to almost 700 feet under the various scenarios. However, there is a very small range in average drawdown of just 23 to 42 feet in the Chicot and typically an increase in the water levels (that is, negative average drawdown) in the Evangeline.

Unlike the average drawdown, the simulation results shown the greatest range in maximum compaction associated with predicted water-level declines occurs in the Chicot. As shown on **Error! Reference source not found.**, the average maximum compaction simulated from the scenarios is about 1.75 feet associated with the small range in average drawdown. Comparison of **Error! Reference source not found.** and **Error! Reference source not found.** suggest that there is a relationship between the compaction of the aquifer to the average drawdown.

To investigate the relationship between the average drawdown and the simulated maximum compaction of the aquifer materials, we prepared cross-plots comparing the results for the Chicot (**Error! Reference source not found.**), Evangeline (**Error! Reference source not found.**), and Jasper (**Error! Reference source not found.**). The linear relationship between water level decline and aquifer compaction is clear in each of the aquifers. However, the slope of the trendline through the data points suggests the impact per foot of water-level decline on compaction is nearly 1,000 times greater in the Chicot compared to the Jasper and about 100 times greater compared to the Evangeline.

Understanding the impact of water level declines in the Chicot on compaction but the relatively small amount of pumping from the Chicot in Montgomery County, we investigated the impact of pumping outside of the county on aquifer compaction and land-surface subsidence. As the primary location of groundwater production near Montgomery County is occurring to the south in Harris County, we performed a simulation where all pumping in the subsidence district was turned off beginning on January 1, 2010. By comparing the results from this simulation with the other simulations, we can discern the portion of modeled subsidence caused by sources beyond the control of LSGCD. **Error! Reference source not found.** illustrates contours of the predicted subsidence due to pumping outside of Montgomery County.

As Figure 16 shows, a significant portion of the simulated subsidence is due to pumping outside of the District. Most of the simulated subsidence due to pumping outside of the District is in the southeastern portion of the county. While the total amount of additional subsidence is relatively small, the available tools suggest that compaction of the Chicot Aquifer due to water level declines is the primary factor contributing to land surface subsidence and that most of the compaction in the Chicot Aquifer will be due to pumping outside of Montgomery County.

5.0 REGULATORY AND MANAGEMENT OVERVIEW

LSGCD is a groundwater conservation district subject to the statues in Chapter 36 of the Texas Water Code (TWC). GCDs must adopt a management plan to address eight (8) specified management goals. TWC Sec. 36.1071(a)(3) mandates that one of the management goals that a district's management plan shall address is "controlling and preventing subsidence". A GCD's management plan must "identify the performance standards and management objectives under which the district will operate to achieve the management goals identified…" (TWC Sec. 36.1071(e)(1)). Section 10.3 of the LSGCD's Management Plan provides the management objectives and performance standard for **Controlling and Preventing Subsidence:**

Management Objectives

1) The District shall, in cooperation with the Harris-Galveston Subsidence District, monitor in real-time and maintain a network of 8 subsidence monitor stations to continually measure subsidence. To date, minor subsidence of less than 1 foot has been measured at monitoring stations located in the southern portion of the District.
2) Each year, the District shall participate in a joint conference with the neighboring groundwater conservation districts or subsidence districts focused on sharing information regarding subsidence and the control and prevention of subsidence through the regulation of groundwater production.
3) Controlling and preventing subsidence will be addressed during the review and processing of permits as authorized in Chapter 36 and District Rules, and in setting desired future conditions for the common reservoirs.

Performance Standards

1) Each year, a summary of the joint conference on subsidence issues will be included in the Annual Report submitted by the General Manager to the Board of Directors of the District (2020 Management Plan Page 15 Revised April 14, 2020).
2) Results from the subsidence monitoring stations will be noted in the summary of the joint conference on subsidence and included in an annual report to the District Board of Directors.
3) The District will continue its subsidence study and provide updates on the results of the study in the Annual Report of the District provided to the Board of Directors.

TWC Sec. 36.1071(f) states, "The district shall adopt rules necessary to implement the management plan." TWC Sec. 36.101(a) states, "A district may make and enforce rules, including rules limiting groundwater production based on tract size or the spacing of wells, to provide for conserving, preserving, protecting and recharging of the groundwater or of a groundwater reservoir or its subdivisions in order to control subsidence…"(emphasis added). According to Texas Water Code, "'Subsidence' means the lowering in elevation of the land surface caused by withdrawal of groundwater" (TWC Sec. 36.001(10)).

Because subsidence is typically a regional issue, the joint planning process through Groundwater Management Area 14 (GMA 14) is where "the rubber meets the road" with respect to controlling subsidence. Each of the layers of the Gulf Coast Aquifer System is hydraulically connected across multiple county lines; therefore, pumping in one county affects water levels in other counties and can affect subsidence, depending in large part on the amount of pumping and aquifer geometry. Under TWC Sec.

36.108(d)(4) "the impact on subsidence" is one of nine (9) factors that GMA's must consider in setting desired future conditions (DFCs).

Subsidence districts are not Chapter 36 GCDs and do not have the same requirements for management plans, rulemaking or setting DFCs as part of a GMA (although they are clearly stakeholders in the GMA process). The HGSD and the Fort Bend Subsidence District (FBSD) regulate groundwater production in essentially the same way and in accordance with a district regulatory plan. The amount of groundwater pumping allowed is based, not directly on an aquifer condition, but on a percentage of the total water demand within the subsidence district.

Each subsidence district is divided into regulatory areas with pumping in the regulatory areas having large subsidence amounts curtailed first. Over time, the pumping in each area becomes a smaller and smaller percentage of total water demand. The management plan for HGSD has already led to a drastic reduction in pumping in central and eastern parts of Harris County and all of Galveston County. Areas to the north and west in Harris County will experience substantial reductions in the percentage of groundwater allowed by 2025 with additional curtailments in 2035. Figure 41 shows the regulatory areas in the HGSD and FBSD. Figure 43**Error! Reference source not found.** shows projected total pumping in both HGSD and F BSD through 2070. Figure 44 shows total pumping in each of the regulatory areas of the HGSD. Note that Area 3 has undergone a slight total reduction in pumping, while Area 1 and Area 2 have been curtailed drastically. While the total pumping amount is very important, a more precise aerial and vertical distribution of pumping is needed to assess the potential for continued and on-going subsidence in Area 3 of HGSD and Area A of FBSD. Phase 2 of this subsidence study will include a detailed look at pumping distributions in Montgomery County and adjacent areas that can affect water levels and subsidence in Montgomery County.

6.0 NEXT PHASE OF STUDY

The objective of Phase II work is to build upon summaries and data collection efforts in Phase I to focus on the potential for future land-surface deformation within Montgomery County and adjacent areas, specific potential impacts of subsidence within Montgomery County, and monitoring of subsidence within Montgomery County. Specific goals of Phase II are to:

- Build upon Phase I summaries with detailed evaluations, assessments, and critiques of previous data and studies;
- Address past and potential future land-surface deformation associated with subsidence and fault movement within Montgomery County;
- Develop both a high-level and locally-specific assessment of possible drainage and flooding concerns as related to potential future subsidence, land development, and other factors;
- Develop recommendations, conceptual plans, and budgetary cost estimates for field studies and monitoring programs, such as:
    - Collecting core samples for geologic and geotechnical analyses;
    - Processing InSAR for topographic changes and fault detection; and/or,
    - Installing an extensometer anchored in the formations making up the Jasper Aquifer;
- Prepare deliverables and a project report describing and illustrating the work conducted with key findings and conclusions. Additionally, the work will include preparing one or more presentations to the Board and stakeholders to communicate the work performed and results.

The following proposed Phase II tasks are designed to meet the project goals outlined above.

Task 1 –Technical Evaluations of Existing Data and Recent Studies

This task will involve detailed technical analyses of available data and information that builds upon the summaries discussed in Section 3.0. The evaluations to be conducted utilizing data and information collected are presented as individual sub-tasks below.

Task 1.1 – Topographic and Re-Leveling Efforts

As discussed in Section 3.1.1, all land-surface subsidence determinations in the region were initially made by geodetic differential leveling. It is important to understand the initial basis and accuracy of historical subsidence measurements and estimates within Montgomery County. Work during this effort will include collection and review of benchmark data from the National Geodetic Survey and consideration of the uncertainty associated with survey measurements.

Task 1.2 – Hydrogeology, Geology, and Geotechnical Studies

As discussed in Section 2.3, the three primary variables that determine the magnitude, location, and timing of subsidence related to groundwater pumping are: 1) the distribution, thickness and compressibility of clay layers; 2) the amount and timing of water-level changes; and, 3) the lowest historical water level (Furnans and others, 2018). Several studies from the 1970s and 1980s formed the basis for understanding the correlation of the distribution and timing of pumping with water-level declines and associated occurrence of land-surface subsidence and/or fault movement (see Section 3.0). Additionally, geologic studies including geophysical log analysis and geotechnical studies by the USGS provide the only available direct data for the clay characteristics for the Chicot and Evangeline layers of the Gulf Coast Aquifer System. While these studies are for the upper portions of the aquifer system, data from these studies have formed the basis for parameters in recent models that estimate clay compaction in deeper formations of the aquifer. This task will include critical evaluations of the thickness and distributions of sand and clay layers, hydraulic parameters, physical properties, overburden depths, and other geologic formation related factors associated with subsidence within Montgomery County.

Task 1.3 – GPS Monitoring Data and Interpretations

As discussed in Section 3.1.3, beginning in the late 1980s permanent sites were installed and land surface locations were measured repetitively via global positioning system (GPS) technologies. Now there are more than 200 sites maintained and monitored by the USGS and University of Houston (UH). Such sites are the only means by which to timely and efficiently determine movement of the land surface at sites in Montgomery County. The sites only allow for determining the overall movement of land surface and do not independently allow for determining the magnitude of compaction in any one layer of the Gulf Coast Aquifer System. To better understand within which formation(s) compaction is occurring, the GPS data must be carefully compared and correlated to historical pumping at well sites, completion intervals of the wells, and changes in water-level within the wells. This task will involve evaluation of data from the GPS monitoring sites and performing the correlations with pumping and water level data.

Task 1.4 – Remote Sensing

LiDAR data collected over multiple years can be compared to assess land surface deformation (see Section 3.1.5). In particular, the LiDAR data from recent years can be compared with historical benchmark elevations from the National Geodetic Survey to assess subsidence that may have occurred in the past. Similarly, researchers have assessed relatively recent land surface deformation due to subsidence or fault movement using InSAR. This task will include reviewing existing research, particularly related to recent studies applying InSAR data, and correlating findings to historical distributions of pumping, water-level changes, and land surface deformation measurements collected at GPS sites.

Task 1.5 – Drainage and Flooding

While consideration of surface water resources is not part of LSGCD's primary mission, the District understands the concerns of its constituents with regard to the potential changes in surface water drainage that may occur due to land surface subsidence. However, there is some uncertainty with regard to existing research on how differential land surface subsidence may affect drainage patterns within Montgomery County. For this sub-task, we propose obtaining available surface water models from the SanJac Drainage Study (https://sanjacstudy.org/), or other available sources, and evaluating the models, assumptions, and documentation to assess the potential for using these models to assess subsidence effects on Montgomery County drainage and flooding.

Task 2 –Subsidence Modeling

Many of the groundwater flow models covering the study area have explicitly included simulation of aquifer compaction associated with potentiometric surface declines. These models apply various implementations of the equations used to estimate compaction of geologic materials associated with aquifer depressurization. This task will focus on how compaction is simulated in existing models and in the model package under development for MODFLOW 6.

The equations for estimating subsidence are fairly straightforward (see Section 2.3). However, the assumptions included in the parameters used to perform the calculations can significantly affect the results. Understanding the implementation of the equations and the assumptions included in the input parameters is important to understanding the model predictions along with the uncertainty in the prediction results.

Task 2.1 – PRESS Model (Espey, Huston, and Associates, Inc., 1982)

The PRESS model is used extensively in Harris County to predict subsidence due to changes in water levels. Review of the model and parameterization of the factors controlling subsidence will include a review of extensometer data, how it correlates to changes in water levels, and how the data are used to calibrate the PRESS model sites. As these PRESS sites were used to help develop and calibrate the HAGM, understanding the parameterization included in these models directly relates to how subsidence is simulated in Montogomery County.

Task 2.2 – Houston Area Jasper Model (Kelley and others, 2018)

The existing model of potential future subsidence due to production and water level changes in the Jasper Aquifer (Kelley and others, 2018) adopts assumptions for the clay properties in the deeper formations based on data from shallower zones. This sub-task will evaluate the assumptions applied in the model and the level of uncertainty in the results associated with these assumptions. Work will also include obtaining a copy of the model files and performing a comparison of the parameters in this model that affect subisidence calculations with the parameters used in the HAGM. We also anticipate parameters from this model will inform the input parameters in future models and will compare the parameters to those in the GULF 2023 model (see Task 2.3) when it becomes available.

Task 2.3 – Gulf Coast Land Subsidence and Groundwater-Flow Model (GULF 2023)

The GULF 2023 model is currently under development by the USGS. While the complete model is not available, the USGS has reported that the MODFLOW 6 package for simulating aquifer compaction is complete and available for download and analysis via GitHub. During the HGSD Joint Regulatory Plan Review meeting on May 20, 2020, the USGS stated that the new package will allow simulation of inelastic and elastic compaction of both the clay and sand units in the aquifer. Since this new MODFLOW 6 package will likely build upon previous MODFLOW packages, we will perform a review of the previous subsidence equation implementations (in existing MODFLOW packages) as well as analyze the implementation of the equations within the newer MODFLOW 6 package. We will assess how the new implementation algorithms (within MODFLOW 6) may affect predictions of land surface subsidence within Montgomery County. While this task does not include work related to Stakeholder participation in the model development, evaluating and understanding the techniques and methods applied within this new MODFLOW 6 package will aid significantly in performing a future review of the GULF 2023 model and how it simulates subsidence in Montgomery County.

Task 2.4 – Subsidence Visualization

Understanding the spatial and temporal occurrence of subsidence will aid in the communication of past and predicted impacts of pumping on land deformation. Using the data and models gathered/developed in previous tasks and during this study, we will develop visualization tools that can be easily incorporated into the District's web-based database hosted by Halff. Specifically, we anticipate creating time series datasets that Halff can incorporate into the database with a slider that will allow users to view on an annual basis the pumping amount and locations, water levels, and subsidence. Specific work to be conducted under this sub-task includes:

1) Using benchmarks from the National Geodetic Survey and recent topographic data (such as LiDAR) to estimate subsidence amounts and distributions in Montgomery County for time periods prior to the formation of LSGCD (and/or prior to land-surface elevation monitoring at PAM sites).
2) Estimating total current compaction and corresponding subsidence in each layer of the Gulf Coast Aquifer System since pre-development in Montgomery County.
3) Creating spatial and temporal datasets of pumping, water level, and subsidence.
4) Coordinating with Halff on incorporating the data and visualizations into the LSGCD web-based database.

Task 3 – Potential Impacts to Drainage and Flooding

This task would not be conducted without approval from LSGCD after review of the evaluation conducted in Task 1.5. If the information available from the existing information available from the SanJac Study and if LSGCD decides to move forward with modeling of subsidence effects on drainage patterns within Montgomery County, we would modify the existing models (identified in Task 1.5) to reflect changes in land use and/or topography due to subsidence. Steps to model the potential impacts include:

1) Modeling land use changes and runoff effects with HEC-HMS
    a. Simulate future land use and compute storm-runoff for 100-yr Atlas-14 storms
    b. Consider varying land use and impervious cover scenarios
2) Model differential subsidence across all of Montgomery County
    a. Based on specific modeled pumping and specific locations
    b. Likely use HAGM predictions of subsidence to calculate changes in topography
3) Adjust existing HEC-RAS models of Montgomery County drainages based on the modeled differential land surface elevation change due to subsidence
4) Run HEC-RAS models to generate new floodplains and compare to existing floodplains

Task 4 – Conceptual Plans and Budgetary Cost Estimates for Data Collection and Monitoring

Data collection is the only way to know for certain what is occurring with regard to subsidence. This task will involve developing recommendations, conceptual plans, and budgetary cost estimates for field studies and monitoring programs. Based on the information gathered during this study, examples of projects include:

1) Collecting core samples for geologic and geotechnical analyses. These analyses will provide direct measurement of the compressibility coefficients that are a key parameter in the prediction of subsidence due to depressurization.
2) Processing InSAR for topographic changes and fault detection. InSAR analyses are a relatively new process that can detect very small changes in land surface elevation. For high subsidence risk areas, Furnans and others (2018) recommended automation of InSAR data processing as a long-term low cost means of assessing subsidence.
3) Installing an extensometer anchored in the formations making up the Jasper Aquifer. There are currently no extensometers that measure compaction of the clay layers in the formations that

make up the Jasper Aquifer. With the importance of the Jasper to District constituents, it would be important to measure the compaction of the Jasper due to depressurization.

4) Expansion of automated water level and land surface deformation monitoring.

Task 5 – Reporting and Presentations

This final task will involve providing a written report to the LSGCD Board of Directors. We will also present the final report to the LSGCD Board and Public at a regular board meeting. The final report will document the key findings and conclusions related to the investigations conducted to meet the project goals.

7.0 CONCLUSIONS

The Phase 1 study has resulted in the following: a successful and effective effort to acquire a comprehensive library of information; compiling a working database that will be effective in developing applicable and accurate correlations related to temporal and spatial changes in aquifer conditions and land surface; conducting preliminary modeling (applicable to GMA 14 work) that illustrated the need to manage the entire common reservoir particularly with respect to water uses, aquifer conditions, subsidence and property rights. Based on Phase 1 work, we provide the following observations and conclusions:

- Subsidence has been recognized in Harris County since at least the 1920s;
- Studies and monitoring have built upon critical work conducted during the 1970s which addressed land surface movement due to subsidence and numerous growth faults;
- Montgomery County had experienced a considerable amount of the total currently observed subsidence in decades before pumping within the county was substantial;
- Causes of the occurrence and activation (that is, new movement) of growth faults can include any one or a combination of factors including subsidence due to fluid production (that is, shallow or deep), salt dome movement or deeper salt diapirism, and/or deep-seated fault movement associated with the massive fault system along the Gulf Coastal Plain;
- The susceptibility of formations to compaction or subsidence varies with the geologic age, depth, character, thickness, and lithology of clay layers;
- Regulation, population growth and migration and the associated shift in groundwater pumping locations have resulted in subsidence essentially ceasing in some areas and increasing in other areas;
- Previous and on-going studies along with monitoring have provided critical understanding of subsidence and growth faults within the region; however, there are many questions and specific considerations for Montgomery County that must be directly assessed in order to derive conclusive answers; and,
- Detailed correlations of land-surface movement over time with aquifer changes (particularly, pumping and water-levels) are needed to better assign cause-and-effect relationships regarding subsidence in Montgomery County.

Phase 1 work involved effectively compiling comprehensive background data and developing a working understanding and knowledge of land-surface movement to be able to conduct the needed subsequent detailed data analyses, technical evaluations, critiques, modeling, and assessments of implications relative to Montgomery County. This work was successfully completed and the next phase of the investigations can begin. As detailed in the Phase 2 plan, the next phase of investigation will focus efforts on deriving the conclusive answers to several specific questions and issues as they relate to Montgomery County and the management of groundwater resources by Lone Star Groundwater Conservation District.

8.0 REFERENCES

Bawden, G.W., Johnson, M.R., Kasmarek, M.C., Brandt, J., and Middleton, C.S., 2012, Investigation of Land Subsidence in the Houston-Galveston Region of Texas By Using the Global Positioning System and Interferometric Synthetic Aperture Radar, 1993–2000: U.S. Geological Survey Scientific Investigations Report 2012–5211, 88 p.

Campbell, M.D., Campbell, M.D., and Wise, H.M., 2018, Growth Faulting and Subsidence in the Houston, Texas Area: Guide to the Origins, Relationships, Hazards, Potential Impacts and Methods of Investigation: An Update: Journal of Geology of Geoscience, v. 2, no. 1, p. 1-53.

Carr, J.E., Meyer, W.R., Sandeen, W.M., and McLane, I.R., 1985, Digital models for simulation of ground-water hydrology of the Chicot and Evangeline aquifers along the Gulf Coast of Texas: Texas Department of Water Resources Report 289, 101 p.

Engelkemeir, R. and Khan, S.D., 2013, Surface deformation in Houston, Texas using GPS: Tectonophysics, v. 490, p. 47-54.

Espey, Huston, and Associates, Inc., 1982, Phase II—Water Management Study - Appedix B - PRESS Model Documentation: Prepared for Harris–Galveston Coastal Subsidence District, 9 p.

Furnans, J., Keester, M., Colvin, D., Bauer, J., Barber, J., Gin, G., Danielson, V., Erickson, L., Ryan, R., Khorzad, K., Worsley, A., and Snyder, G., 2018, Final Report: Identification of the Vulnerability of the Major and Minor Aquifers of Texas to Subsidence with Regard to Groundwater Pumping: Texas Water Development Board Contract Report No, 1648302062, 434 p.

Gabrysch, R.K., 1967, Development of ground water in the Houston district, Texas, 1961-65: Texas Water Development Board Report 63, 35 p.

Gabrysch, R.K., 1980, Development of ground water in the Houston district, Texas, 1970-74: Texas Department of Water Resources Report 241, 49 p.

Gabrysch, R.K., 1984, Land-Surface Subsidence in the Houston-Galveston Region, Texas, 1906-80:

Gabrysch, R.K. and Bonnet, C.W., 1974, Land-Surface Subsidence in the Area of Burnett, Scott, and Crystal Bays Near Baytown, Texas: U.S. Geological Survey Water-Resources Investigations Report 74-21, 48 p.

Gabrysch, R.K. and Bonnet, C.W., 1975, Land-surface subsidence in the Houston-Galveston region, Texas: Texas Water Development Board Report 188, 19 p.

Gabrysch, R.K. and Bonnet, C.W., 1976, Land-surface subsidence at Seabrook, Texas: U.S. Geological Survey Water Resources Investigation, 53 p.

George, P.G., Mace, R.E., and Petrossian, R., 2011, Aquifers of Texas: Texas Water Development Board Report 380, 172 p.

Harris-Galveston Subsidence District, 2020, Subsidence Rates in Harris and Surrounding Counties, 2015-2019, https://www.arcgis.com/home/item.html?id=a3e7214071f6421fb745d9866e2d3985, accessed June 2020.

Hassan, M.M., 2011, GAM Run 10-038 MAG Report: GAM Run Report, 19 p.

Hoel, H.D., 1982, Goliad Formation of the south Texas Gulf Coastal Plain: regional genetic: Master's thesis, The University of Texas at, 173 p.

Hoffman, J., Leake, S.A., Galloway, D.L., and Wilson, A.M., 2003, MODFLOW-2000 Ground-Water Model—User Guide to the Subsidence and Aquifer-System Compaction (SUB) Package: U.S. Geological Survey, Open-File Report 03—233, 46 p.

INTERA, 2019, Discussion and Consideration of the "Balancing Test": Presentation on August 15, 2019 to Groundwater Management Area 14, 26 p.

Kasmarek, M.C., 2013, Hydrogeology and Simulation of Groundwater Flow and Land-Surface Subsidence in the Northern Part of the Gulf Coast Aquifer System, Texas, 1891-2009: U.S. Geological Survey Scientific Investigations Report 2012-5154, 55 p.

Kasmarek, M.C., Gabrysch, R.K., and Johnson, M.R., 2009, Estimated land-surface subsidence in Harris County, Texas, 1915-17 to 2001: U.S. Geological Survey Scientific Investigations Map 3097, 2 p.

Kasmarek, M.C. and Ramage, J.K., 2017, Water-level altitudes 2017 and water-level changes in the Chicot, Evangeline, and Jasper Aquifers and compaction 1973–2016 in the Chicot and Evangeline Aquifers, Houston-Galveston region, Texas: U.S. Geological Survey Scientific Investigations Report 2017-5080, 32 p.

Kasmarek, M.C., Reece, B.D., and Houston, N.A., 2005, Evaluation of ground-water flow and land-surface subsidence caused by hypothetical withdrawals in the northern part of the Gulf Coast Aquifer system, Texas: U.S. Geological Survey Scientific Investigations Report 2005-5024, 70 p.

Kasmarek, M.C. and Robinson, J.L., 2004, Hydrogeology and Simulation of Ground-Water Flow and Land-Surface Subsidence in the Northern Part of the Gulf Coast Aquifer System, Texas: U.S. Geological Survey Scientific Investigations Report 2004-5102, 111 p.

Kasmarek, M.C. and Strom, E.W., 2002, Hydrogeology and Simulation of Ground-Water Flow and Land-Surface Subsidence in the Chicot and Evangeline Aquifers, Houston Area, Texas: U.S. Geological Survey Water-Resources Investigations Report 02–4022, 61 p.

Keester, M., 2019, Recommendation for updating the Houston Area Groundwater Model to meet the objectives of the Lone Star Groundwater Conservation District and other Groundwater Management Area 14 members: Letter dated February 12, 2019 to Mr. Webb Melder, President, Lone Star Groundwater Conservation District, 2 p.

Keester, M.R., 2020, Contour Maps of Predicted Drawdown, Subsidence, and Compaction Associated with Proposed DFC Options: Technical Memorandum dated May 21, 2020 to Samantha Reiter, General Manager, Lone Star Groundwater Conservation District, 28 p.

Keester, M., Thornhill, M., and Beach, J., 2020, Identification and simulation of water management strategies from the 2017 State Water Plan: Presentation on February 24, 2020 to Groundwater Management Area 14 , 31 p.

Kelley, V., Deeds, N., Young, S.C., Pinkard, J., Sheng, Z., Seifert, J., and Marr, S., 2018, Subsidence Risk Assessment and Regulatory Considerations for the Brackish Jasper Aquifer - Harris-Galveston and Fort Bend Subsidence Districts: Report prepared for Harris-Galveston Subsidence District and Fort Bend Subsidence District, 69 p.

Khan, S.D., Huang, Z., and Karacay, A., 2014, Study of ground subsidence in northwest Harris county using GPS, LiDAR, and InSAR techniques: Natural Hazards, v. 73, p. 1143-1173.

Kreitler, C.W., 1977, Fault Control of Subsidence, Houston, Texas: Groundwater, v. 15, no. 3, p. 203-214.

Leake, S.A. and Galloway, D.L., 2007, MODFLOW Ground-Water Model—User Guide to the Subsidence and Aquifer-System Compaction Package (SUB-WT) for Water-Table Aquifers: U.S. Geological Survey, Techniques and Methods 6–A23, 42 p.

Lone Star Groundwater Conservation District, 2020, LSGCD Proposed DFC Process and GAM-Run Request to GMA 14: Presenation on April 29, 2020 to Groundwater Management Area 14, 12 p.

McClelland Engineers, 1966, Land surface subsidence and surface faulting, in Turner, Collie, and Braden, Inc., ed.: A comprehensive study of Houston's municipal water system, 50 p.

Morton, R.A., Jirik, L.A., and Galloway, W.E., 1988, Middle-Upper Miocene depositional sequences of the Texas Coastal Plain and continental shelf: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 174, 40 p.

Mullican III, W.F., 1988, Subsidence and Collapse at Texas Salt Domes: The University of Texas at Austin, Bureau of Economic Geology, Geological Circular 88-2, 36 p.

Petersen, C., Greuter, A., and Thompson, R., 2020, Determination of Groundwater Withdrawal and Effects on Subsidence – 2019: Harris-Galveston Subsidence District Report 2020-01, 27 p.

Popkin, B.P., 1971, Ground-Water Resources of Montgomery County, Texas: TWDB Report No. 136, 143 p.

Qu, F., Lu, Z., Kim, J.W., and Zheng, W., 2019, Identify and Monitor Growth Faulting Using InSAR over Northern Greater Houston, Texas, USA: Remote Sensing, v. 11, no. 12, p. 23.

Ratzlaff, K.W., 1982, Land-Surface Subsidence in the Texas Coastal Region: Report 272, 26 p.

Seifert, Jr., W.J., 2015, Technical Memorandum Regarding Groundwater Production and Water-Level Monitoring Program: Technical Memorandum prepared by LBG-Guyton Associates for Task 1 of the Lone Star Groundwater Conservation District Strategic Water Resources Planning Study, 35 p.

Seifert, Jr., W.J., 2017, Task 3 Technical Memorandum Regarding Future Groundwater Availability: Technical Memorandum prepared by LBG-Guyton Associates for Task 3 of the Lone Star Groundwater Conservation District Strategic Water Resources Planning Study, 53 p.

Terzaghi, K., 1925, Erdbaumechanik auf bodenphysikalisher Grundlage: Vienna, Austria, Deuticke, 399 p.

Texas Water Development Board, 2020, Groundwater Database Reports, http://www.twdb.texas.gov/groundwater/data/gwdbrpt.asp, accessed February 2020.

Thornhill Group, Inc. and LRE Water, 2020, Summary of Modeling Related to GMA 14 Joint Planning: Presentation on March 10, 2020 to Lone Star Groundwater Conservation District, 17 p.

Van Siclen, D., 1967, The Houston fault problem: American Institute of Professional Geologists, Texas Section, 3rd Annual Meeting Proceedings, p. 9-31.

Wade, S.C., 2016, GAM Run 16-024 MAG: Modeled Available Groundwater for the Gulf Coast Aquifer System in Groundwater Management Area 14: TWDB GAM Run, 30 p.

Wang, G., Welch, J., Kearns, T.J., Yang, L., and Serna Jr, J., 2015, Introduction to GPS geodetic infrastructure for land subsidence monitoring in Houston, Texas, USA: Proceedings of the International Association of Hydrological Sciences, v. 372, p. 297-303.

Whalen, C.T., 1978, Control Leveling: NOAA Technical Report NOS 73 NGS 8 , 20 p.

Winslow, A.G. and Doyel, W.W., 1954, Land-surface subsidence and its relation to the withdrawal of ground water in the Houston-Galveston region, Texas: Economic Geology, v. 49, no. 4, p. 413-422.

Winslow, A.G. and Wood, L.A., 1959, Relation of land subsidence to ground-water withdrawals in teh upper Gulf Coast region Texas: Mining Engineer, v. 11, no. 10, p. 1030-1034.

Young, S.C., Ewing, T., Hamlin, S., Baker, E., and Lupton, D., 2012, Final Report - Updating the Hydrogeologic Framework for the Northern Portion of the Gulf Coast Aquifer: Contract report for the Texas Water Development Board, 285 p.

Young, S.C., Jigmond, M., Deeds, N., Blainey, J., Ewing, T.E., Banerj, D., Piemonti, D., Jones, T., Griffith, C., Lupton, D., et al., 2016, FINAL REPORT: Identification of Potential Brackish Groundwater Production Areas – Gulf Coast Aquifer System: Contract report to the Texas Water Development Board, 636 p.

Yu, J., Wang, G., Kearns, T.J., and Yang, L., 2014, Is There Deep-Seated Subsidence in the Houston-Galveston Area?: International Journal of Geophysics, v. 2014, p. 11.

Table 1. Hydrostratigraphic and geologic units of the Gulf Coast Aquifer System within and near Montgomery County (Popkin, 1971; Young and others, 2012).

Epoch	Hydrostratigraphic Unit	Geologic Unit			Characteristics	Thickness*	Percent Sand*
Holocene	Alluvium	Alluvium			Clay, sand, and gravel		
Pleistocene	Chicot	Beaumont			Clay rich with sandy lenses		
Pleistocene	Chicot	Lissie			Fine-grained sands and sandy clays	25-537 (252)	38-74 (60)
Pliocene	Chicot	Willis			Gravelly coarse sands	25-538 (230)	26-79 (59)
Miocene	Evangeline Aquifer	Goliad		Upper	Thinner, less conglomeritic sands		45-62 (53)
Miocene	Evangeline Aquifer	Goliad		Lower	Thicker, more conglomeritic sands	50-1,034 (326)	36-71 (54)
Miocene	Evangeline Aquifer	Fleming Group	Lagarto	Upper	Clayey sand	150-707 (367)	40-86 (60)
Miocene	Burkeville Confining Unit	Fleming Group	Lagarto	Middle	Clay rich	150-792 (453)	36-86 (58)
Miocene	Jasper Aquifer	Fleming Group	Lagarto	Lower	Clayey sand	150-566 (339)	45-62 (53)
Miocene	Jasper Aquifer	Fleming Group	Oakville		Sand rich	67-711 (485)	17-67 (50)
Oligocene	Catahoula		Catahoula				

Figure 1. Clay thickness of the Beaumont Formation. Clay thickness calculated by subtracting the sand thickness from the total thickness as provided in the data set by Young and others (2012).

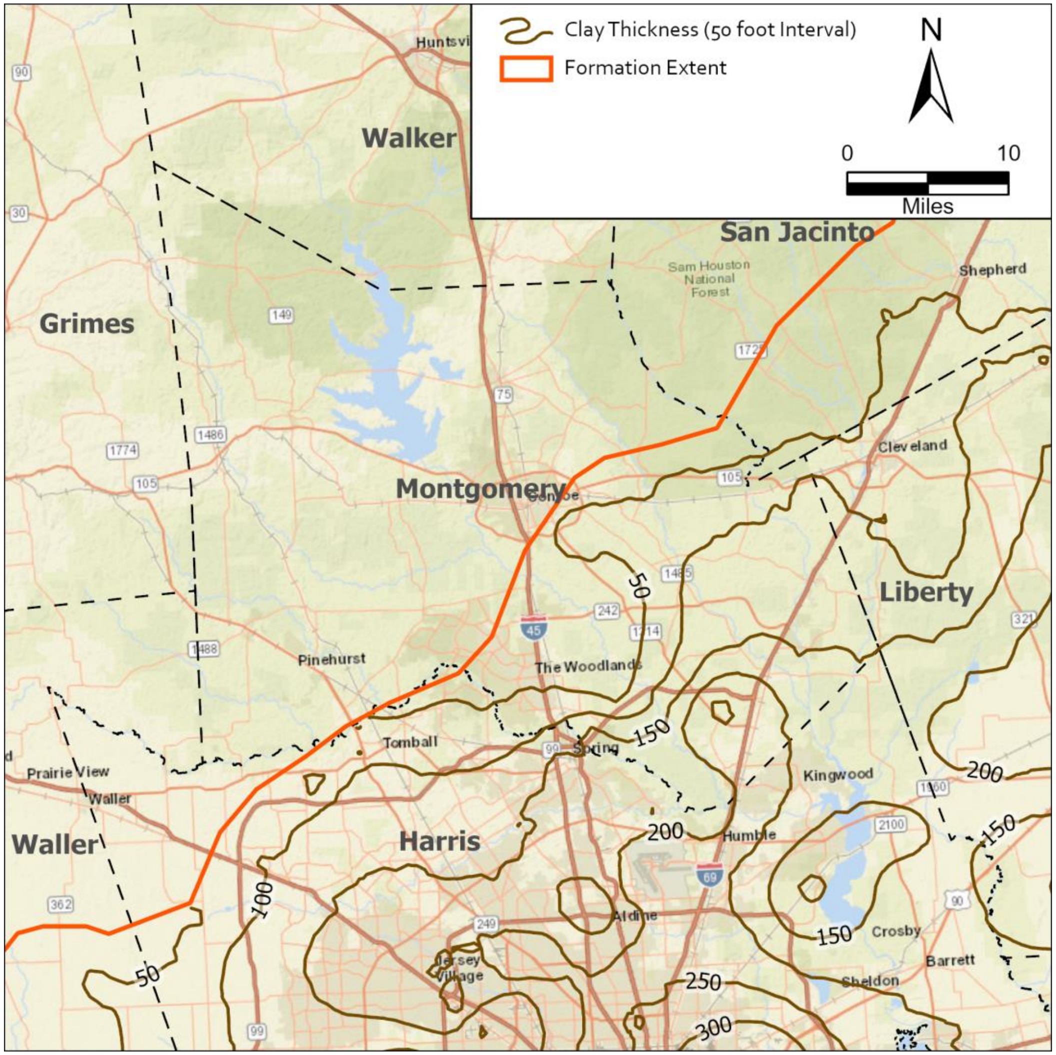


Figure 2. Clay thickness of the Lissie Formation. Clay thickness calculated by subtracting the sand thickness from the total thickness as provided in the data set by Young and others (2012).

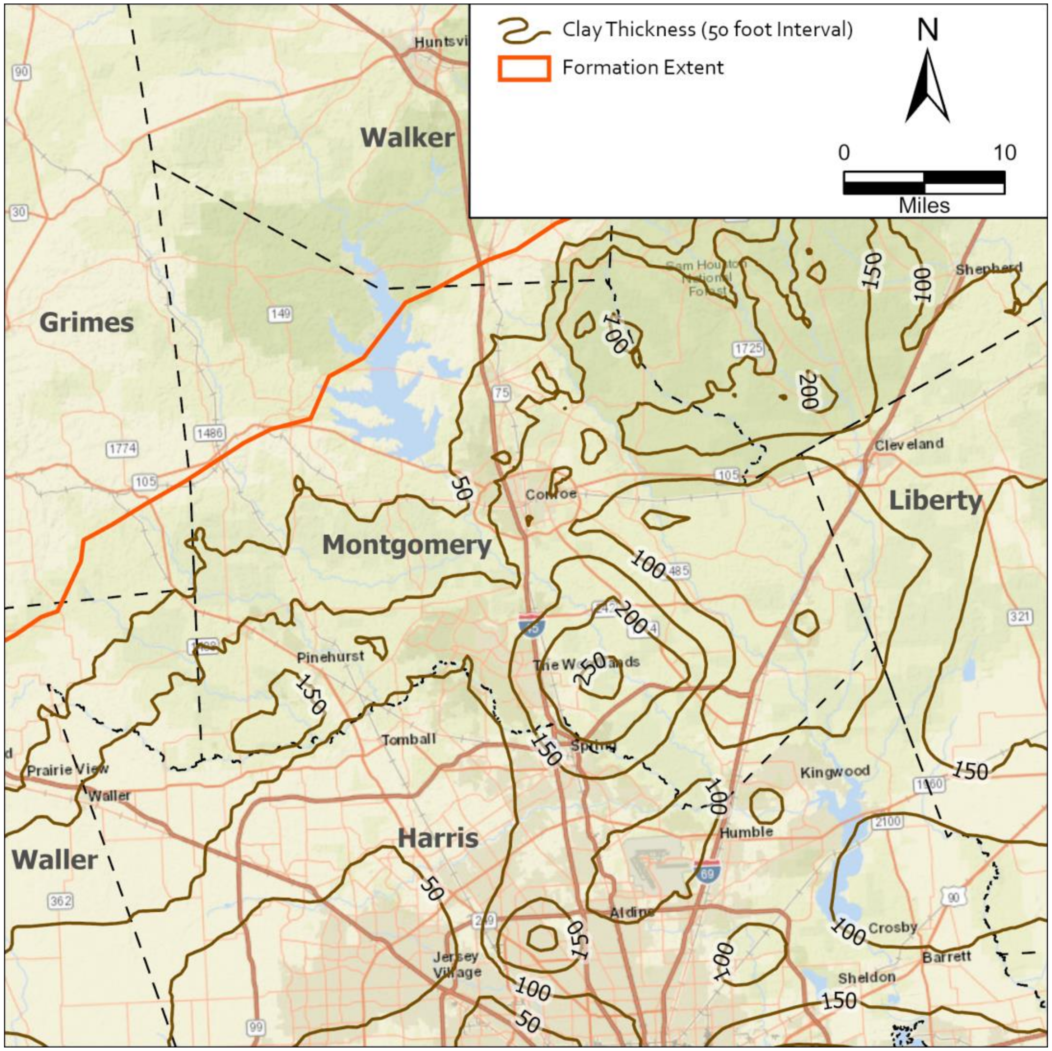


Figure 3. Clay thickness of the Willis Formation. Clay thickness calculated by subtracting the sand thickness from the total thickness as provided in the data set by Young and others (2012).

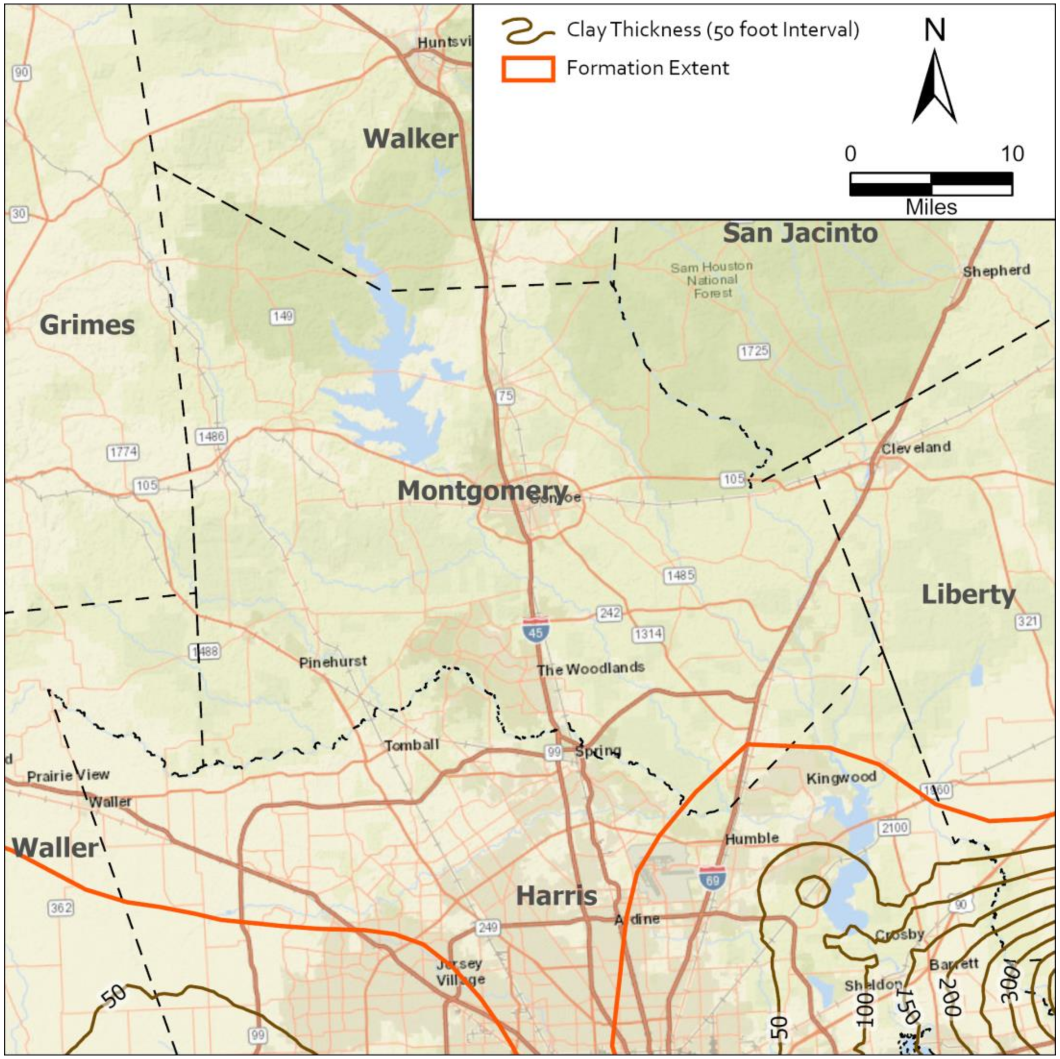


Figure 4. Clay thickness of the Upper Goliad Formation. Clay thickness calculated by subtracting the sand thickness from the total thickness as provided in the data set by Young and others (2012).

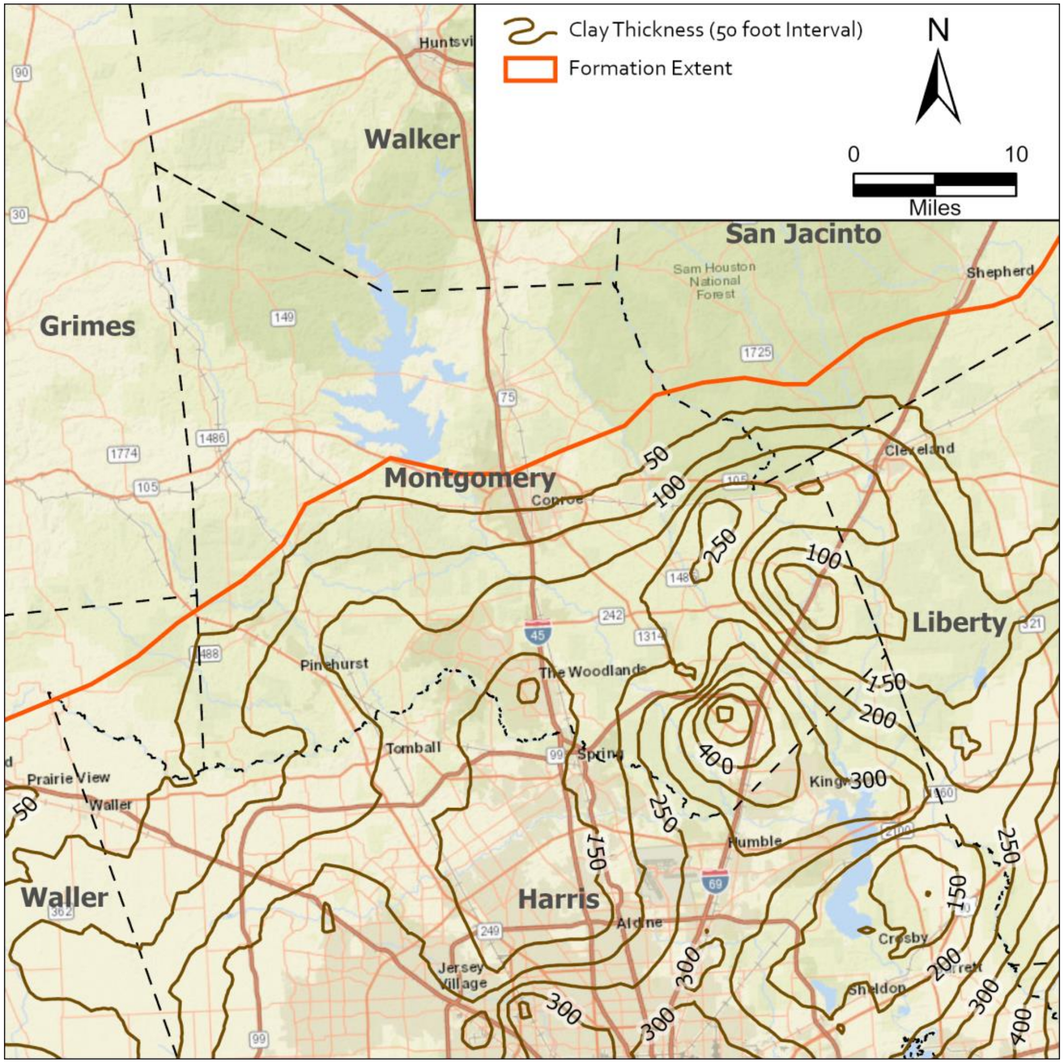


Figure 5. **Clay thickness of the Lower Goliad Formation. Clay thickness calculated by subtracting the sand thickness from the total thickness as provided in the data set by Young and others (2012).**

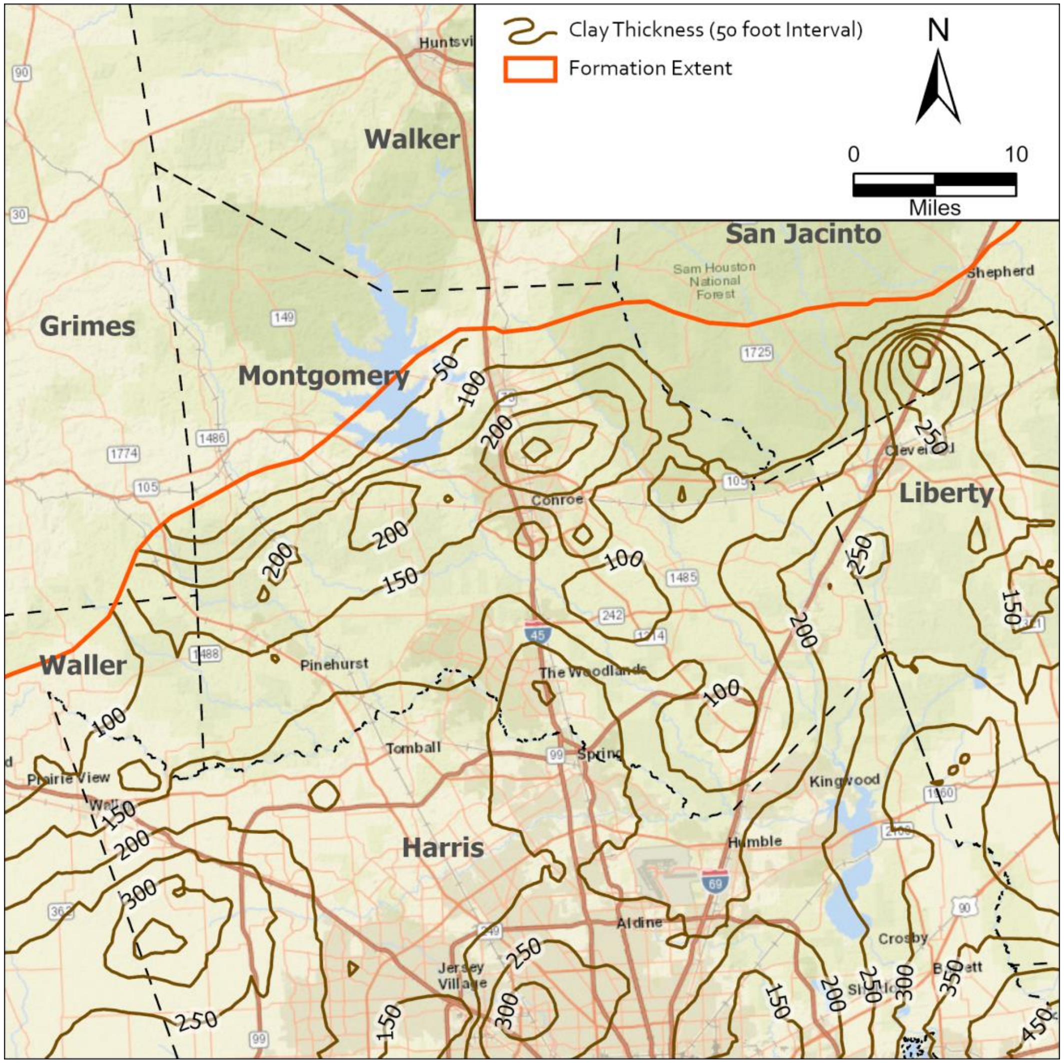


Figure 6. Clay thickness of the Upper Lagarto Formation. Clay thickness calculated by subtracting the sand thickness from the total thickness as provided in the data set by Young and others (2012).

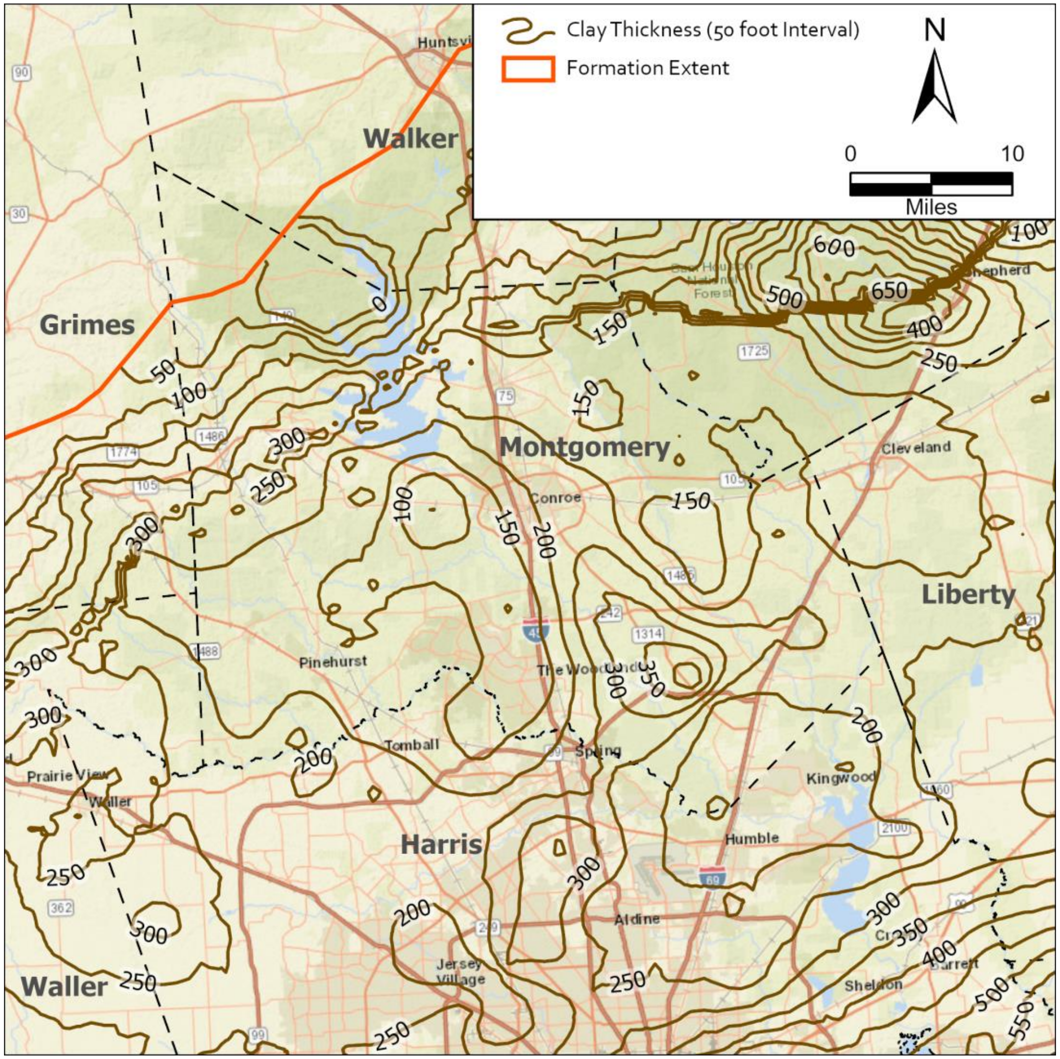


Figure 7. **Clay thickness of the Middle Lagarto Formation. Clay thickness calculated by subtracting the sand thickness from the total thickness as provided in the data set by Young and others (2012).**

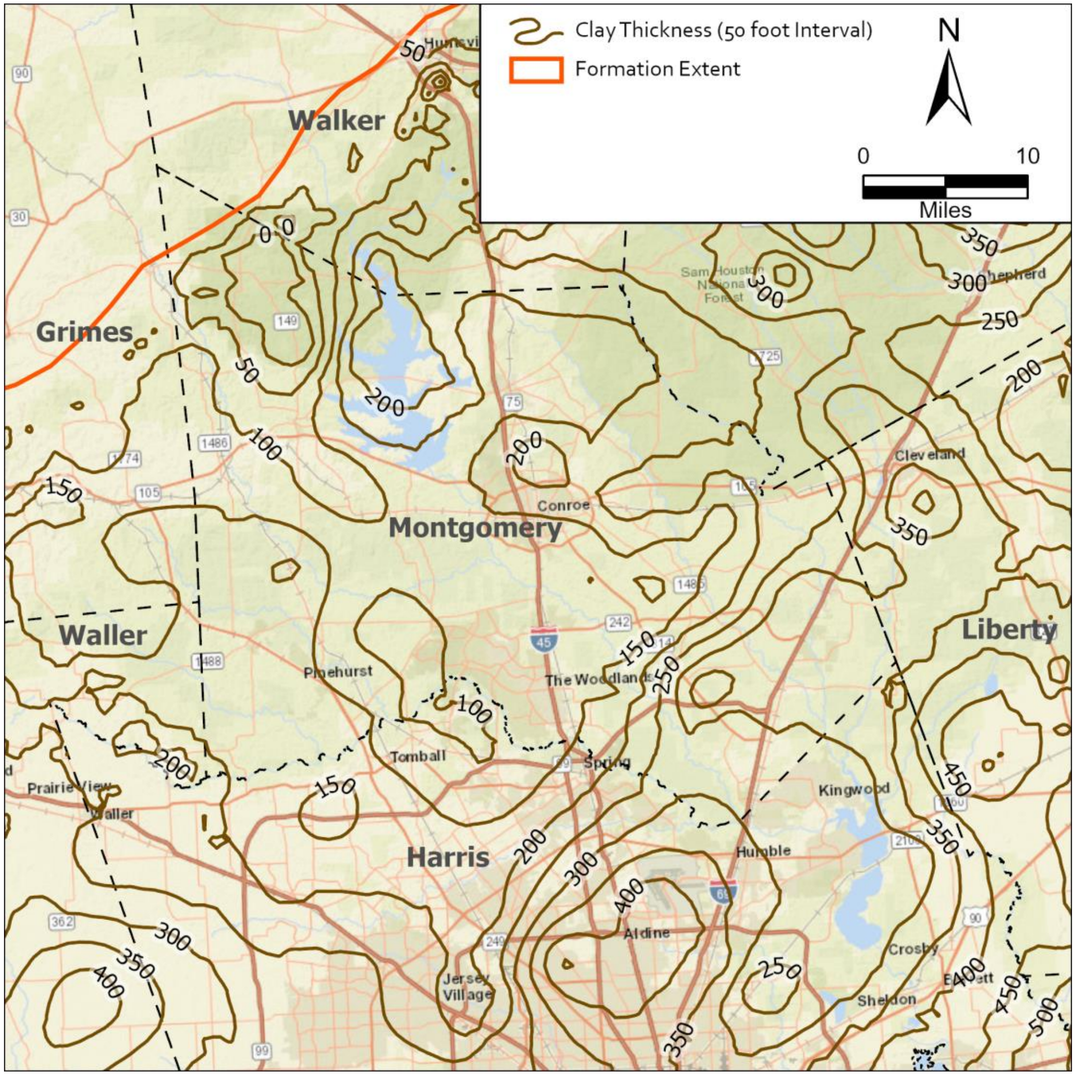


Figure 8. Clay thickness of the Lower Lagarto Formation. Clay thickness calculated by subtracting the sand thickness from the total thickness as provided in the data set by Young and others (2012).

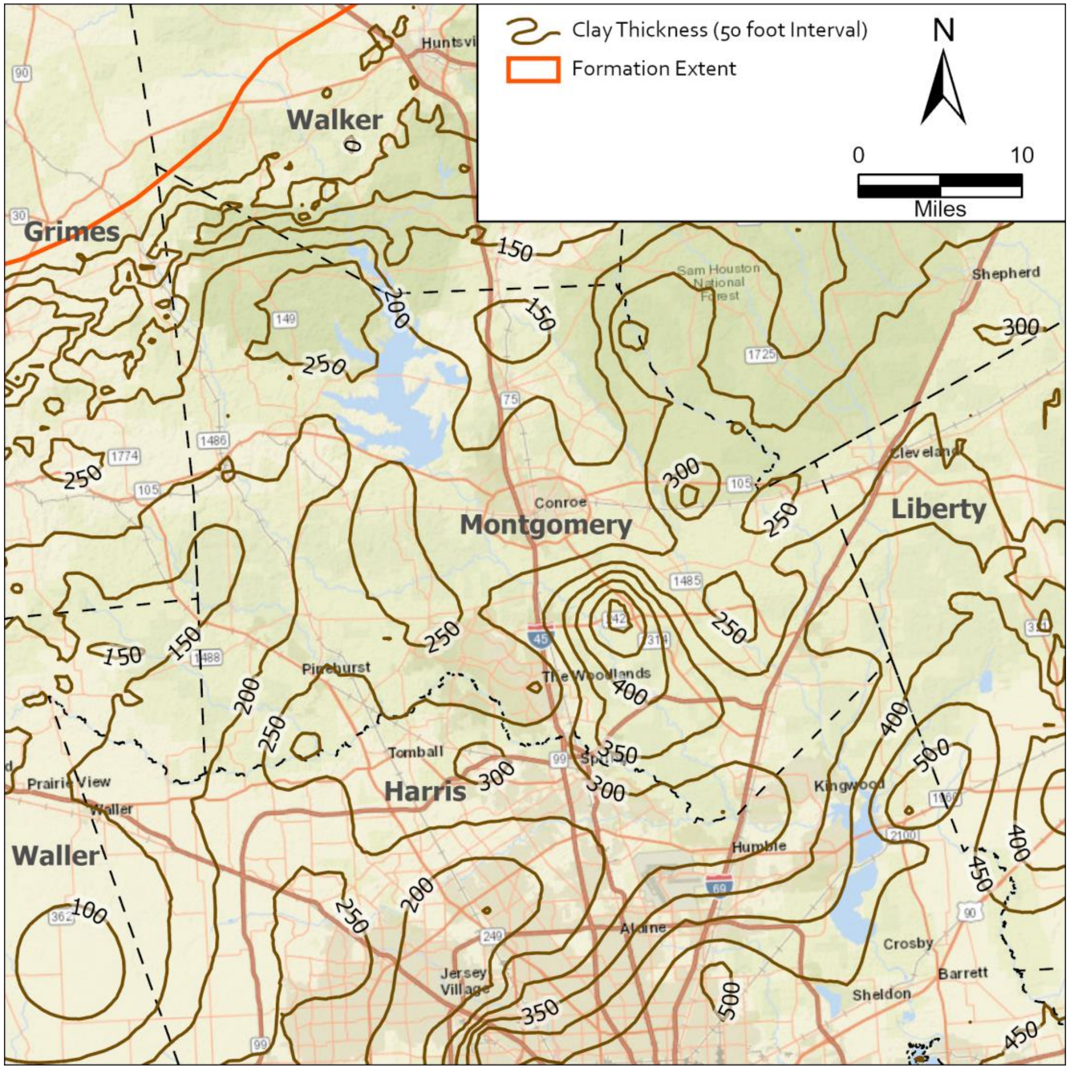


Figure 9. Clay thickness of the Oakville Formation. Clay thickness calculated by subtracting the sand thickness from the total thickness as provided in the data set by Young and others (2012).

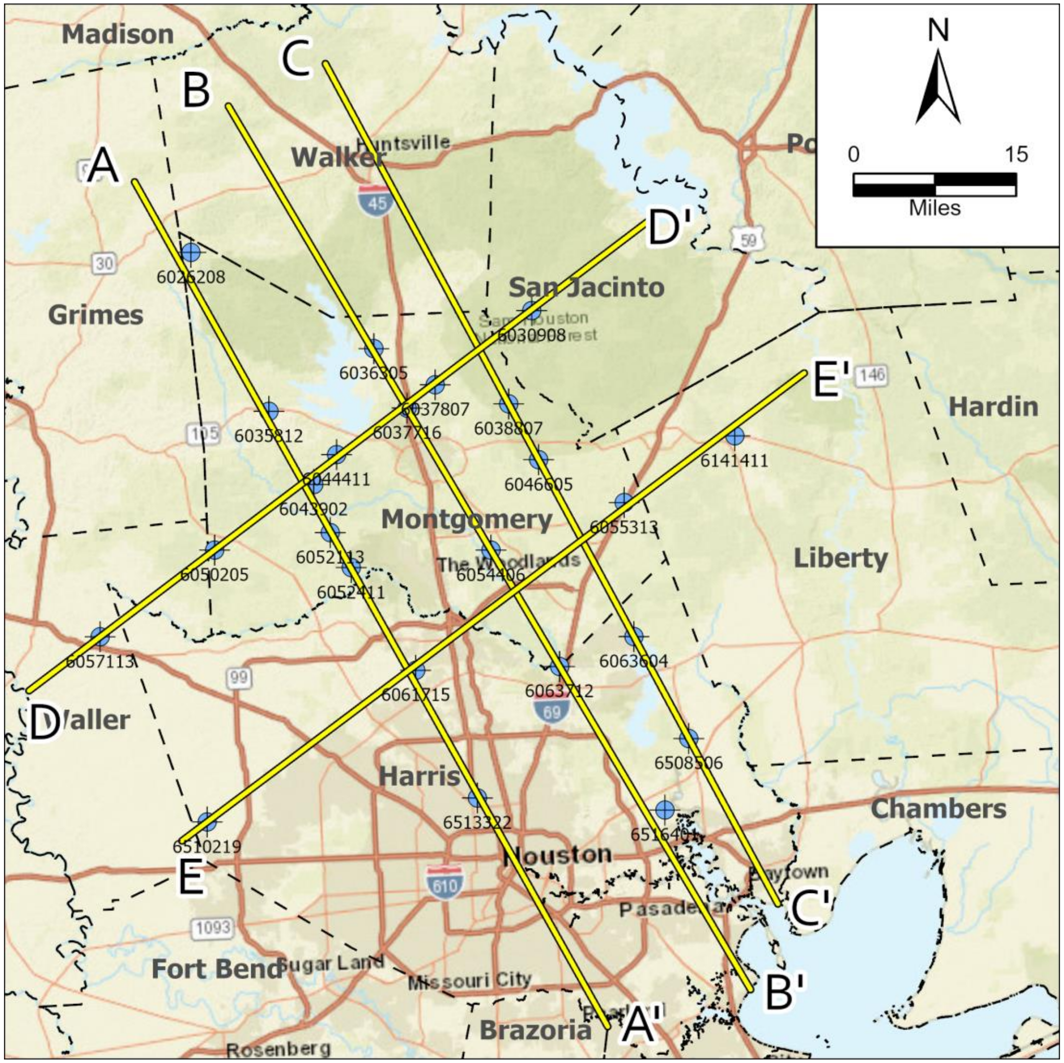


Figure 10. Location of cross-sections.

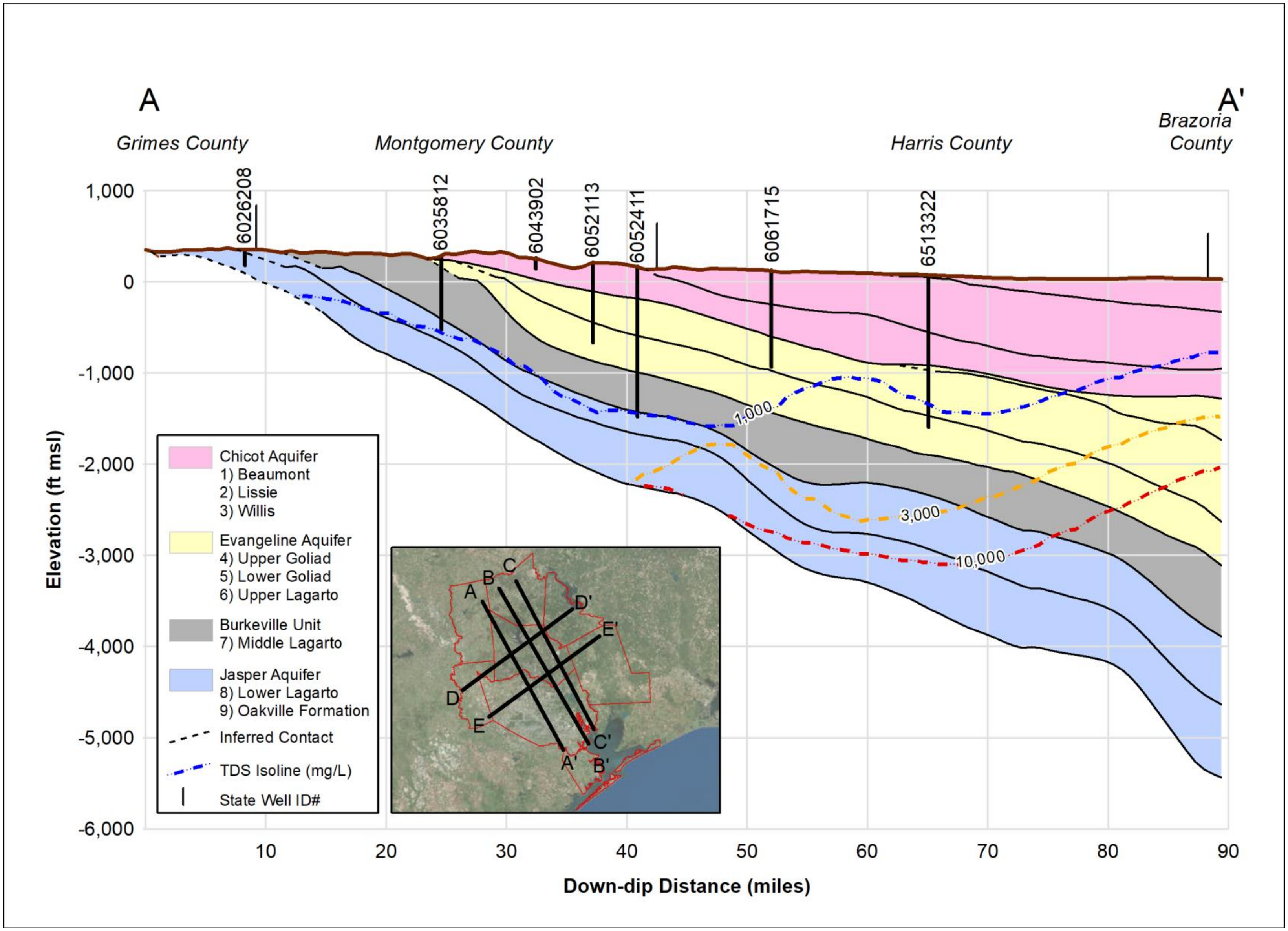


Figure 11. A-A' dip cross-section. Formation elevations from Young and others (2012). TDS isolines from Young and others (2016).

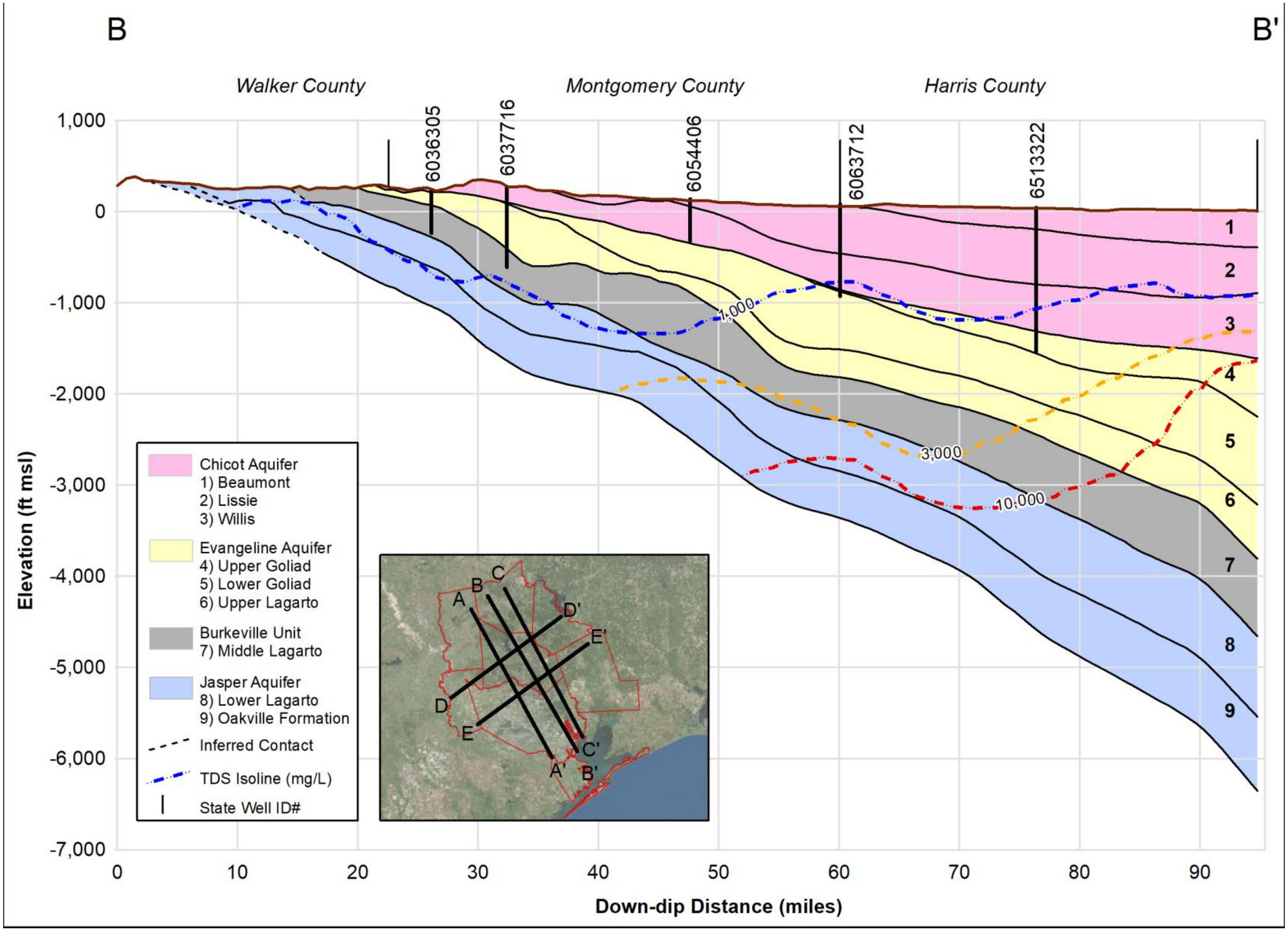


Figure 12. B-B' dip cross-section. Formation elevations from Young and others (2012). TDS isolines from Young and others (2016).

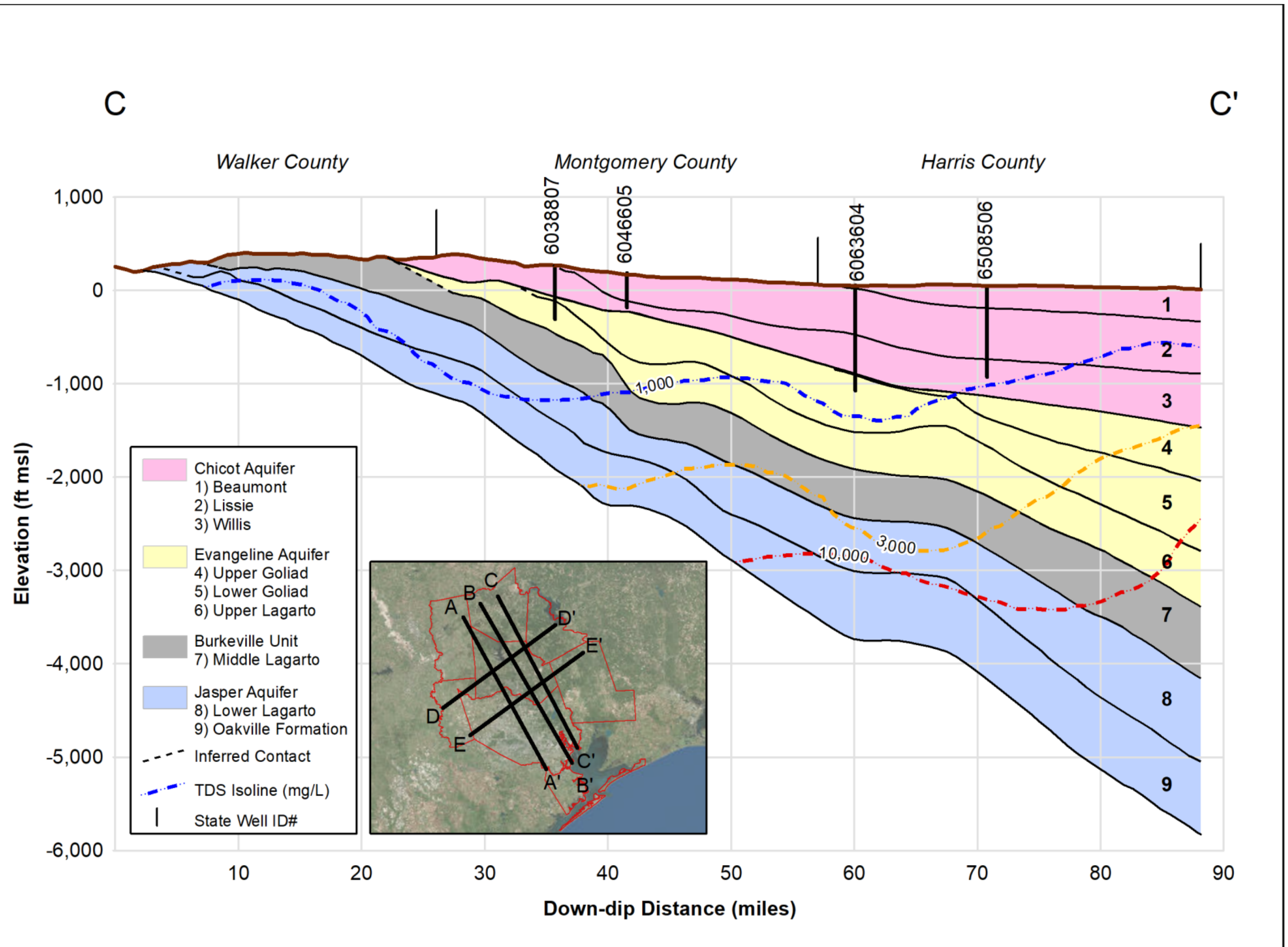


Figure 13. C-C' dip cross-section. Formation elevations from Young and others (2012). TDS isolines from Young and others (2016).

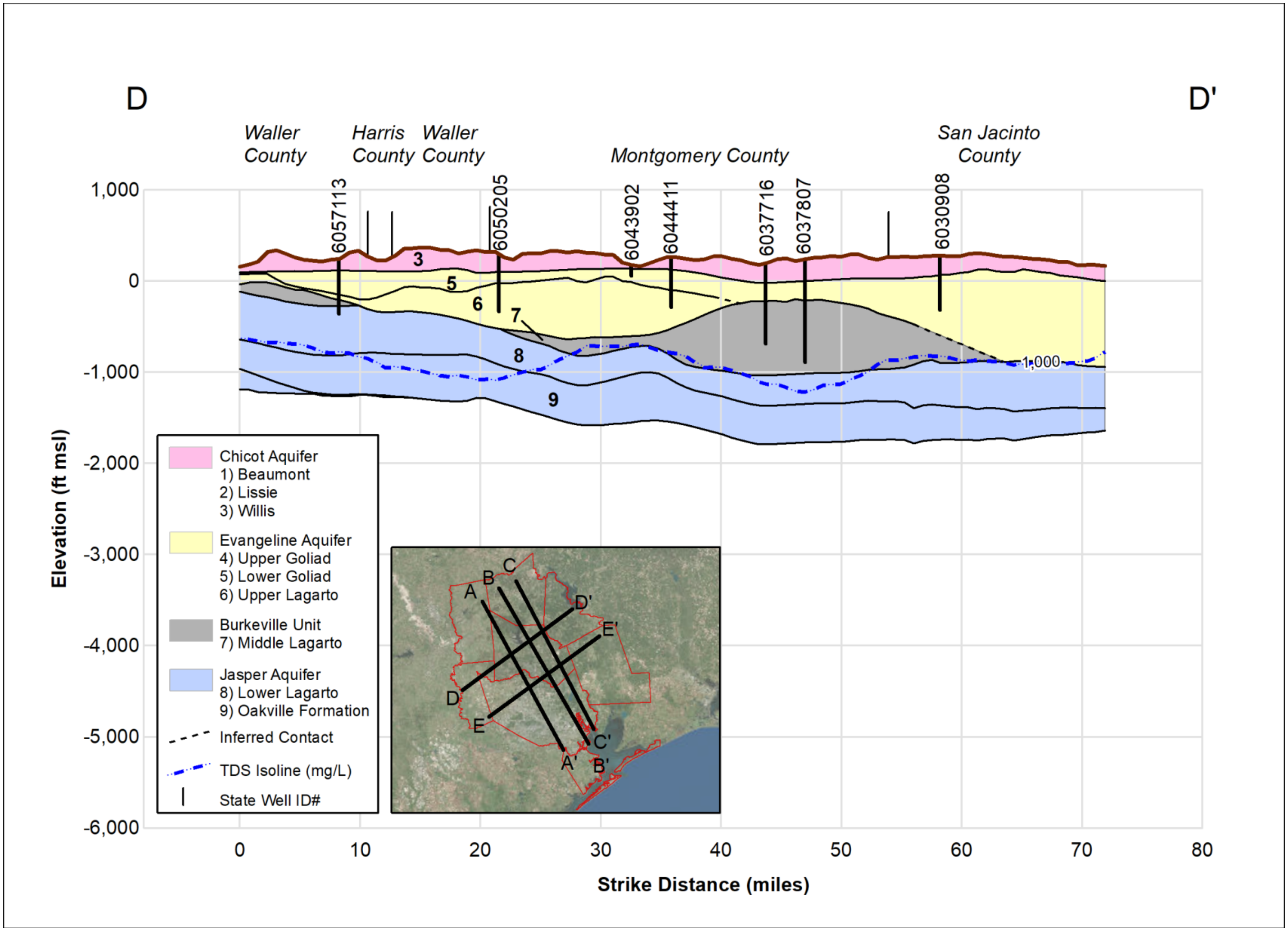


Figure 14. D-D' strike cross-section. Formation elevations from Young and others (2012). TDS isolines from Young and others (2016).

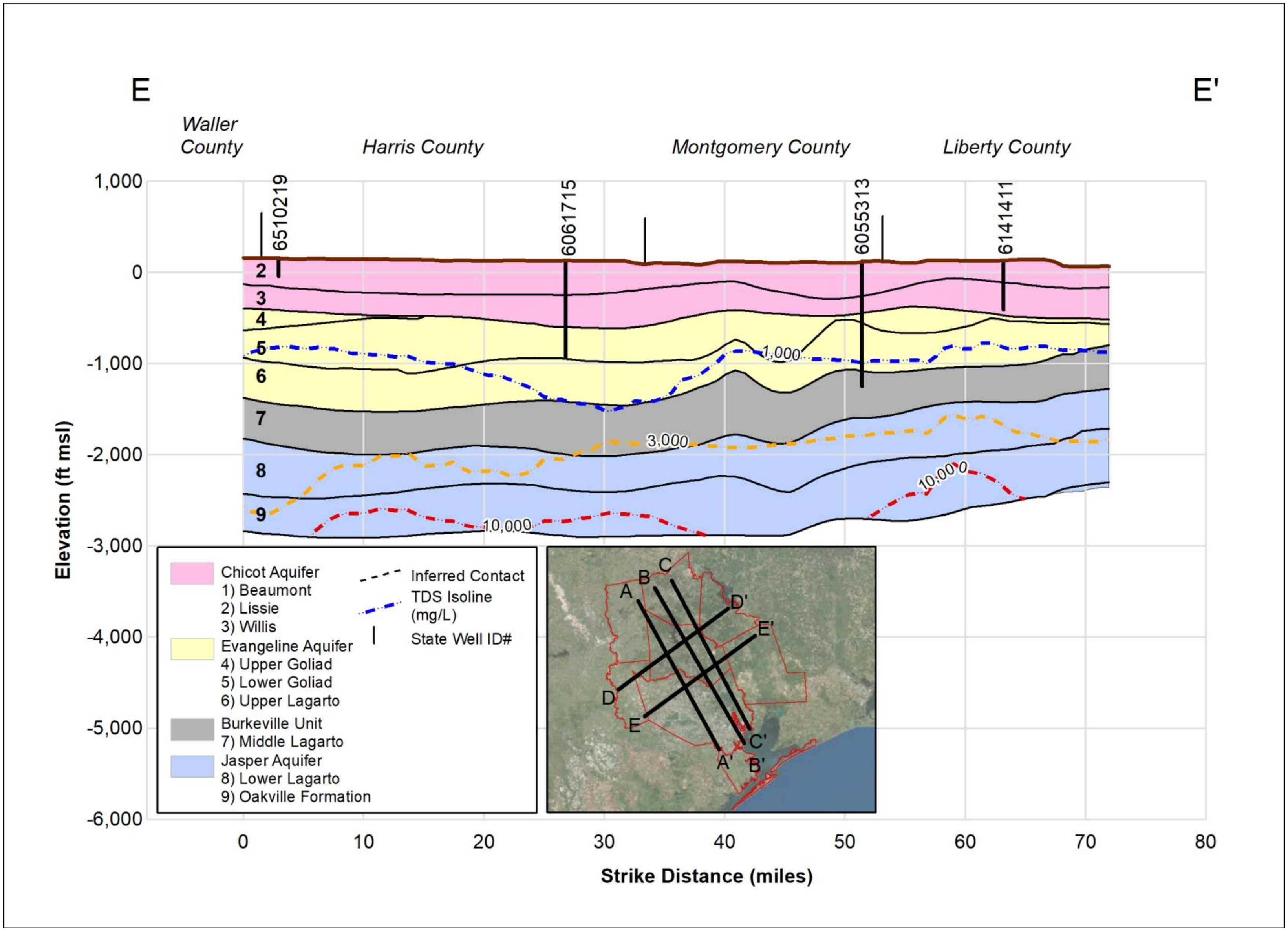


Figure 15. E-E' strike cross-section. Formation elevations from Young and others (2012). TDS isolines from Young and others (2016).

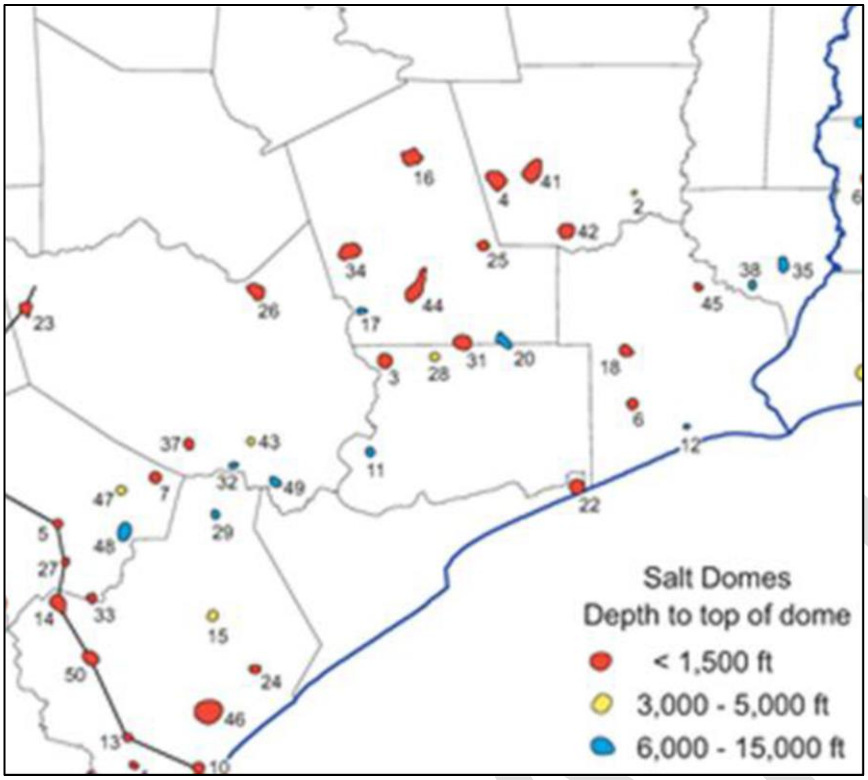


Figure 16. Salt domes in the Gulf Coast area. Reproduced from Young and others (2012).

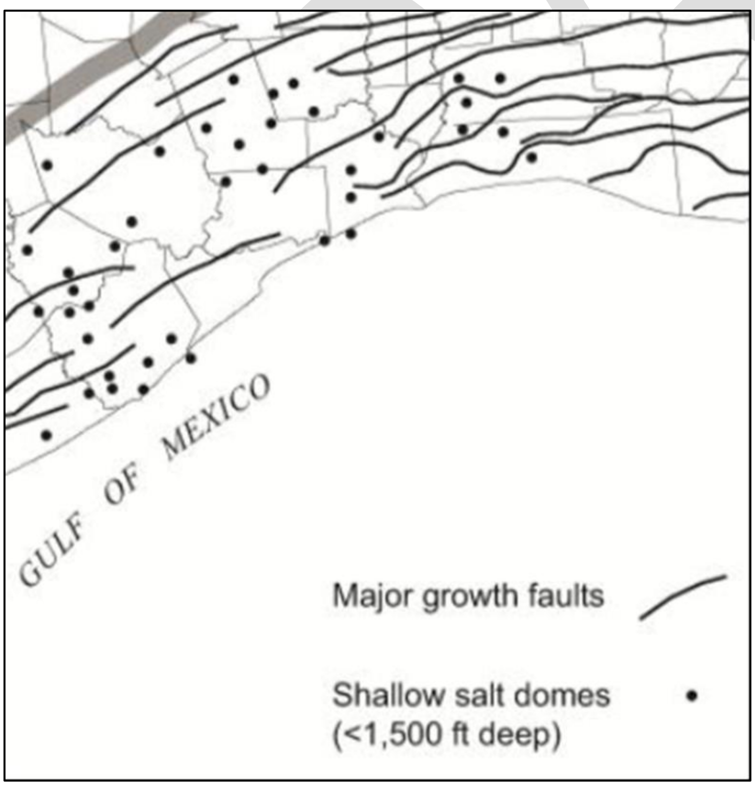


Figure 17. Illustration of major growth faults in the Gulf Coast area. Reproduced from Young and others (2012).

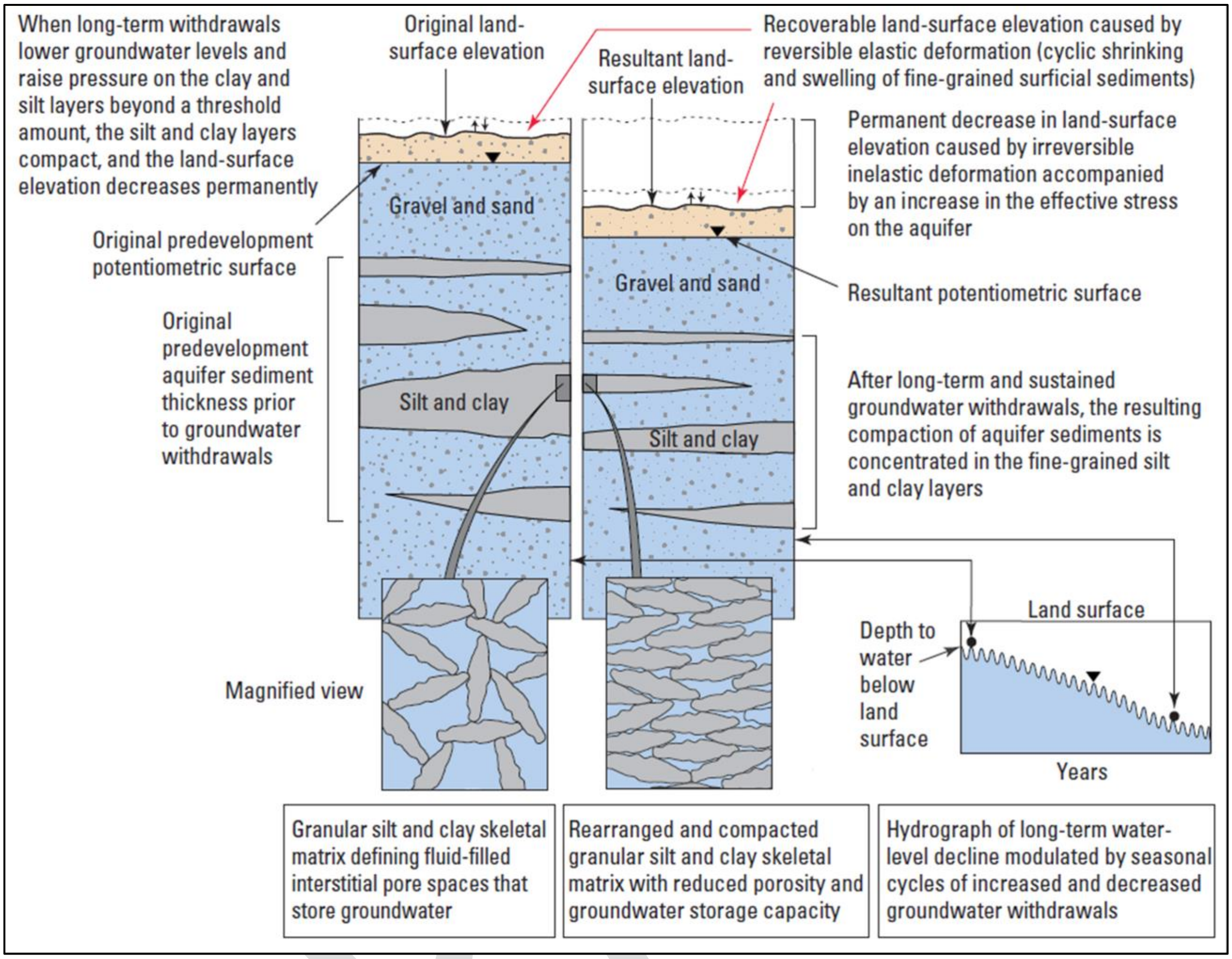


Figure 18. Illustration of subsidence due to reorientation of fine-grained aquifer sediments. Reproduced from Kasmarek and Ramage (2017).

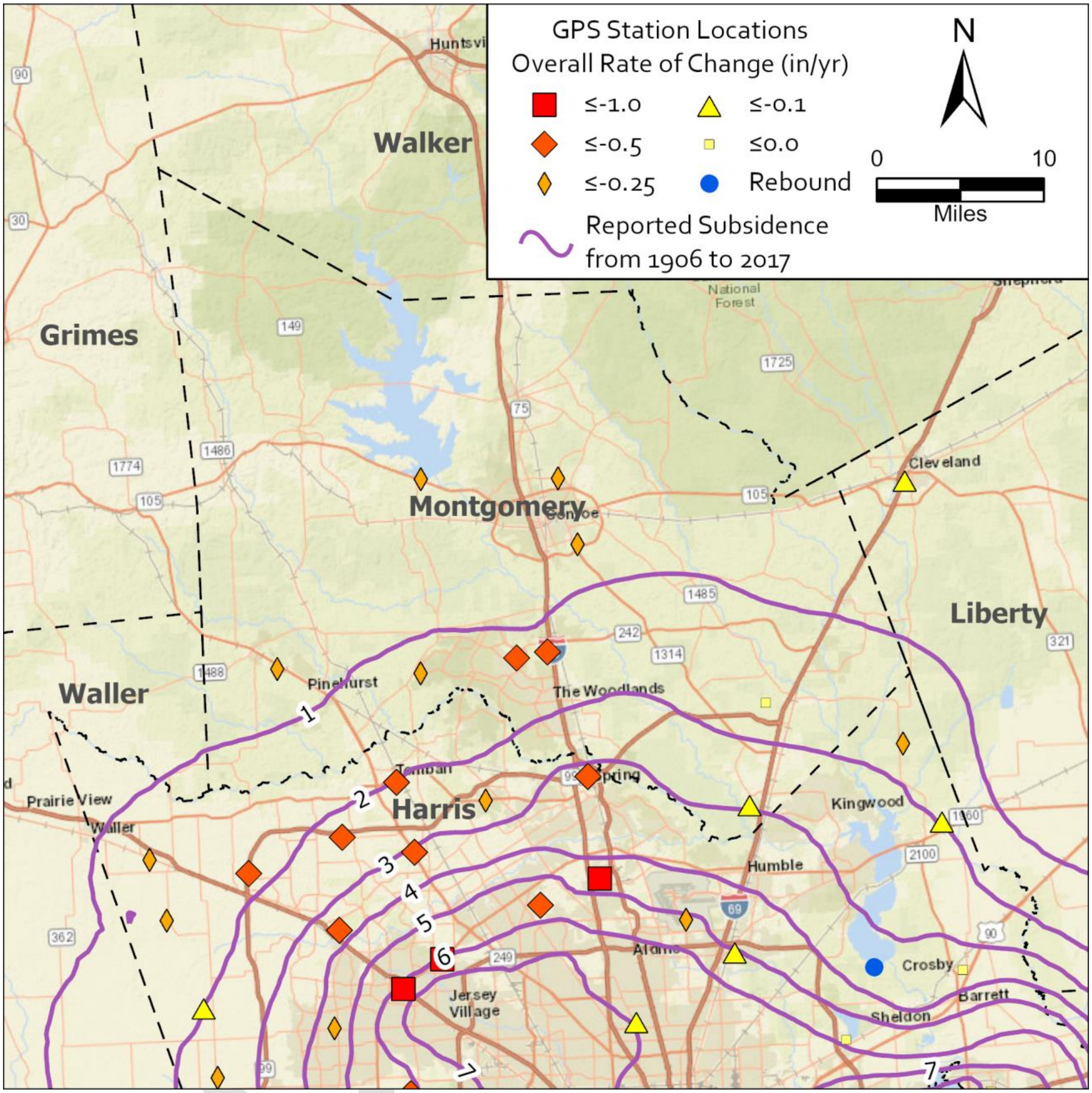


Figure 19. **Subsidence rate at monitoring locations with a minimum of 5 year measurement history and reported land surface subsidence from 1906 through 2017.**

Table 2. Geologic age and depositional systems associated with the layers of the Gulf Coast Aquifer System.

Hydrostatigraphic Unit	Geologic Age (Million Years)	Depositional System
Chicot Aquifer	Holocene/Pleistocene (<1)	Fluvial/Meanderbelt
Evangeline Aquifer	Pliocene/Miocene (1.5 to 10)	Lower Coastal Plain Fluvial/Coastal
Burkeville Confining Layer	Miocene	Lower Coastal Plain Fluvial/ Coastal/Bay Fill/Lagoonal
Jasper Aquifer	Miocene	Wave Dominated Delta Facies

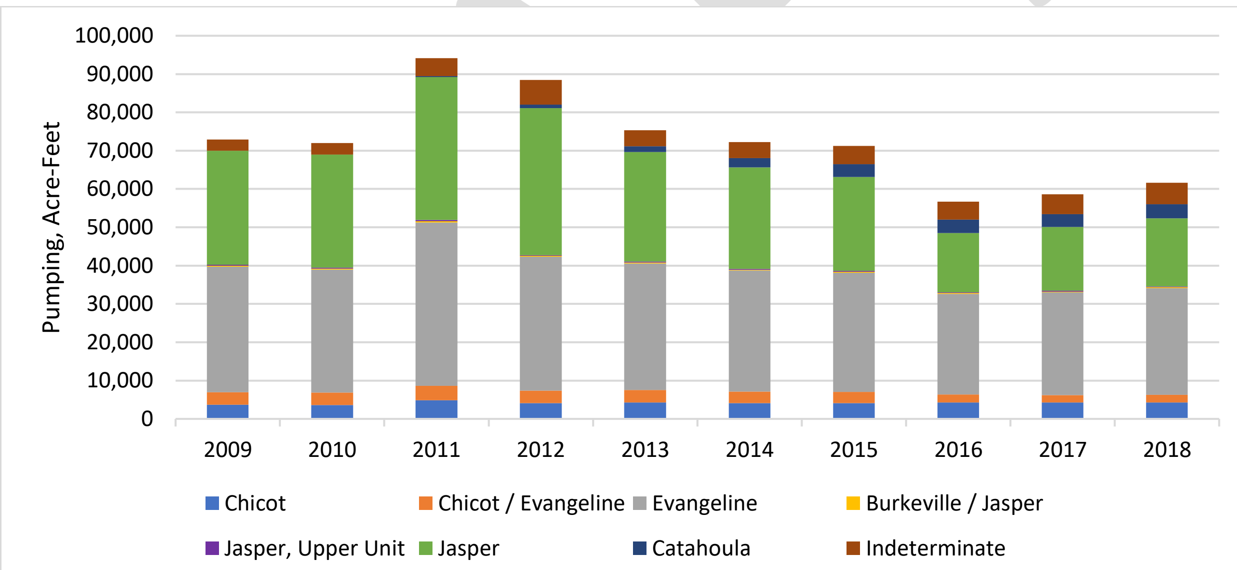


Figure 20. LSGCD reported pumping associated with permits by assigned aquifer.

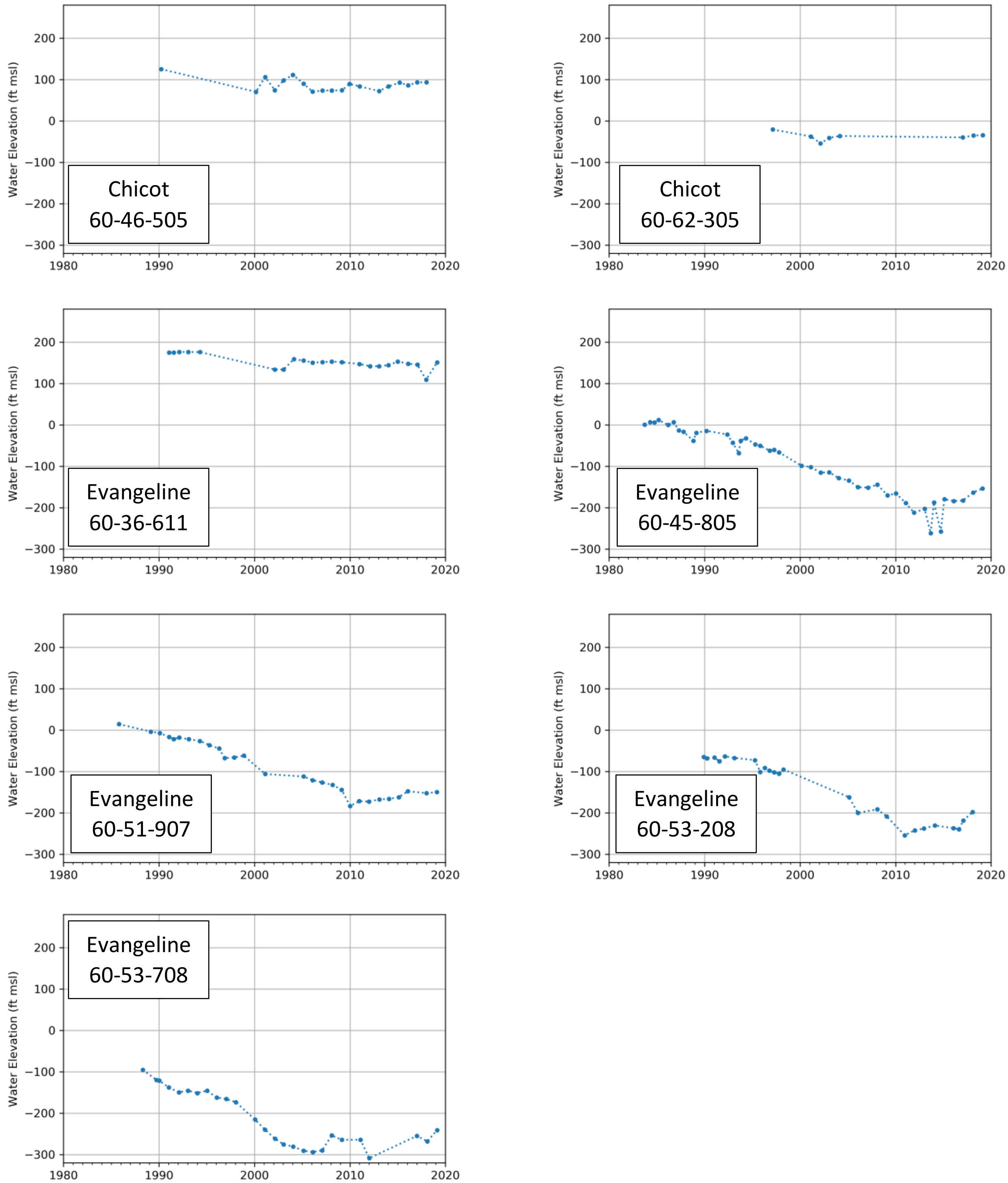


Figure 201. Reported water levels from the TWDB Groundwater Database (TWDB, 2020).

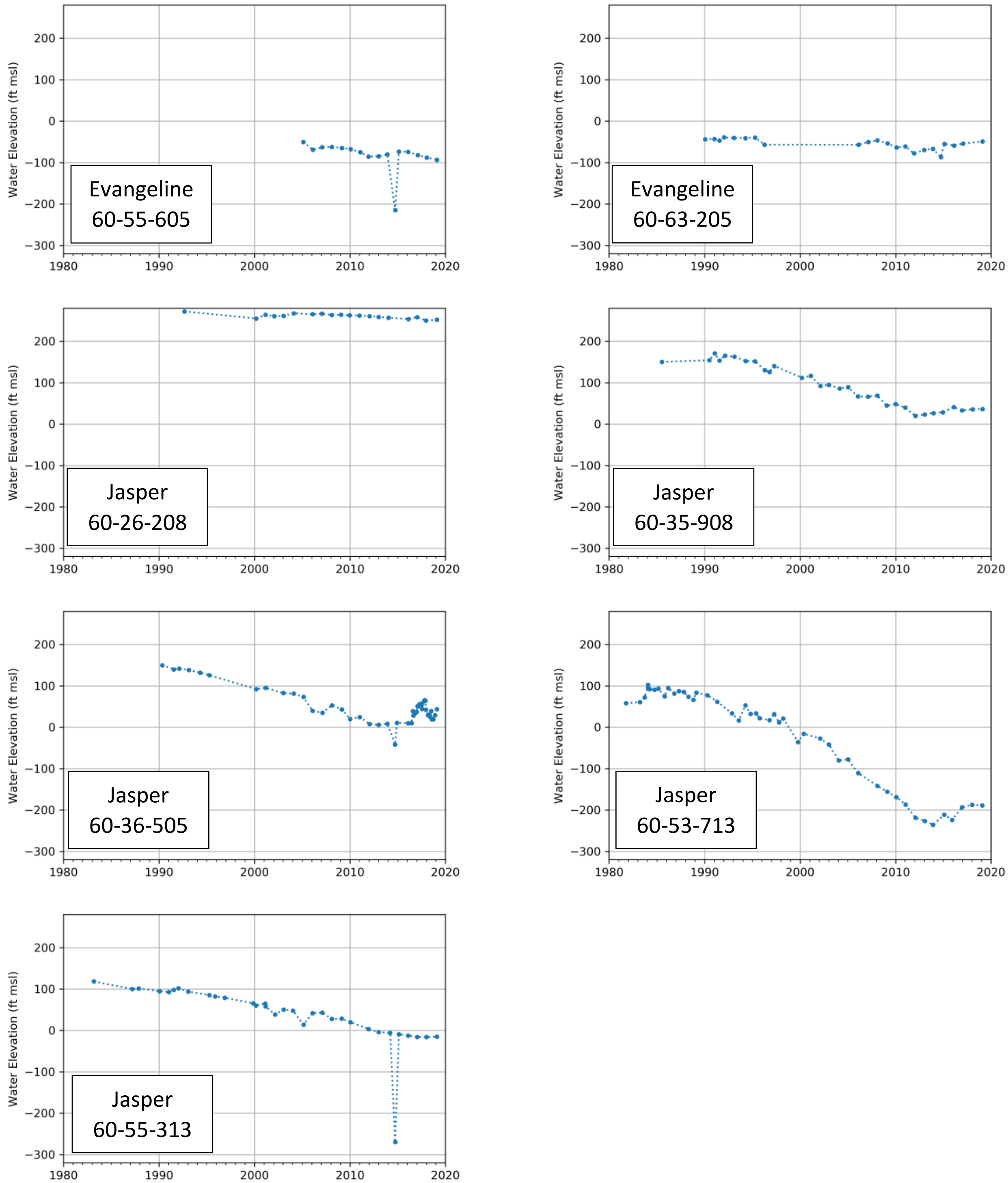


Figure 201. (continued) Reported water levels from the TWDB Groundwater Database (TWDB, 2020).

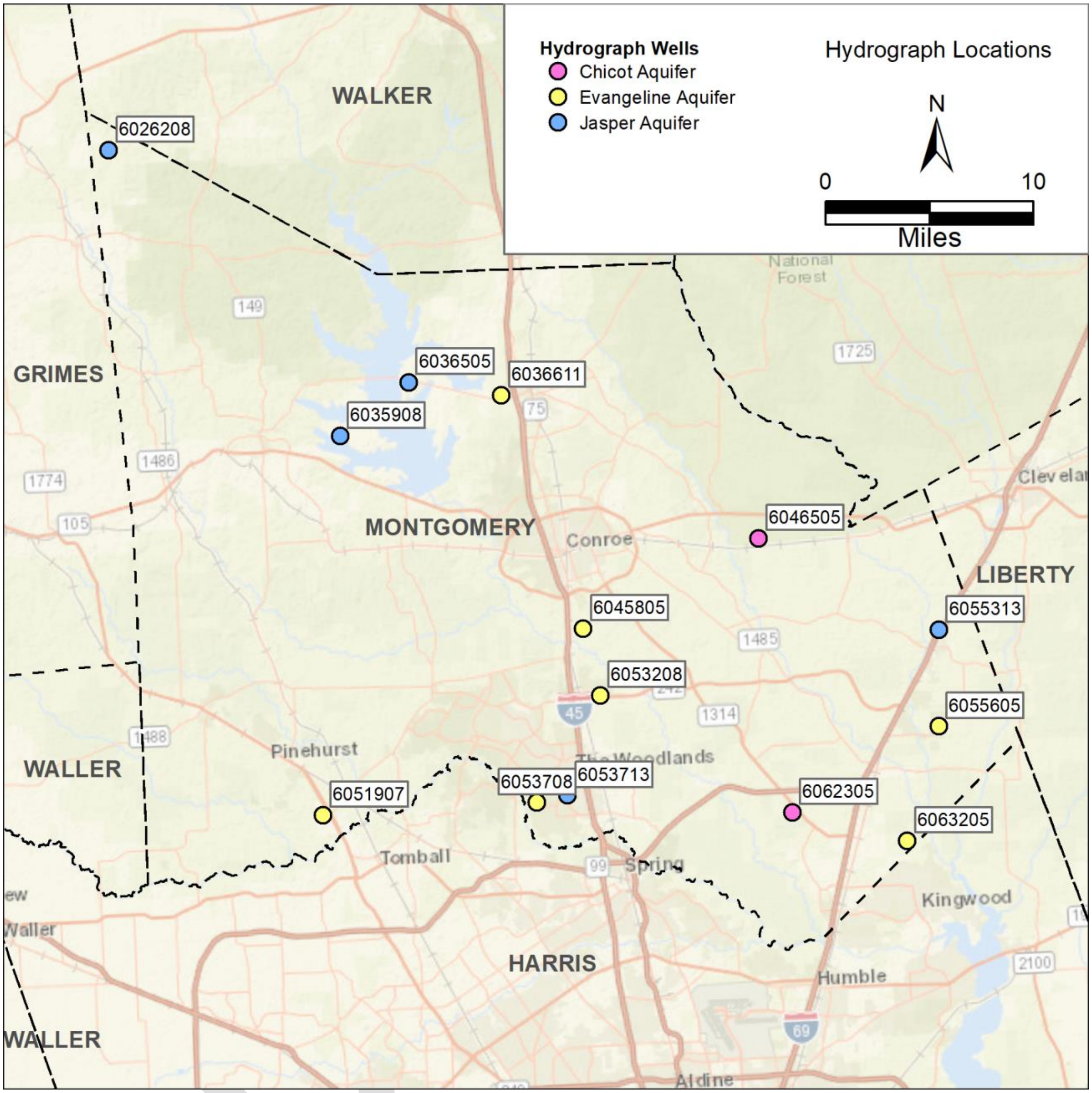


Figure 22. Map illustrating the location of the reported water levels from the TWDB Groundwater Database (TWDB, 2020).

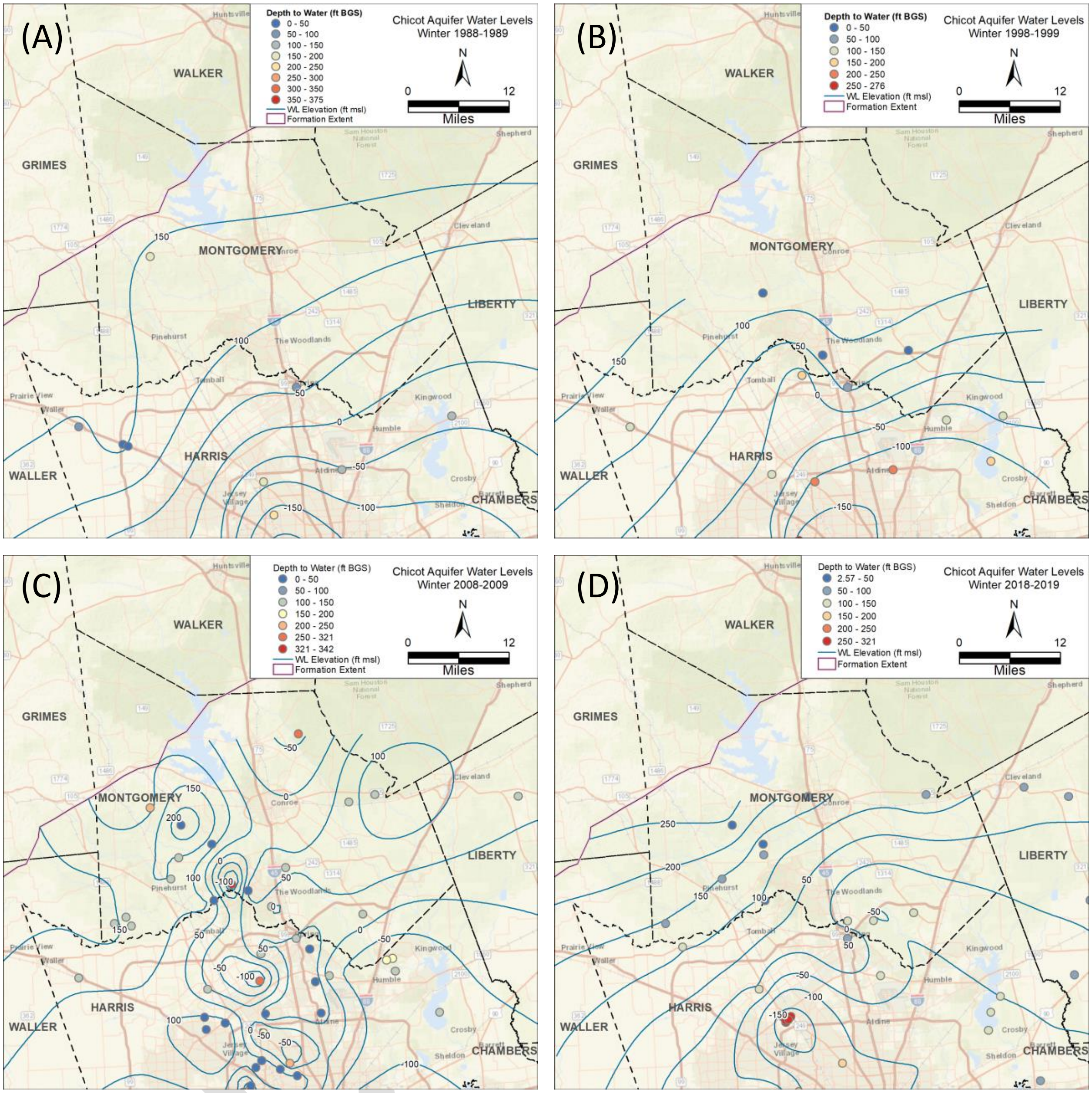


Figure 23. Estimated water levels in the Chicot Aquifer. Well locations, aquifer designation, and measured water level from the TWDB Groundwater Database (TWDB, 2020).

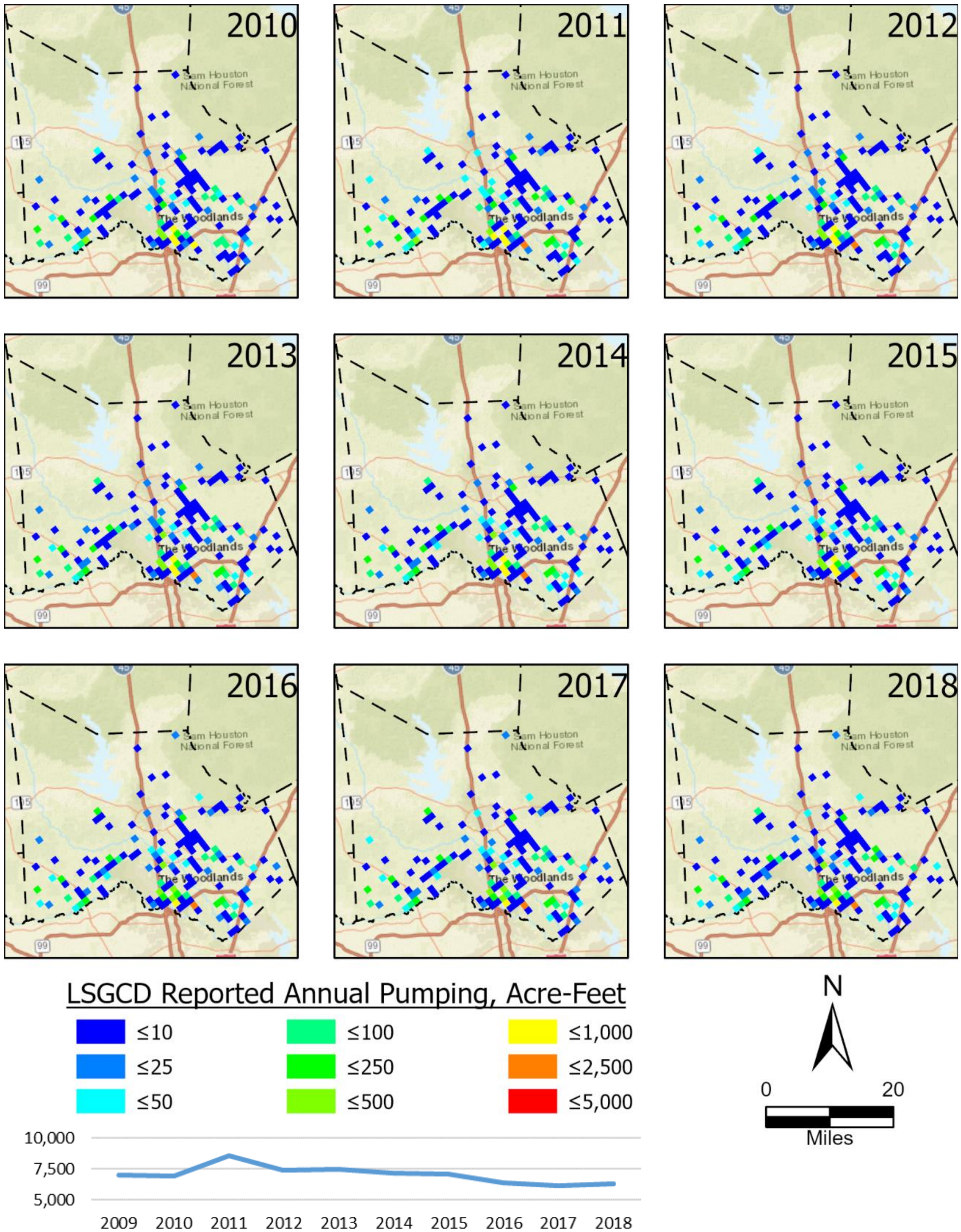


Figure 24. LSGCD reported pumping from permitted wells completed in the Chicot Aquifer.

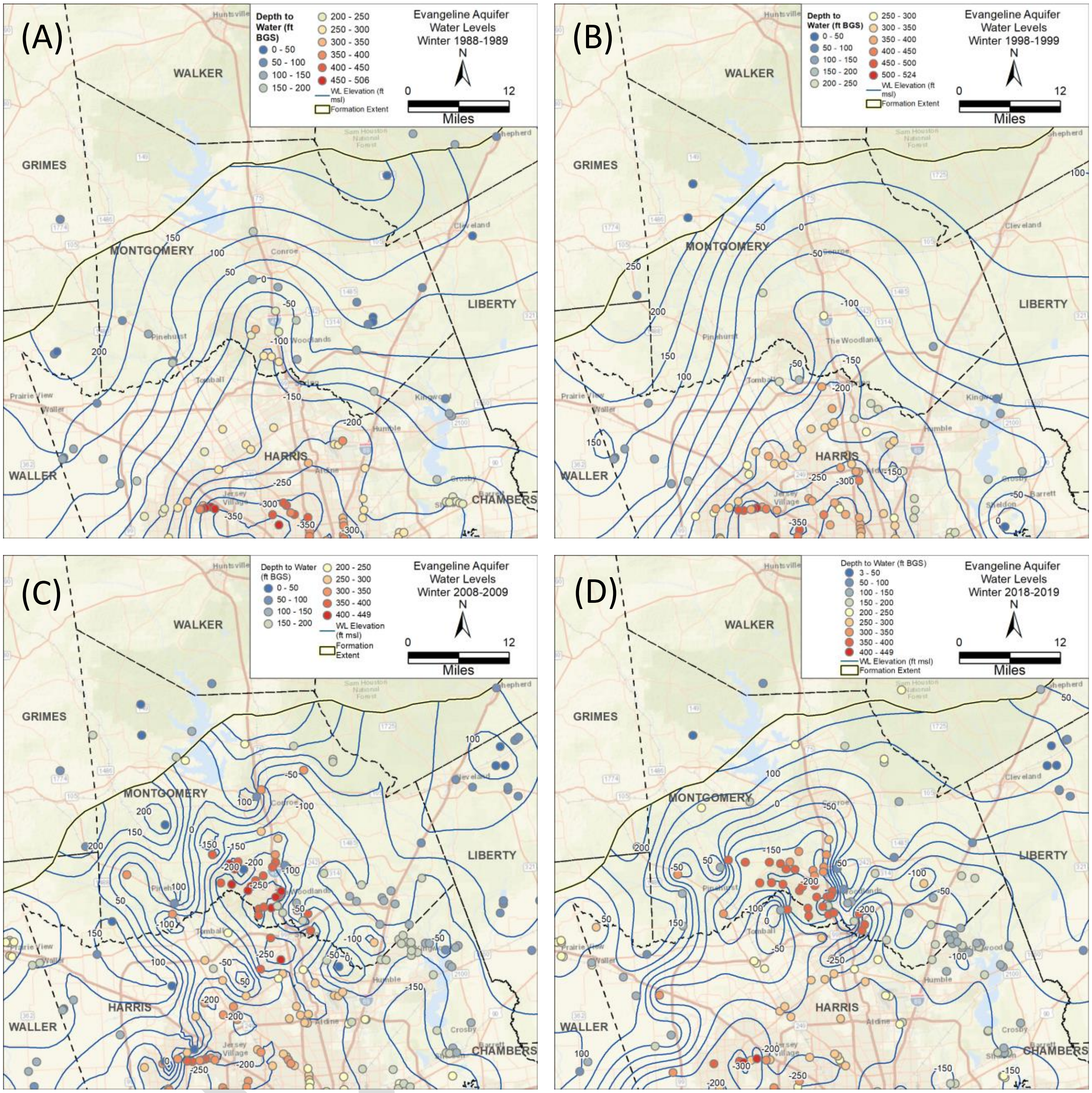


Figure 25. Estimated water levels in the Evangeline Aquifer. Well locations, aquifer designation, and measured water level from the TWDB Groundwater Database (TWDB, 2020).

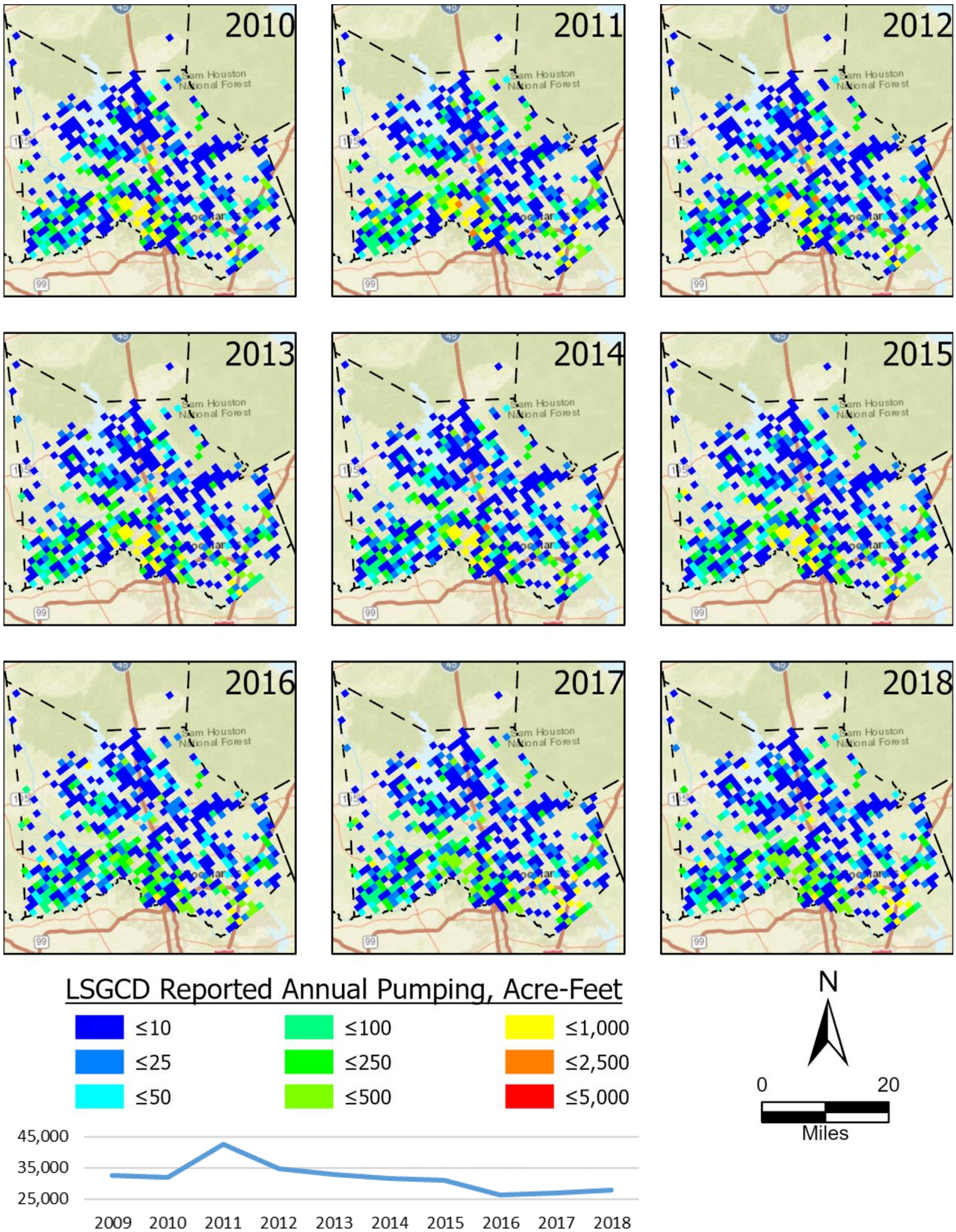


Figure 26. LSGCD reported pumping from permitted wells completed in the Evangeline Aquifer.

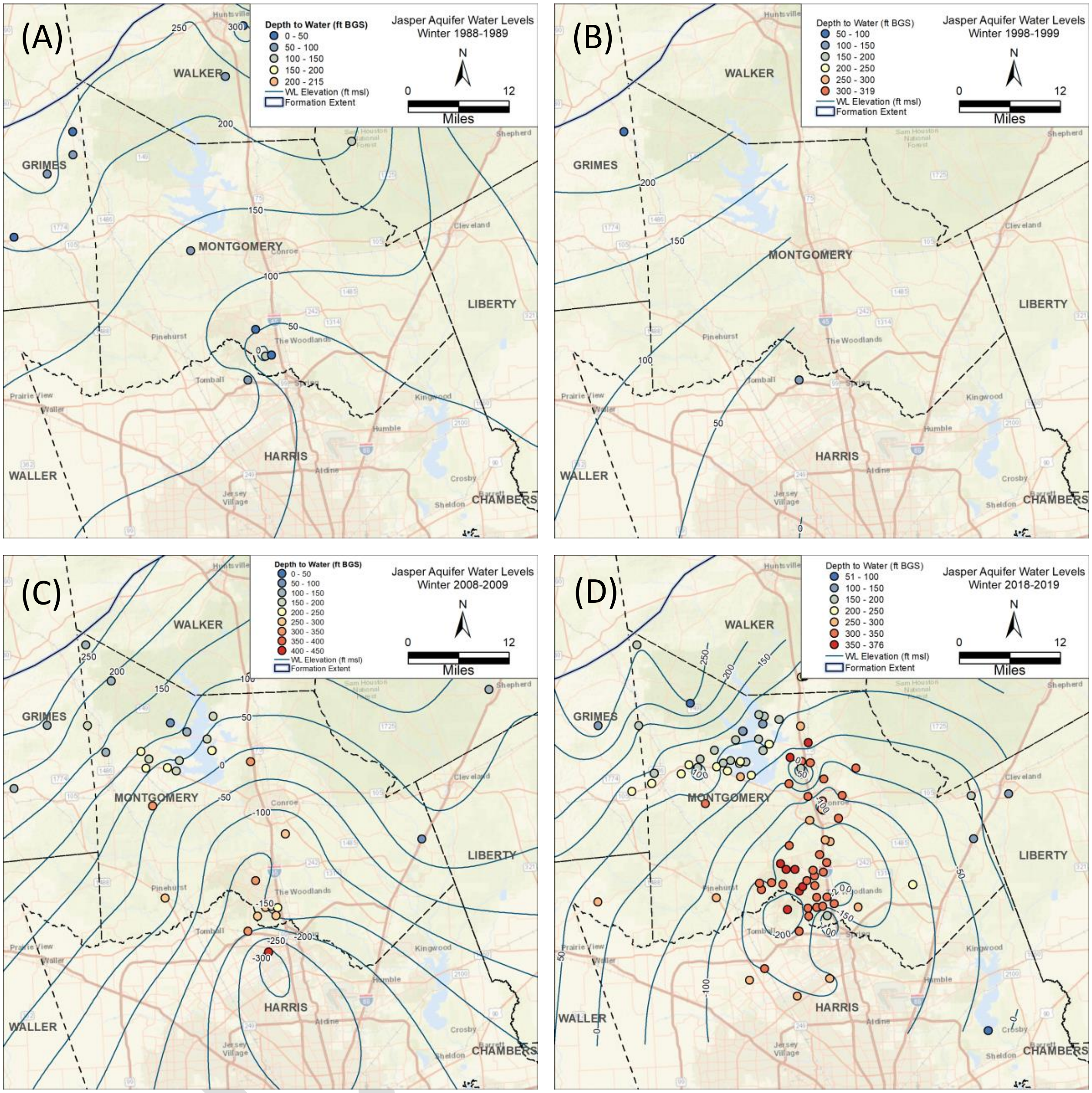


Figure 27. **Estimated water levels in the Jasper Aquifer. Well locations, aquifer designation, and measured water level from the TWDB Groundwater Database (TWDB, 2020).**

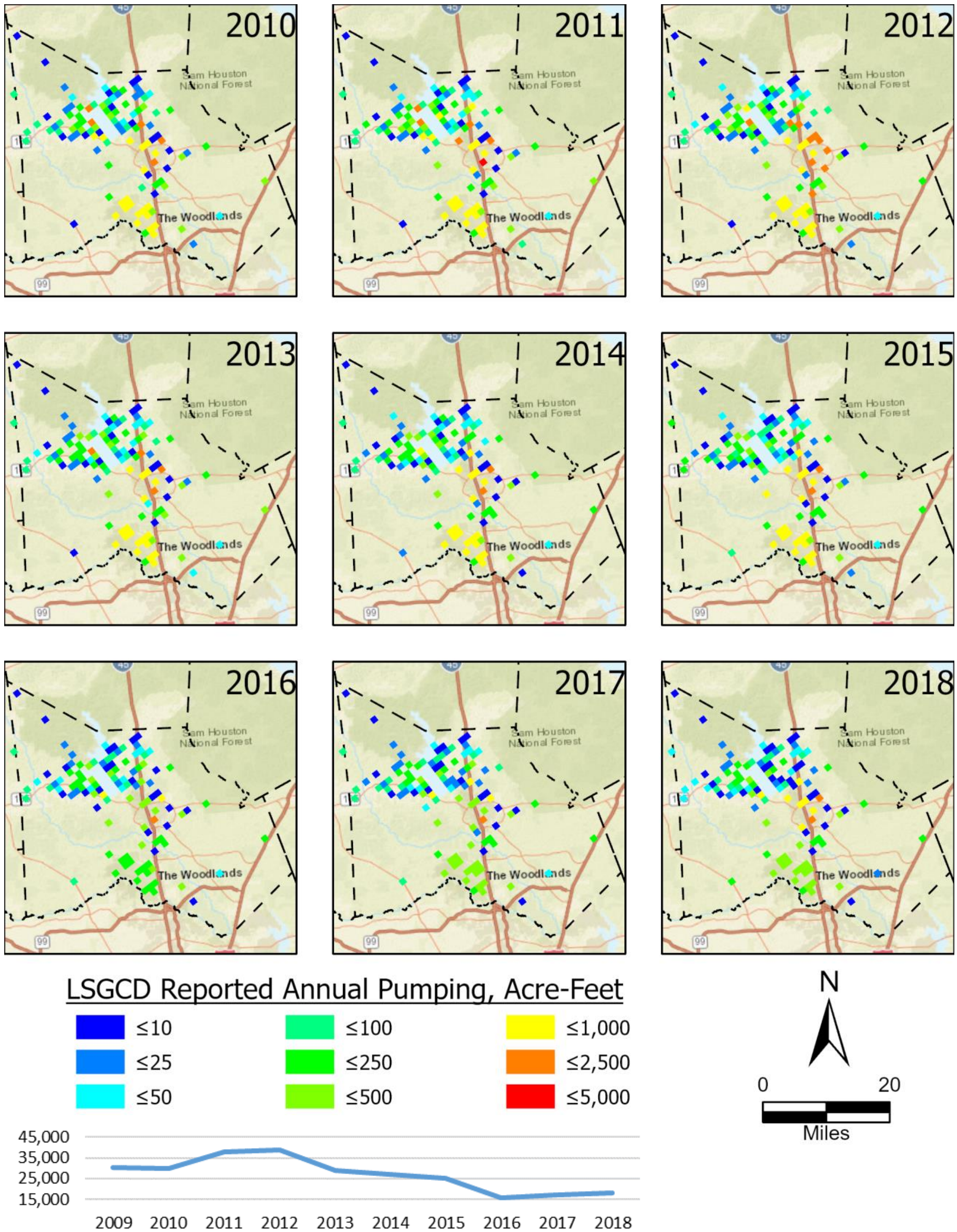


Figure 28. LSGCD reported pumping from permitted wells completed in the Jasper Aquifer.

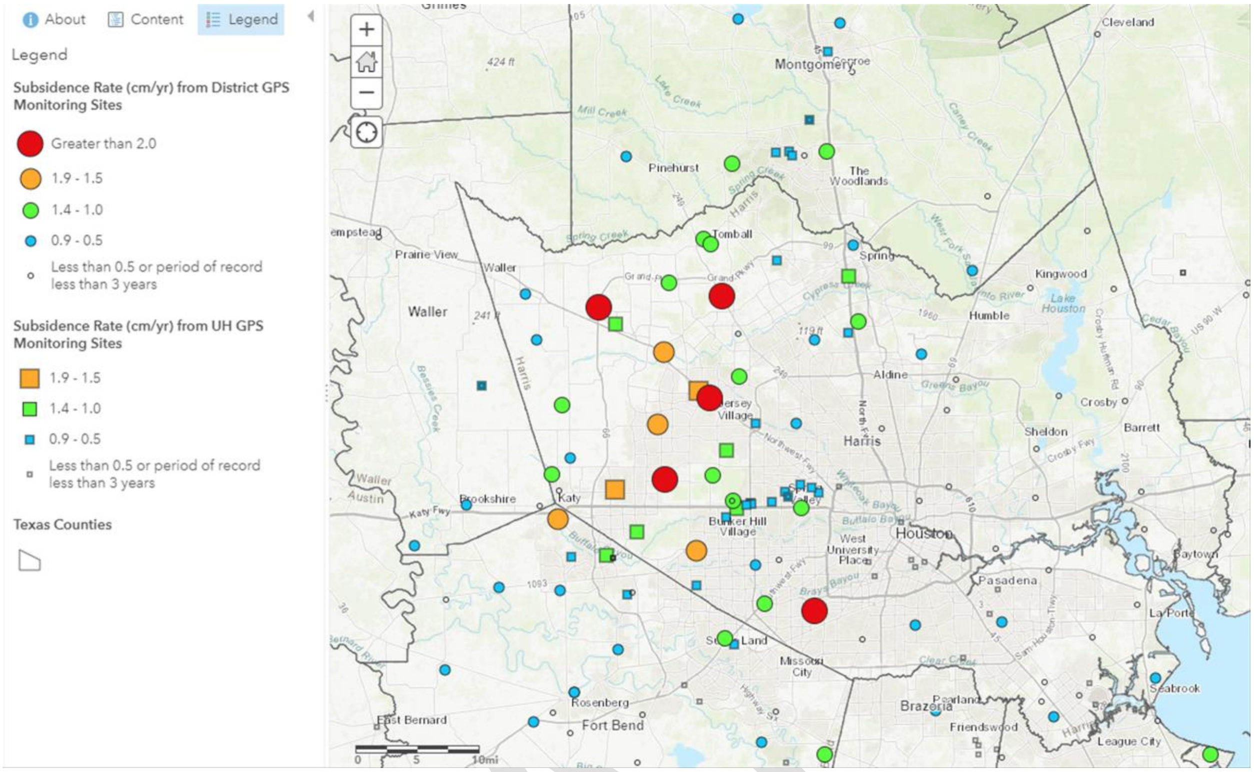


Figure 21. Rate of subsidence in the Houston area. Larger, warm color circles indicate a higher rate of subsidence (https://www.arcgis.com/home/webmap/viewer.html?webmap=a3e7214071f6421fb745d9866e2d3985).

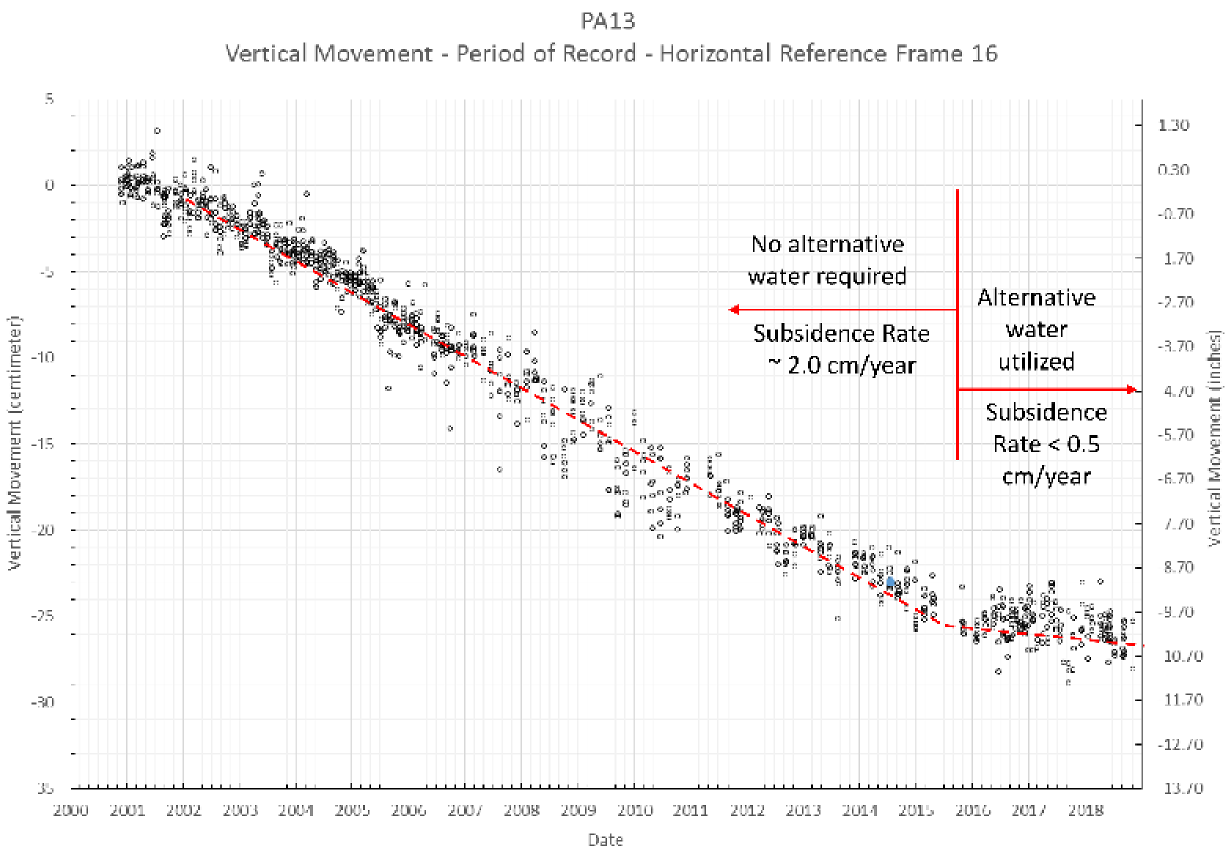


Figure 22. GPS measurements of the vertical change in land surface at PA13 site near The Woodlands.

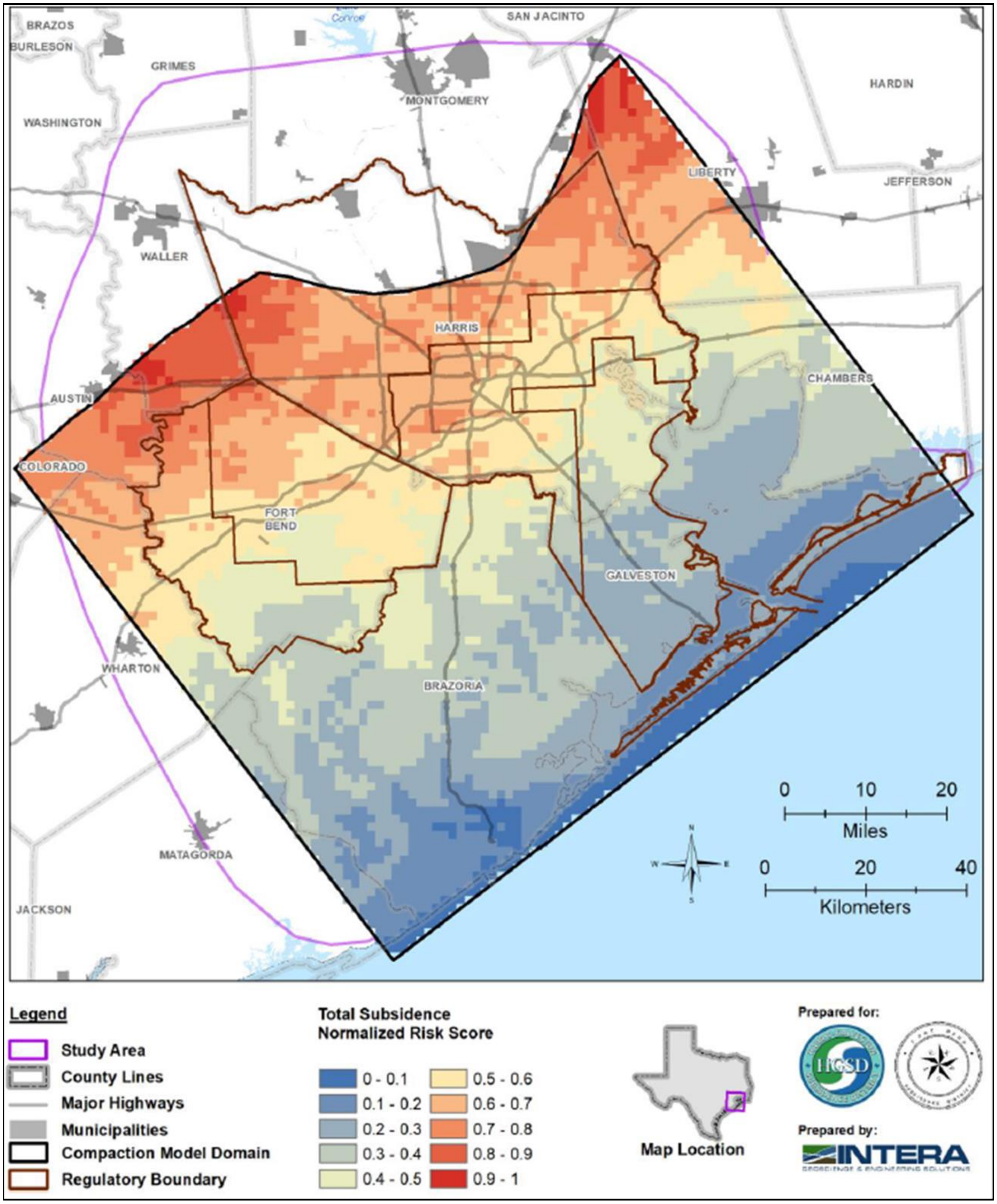


Figure 23. Relative subsidence risk due to pumping in the Brackish Jasper Aquifer. Reproduced without alteration from Figure 4-6 of Kelley and others (2018). Relative risk is dependent upon the depth to the aquifer, the estimated aquifer compaction due to pumping, and the surface extent within the FEMA 100-yr floodplain.

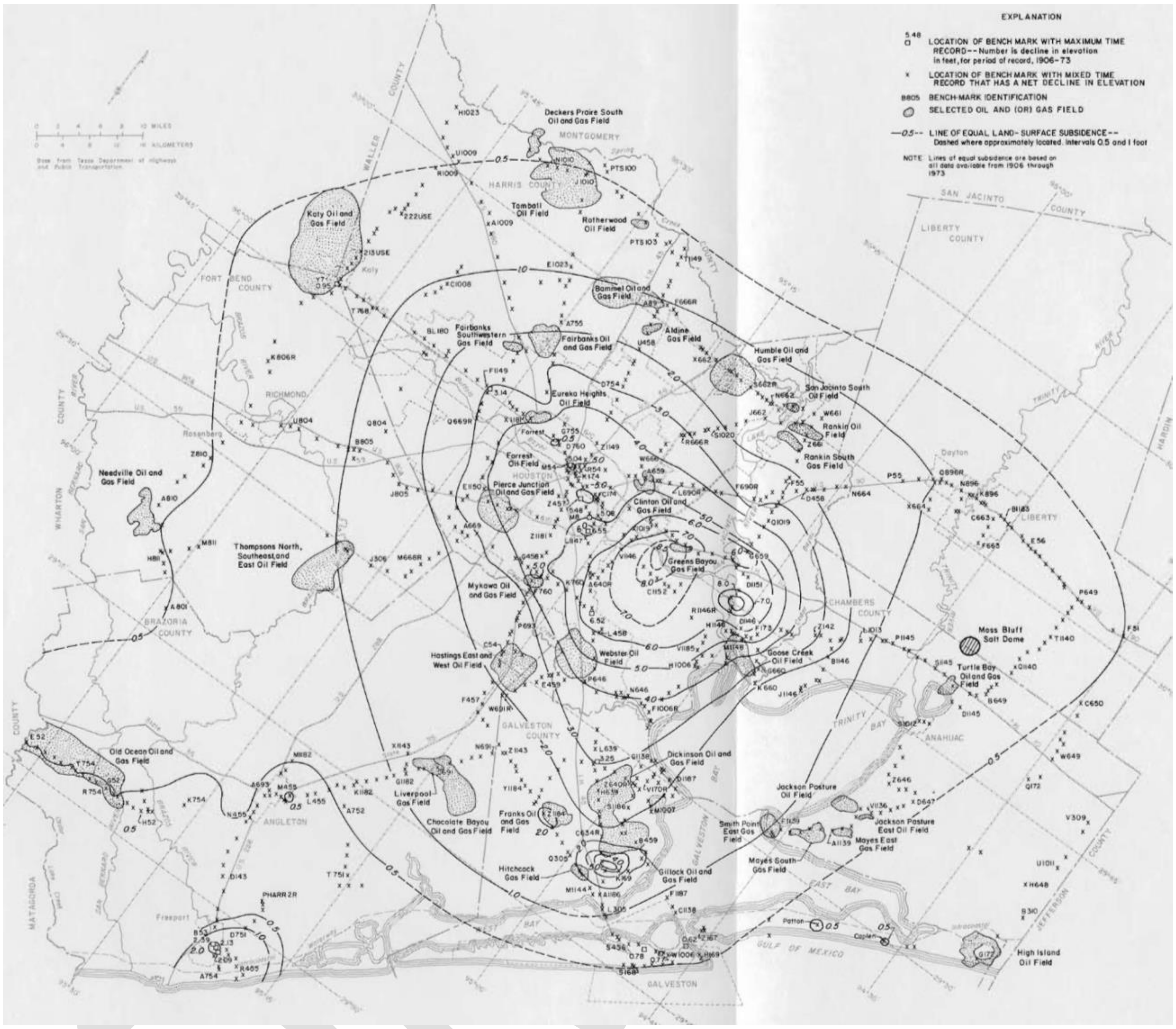


Figure 24. Land-surface subsidence in Subregion 2, 1906-1973, as calculated by Ratzlaff (1982). Reproduced without alteration from Figure 5 of Ratzlaff (1982).

Table 3. Modeling scenarios reviewed for evaluation of potential effects of groundwater production in Montgomery County.

Scenario ID	Description	Source
2010 MAG	GMA 14 modeled available groundwater simulation	Hassan (2011)
2016 MAG	GMA 14 modeled available groundwater simulation	Wade (2016)
2016 MAG with 2010 LSGCD	2016 MAG with 2010 MAG for Montgomery County	Hassan (2011); Wade (2016)
Run D (LSGCD Option 3)	2016 MAG with additional pumping in Montgomery County	Seifert, Jr. (2017)
75 Pct	Median of water level above the bottom of existing wells equal to 75 percent	INTERA (2019)
Alt WMS 1	2016 MAG with added pumping across GMA 14 for WMS	Keester and others (2020)
Alt WMS 2	2016 MAG with added pumping across GMA 14 for WMS except “County-Other” entities	Keester and others (2020)
Alt WMS 3	2016 MAG with added pumping across GMA 14 for WMS identified as PWS entities	Keester and others (2020)
Alt WMS 4	2010 MAG with added pumping across GMA 14 for WMS	Keester and others (2020)
Alt WMS 5	2016 MAG with 2010 LSGCD with added pumping across GMA 14 for WMS	Keester and others (2020)
Alt WMS 6	75 Pct with added pumping across GMA 14 for WMS	Keester and others (2020)
Alt WMS 7	2016 MAG with added pumping for the City of Conroe and The Woodlands WMS	TGI & LRE (2020)
Alt WMS 8	2016 MAG with added pumping for the City of Conroe WMS	TGI & LRE (2020)
LSGCD Option 1	Run D with less remaining available drawdown in the GCAS	LSGCD (2020)
LSGCD Option 2	Run D with less remaining available drawdown in the Jasper	LSGCD (2020)

Table 4. Simulated pumping in acre-feet per year at the end of the predictive period for each of the modeling scenarios reviewed for evaluation of potential effects of groundwater production in Montgomery County.

Scenario ID	Chicot	Evangeline	Jasper	GCAS
2010 MAG	1,722	40,707	21,615	64,043
2016 MAG	14,175	26,529	23,301	64,004
2016 MAG with 2010 LSGCD	1,722	40,707	21,615	64,043
Run D (LSGCD Option 3)	11,250	43,917	44,330	99,497
75 Pct	16,229	32,014	29,010	77,253
Alt WMS 1	14,175	27,306	91,689	133,169
Alt WMS 2	14,175	27,107	68,849	110,130
Alt WMS 3	14,175	27,107	67,562	108,843
Alt WMS 4	1,722	41,484	90,003	133,208
Alt WMS 5	1,722	41,484	90,003	133,208
Alt WMS 6	16,229	32,791	97,398	146,418
Alt WMS 7	14,175	26,529	50,796	91,499
Alt WMS 8	14,175	26,529	39,729	80,432
LSGCD Option 1	17,975	44,902	53,160	116,037
LSGCD Option 2	11,883	52,058	47,504	111,445

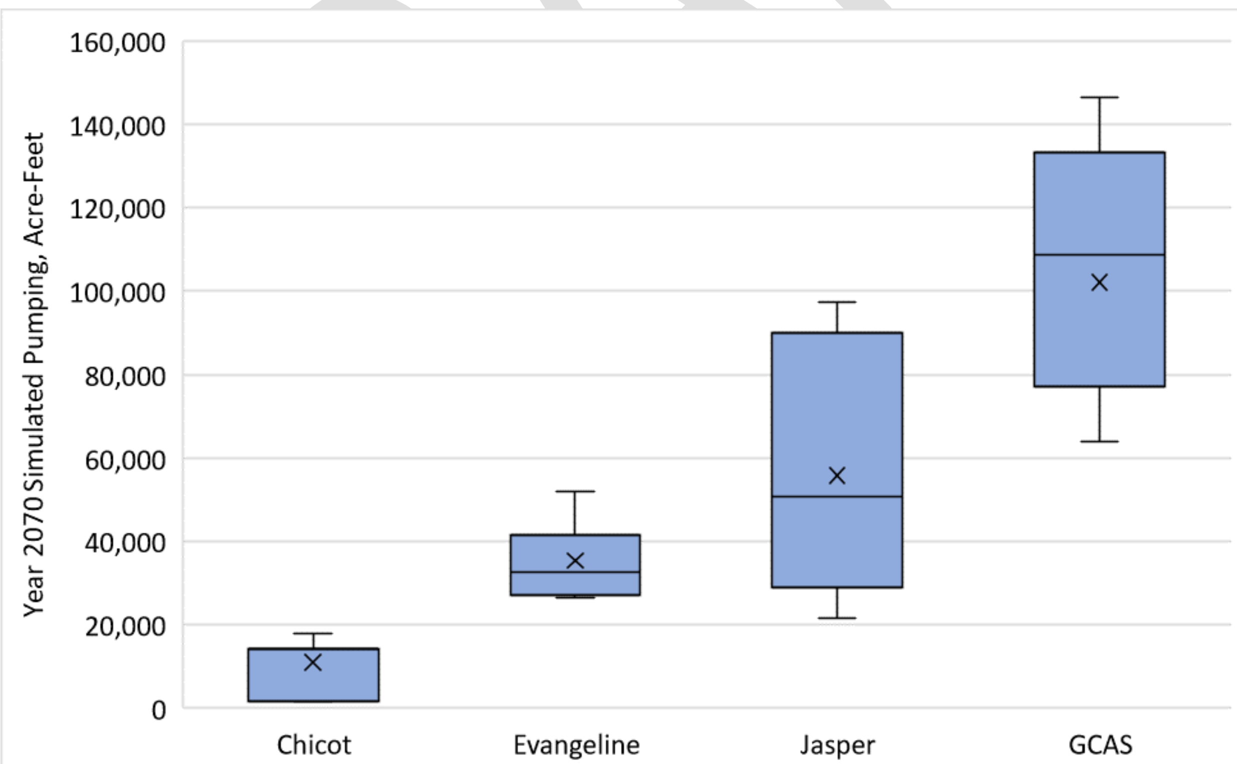


Figure 33. Box-and-whisker plot illustrating the distribution of simulated pumping within Montgomery County in each of the scenarios.

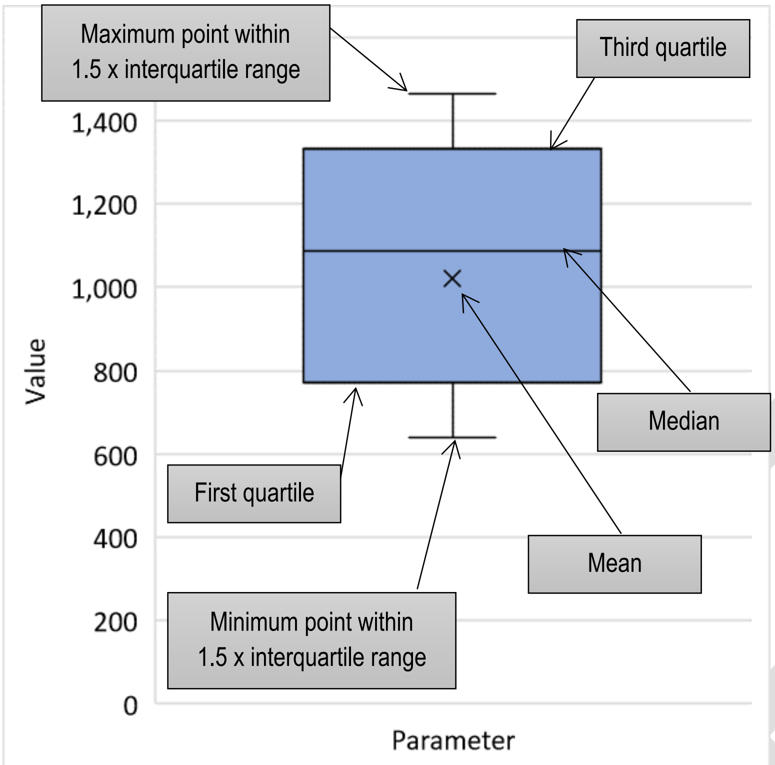


Figure 34. Legend illustrating the parts of the box and whisker plot. Interquartile range is the difference between the third and first quartile. Outliers beyond the minimum and maximum extents are not shown.

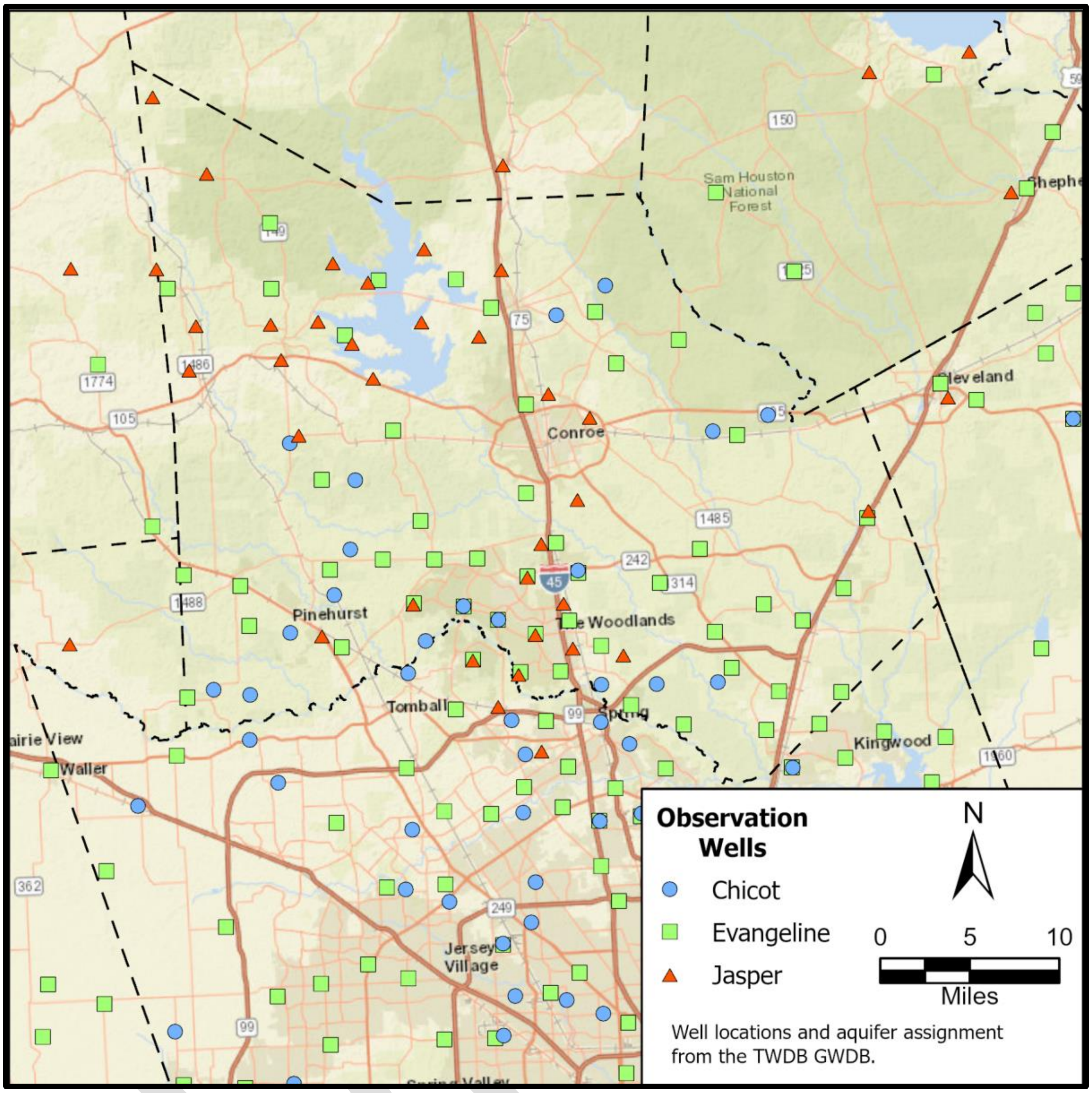


Figure 35. Location of monitoring wells used for analysis of model results within Montgomery County. Modified from Keester (2020).

Table 5. Average predicted change in water level in feet from January 1, 2010 to December 31, 2070 at identified monitoring well locations in Montgomery County under each scenario.

Scenario ID	Chicot	Evangeline	Jasper	GCAS
2010 MAG	23	-9	54	14
2016 MAG	31	-76	9	-37
2016 MAG with 2010 LSGCD	31	-19	18	-2
Run D (LSGCD Option 3)	36	-8	220	66
75 Pct	39	-65	146	12
Alt WMS 1	34	-68	531	126
Alt WMS 2	31	-71	317	59
Alt WMS 3	32	-73	294	51
Alt WMS 4	26	-1	547	168
Alt WMS 5	34	-11	541	161
Alt WMS 6	42	-57	669	175
Alt WMS 7	33	-74	250	37
Alt WMS 8	31	-76	129	0
LSGCD Option 1*	42	16	328	118
LSGCD Option 2*	40	12	350	123

*values are for predictive period ending 12/31/2080

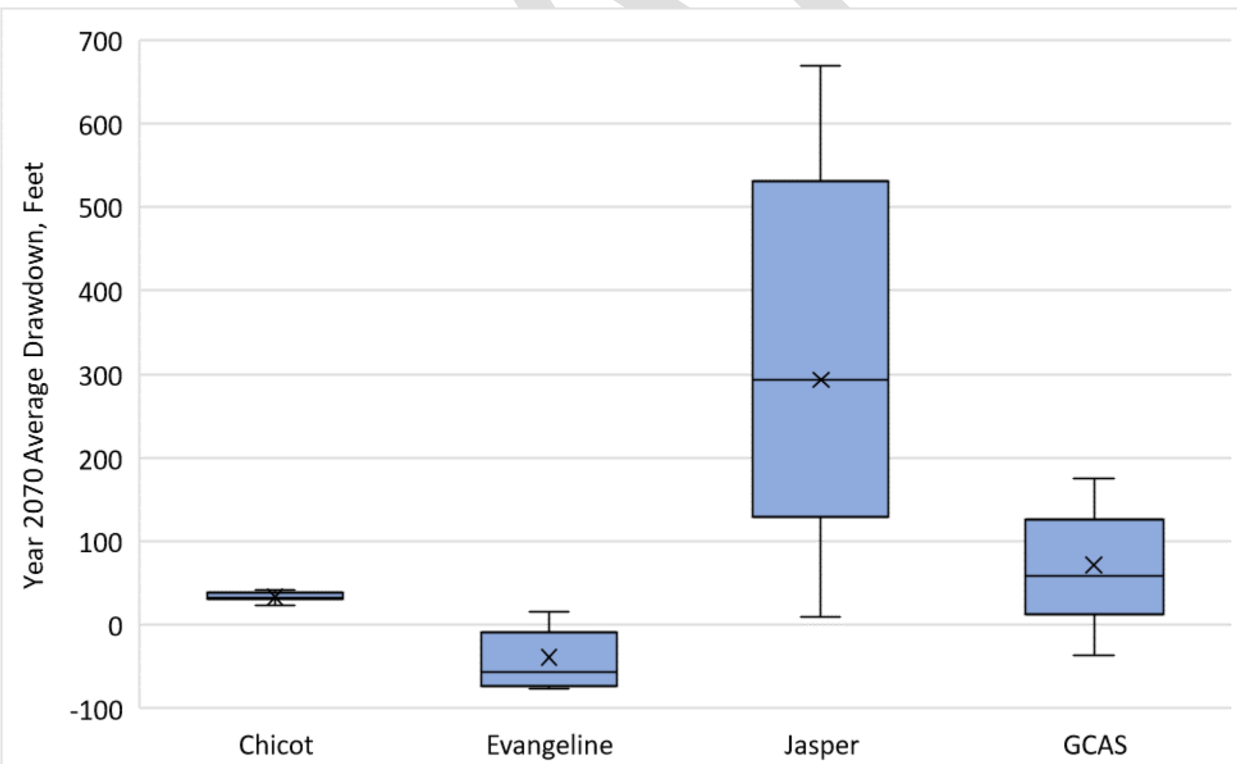


Figure 36. Box-and-whisker plot illustrating the distribution of average drawdown within Montgomery County in each of the scenarios. See Figure 2 for an explanation of the box-and-whisker plot.

Table 6. **Maximum predicted compaction in feet from January 1, 2010 to December 31, 2070 at identified monitoring well locations in Montgomery County under each scenario. Compaction of the GCAS represents the predicted land surface subsidence.**

Scenario ID	Chicot	Evangeline	Jasper	GCAS
2010 MAG	0.5	-0.6	0.05	-0.3
2016 MAG	1.6	0.2	0.05	1
2016 MAG with 2010 LSGCD	1.4	0.4	0.05	0.7
Run D (LSGCD Option 3)	1.9	0.7	0.15	1.6
75 Pct	2.2	0.3	0.15	1.8
Alt WMS 1	1.9	0.2	0.25	1.5
Alt WMS 2	1.6	0.2	0.15	1.1
Alt WMS 3	1.6	0.2	0.15	1.1
Alt WMS 4	1.1	-0.6	0.15	0.6
Alt WMS 5	1.8	0.4	0.25	1.5
Alt WMS 6	2.8	0.3	0.35	2.6
Alt WMS 7	1.6	0.2	0.15	1.1
Alt WMS 8	1.6	0.2	0.05	1
LSGCD Option 1*	3	0.7	0.15	2.9
LSGCD Option 2*	2.1	0.7	0.15	1.9

*values are for predictive period ending 12/31/2080

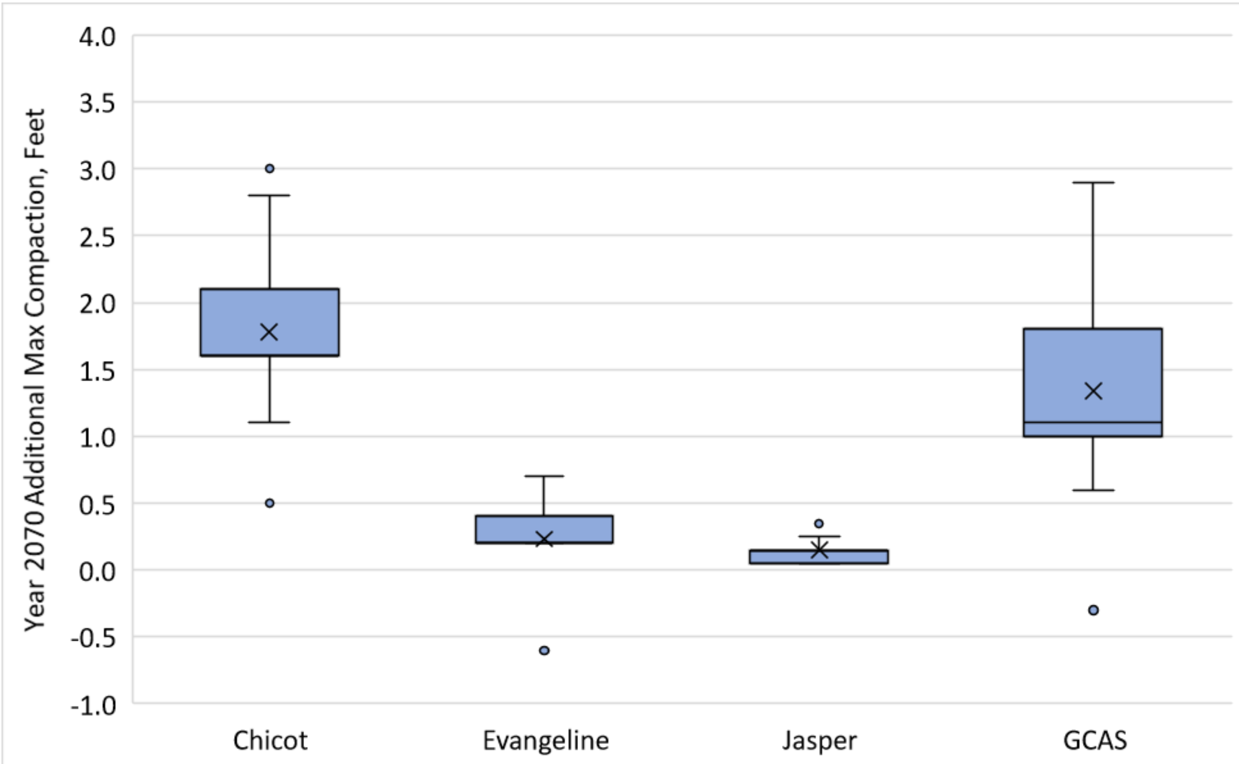


Figure 37. Box-and-whisker plot illustrating the distribution of maximum compaction within Montgomery County in each of the scenarios. The maximum compaction range for the GCAS represents land-surface subsidence.

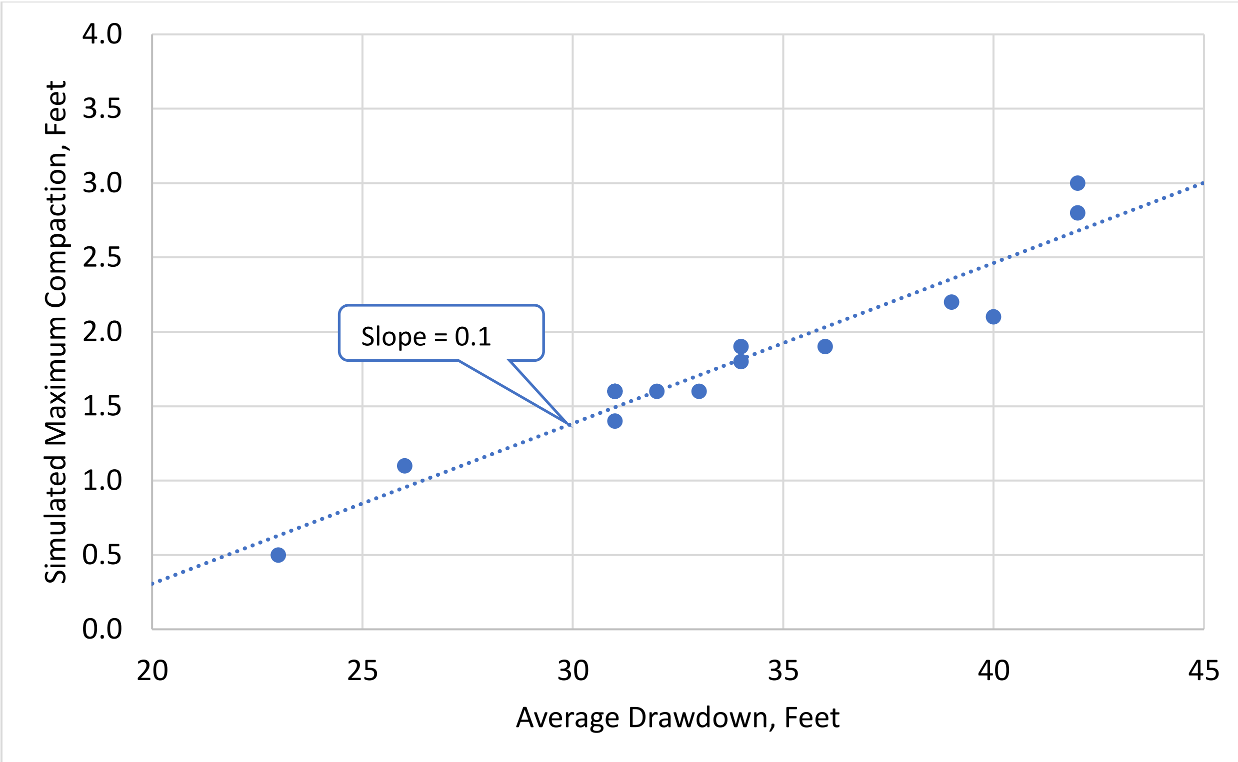


Figure 38. **Comparison of simulation results for the Chicot Aquifer showing the relationship between average drawdown and maximum compaction.**

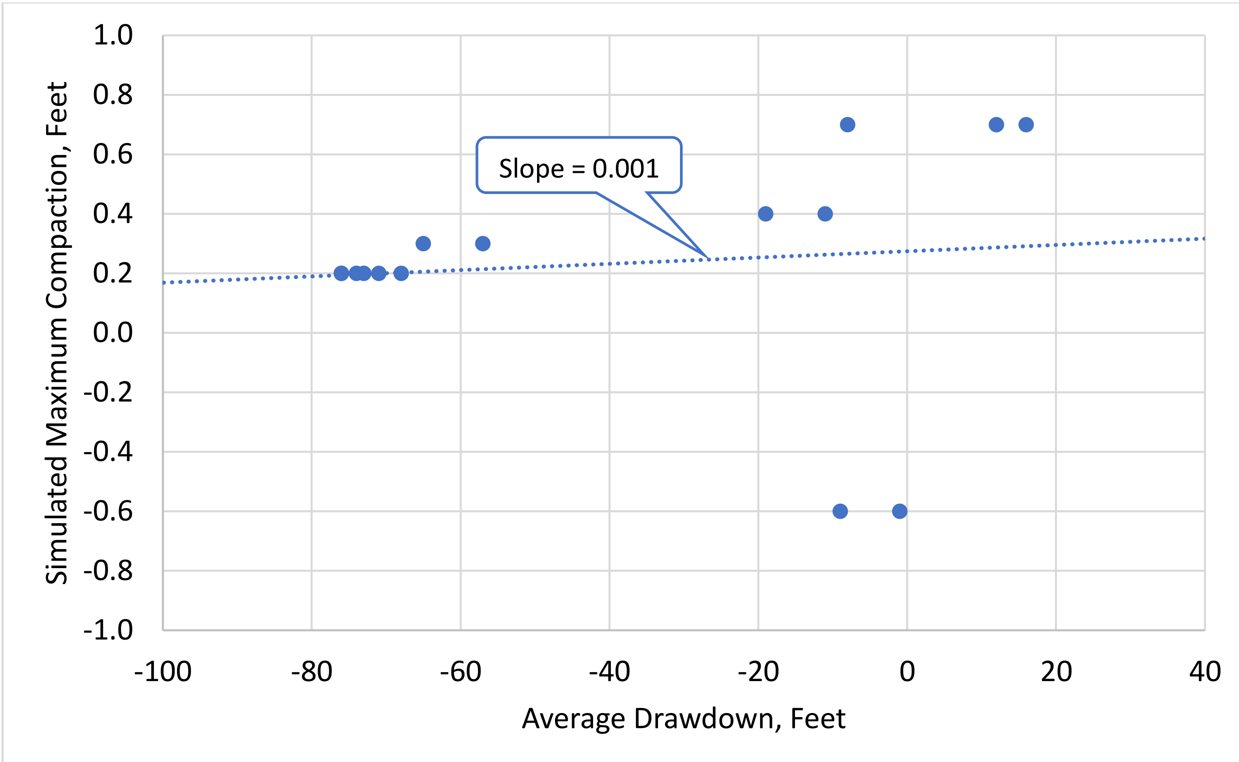


Figure 39. Comparison of simulation results for the Evangeline Aquifer showing the relationship between average drawdown and maximum compaction.

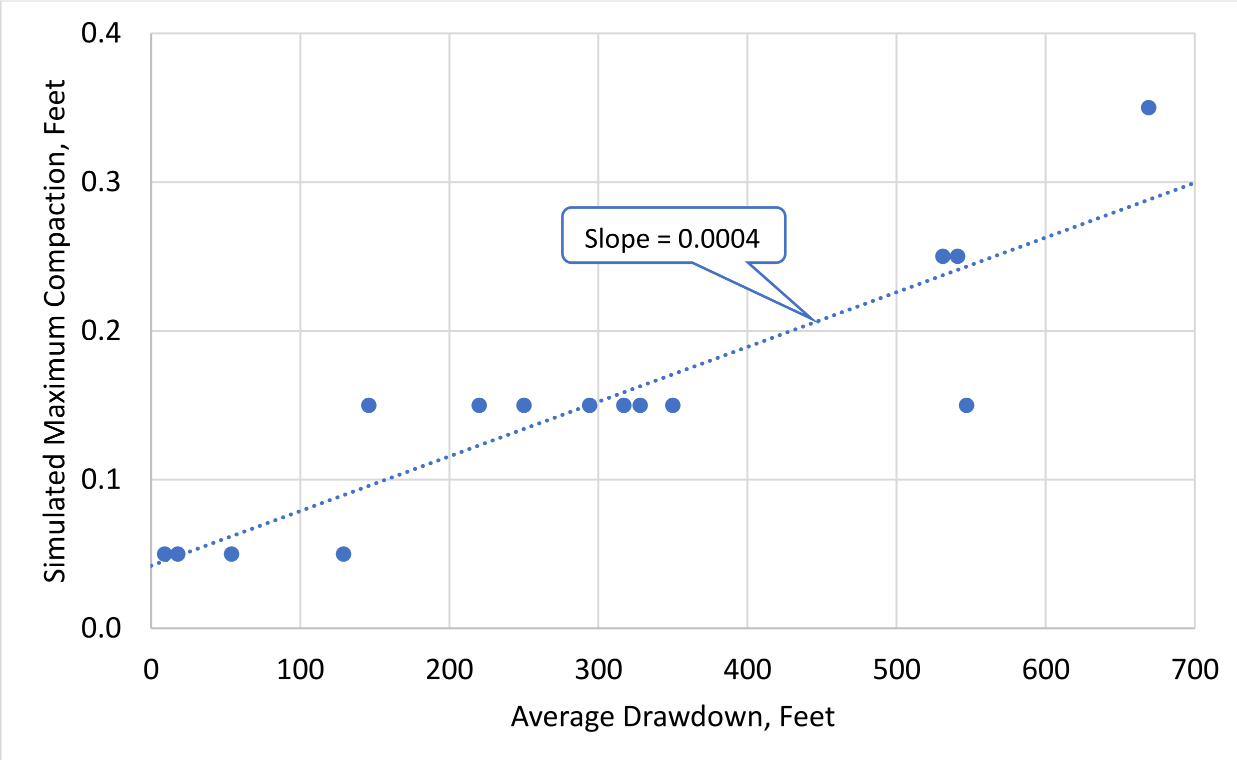


Figure 40. Comparison of simulation results for the Jasper Aquifer showing the relationship between average drawdown and maximum compaction.

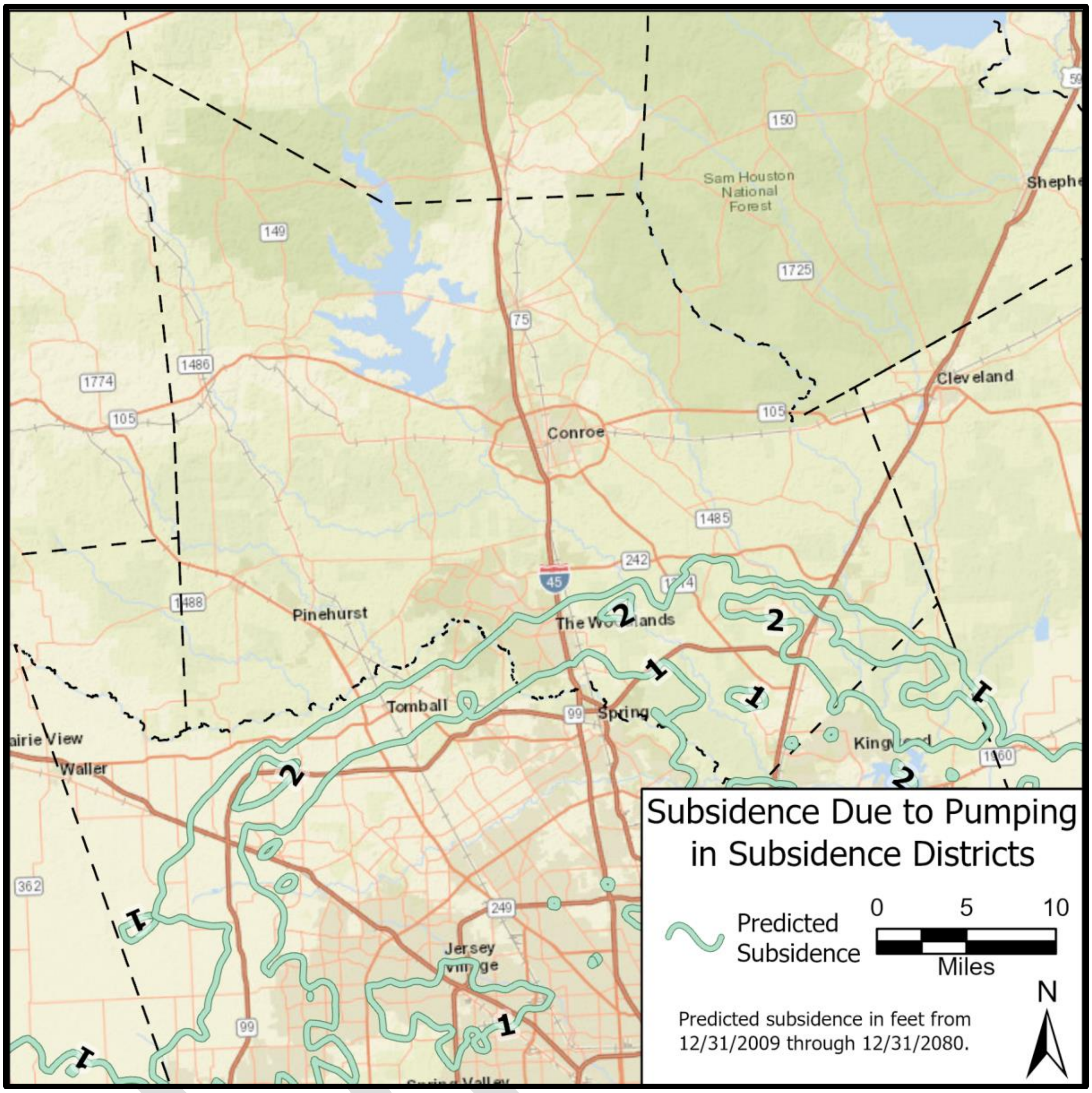


Figure 41. Calculated subsidence due to simulated pumping in the subsidence districts near Montgomery County (Keester, 2020).

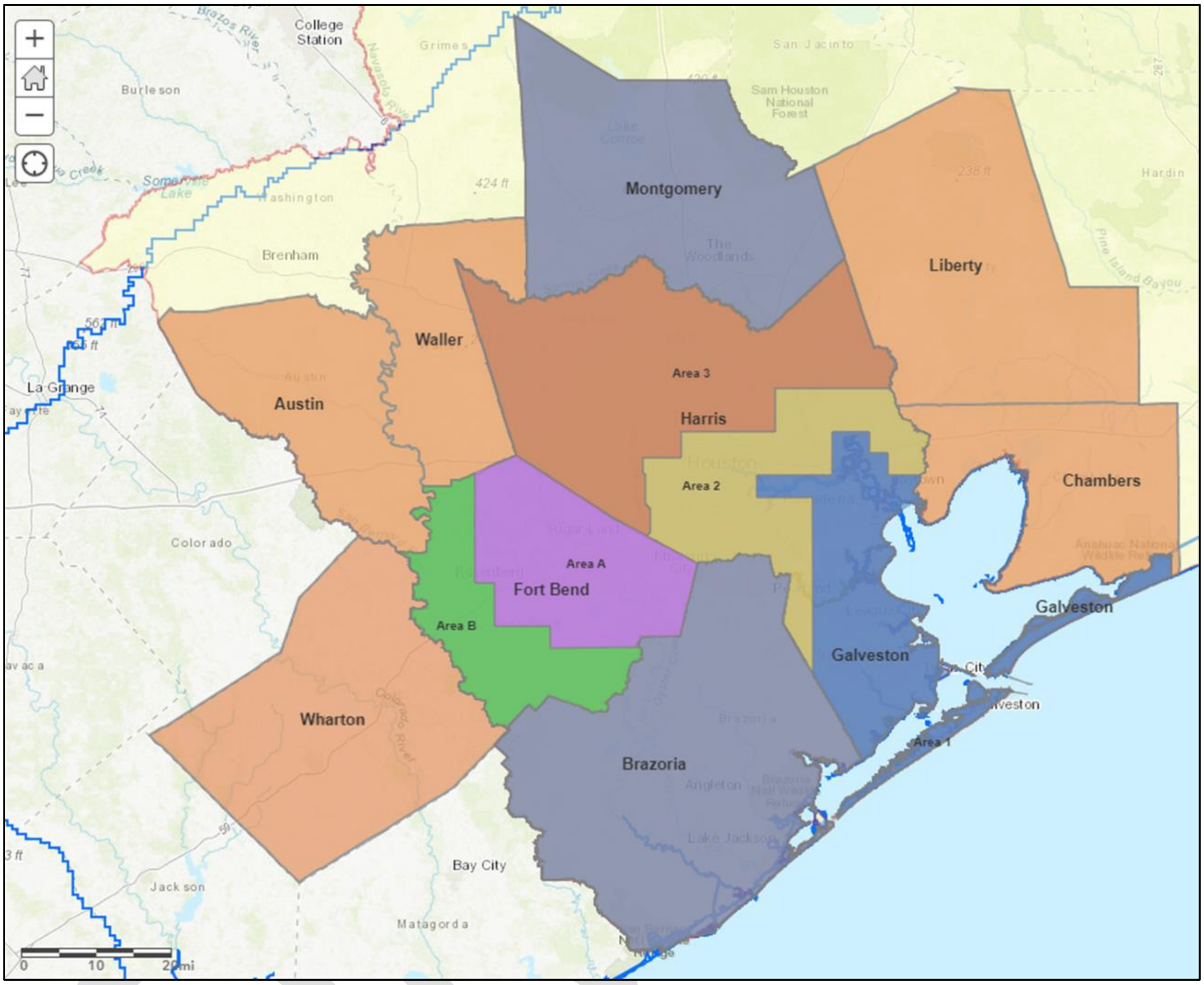


Figure 25. Regulatory areas in the HGSD and FBSD. Image from the HGSD Regulatory Plan Review web map accessed June 16, 2020 (https://www.arcgis.com/home/item.html?id=5c534d3137d34c04b5460dee0813984f).

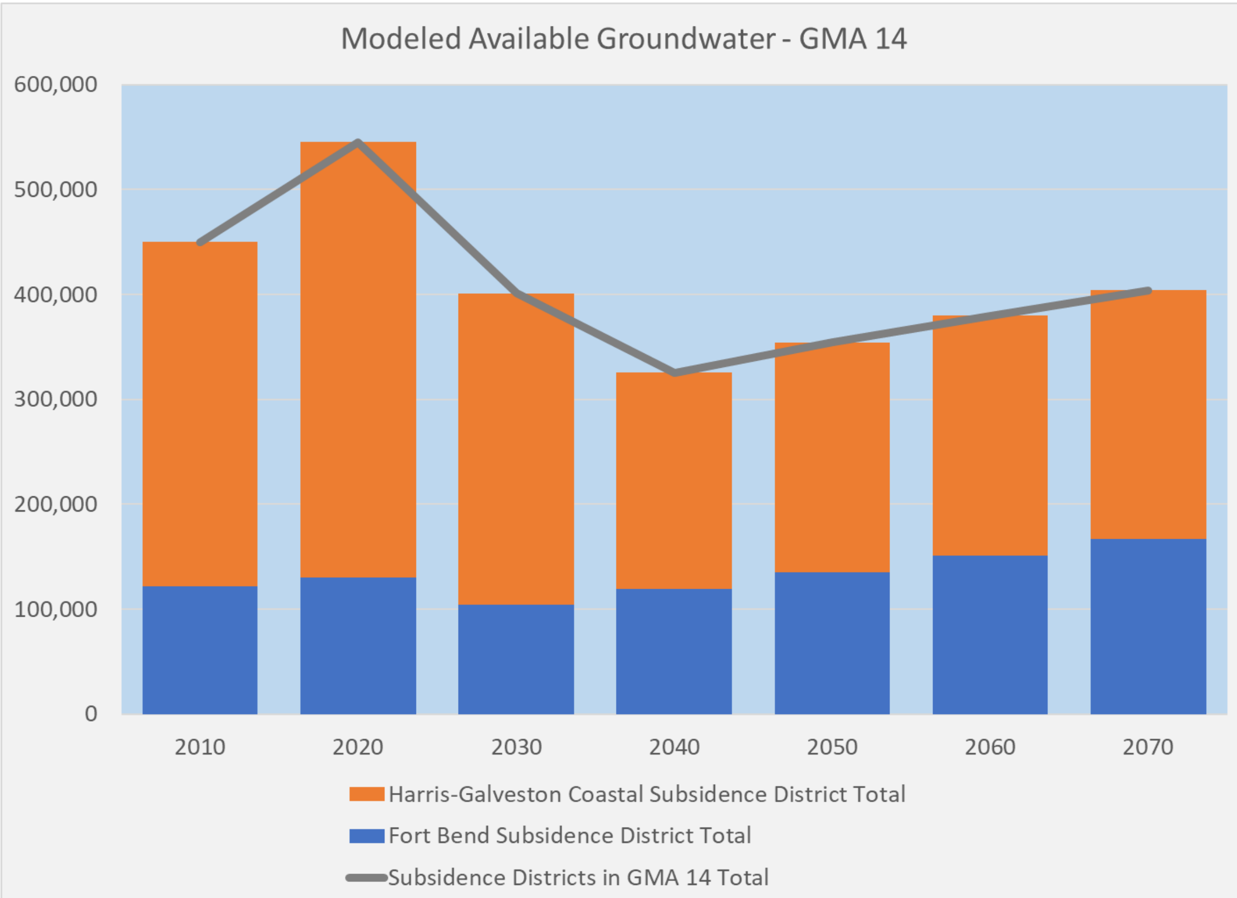


Figure 26. Projected total pumping in HGSD and FBSD through 2070 (Wade, 2016).

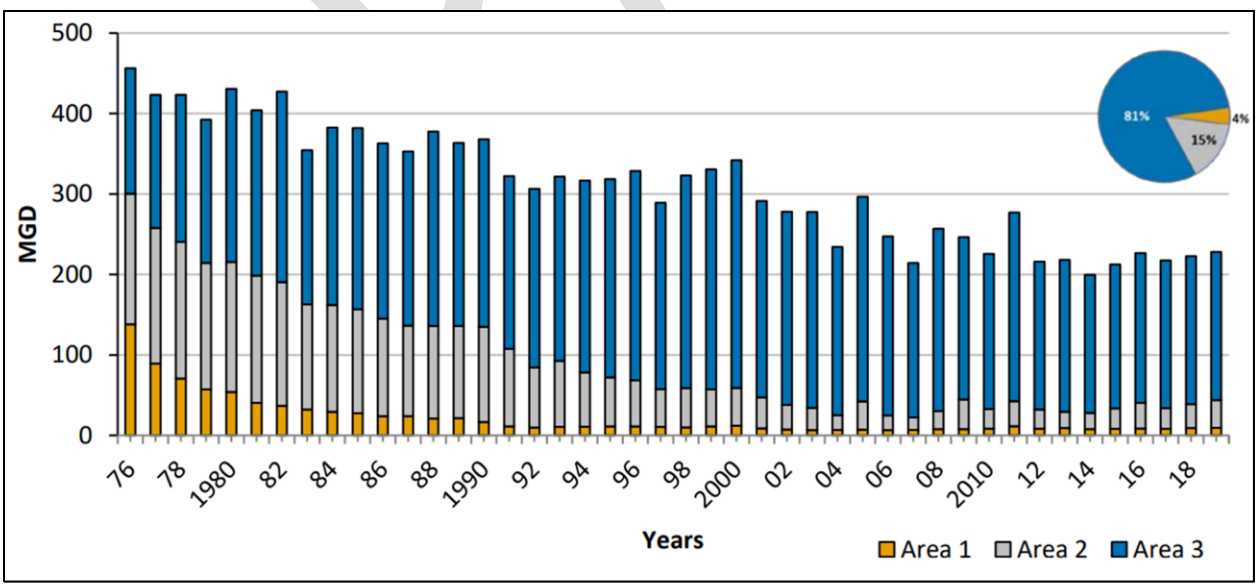


Figure 27. Historical pumping in HGSD (Petersen and others, 2020).

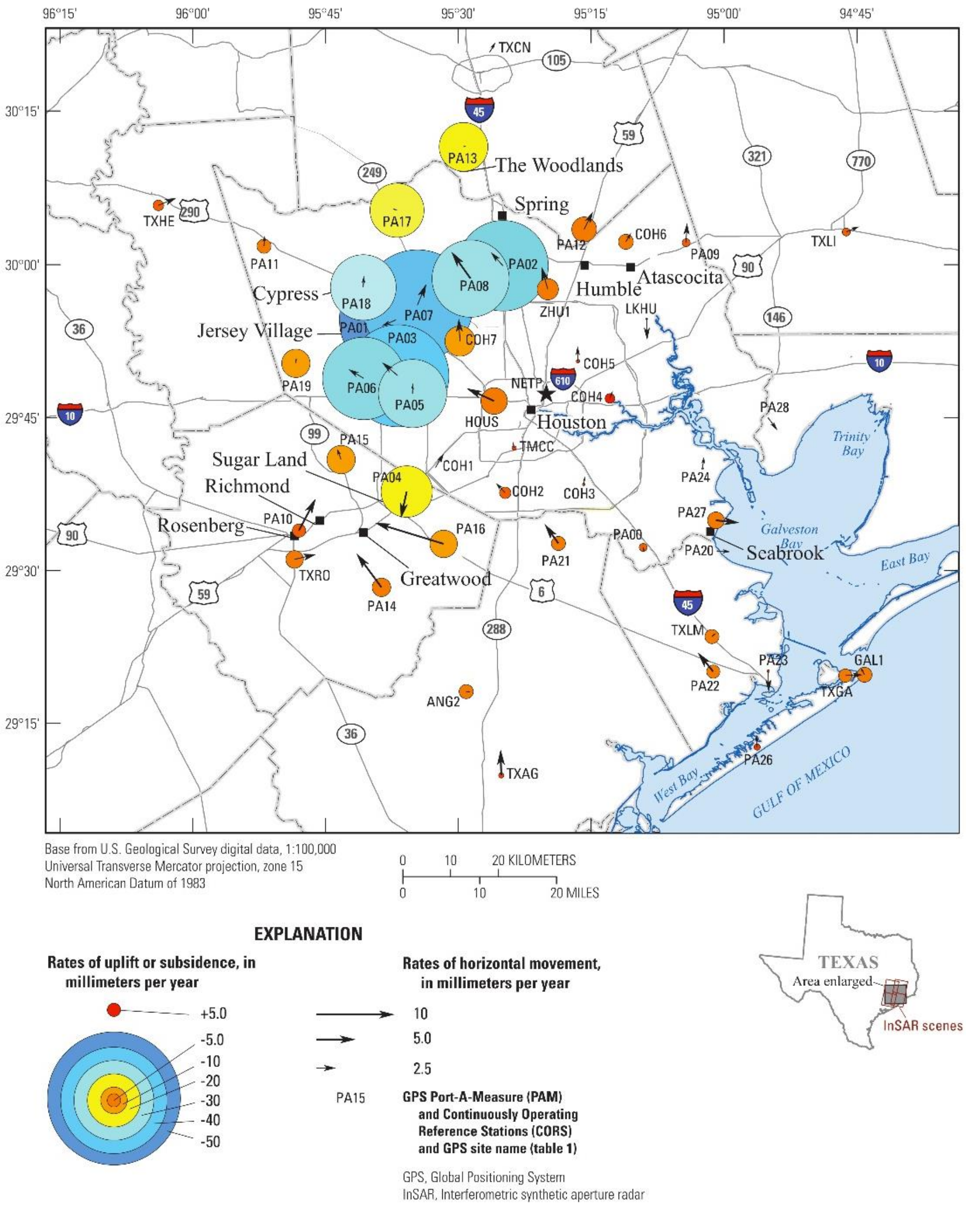

96°15'
96°00'
95°45'
95°30'
95°15'
95°00'
94°45'
30°15'
30°00'
29°45'
29°30'
29°15'
TXCN
The Woodlands
Spring
Humble
Atascocita
Cypress
Jersey Village
Houston
Sugar Land
Richmond
Rosenberg
Greatwood
Seabrook
PA13
PA17
PA18
PA07
PA08
PA02
PA01
PA03
PA06
PA05
PA04
PA10
PA11
PA12
PA14
PA15
PA16
PA19
PA20
PA21
PA22
PA23
PA24
PA26
PA27
PA28
PA00
PA09
TXHE
TXLI
TXRO
TXLM
TXGA
TXAG
GAL1
ANG2
COH1
COH2
COH3
COH4
COH5
COH6
COH7
ZHU1
LKHU
HOUS
NETP
TMCC
Trinity Bay
Galveston Bay
East Bay
West Bay
GULF OF MEXICO
Base from U.S. Geological Survey digital data, 1:100,000
Universal Transverse Mercator projection, zone 15
North American Datum of 1983
0 10 20 KILOMETERS
0 10 20 MILES
EXPLANATION
Rates of uplift or subsidence, in millimeters per year
+5.0
-5.0
-10
-20
-30
-40
-50
Rates of horizontal movement, in millimeters per year
10
5.0
2.5
PA15
GPS Port-A-Measure (PAM) and Continuously Operating Reference Stations (CORS) and GPS site name (table 1)
GPS, Global Positioning System
InSAR, Interferometric synthetic aperture radar
TEXAS
Area enlarged
InSAR scenes

Figure A.

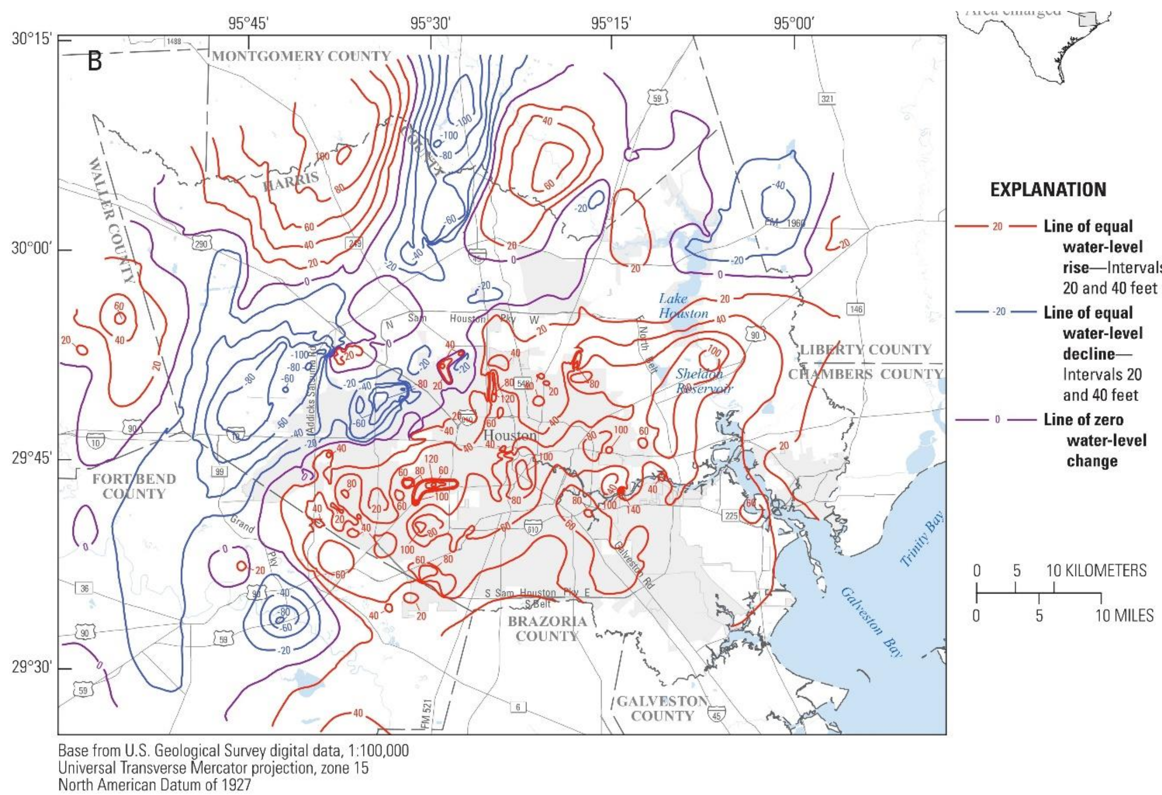
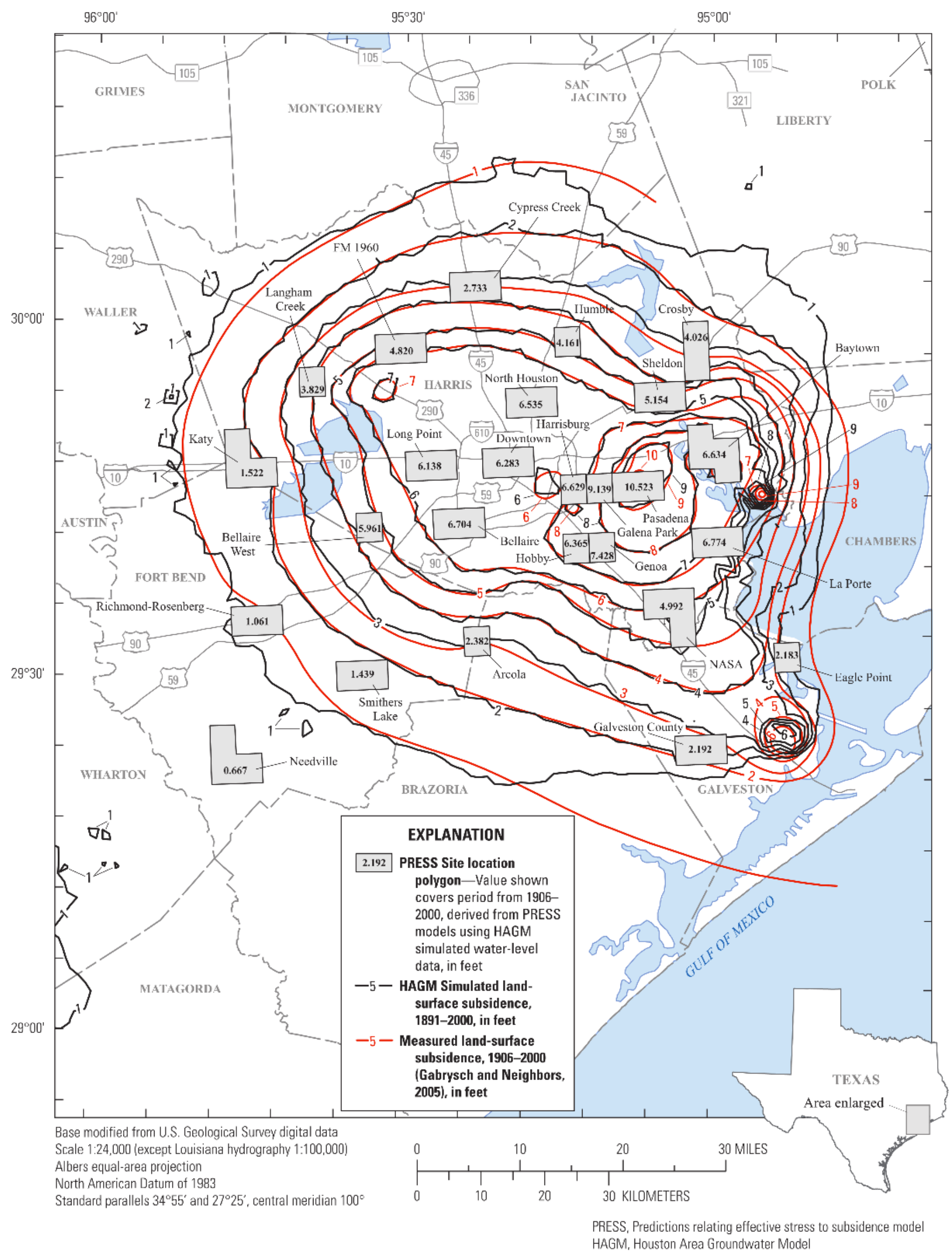

B
95°45'
95°30'
95°15'
95°00'
30°15'
30°00'
29°45'
29°30'
MONTGOMERY COUNTY
HARRIS
WALLER COUNTY
FORT BEND COUNTY
BRAZORIA COUNTY
GALVESTON COUNTY
LIBERTY COUNTY
CHAMBERS COUNTY
Houston
Lake Houston
Sheldon Reservoir
Galveston Bay
Trinity Bay
EXPLANATION
Line of equal water-level rise—Intervals 20 and 40 feet
Line of equal water-level decline—Intervals 20 and 40 feet
Line of zero water-level change
0 5 10 KILOMETERS
0 5 10 MILES
Base from U.S. Geological Survey digital data, 1:100,000
Universal Transverse Mercator projection, zone 15
North American Datum of 1927

Figure B.



96°00'
95°30'
95°00'
30°00'
29°30'
29°00'
GRIMES
MONTGOMERY
SAN JACINTO
POLK
LIBERTY
WALLER
HARRIS
AUSTIN
FORT BEND
CHAMBERS
WHARTON
BRAZORIA
GALVESTON
MATAGORDA
GULF OF MEXICO
Cypress Creek
FM 1960
Langham Creek
Humble
Crosby
Baytown
Sheldon
North Houston
Katy
Long Point
Harrisburg
Downtown
Pasadena
Galena Park
Bellaire
Bellaire West
Hobby
Genoa
La Porte
Richmond-Rosenberg
NASA
Eagle Point
Arcola
Smithers Lake
Galveston County
Needville
TEXAS
Area enlarged
EXPLANATION
2.192 PRESS Site location polygon—Value shown covers period from 1906–2000, derived from PRESS models using HAGM simulated water-level data, in feet
5 HAGM Simulated land-surface subsidence, 1891–2000, in feet
5 Measured land-surface subsidence, 1906–2000 (Gabrysch and Neighbors, 2005), in feet
Base modified from U.S. Geological Survey digital data
Scale 1:24,000 (except Louisiana hydrography 1:100,000)
Albers equal-area projection
North American Datum of 1983
Standard parallels 34°55′ and 27°25′, central meridian 100°
0 10 20 30 MILES
0 10 20 30 KILOMETERS
PRESS, Predictions relating effective stress to subsidence model
HAGM, Houston Area Groundwater Model

Figure C.

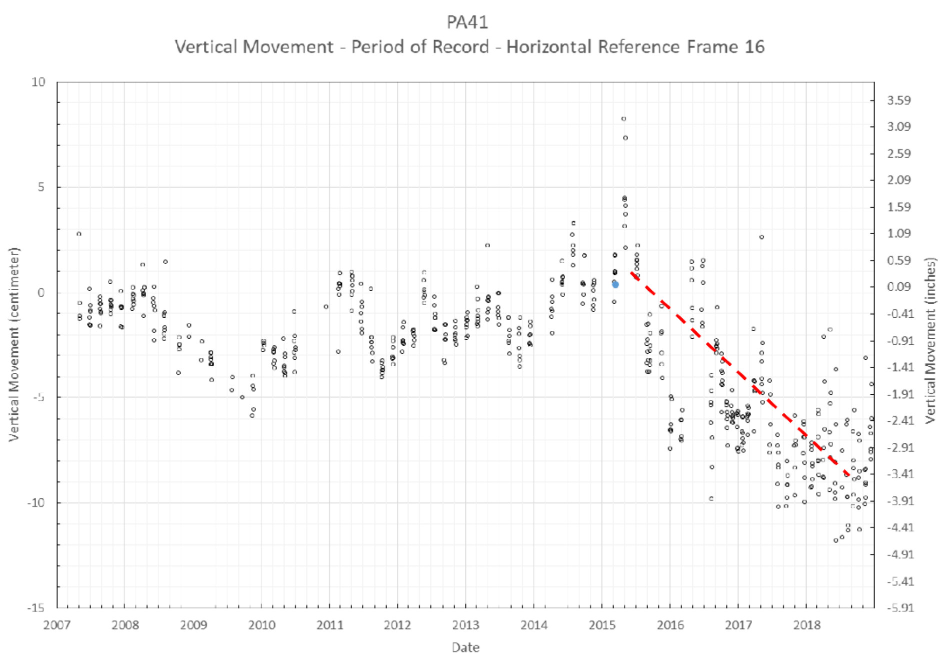

PA41
Vertical Movement - Period of Record - Horizontal Reference Frame 16
Vertical Movement (centimeter)
Vertical Movement (inches)
Date
10
5
0
-5
-10
-15
3.59
3.09
2.59
2.09
1.59
1.09
0.59
0.09
-0.41
-0.91
-1.41
-1.91
-2.41
-2.91
-3.41
-3.91
-4.41
-4.91
-5.41
-5.91
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018

Figure D.

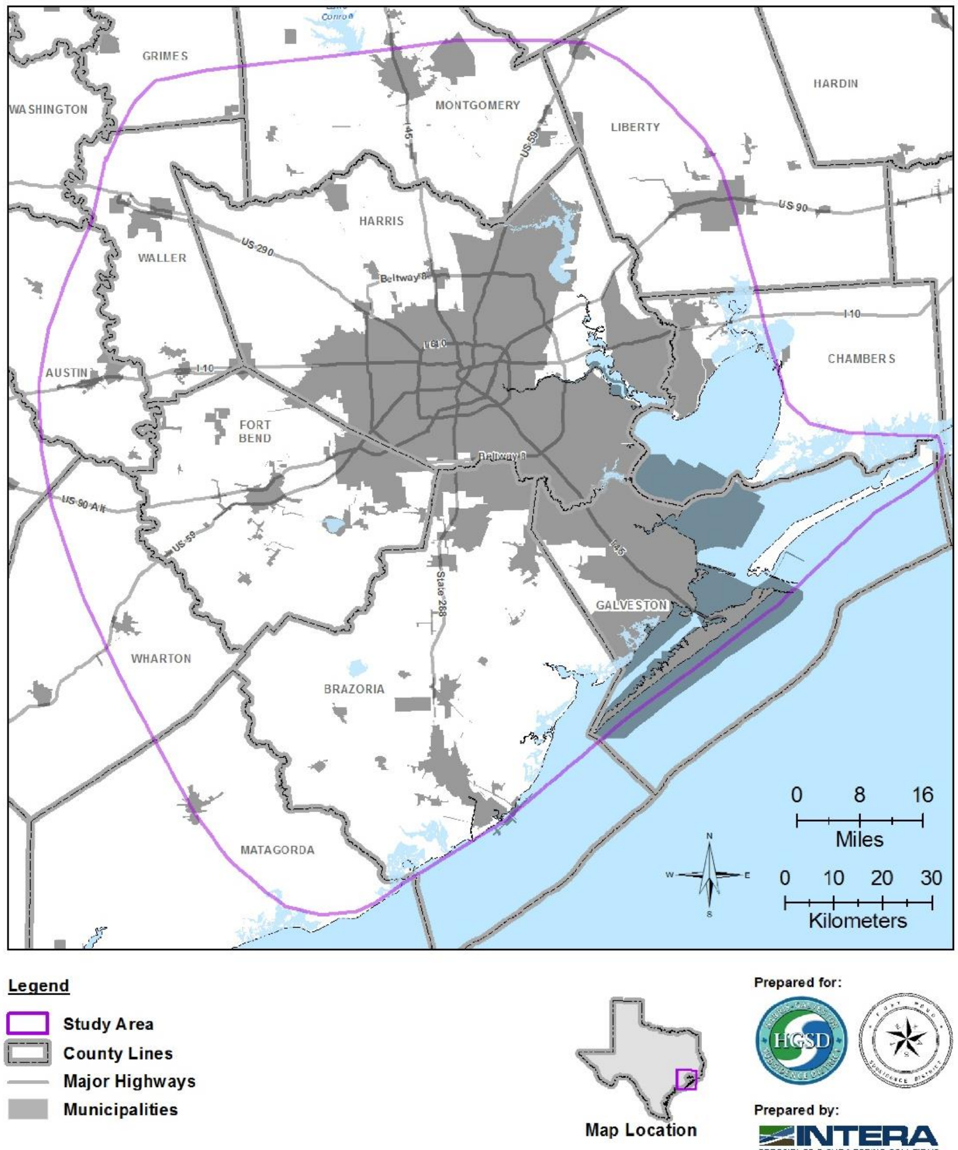
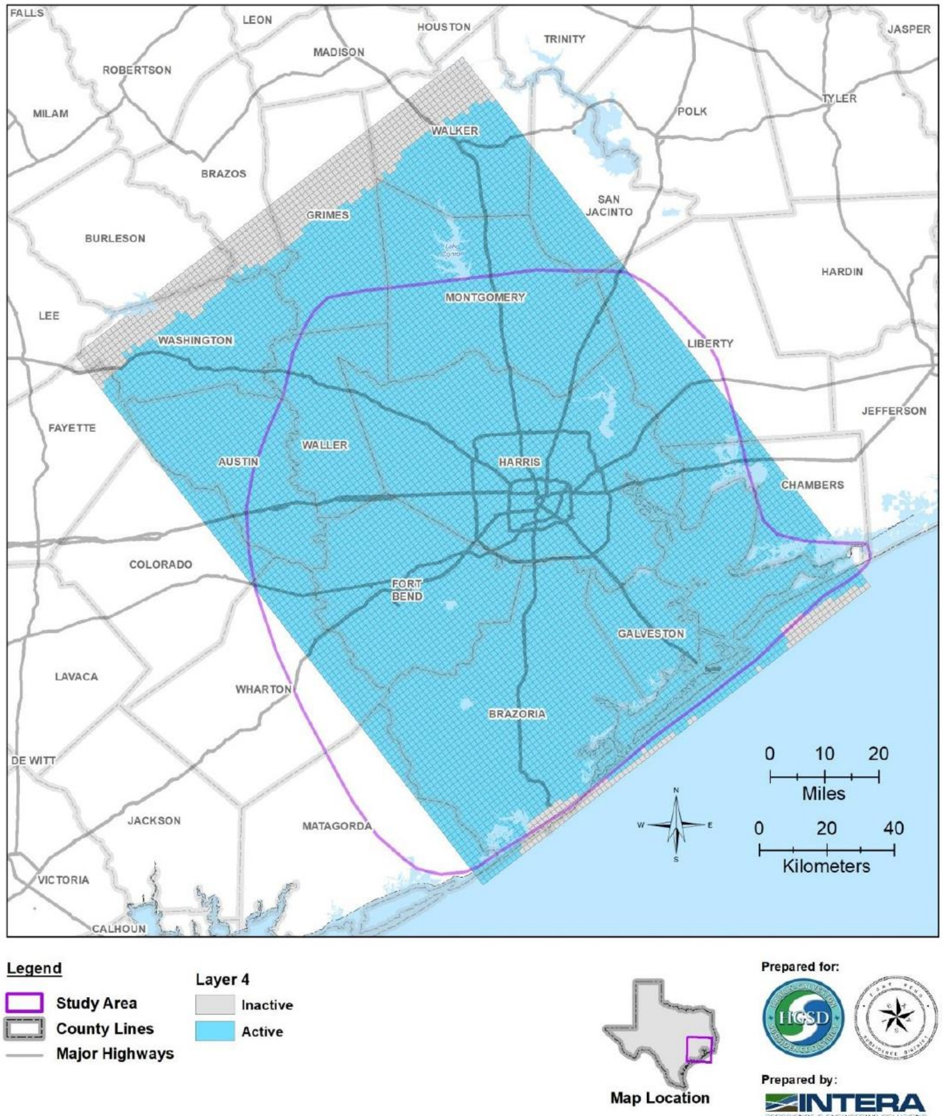

GRIMES
WASHINGTON
MONTGOMERY
LIBERTY
HARDIN
HARRIS
WALLER
AUSTIN
FORT BEND
CHAMBERS
GALVESTON
WHARTON
BRAZORIA
MATAGORDA
US 290
US 90
US 59
I-45
I-10
Beltway 8
US 90 Alt
State 288
0 8 16
Miles
0 10 20 30
Kilometers
Legend
Study Area
County Lines
Major Highways
Municipalities
Map Location
Prepared for:
Prepared by:
INTERA

Figure D.



FALLS
LEON
HOUSTON
TRINITY
JASPER
MADISON
ROBERTSON
MILAM
POLK
TYLER
WALKER
BRAZOS
SAN JACINTO
GRIMES
BURLESON
HARDIN
MONTGOMERY
LEE
WASHINGTON
LIBERTY
JEFFERSON
FAYETTE
AUSTIN
WALLER
HARRIS
CHAMBERS
COLORADO
FORT BEND
GALVESTON
LAVACA
WHARTON
BRAZORIA
DE WITT
JACKSON
MATAGORDA
VICTORIA
CALHOUN
0 10 20
Miles
0 20 40
Kilometers
Legend
Study Area
County Lines
Major Highways
Layer 4
Inactive
Active
Map Location
Prepared for:
Prepared by:
INTERA

Figure D.

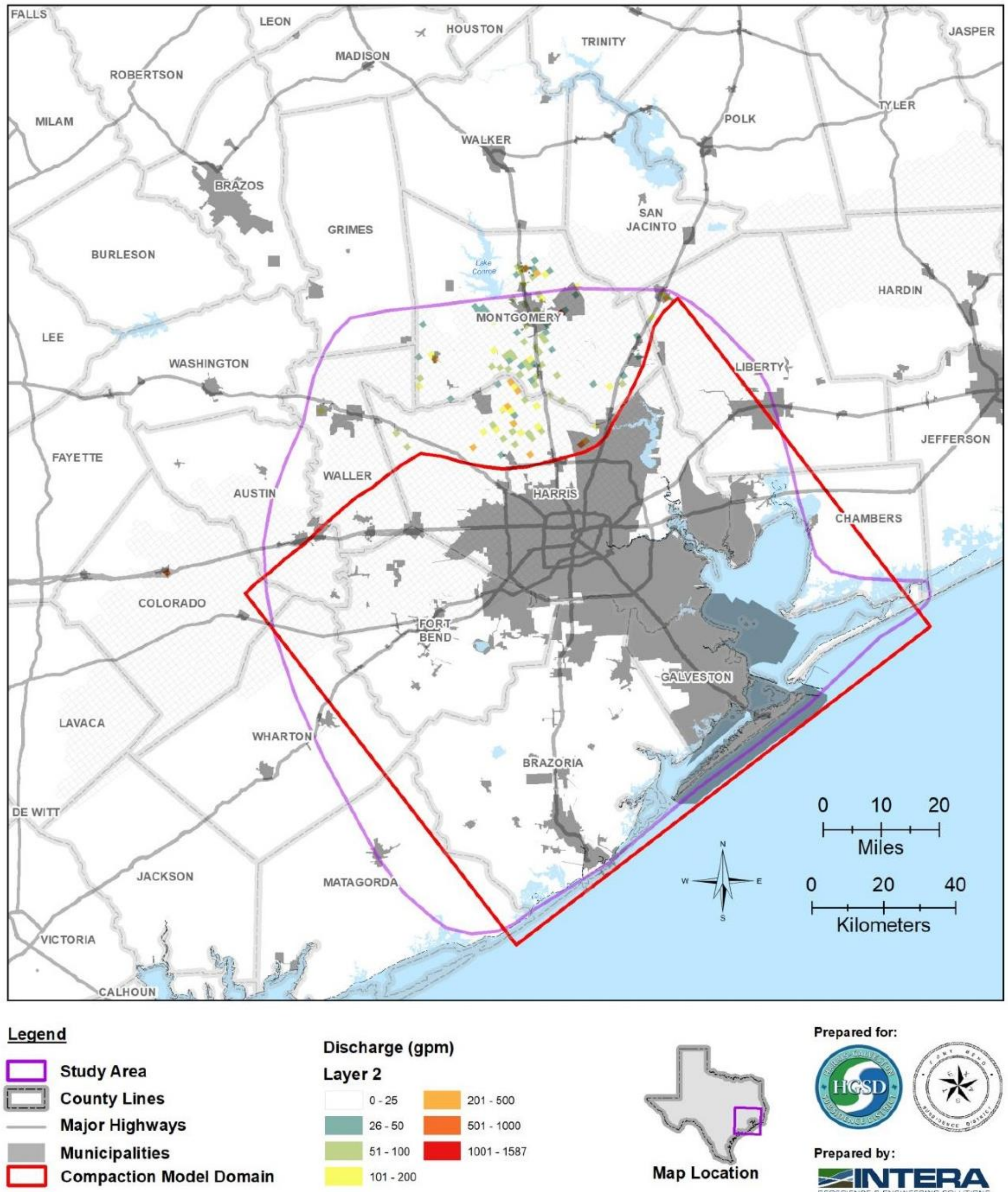
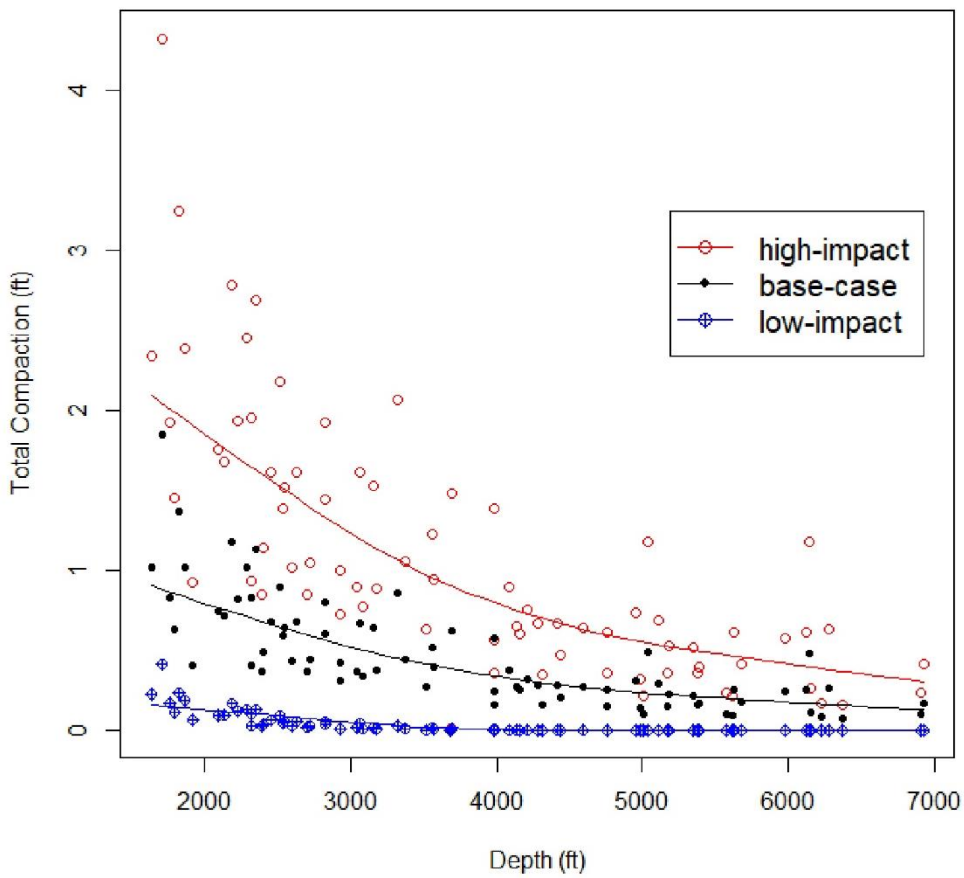

FALLS
LEON
HOUSTON
TRINITY
JASPER
MADISON
ROBERTSON
TYLER
MILAM
POLK
WALKER
BRAZOS
SAN JACINTO
GRIMES
BURLESON
HARDIN
MONTGOMERY
LEE
WASHINGTON
LIBERTY
JEFFERSON
FAYETTE
WALLER
AUSTIN
HARRIS
CHAMBERS
COLORADO
FORT BEND
GALVESTON
LAVACA
WHARTON
BRAZORIA
DE WITT
JACKSON
MATAGORDA
VICTORIA
CALHOUN
0 10 20
Miles
0 20 40
Kilometers
N
S
E
W
Legend
Study Area
County Lines
Major Highways
Municipalities
Compaction Model Domain
Discharge (gpm)
Layer 2
0 - 25
26 - 50
51 - 100
101 - 200
201 - 500
501 - 1000
1001 - 1587
Map Location
Prepared for:
HGSD
Prepared by:
INTERA
GEOSCIENCE & ENGINEERING SOLUTIONS

Figure D.



high-impact
base-case
low-impact
Total Compaction (ft)
0
1
2
3
4
2000
3000
4000
5000
6000
7000
Depth (ft)

Figure H.

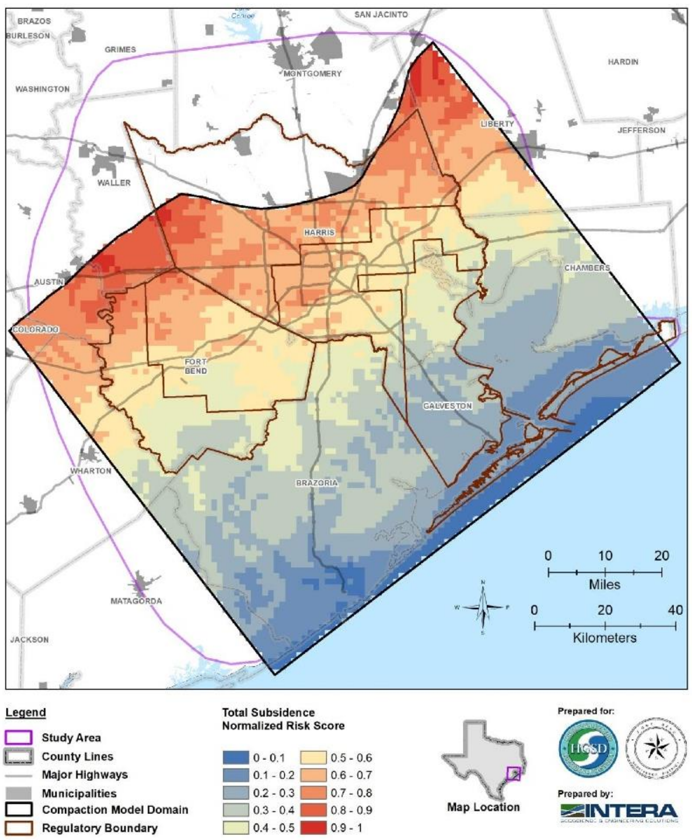

BRAZOS
BURLESON
GRIMES
WASHINGTON
SAN JACINTO
MONTGOMERY
HARDIN
LIBERTY
JEFFERSON
WALLER
HARRIS
AUSTIN
CHAMBERS
COLORADO
FORT BEND
GALVESTON
WHARTON
BRAZORIA
MATAGORDA
JACKSON
0 10 20
Miles
0 20 40
Kilometers
Legend
Study Area
County Lines
Major Highways
Municipalities
Compaction Model Domain
Regulatory Boundary
Total Subsidence Normalized Risk Score
0 - 0.1
0.1 - 0.2
0.2 - 0.3
0.3 - 0.4
0.4 - 0.5
0.5 - 0.6
0.6 - 0.7
0.7 - 0.8
0.8 - 0.9
0.9 - 1
Map Location
Prepared for:
Prepared by:
INTERA

Figure I.