

LONE STAR GROUNDWATER CONSERVATION DISTRICT

July 9, 2020

MINUTES OF PUBLIC WORKSHOP

The Board of Directors of the Lone Star Groundwater Conservation District (“District”) met in regular session, open to the public held via a publicly accessible webinar/telephone conference call, within the boundaries of the District on July 9, 2020.

CALL TO ORDER:

General Manager, Samantha Reiter, began the Public Workshop at 3:03 PM announcing the meeting open to the public and that the workshop had been properly noticed.

ROLL CALL:

The roll call was omitted as quorum not necessary for workshop.

In attendance at said meeting were Samantha Reiter, General Manager; Stacey V. Reese, District Counsel; James Beach, Mike Keester and Mike Thornhill, District consultants; District staff and members of the public. *Copies of the public sign-in sheets and comment cards received are attached hereto as Exhibit “A”.*

PRESENTATION ON SUBSIDENCE STUDY PHASE 1 DRAFT REPORT AND PHASE 2 SCOPE OF WORK FROM DISTRICT’S TECHNICAL CONSULTING TEAM:

Ms. Reiter introduced the District consultant, Mike Thornhill as the presenter for the Subsidence Study Phase I Report. He reviewed the one-page Subsidence Study – Phase I, and briefly detailed the initial step in assessing the past and present investigations of the subsidence documents concentrating on Montgomery County. *A copy of the study summary is attached hereto as Exhibit “B”.*

PUBLIC COMMENTS:

Ms. Reiter acknowledged the receipt of two edited documents from Jonathan Smith of Porter Special Utility District. The revisions are for *LSGCD Subsidence Study – Executive Summary and LSGCD Subsidence Study – Phase 1 – Assessment of Past and Current Investigations*. *A copy of the revisions are attached hereto as Exhibit “C” and “D”.*

John Yoars, resident of the Grogan’s Mill Village of The Woodlands, cited three topics of concern: the Texas Water Code 36; the current subsidence readings; and the LSGCD

Management Plan. He suggested that the Phase 2 study focus on current aquifer response habits rather than theoretical outcomes. A copy of his comments is attached hereto as Exhibit "E".

Ron Kelling, of SJRA, shared two issues he had with the Phase 1 study; the inadequate timetable and the LSGCD consultants' mixed message regarding the correlation of subsidence to compaction in the Jasper aquifer relating to pumpage. A copy of his comments is attached hereto as Exhibit "F".

Neil Gaynor, resident of The Woodlands, commented on the Executive Summary Conclusion and asked that the subsidence related flood risk due to accelerated aquifers related pumping be fully considered in Phase 2 of the study. He asked that LSGCD form a partnership with the Harris-Galveston Subsidence District on the duration of the study. A copy of the comments is attached hereto as Exhibit "G".

Lisa Gonzalez, President and CEO of Houston Advance Research Center (HARC), requested that an additional 30-day period be given for review of the LSGCD Subsidence Study. She stressed the importance of using critical and relevant studies as well as peer review since these provide the scientific foundation for the groundwater management plan. Further, she advocated for strong stakeholder input throughout the Phase 2 development.

Mike Turco, General Manager at Harris-Galveston Subsidence District, highlighted several considerations of compaction in the Jasper aquifer: clay, sediments, historical measurement of subsidence in southern Montgomery County; InSAR data; and the recent reduction of groundwater use in The Woodlands. Further, he raised a question as to the credibility of Mr. Keester's portion of a presentation made at the May GMA 14 meeting. He extended his willingness to collaborate work with the District on the LSGCD Subsidence Study. A copy of the comments is attached hereto as Exhibit "H".

Simon Seguierra, of Quadvest, cited the 5th Circuit Court case; Brazos GCD vs. Frazzino. He quoted from the decision that "groundwater rights are property rights". He suggested that there were only two ways to limit or manage groundwater pumpage – either cut back and allocate by aquifer boundary or allocate groundwater pumpage based on land size.

Webb Melder, citizen of Montgomery County, thanked everyone for their participation. His concerns were phrased with four questions; what subsidence studies have been conducted solely by LSGCD's previous Board of Directors; had SJRA provided LSGCD with any of their subsidence study information; did SJRA suggest installing extensometers in The Woodlands; and what were the plans to reduce subsidence in areas of south Montgomery County. A copy of the comments is attached hereto as Exhibit "I".

Ms. Reiter recognized the attendance of three LSGCD directors: Harry Hardman, Larry A. Rogers and Jim Spigener. Mr. Thornhill announced that the WSP consultant group would be joining the Subsidence Study Phase 2. Mr. Reiter also thanked everyone for their input and assured all comments would be reviewed by the Board.

General Manager, Samantha Reiter, adjourned the public workshop at 4:33 PM.

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

/s/ Larry A. Rogers

Larry A. Rogers, Board Secretary

Exhibit "A"

Panelist

Samantha Reiter

Jennifer Thayer

Mike Thornhill

Stacey Reese

James Beach

Mike Keester

Attendees

Ron Kelling

John Yoars

Michael Sullivan

Mike Turco

Andrew Vree

Claude Humbert

Dr. Shelley Gibbs

Heather Cook

Johnathan Smith

Kyle Jones

Laura Norton

Lisa Gonzalez

Mark Smith

Matt Corley

Ronda Trow

Sandra George

Simon Sequira

Stephanie Zertache

Suellen Myers

Tin Felkai

Whitney Milberger

Webb Melder

936-441-7833

936-828-3835

BOD

Harry Hardman

Jim Spigener

Larry Rogers

Lone Star Groundwater Conservation District SUBSIDENCE STUDY SUMMARY – PHASE 1

Initial Phase of Study – To Assess Past and Current Investigations

- ✓ First study from Montgomery County perspective
- ✓ Address specific concerns – future subsidence, faulting, and possible flooding factors
- ✓ Assist in fulfilling LSGCD’s responsibilities in regulation, management, planning and education
- ✓ Goals specific to Phase 1 of the study –
 - Develop a detailed database and working knowledge and understanding of historical information and models
 - Estimate timing, amounts and causes of past subsidence – particularly in and near Montgomery County
 - Understand where, in which zones, and to what extent subsidence is possible

Highlights from Past and Ongoing Studies and Monitoring Efforts

- ✓ Numerous methods utilized to measure land-surface changes due to subsidence and faulting – topography/leveling, extensometers, GPS network, and remote sensing (LiDAR and InSAR)
- ✓ On-going measurement of land surface and aquifer conditions over many decades with the various methods and as technology has evolved – cross-correlation of data allows for robust datasets
- ✓ Maximum measured subsidence in Montgomery County was reported to be slightly more than 1.5 feet in 1978 near the southeastern corner of the county - prior to significant pumping within the county (between 10,000 and 20,000 AFY)
- ✓ Geologic/geotechnical field data collected in 1970s and field measurements of water levels and subsidence since then have been used to derive parameters for subsidence modeling – especially the PRESS and HAGM models
- ✓ A new (2018) model for the brackish Jasper aquifer shows theoretical compaction over 10 years ranging from a fraction of a foot to a couple of feet with 500 feet of pressure decline centered in each 9-mile x 9-mile grid cell

Discussion of Preliminary LSGCD Modeling Using the HAGM – The Current GAM

- ✓ HAGM is first model to simulate compaction in all layers – including Burkeville confining layer and Jasper aquifer
- ✓ Parameters and modeling results show that within Montgomery County the Chicot is approximately 1,000 times more susceptible to compaction than the Jasper; and is 100 times more susceptible than the Evangeline
- ✓ Model runs show that significant portions of simulated future subsidence are attributed to projected pumping from outside of Montgomery County

LSGCD’s Role in Controlling Subsidence – Per Chapter 36 of Texas Water Code

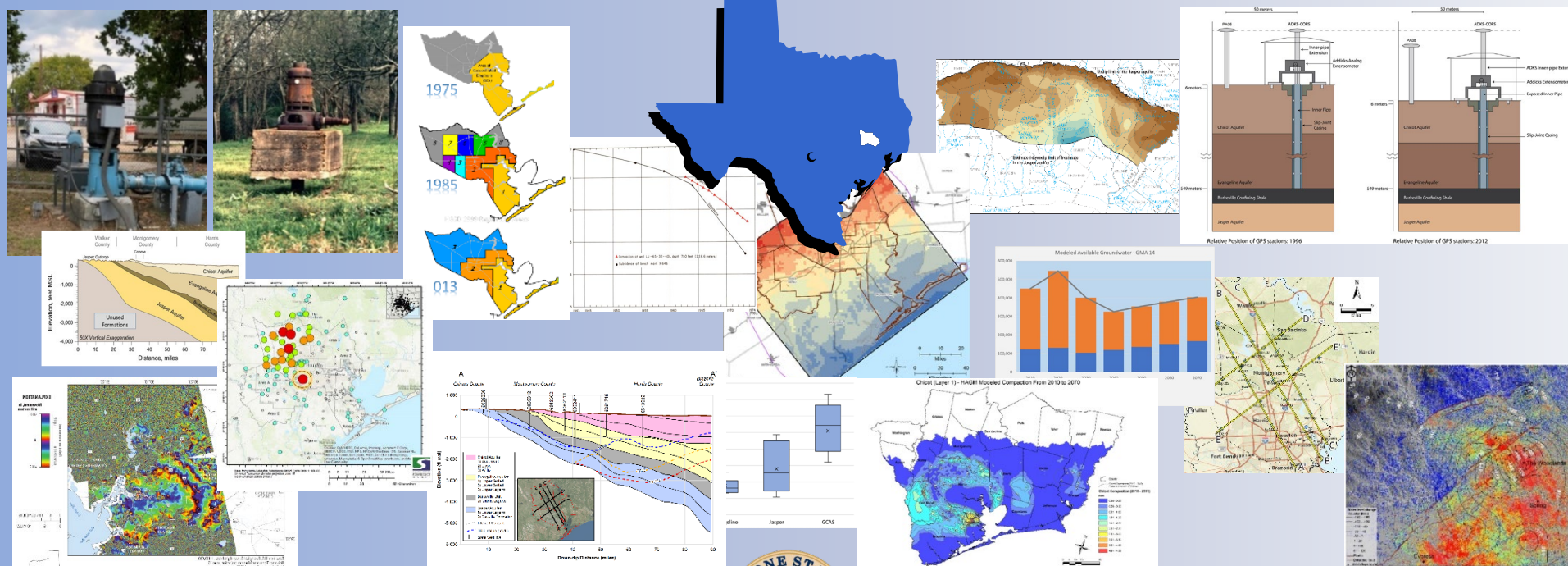
- ✓ LSGCD Management Plan (Section 10.3) – management objectives and performance standards
- ✓ Leadership and participation in joint planning efforts (GMA 14) – subsidence is one of nine required considerations
- ✓ Cooperated for many years in previous studies, modeling, and on-going monitoring efforts

Observations and Conclusions after Phase 1

- ✓ While the majority of Montgomery County has not been detectably affected by subsidence; southern parts of the county have experienced and are experiencing measurable subsidence
- ✓ Movement along growth faults may be due to subsidence caused by groundwater withdrawal, oil-field activities, salt domes, or normal movement along the deep-seated fault planes
- ✓ Geologically younger and shallower clay layers are more susceptible to compaction than older and deeper sediments
- ✓ Numerous and varied previous studies have provided critical data and understanding of subsidence and growth faults in the region; however, specific considerations for Montgomery County should be addressed with additional study

Moving Forward with Phase 2 of the Study

- ✓ Will involve detailed data analysis, evaluations, assessments and critiques of existing data and previous studies
- ✓ Correlate in time and space pumping, aquifer water levels, and measured movement of land surface
- ✓ Compare and contrast data from various land-surface measuring techniques
- ✓ Modeling – evaluate parameters in current models, create visualization of past and potential future subsidence, and actively participate in subsidence modeling process in the new USGS Gulf 2023 model
- ✓ Preliminary assessment of drainage factors and possible impacts of flooding due to subsidence
- ✓ Detailed plans/costs for possible future field data collection and monitoring programs



Subsidence Investigations – Phase 1 – Executive Summary

Introduction

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. 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, redundant Montgomery, Waller, Austin and ~~some~~ neighboring counties will experience additional subsidence through 2070. Additionally, the active movement along existing growth-fault planes, some potentially associated with subsidence, is a concern in the region and in Montgomery County. As a part of its commitment to fulfill its statutory mandate to control subsidence the board members of the Lone Star Groundwater Conservation District (LSGCD) approved a scope of work for Phase 1 of a subsidence study to primarily address subsidence as it relates to Montgomery County. This report provides a summary of the work conducted and discussions of the data and information. The purposes of the LSGCD subsidence study generally are to:

in Montgomery County and other areas of the region

- ❖ 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 local growth 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:

Is this the correct term?

- 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 possible compaction with various projected future pumping distributions using the HAGM.

There are few conclusions in this report as the work in Phase 1 was intended to comprehensively collect and compile information and data sets, and to develop a functional overview and “working knowledge” of subsidence information. The work tasks in this Phase 1 study included:

- Background data compilation and workup;
- Synopsis of past studies and information;
- Houston Area Groundwater Modeling (HAGM) simulations;
- Overview of Regulatory and Management Frameworks;
- Meeting with cooperators and stakeholders;
- Developing a scope of work and costs for subsequent work; and,
- Summary reporting and presentations.

Hydrogeology and Subsidence

The TWDB 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. 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 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. ← singular or plural?

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. The hydrostratigraphic units of the GCAS are not the same as the lithostratigraphic or geologic units which are delineated by the type of rock or sediment that make up the geologic units. Table ES-1 summarizes the local hydrostratigraphic and geologic units within Montgomery County.

The geologic units of the GCAS dip toward the Gulf of Mexico. As the geologic units dip, they typically also become thicker creating a wedge shape. 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. The total thickness of the aquifer is more than 4,000 feet in southern Montgomery County. However, 95 percent of registered wells have a depth of 520 feet or less and produce groundwater from the upper portions of the GCAS. Figure ES-1 illustrates the structure and geologic formations of the GCAS.

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. 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. 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. In the GCAS, one cause of a long-term increase in effective stress on the subsurface formations is the decline in artesian pressure in the hydrostratigraphic units.

Existing Studies and Data

Most historical subsidence studies for what is commonly known as the “Houston-Galveston region” include all of Harris County and parts of Brazoria, Chambers, Fort Bend, Galveston, Liberty, Montgomery, and Waller counties. Subsidence studies in the region began as early as the 1940s. Many studies have been conducted over the decades. Monitoring programs and several studies are ongoing. Historical and current studies provide several types of data and information over a long period of time to allow for correlation and analyses of the timing, causes and effects of subsidence. Examples of the types of data and information available and some key findings are provided below:

- **Topography and re-leveling** – initially, all land-surface subsidence determinations in the region were made by geodetic differential leveling, which has also used to determine fault movement. As of 1982, there were reportedly up to 2,500 benchmarks in the leveling network, with some dating back to 1906. Therefore, total subsidence from the early 1900s to the present can be measured and estimated. Because subsidence has occurred over a broad area, essentially all of the benchmarks have moved requiring extensive re-leveling efforts. New technologies and techniques allow for measurements of land-surface movement that can be correlated and compared to past subsidence leveling measurements. Because of the relatively small amounts of subsidence reported in Montgomery County, Phase 2 of this subsidence study should include an assessment of the accuracy of historical measurements of land-surface elevations.
- **Hydrogeology and geotechnical** – in the 1970s, the United States Geological Survey (USGS) conducted detailed hydrogeologic studies in three specific areas that had experienced significant subsidence. Those and subsequent studies included analyses of drilled holes, geophysical logs, coring and geotechnical analyses of clay layers, water level data, pumping records and measured subsidence (from leveling). The studies were focused on the Chicot and Evangeline aquifers. The first extensometers were installed at ~~the~~ three USGS study sites. The USGS concluded, “...most of the subsidence is due to compaction of shallow material. It is suspected that the compressibility of material is related both to the age of sediments and the depth of burial” (Gabrysch, 1984). The geologic setting and pumping distribution in Montgomery County is and will be different than that found downip in Harris County. Phase 2 of the subsidence study will assess the local hydrogeologic conditions in the GCAS layers, particularly with respect to the Burkeville and Jasper units.

The University of Texas Bureau of Economic Geology reported in 1977 that there were at least 150 miles of active faults with topographic escarpments in Harris and Galveston counties (Kreitler, 1977). The University of Houston (UH) reports more than 300 active faults intersecting land surface in the Houston area (Engelkemeir and Khan, 2013). The Hockley-Conroe Fault System includes several named faults that extend into Montgomery County, particularly in The Woodlands and near Conroe. Fault movements have caused ~~damaged~~ to homes, roads and other structures. Most known faults are located atop and near salt domes. Active fault movement may

damage

be caused by land-surface subsidence due to groundwater pumping, changes in pressure due to deeper oil and gas fluid extraction, movement of salt layers and domes, or deeper-seated movement relative to the fault planes. Phase 2 of this study will include detailed evaluations of available data for parts of Montgomery County with known faulting, including elevation measurements, remote sensing imagery, water-level data, and pumping records.

- **Extensometers** – borehole extensometers are specialized subsurface structures and are the only means of direct measurement of compaction within a particular geologic interval. The USGS currently monitors 14 extensometers at 12 locations in Harris, Galveston and Fort Bend counties, with one site having paired shallower and deeper co-located extensometers. All current extensometers are **completed** to measure compaction ~~associated~~ with the Chicot or Evangeline aquifers. The closest extensometer to ~~Montgomery~~ County is at the Lake Houston site. Extensometer monitoring has been correlated with geologic, geotechnical, water-level, pumping and subsidence data to develop parameters used for predictive modeling of subsidence.

This doesn't make sense.

associated
Montgomery

- **Global Positioning System Network** – since 1980, the UH and Harris-Galveston Subsidence District (HGSD) have established a network of sites at which land-surface elevation can be monitored using global positioning system (GPS) technologies. Currently, there are more than 200 sites consisting of continuously operated reference stations (CORS) and port-a-measure (PAM) sites; there are 15 GPS sites in Montgomery County. Figure ES-2 is a map from the HGSD showing the measured rate of land-surface change at GPS sites during the period from 2015 to 2019. Figure ES-3 provides a chart from HGSD showing changes in the rate of land-surface decline at PAM-13 near The Woodlands beginning during 2015 when alternative water sources were implemented. Phase 2 will include evaluations of raw data and data processing for GPS sites, and will include correlations of aquifer data to the GPS measurements.

- **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 growth faults. Processing of such imagery can provide cost-effective coverage for high-resolution and refined-scale interpretations to identify even small amounts of land movement. Figure ES-4 provides a map from the USGS showing the rate of land-surface subsidence for a 1993 to 2000 study (Bawden and others, 2012). Figure ES-5 is a map from the same USGS study that shows ~~changes~~ in Evangeline aquifer water levels from 1990 to 2003. Imagery from remote sensing technologies can be correlated to past and on-going monitoring data. The HGSD is ~~undertaking~~ expanded InSAR studies within the region. LSGCD should monitor the progress of the expanded studies and may wish to inquire as to potential cooperative participation.

changes

undertaking

- **Analytical and Numerical Modeling** – numerous models have been developed to understand and predict aquifer and land-surface responses to pumping in the Houston region. Data from the various monitoring programs and hydrogeologic studies were used to develop model parameters. The USGS reports that the first subsidence simulation model for the region is known as the Predictions Relating Effective Stress to Subsidence (PRESS) model, which is essentially a site-specific analytical model. The current official groundwater availability model (GAM) for the northern Gulf Coast Aquifer system is the Houston Area Groundwater Model (HAGM), which is a finite-difference flow model that simulates compaction in each layer. 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). Figure ES-6 is a map from the USGS showing the correlation between measured subsidence and simulated subsidence from the PRESS

What is FBSD?
This needs to be defined before abbreviating.

and HAGM models. Based on parameters in the HAGM and simulation results, the model indicates that the Burkeville confining layer and the Jasper aquifer are much less susceptible to compaction than the overlying Chicot and Evangeline aquifers. In 2018 the HGSD released a model study by INTERA relating to the “...relative risk of subsidence from brackish groundwater development in the Jasper Aquifer” (Kelly and others, 2018). The report notes a general “...lack of data...” regarding subsidence potential for the Jasper and states that while there is a relative risk of potential subsidence for the Jasper, “...the absolute amount of compaction that may be predicted to occur is considered uncertain” (Kelly and others, 2018). Figure ES-7 is a chart from the INTERA report showing potential ranges in compaction with depth based on the model assumptions.

All other paragraphs above started with a lowercase word.

- **Water-Level and Pumping Records** – **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. Annual pumping volumes from the Chicot are less than 10,000 acre-feet and are generally less than 7,500 acre-feet. Figure ES-8 illustrates the total reported pumping in Montgomery County. As would be expected with the pumping pattern, 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 ES-9 illustrates the changes in water levels in two of the deeper wells in southern Montgomery County.

Preliminary Modeling

The HAGM was published in 2013 and has been used for joint planning by GMA 14 during the current and previous cycles. While the HAGM has limitations with regards 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. For this report, we reviewed several previously conducted model simulations to assess the potential impacts of various pumping scenarios.

In the simulations reviewed, pumping at the end of the predictive period ranges from about 64,000 to nearly 150,000 acre-feet per year. The greatest range in simulated pumping is from the Jasper Aquifer with comparatively small ranges in the Chicot and Evangeline. Figure ES-10 illustrates the range in the simulated pumping for each of the aquifers of the GCAS in Montgomery County.

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. 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~~ ^{show} the greatest range in maximum compaction associated with predicted water-level declines occurs in the Chicot. The average maximum compaction of the Chicot simulated from the scenarios is about 1.75 feet associated with the small range in average drawdown.

Comparison of the average drawdown and maximum compaction shows a clear linear relationship between water level decline and aquifer compaction in each of the aquifers (see Figure ES-11). 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. The available tools suggest that compaction of the Chicot Aquifer due to water level declines is the primary factor contributing to land surface subsidence. However, there is a relatively small amount of pumping from the Chicot in Montgomery County and most of the compaction in the Chicot Aquifer will be due to pumping outside of LSGCD causing regional water-level declines.

Regulation and Management

Consistency: Sec. or Section?

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". **Section 10.3** of the LSGCD's Management Plan provides the management objectives and performance standard for Controlling and Preventing Subsidence. Because subsidence occurs regionally and across multiple counties, the GCDs within GMA 14 must consider subsidence as one of nine (9) factors in establishing desired future conditions for the common groundwater reservoirs in the joint-planning area. Subsidence districts are not governed by Chapter 36 of the TWC, although they are stakeholders in the joint-planning process. The HGSD and FBSD each regulate groundwater production by limiting pumping in various regulatory areas to percentages of the total water demands. The HGSD and FBSD regulatory plans each call for progressively smaller percentages of groundwater over time, ~~which~~ reductions to occur in 2025 and 2035. Changes in subsidence have correlated to changes in distribution of pumping. Figure ES-12 illustrates pumping reductions in HGSD from 1978 to 2018. Figure ES-13 shows projected total groundwater pumping in HGSD and FBSD through 2070.

with

Conclusions

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.

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

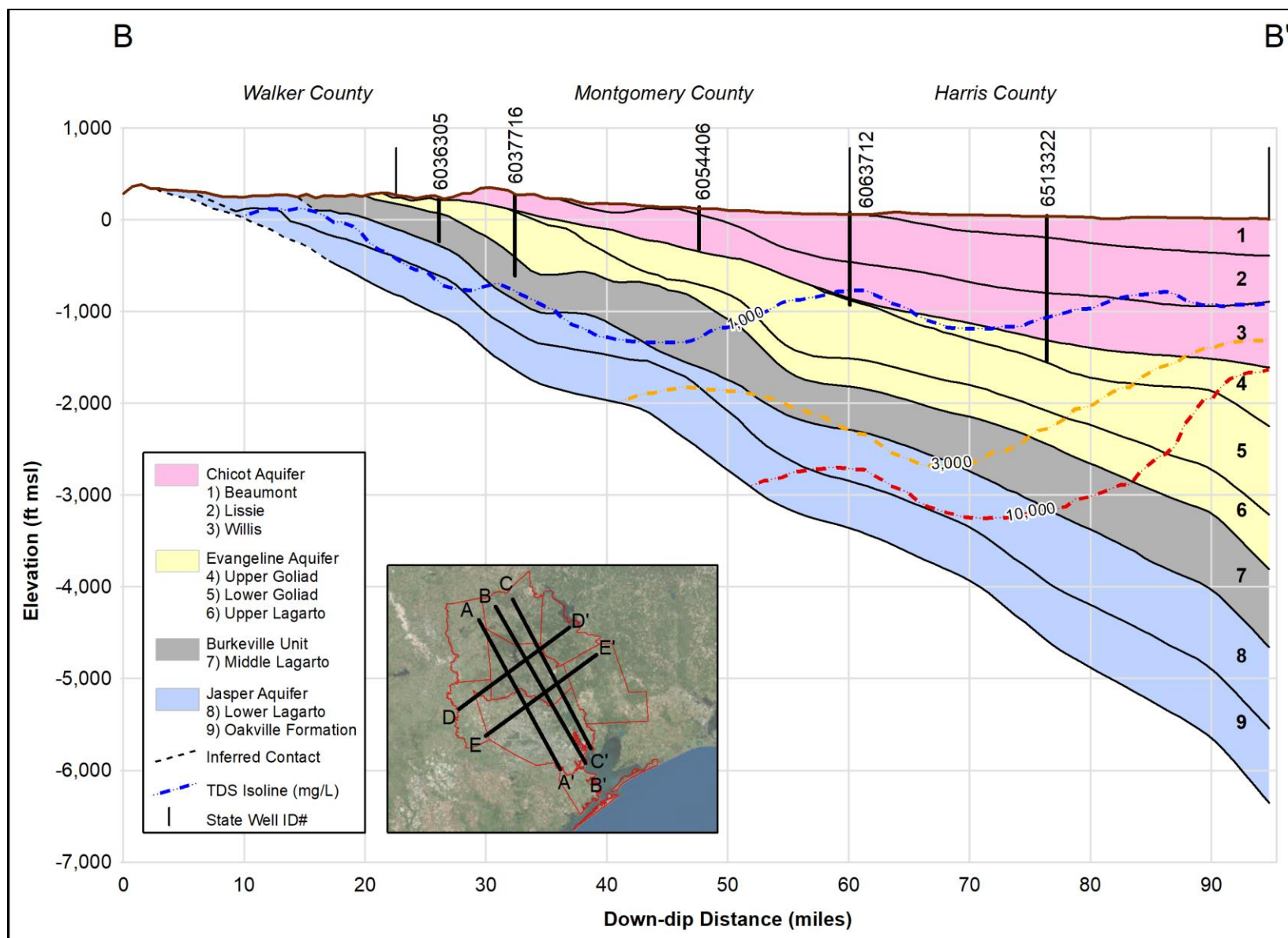


Figure ES-1. B-B' dip cross-section. Formation elevations from Young and others (2012). TDS isolines from Young and others (2016).

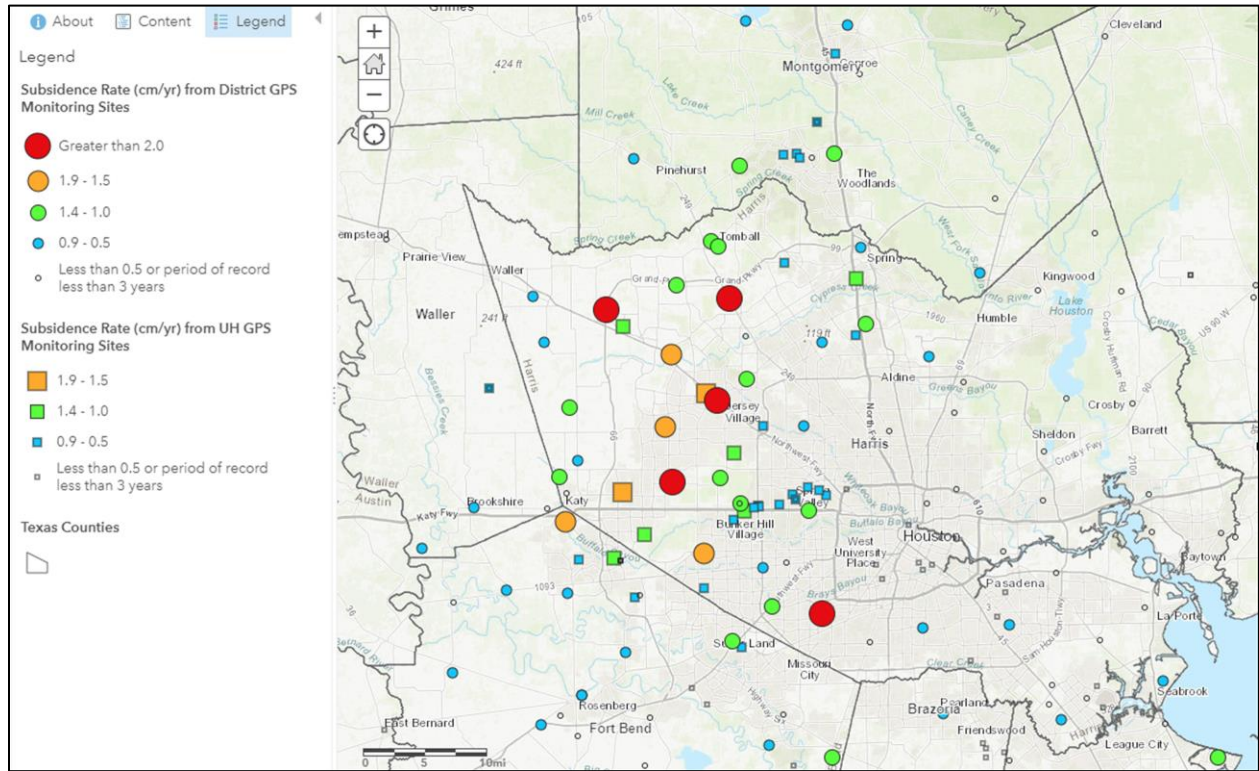


Figure ES-2. Rate of subsidence in the Houston area. Larger, warm color circles indicate a higher rate of subsidence (<https://www.arcgis.com/home/webmap/viewer.html?webmap=a3e7214071f6421fb745d9866e2d3985>).

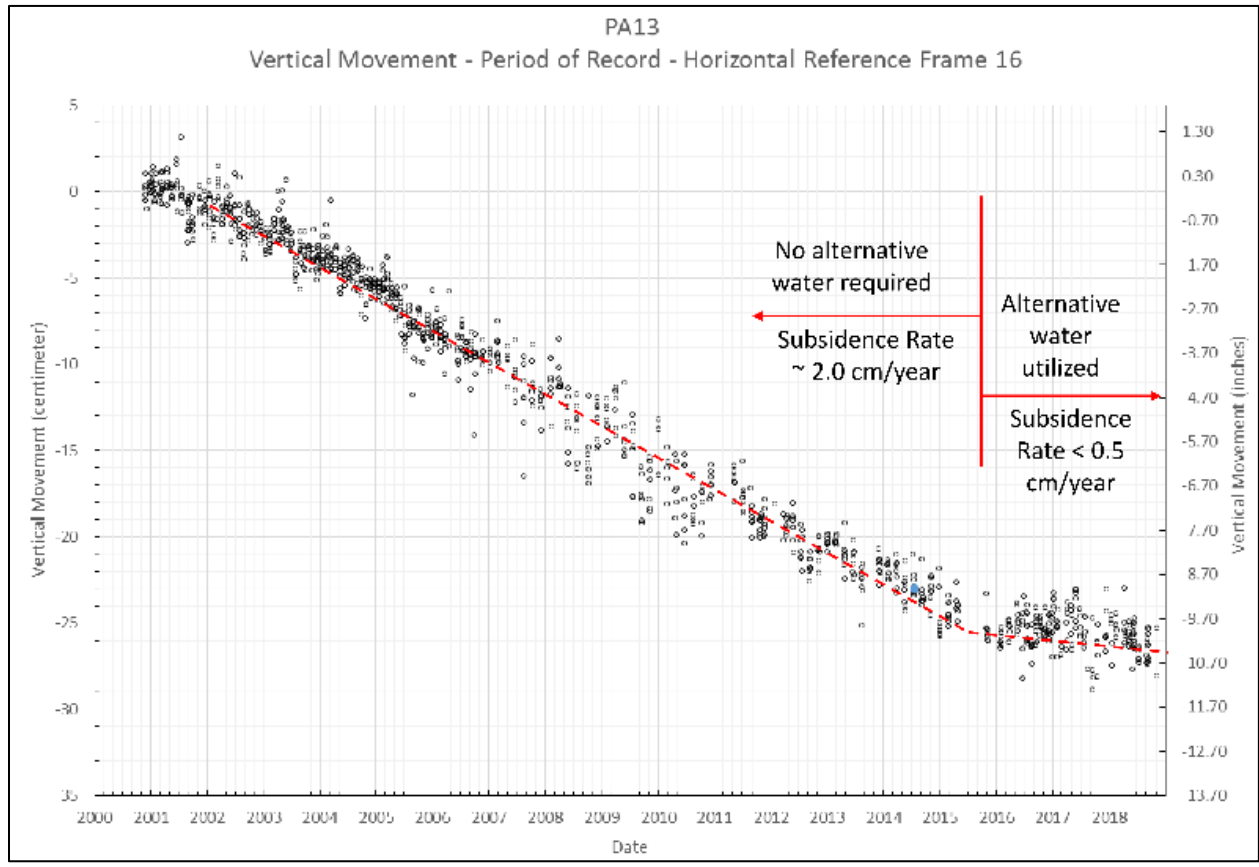


Figure ES-3. GPS measurements of the vertical change in land surface at PA13 site near The Woodlands.

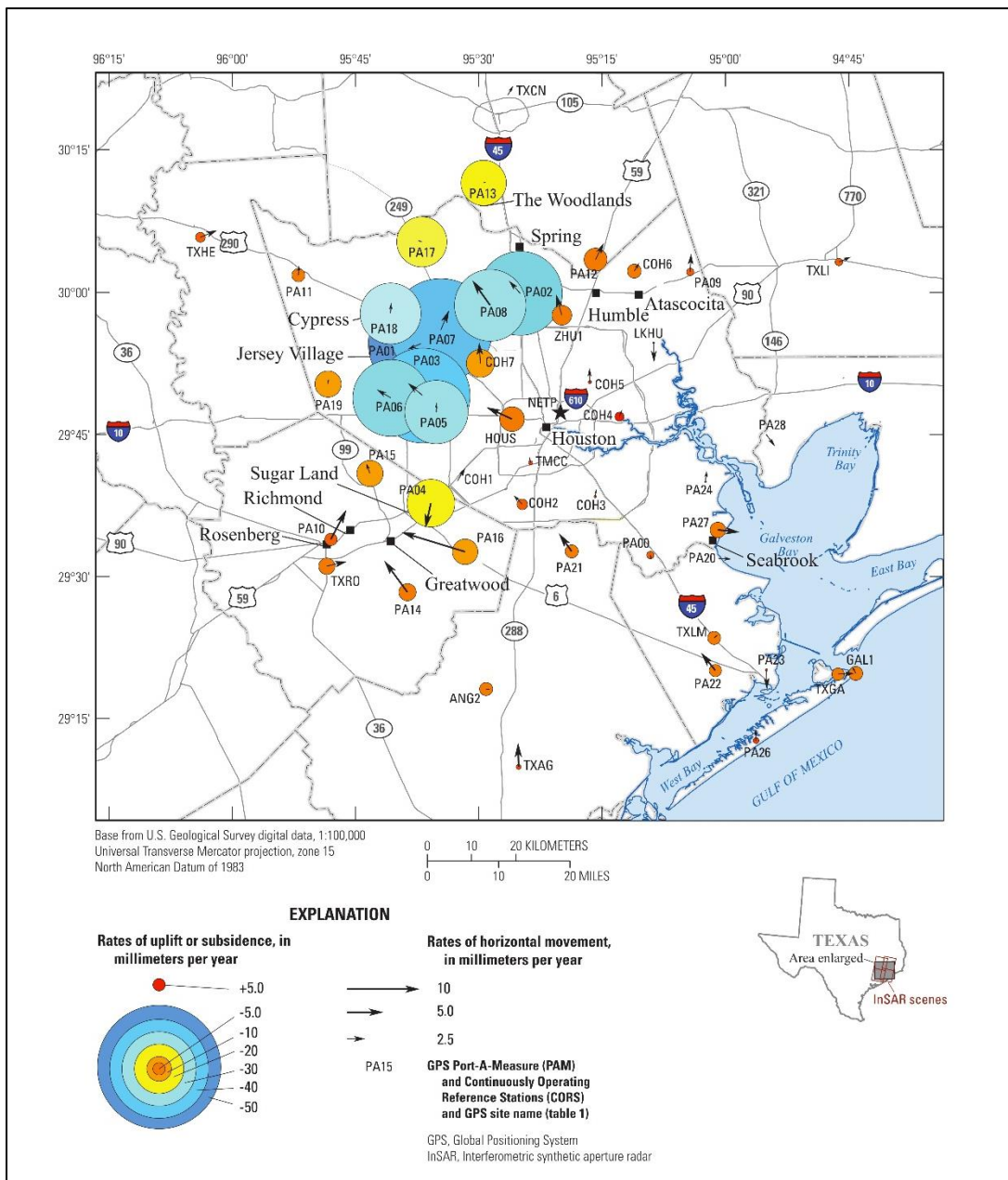


Figure ES-4. Map illustrating rates of subsidence from GPS readings (from Bawden, Johnson, Kasmarek, Brandt, and Middleton, 2012).

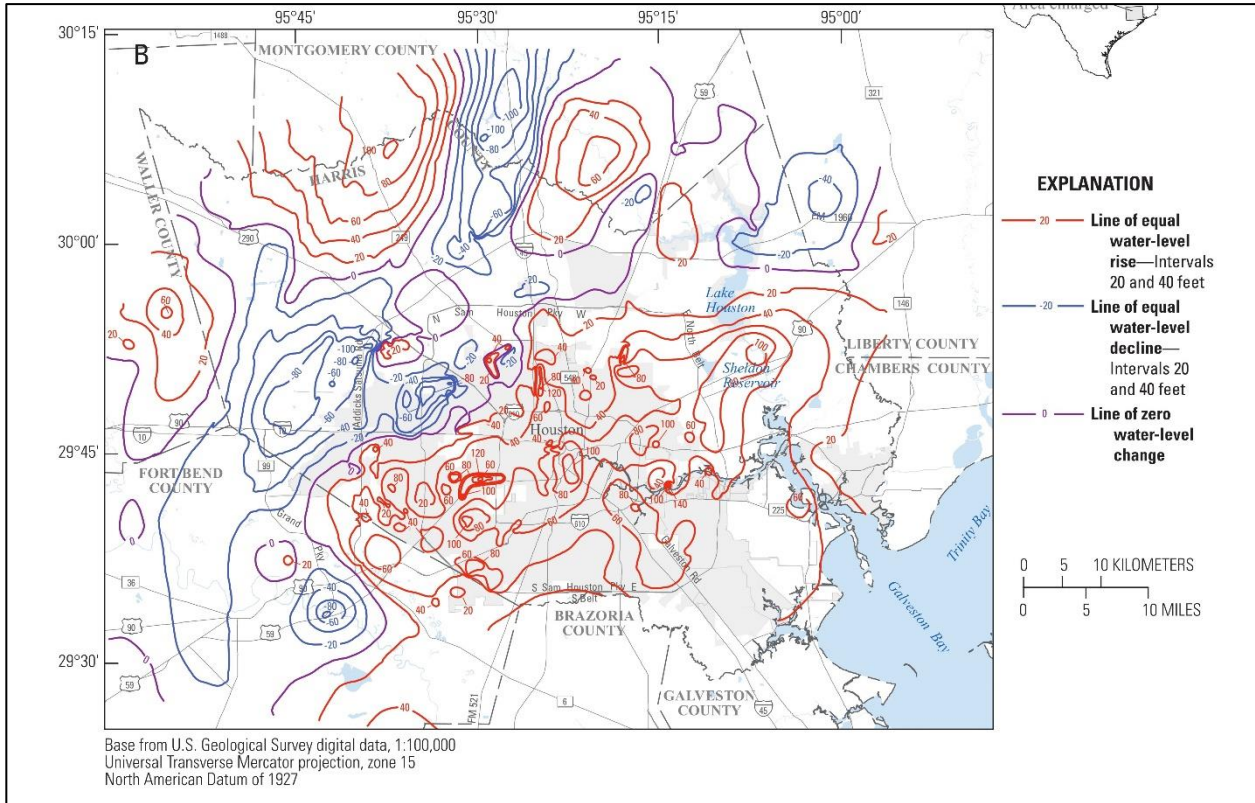


Figure ES-5. Map illustrating changes in water levels in the Evangeline aquifer between 1990 and 2003 (from Bawden, Johnson, Kasmarek, Brandt, and Middleton, 2012).

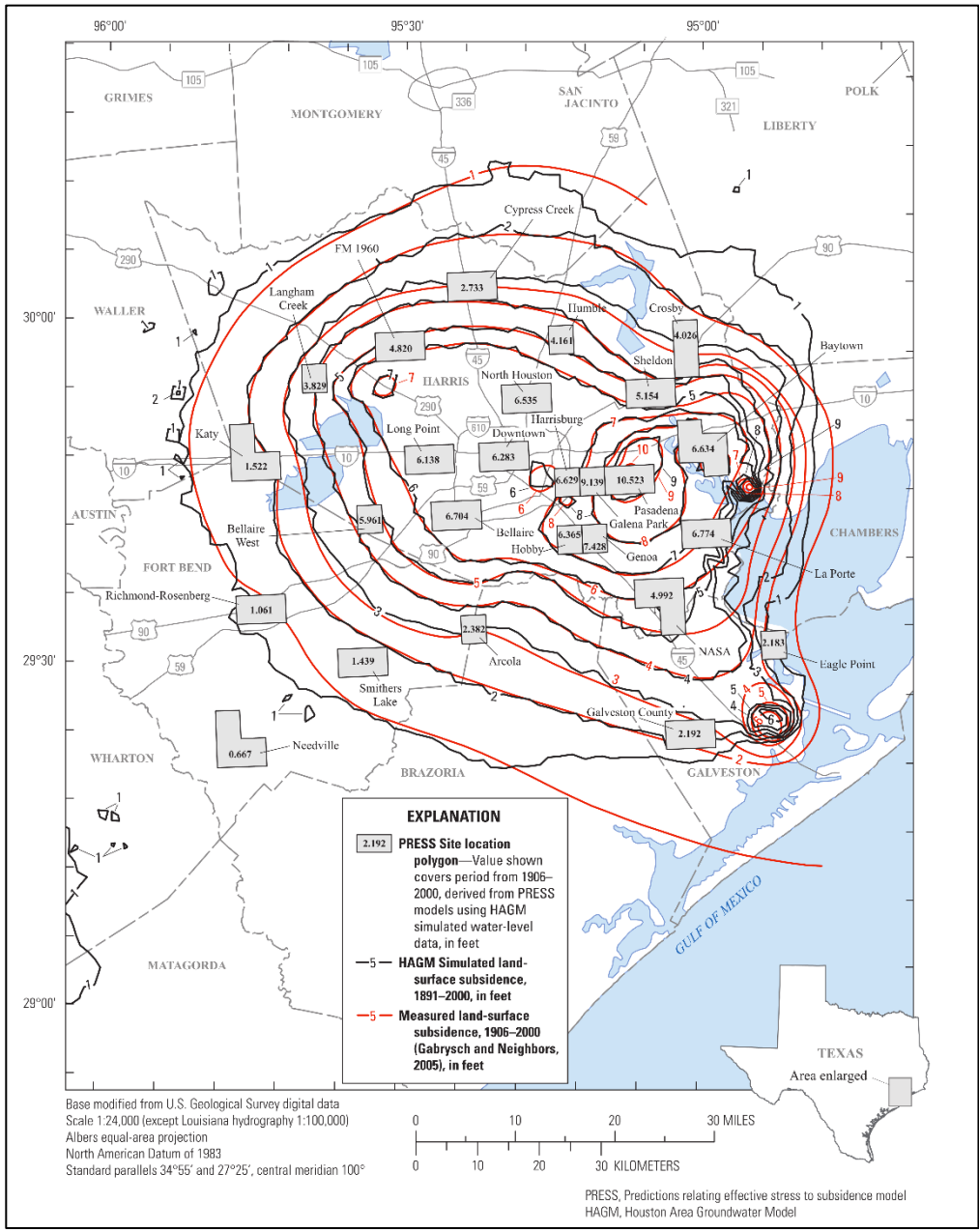


Figure ES-6. Map showing long-term subsidence values from PRESS models, HAGM simulations, and measurements (from Kasmarek, 2013).

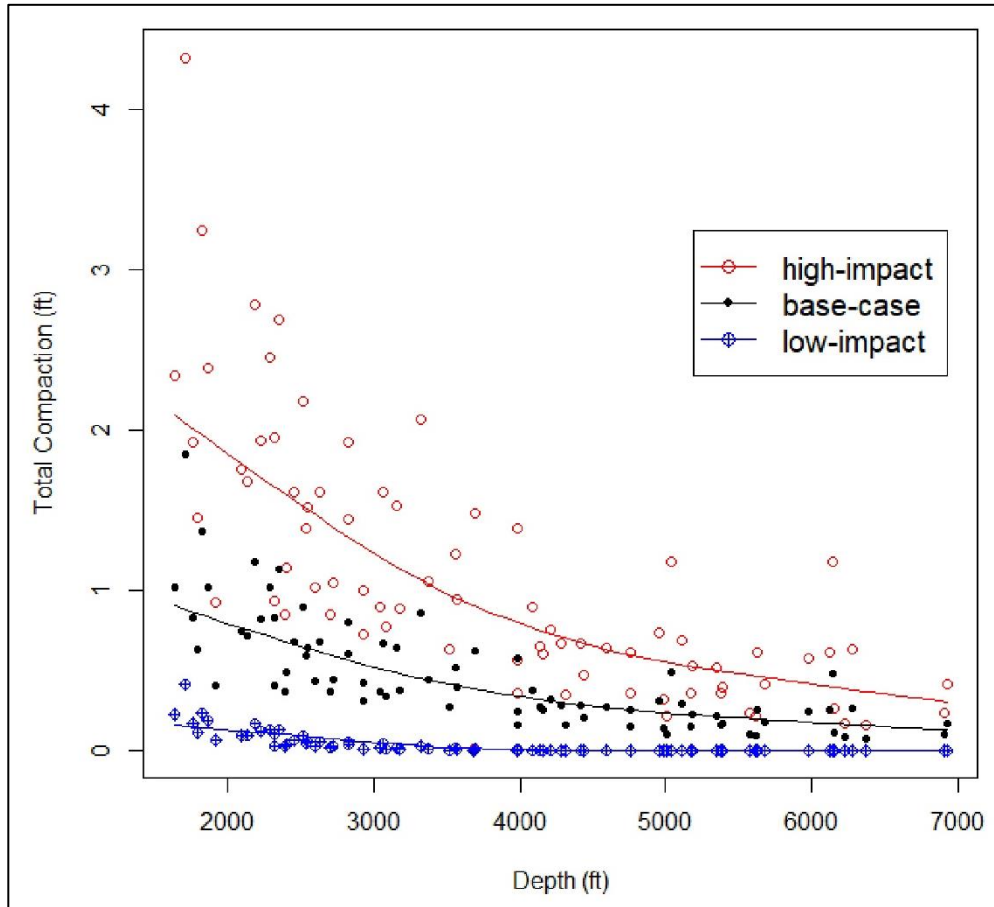


Figure ES-7. Chart showing INTERA's simulated variation of 10-year compaction with depth for three sensitivity cases – Jasper aquifer (from Kelley, Deeds, young, and Pinkard, 2018)

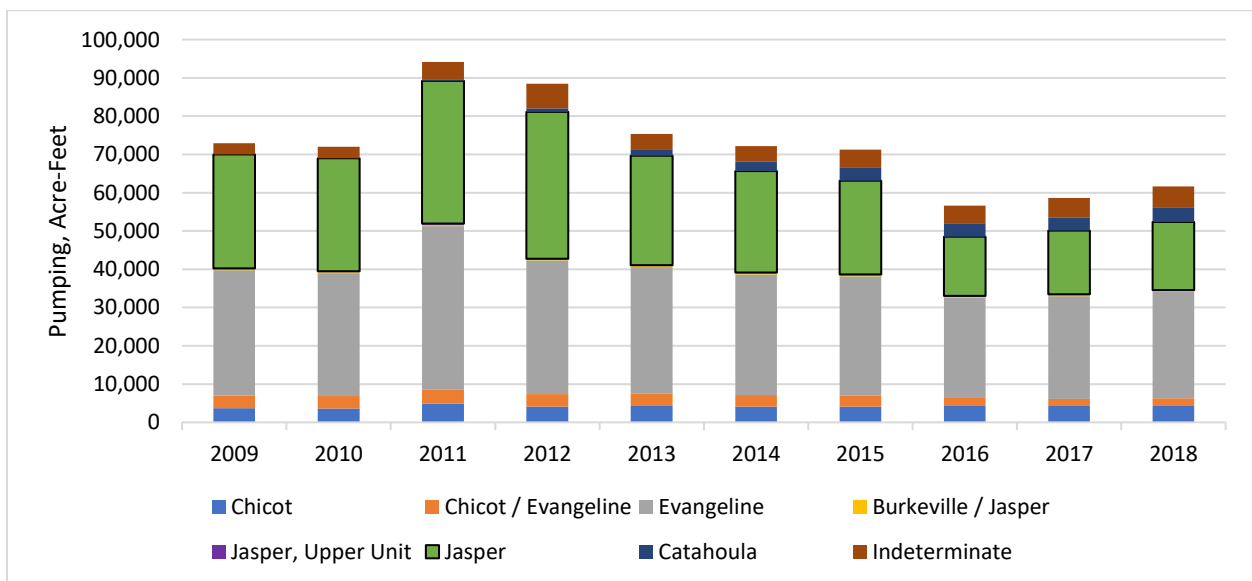


Figure ES-8. LSGCD reported pumping associated with permits by assigned aquifer.

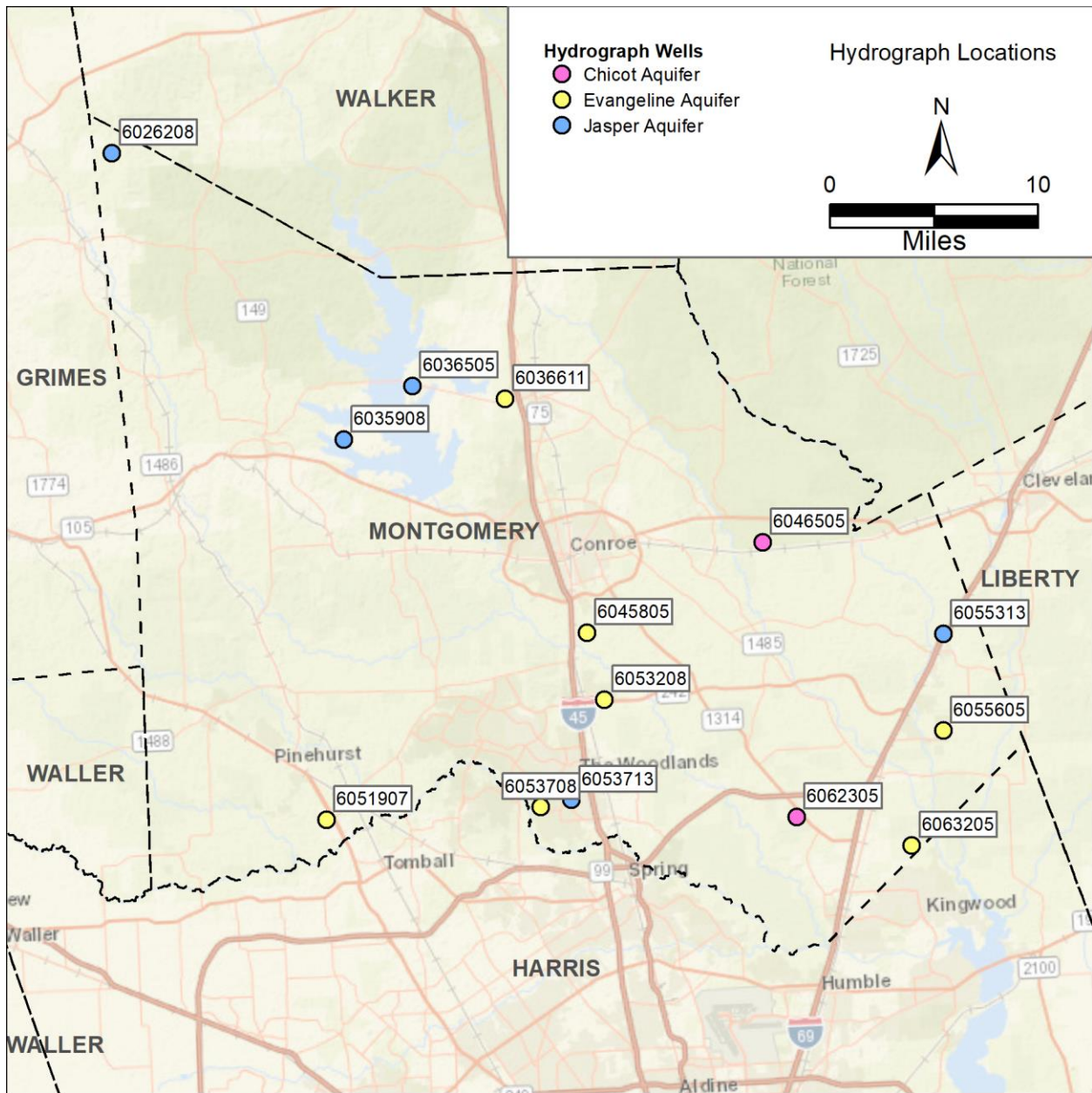


Figure ES-9. Water-level changes in deeper wells completed in the Evangeline and Jasper aquifers in southern Montgomery County.

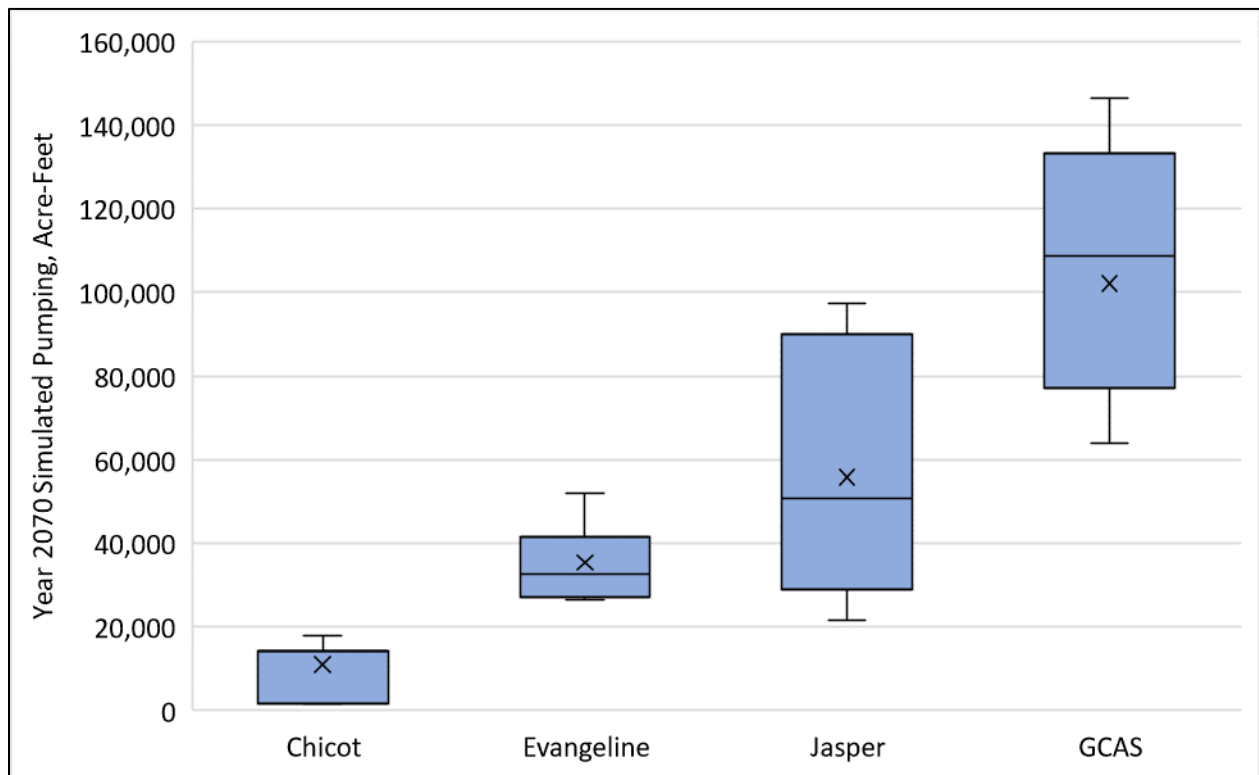


Figure ES-10. Box-and-whisker plot illustrating the distribution of simulated pumping within Montgomery County in each of the scenarios.

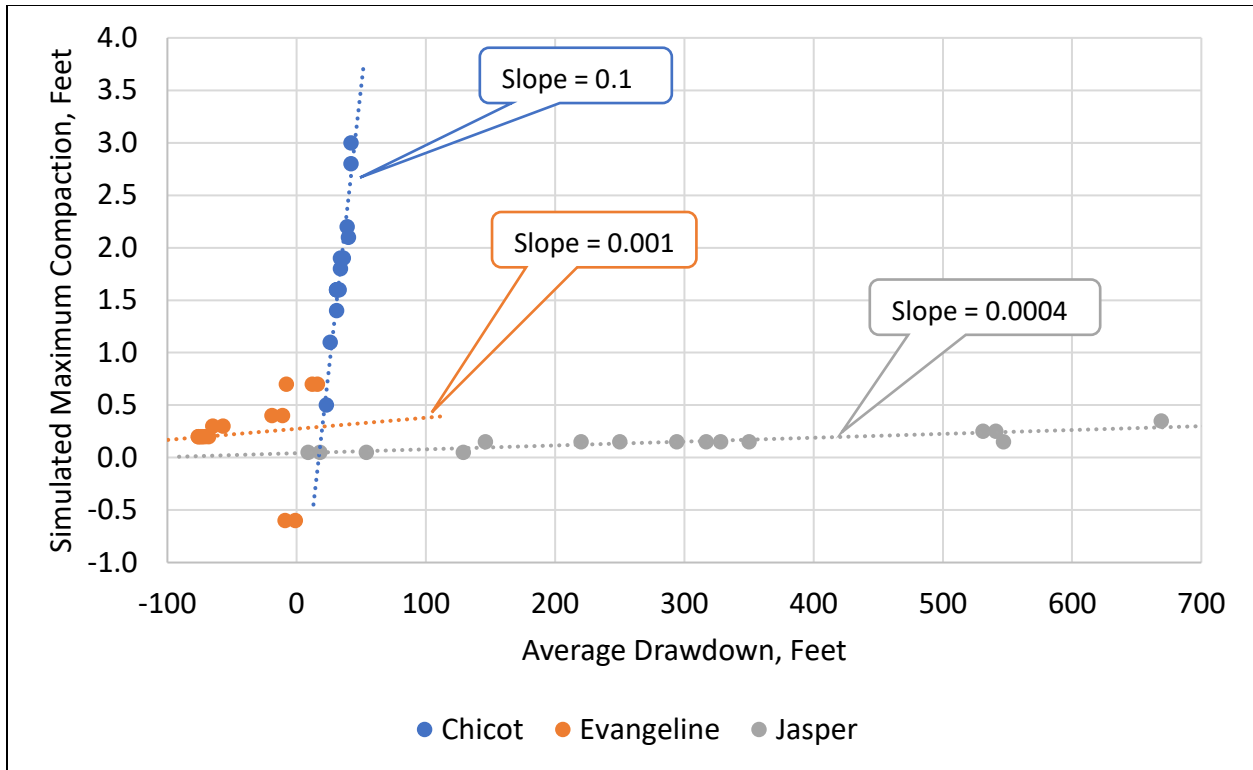


Figure ES-11. Comparison of simulation results showing the relationship between average drawdown and maximum compaction.

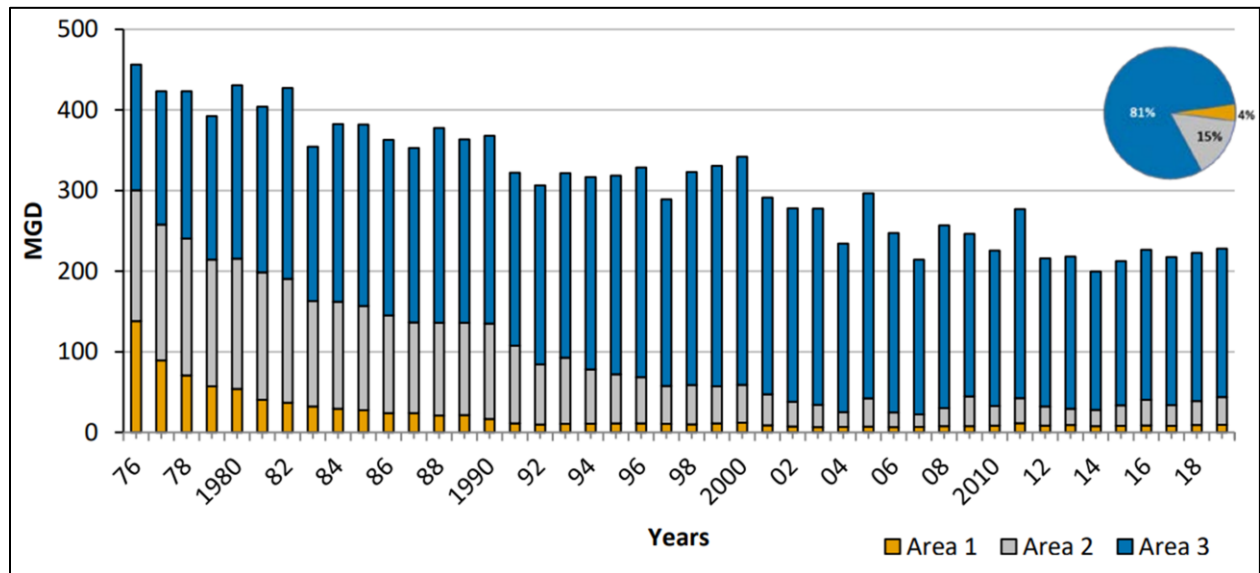


Figure ES-12. Historical pumping in HGSD (Petersen and others, 2020).

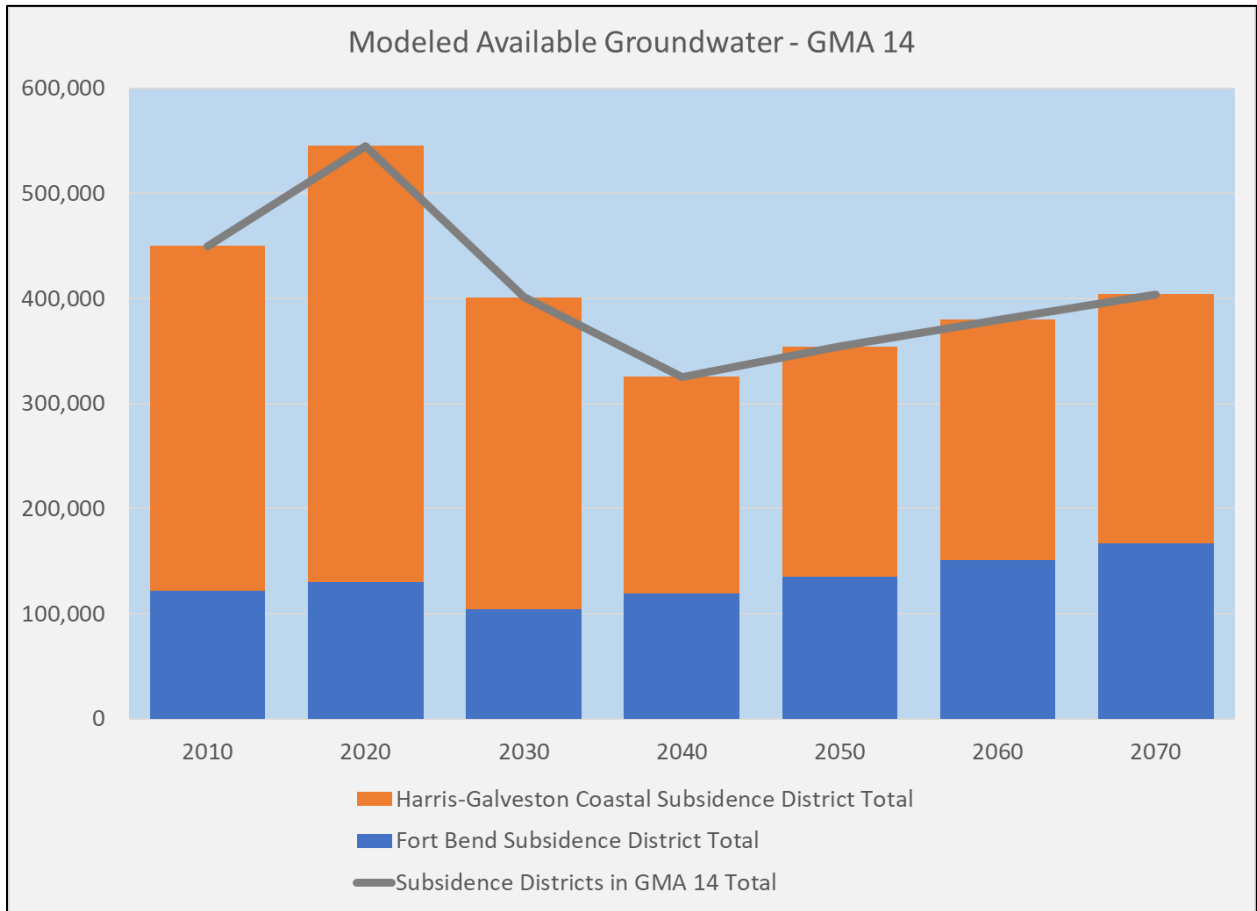


Figure ES-13. Projected total pumping in HGSD and FBSD through 2070 (Wade, 2016).

SUBSIDENCE INVESTIGATIONS – PHASE 1 ASSESSMENT OF PAST AND CURRENT INVESTIGATIONS

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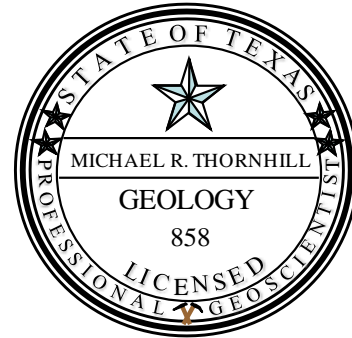


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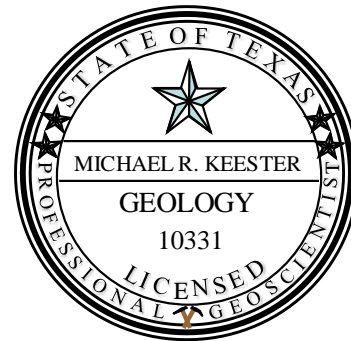
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Michael R. Thornhill, P.G.
President



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SUBSIDENCE INVESTIGATIONS – PHASE 1

ASSESSMENT OF PAST AND CURRENT INVESTIGATIONS

1.0 INTRODUCTION

Lone Star Groundwater
Conservation District (LSGCD)

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. Historically, 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 modeling efforts that include subsidence simulations. However, LSGCD had not conducted its own independent investigations to study subsidence. Therefore, LSGCD approved this 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

Texas Water Development
Board (TWDB) approved

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” (that is, 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 across a “common reservoir” and are not restricted to county boundaries, the Phase 1 work is useful to LSGCD and other groundwater conservation districts (GCDs) in the Joint Planning efforts of GMA 14.

Is this the correct
terminology related to
groundwater?

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 local growth 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 possible compaction with various projected future pumping distributions using the HAGM.

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 a 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:

"on-going GMA 14 planning process" since GMA 14 itself is not a process

The Executive Summary states that subsidence studies in the region began as early as the 1940s.

- 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 (see References). 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.

accepted or approved?

[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.

Port-A-Measure (PAM)

[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. Historical reports by the USGS and TWDB show that groundwater owners in Harris and Fort Bend counties have in the past pumped more groundwater than other counties within GMA 14. Additionally, data show that large portions of artesian pressure declines and subsidence in counties neighboring Harris and Fort Bend counties were caused by pumping within the subsidence districts. Regulatory plans in subsidence districts have led to overall reductions in groundwater use and significant changes in the areal distributions of pumping. Predicting future pumping, artesian pressure changes, and land-surface subsidence depends on understanding the continued implementation of regulatory plans.

[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 TWDB 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) though 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 Burkeville 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 and produce groundwater from the upper portions of the GCAS.

As previously mentioned, 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 within Montgomery County.

The Beaumont Formation does not extend into Montgomery County (see Figure 1). However, the Lissie and Willis formations of the Chicot Aquifer are present. The Lissie and Willis formations are both up to 500 feet 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 the estimated clay thickness of the Willis Formation 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 Pliocene 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 (see Figure 4). 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). Similar to 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 a maximum thickness of more than 500 feet found in an area southeast of Conroe, TX (see Figure 9). The formations that make up the Jasper are the oldest of the GCAS.

2.2 Structure

As mentioned above, the formations of the GCAS dip and thicken 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 (see Figure 11, Figure 12 and Figure 13). Two cross-sections illustrate the configuration of the units along their strike and are essentially parallel to the coastline (see 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 (see 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' (see Figure 12; Figure 16). In addition, the cross-sections do not appear to reflect the major growth faults mapped in Montgomery County (see Figure 17). 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 given the changes in water level. According to Terzaghi's relation, the effective stress within an aquifer may be simplified into two components, namely, geostatic stress and hydrostatic stress (Leake and Galloway, 2007):

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

where

σ' = effective stress (psi)

σ = 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 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 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 UH 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 LSGCD 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 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 during 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). Figure 20 shows locations of benchmarks and subsidence determined 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 elevation 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 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

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 (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:

- The area of Burnett, Scott, and Crystal Bays near Baytown, Texas (Gabrysch and Bonnet, 1974);
- At Seabrook, Texas (Gabrysch and Bonnet, 1976); and,
- The 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 UH site, approximately 19 miles to the west of the Baytown site, 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, which they 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 the geologic, geotechnical, pumping and water-level data collected. Additionally, the three original extensometers and those added layers 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, the initial GAM and HAGM.

The geologic setting and pumping distribution in Montgomery County is and will be different than that found downdip (that is, 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), Table 2 summarizes the geologic age and depositional systems associated with the layers of the GCAS.

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 GCAS layers in Montgomery County, and particularly with respect to the Burkeville and Jasper units.

Growth Faults

The 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 the resulting subsidence.

The UH reports that more than 300 active faults intersect land surface in the Houston area (Engelkemeir and Khan, 2013), and used LiDAR to map faults. The UH notes, "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". The 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 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 the use of InSAR to identify and monitor growth faults (Qu and others, 2019). The SMU study focused on the Hockley-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 determined from the 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) with 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) 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 during specific time periods as related to 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 a continuous and precise record of compaction. Combined with collecting geologic and geotechnical data, water-level measurements, and vertical and lateral pumping distributions, extensometer data allow for determining critical parameters for understanding and predicting subsidence. Extensometer data are quite helpful as they allow 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 closest extensometer is the Lake Houston site. Extensometer information is important regarding LSGCD's subsidence study because the ~~was~~ 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 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 UH. There are two types of sites; 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, a professional engineer representing the 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). Phase 2 of this study will include evaluations of the raw data and data-processing technology.

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 21 is a map generated and presented by the 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 22).

Montgomery County, and other counties

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 GCAS. Therefore, the GPS data must be carefully and accurately processed, compared, and correlated to historical pumping and water-level data to assess in which formations compaction is primarily occurring.

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 opportunities for correlation of multiple data types 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 23 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 24 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 after 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

Due to population growth and regulation resulting 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 the clay layers of the designated GCAS 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 25 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).

PRESS model

Original GAM and the HAGM (Numeric Groundwater Flow Models)

The 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 subsequently utilized the NGC GAM to simulate various hypothetical withdrawal scenarios and reported the projected water-level changes and subsidence in report SIR 2005-5024. 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 GMA 14 model area). The USGS reported that the model runs (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 GCAS (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 GCAS (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 GCAS.

Based on the reported model parameters and on numerous model runs conducted 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 26 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)

On behalf of the Harris-Galveston and Fort Bend subsidence districts, INTERA created a model to simulate compaction and resulting subsidence due to artesian-head reductions in the Jasper Aquifer (Kelley and others, 2018). We have only reviewed the published report for the Jasper model, and do not yet have the

model files. Figure 26 shows that the “Study Area” as delineated in the published report extends into the northern half of Montgomery County and Figure 28 illustrates that the model grid covers the entirety of Montgomery County in addition to other counties. A review of the report shows that INTERA populated the entire model grid domain with hydraulic parameters; however, Figure 28 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 2016 for the TWDB (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 assumptions employed. 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 30 illustrates potential compaction amounts from INTERA’s Jasper model with a range from low to high. Figure 31 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 files and report.

3.1.6 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 32 illustrates the total reported pumping in Montgomery County.

As would be expected with the pumping pattern illustrated in Figure 32 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 33 provides several hydrographs illustrating the reported changes in water levels. The location of each well associated with a hydrograph is shown on Figure 34.

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~~ ^{observed} 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 35 illustrates the changes in water levels in the Chicot aquifer at 10-year intervals beginning in the winter 1988-89. Comparison of Figure 35(A) and Figure 35(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. Figure 35 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 36 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. In Figure 37, we observe water levels decline from about -100 feet mean sea level (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 38 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 39). 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 40. 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 40 also shows the decrease in Jasper pumping that occurred in 2016. With the decrease in pumping, we would anticipate water levels to 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 HGSD and FBSD 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 (see Figure 41) are limited to the geographic area south of Montgomery 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 HAGM (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 USGS under a cooperative agreement with the TWDB 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 USGS 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 20, 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 USGS 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 InSAR along with long-term GPS measurements from 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 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 HGSD is working with the USGS to 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 GMA 14 during the current and previous cycles. However, like the ongoing GULF 2023 model being developed, the HAGM was primarily developed as part of 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 simply must be interpreted within the model limitations. For this report, 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 in each scenario 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 reviewed, pumping at the end of the predictive period ranges from about 64,000 to nearly 150,000 acre-feet per year. Figure 42 illustrates the range in the simulated pumping for each of the aquifers of the GCAS in Montgomery County. As observed 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 (Figure 43 illustrates the parts of the box-and-whisker plot presented in Figure 42).

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 44 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 Figure 45, 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 Figure 46, the average maximum compaction simulated from the scenarios is about 1.75 feet associated with the small range in average drawdown. Comparison of Figure 45 and Figure 46 suggest that there is a relationship between the compaction of the aquifer and 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 (See Figure 47), Evangeline (see Figure 48), and Jasper (see Figure 49). 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.

With regard to the Chicot, the model results show the impact of water level declines on compaction with the relatively small amount of pumping in Montgomery County. We therefore 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 outside of LSGCD's regulatory area. Figure 50 illustrates contours of the predicted subsidence due to pumping outside of Montgomery County.

As Figure 50 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 statutes in Chapter 36 of the Texas Water Code (TWC). GCDs must adopt a management plan to address eight (8) specified management goals. TWC §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 §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 §36.1071(f) states, "The district shall adopt rules necessary to implement the management plan." TWC §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 TWC, "'Subsidence' means the lowering in elevation of the land surface caused by withdrawal of groundwater" (TWC §36.001(10)).

Because subsidence is typically a regional issue, the joint planning process through GMA 14 is where "the rubber meets the road" with respect to controlling subsidence. Each of the layers of the GCAS 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 §36.108(d)(4) “the impact on subsidence” is one of nine (9) factors that GMA’s must consider in setting 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 important stakeholders in the GMA process). The HGSD and the 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 51 shows the regulatory areas in the HGSD and FBSD. Figure 52 shows projected total pumping in both HGSD and FBSD through 2070. Figure 53 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 2 work is to build upon summaries and data collection efforts in Phase 1 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 2 are to:

- Build upon Phase 1 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 2 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 GCAS. 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 GPS technologies. Now there are more than 200 sites maintained and monitored by the USGS and 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 GCAS. 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 Montgomery 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 subsidence 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 GCAS 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

This 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:

The Executive Summary states 1940s

- 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 (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.

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

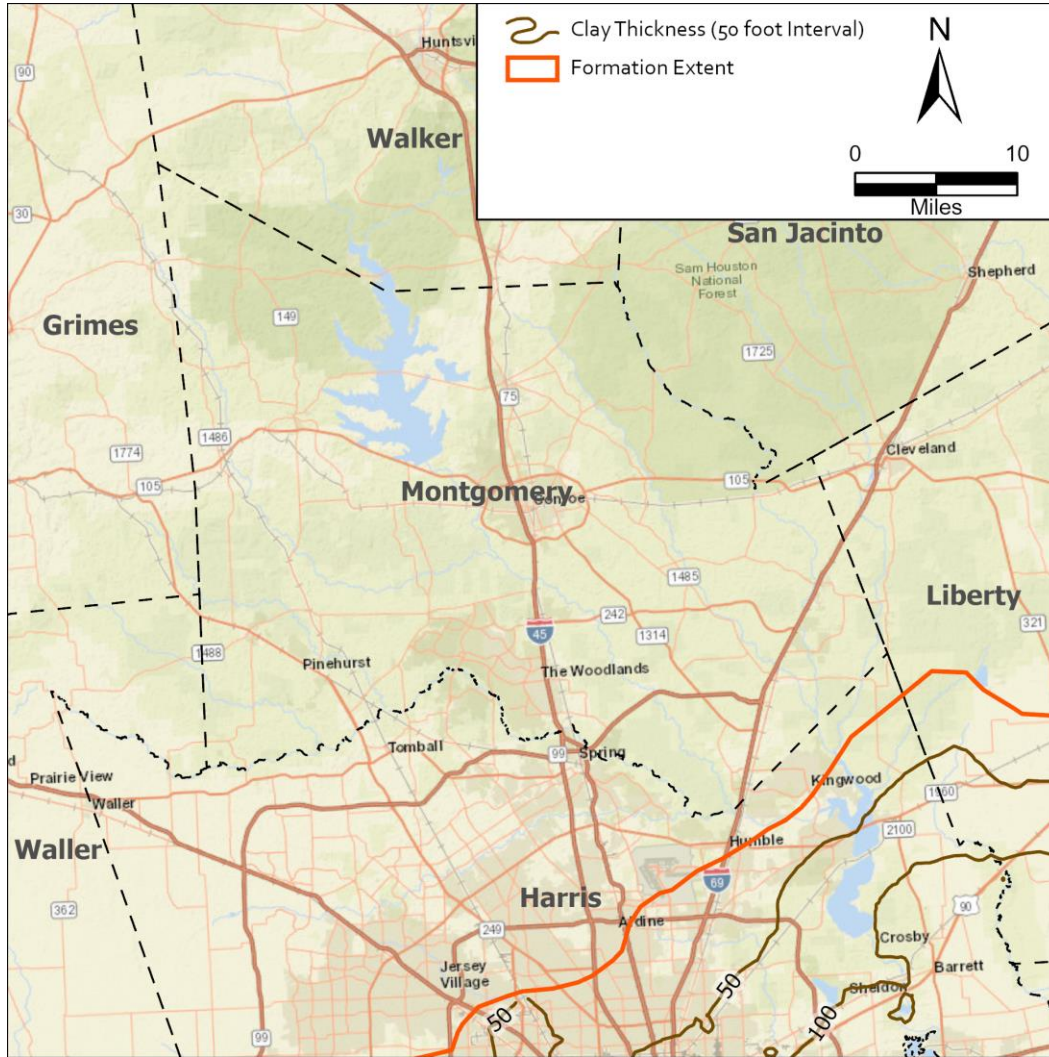


Figure 1. Clay thickness of the Beaumont Formation. Clay thickness calculated by subtracting the sand thickness from the total thickness as provided in the data set by Young and others (2012).

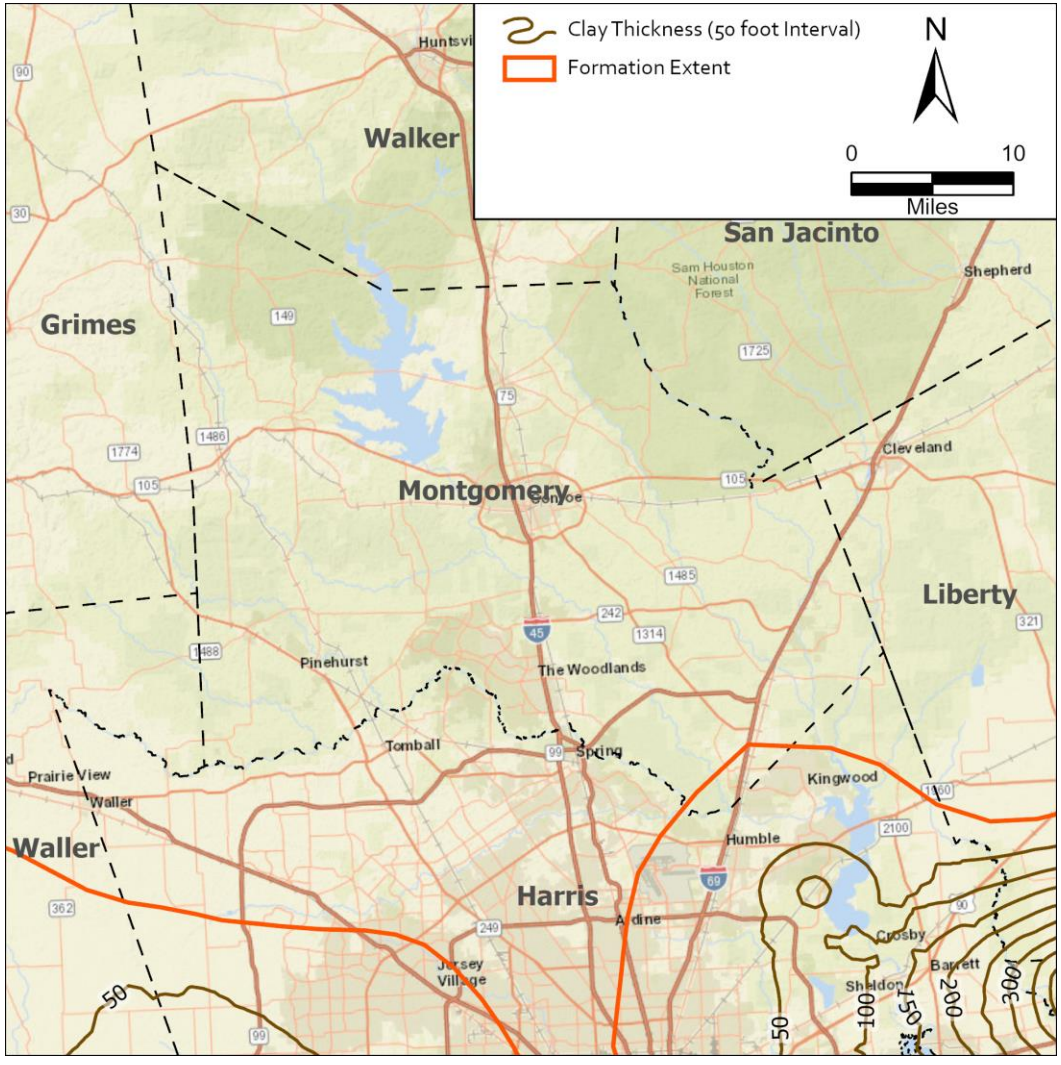


Figure 4. Clay thickness of the Upper Goliad Formation. Clay thickness calculated by subtracting the sand thickness from the total thickness as provided in the data set by Young and others (2012).

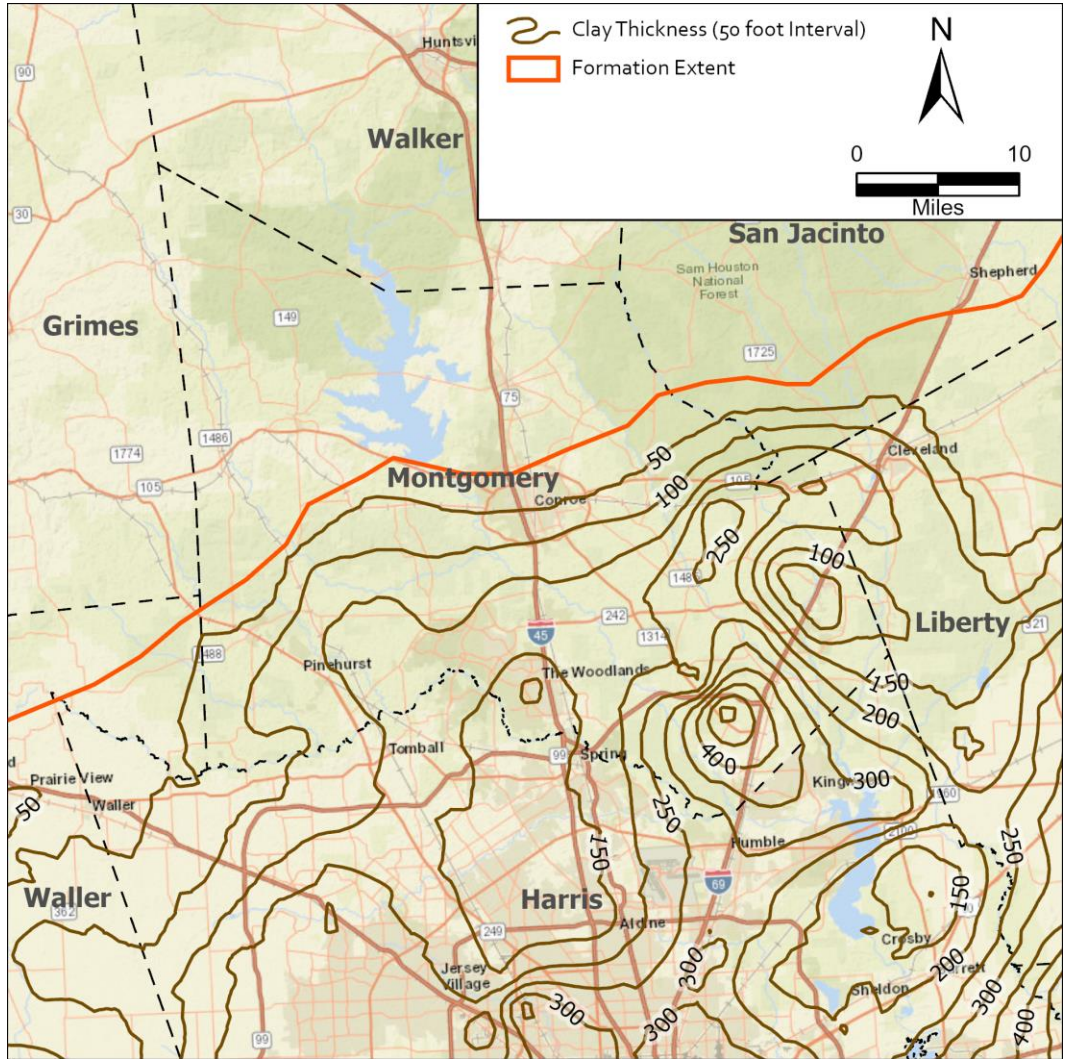


Figure 5. Clay thickness of the Lower Goliad Formation. Clay thickness calculated by subtracting the sand thickness from the total thickness as provided in the data set by Young and others (2012).

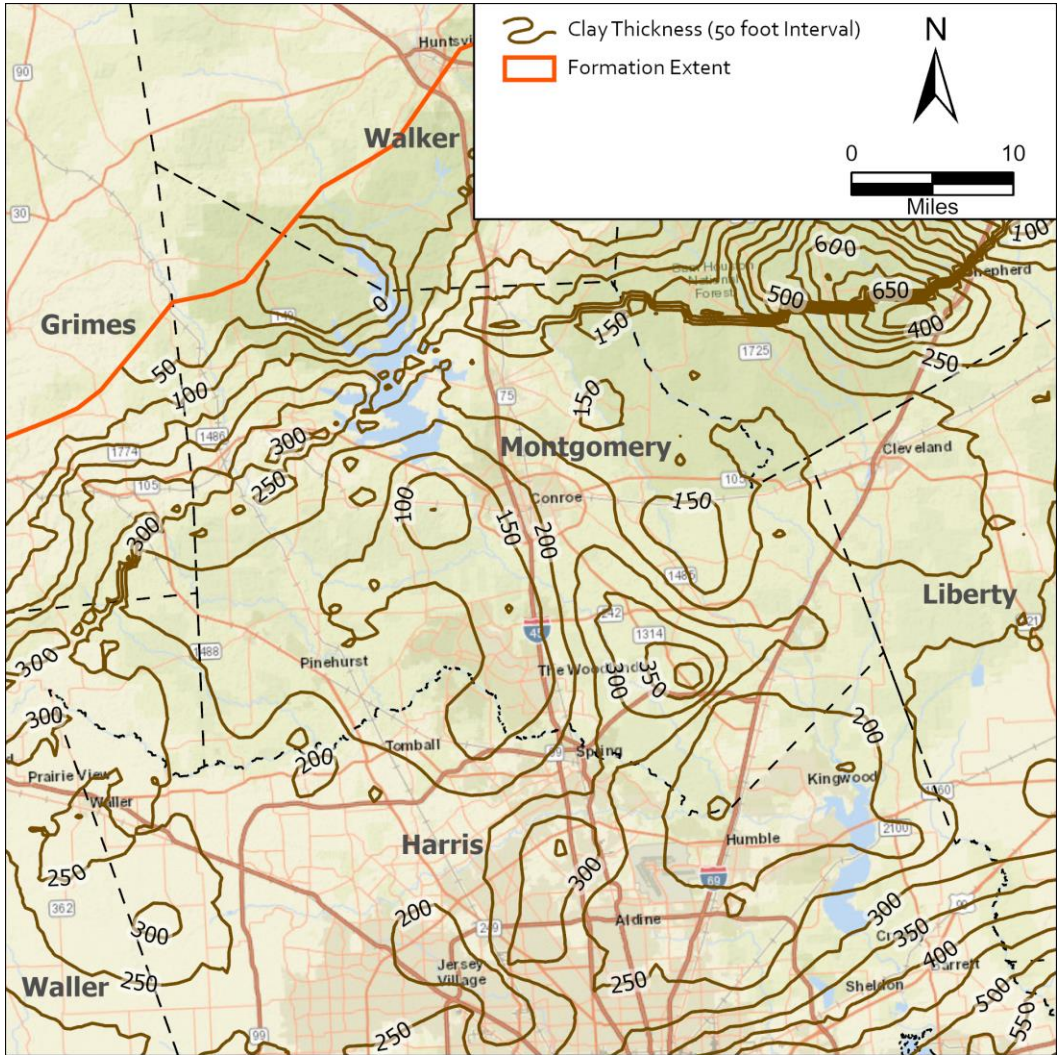


Figure 7. Clay thickness of the Middle Lagarto Formation. Clay thickness calculated by subtracting the sand thickness from the total thickness as provided in the data set by Young and others (2012).

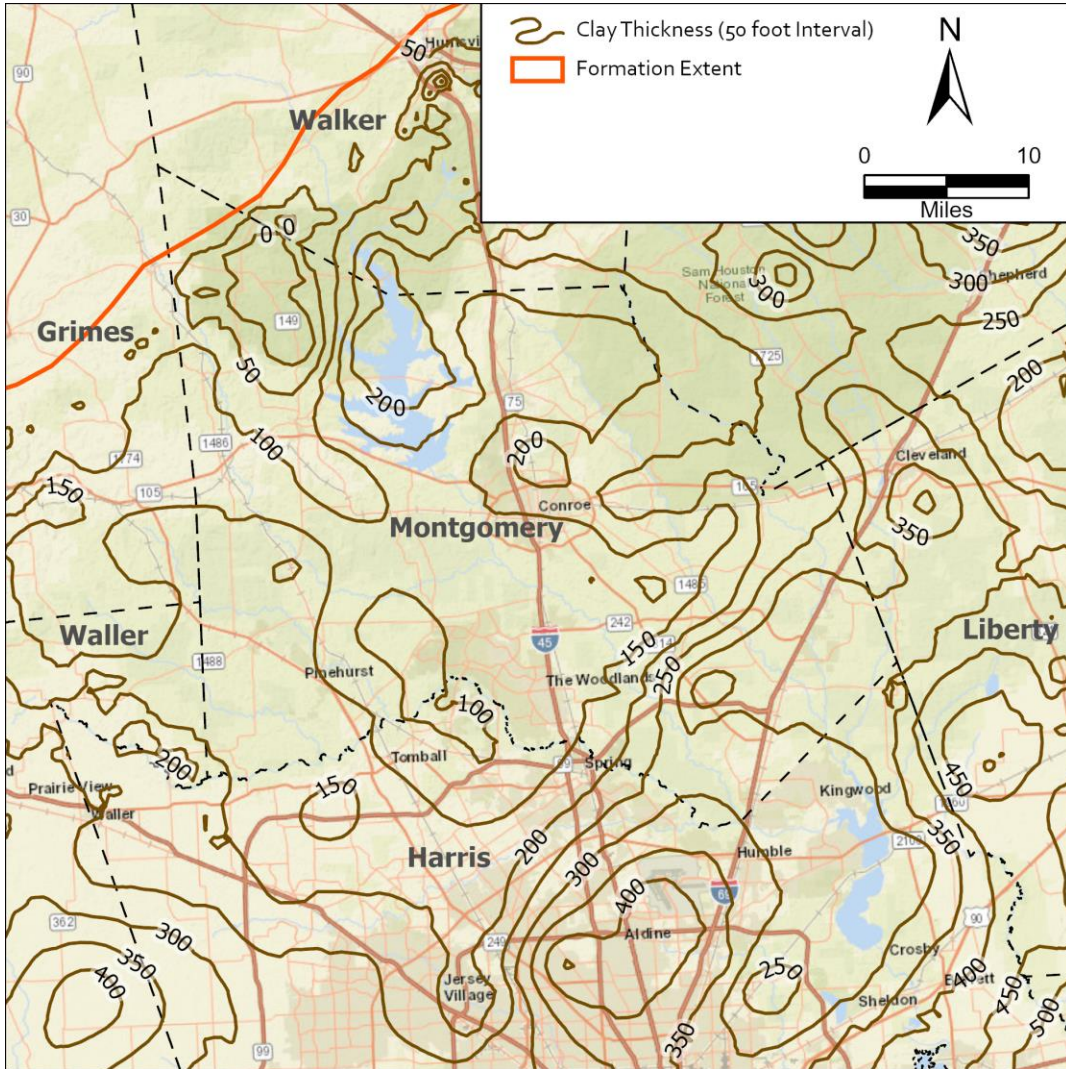


Figure 8. Clay thickness of the Lower Lagarto Formation. Clay thickness calculated by subtracting the sand thickness from the total thickness as provided in the data set by Young and others (2012).

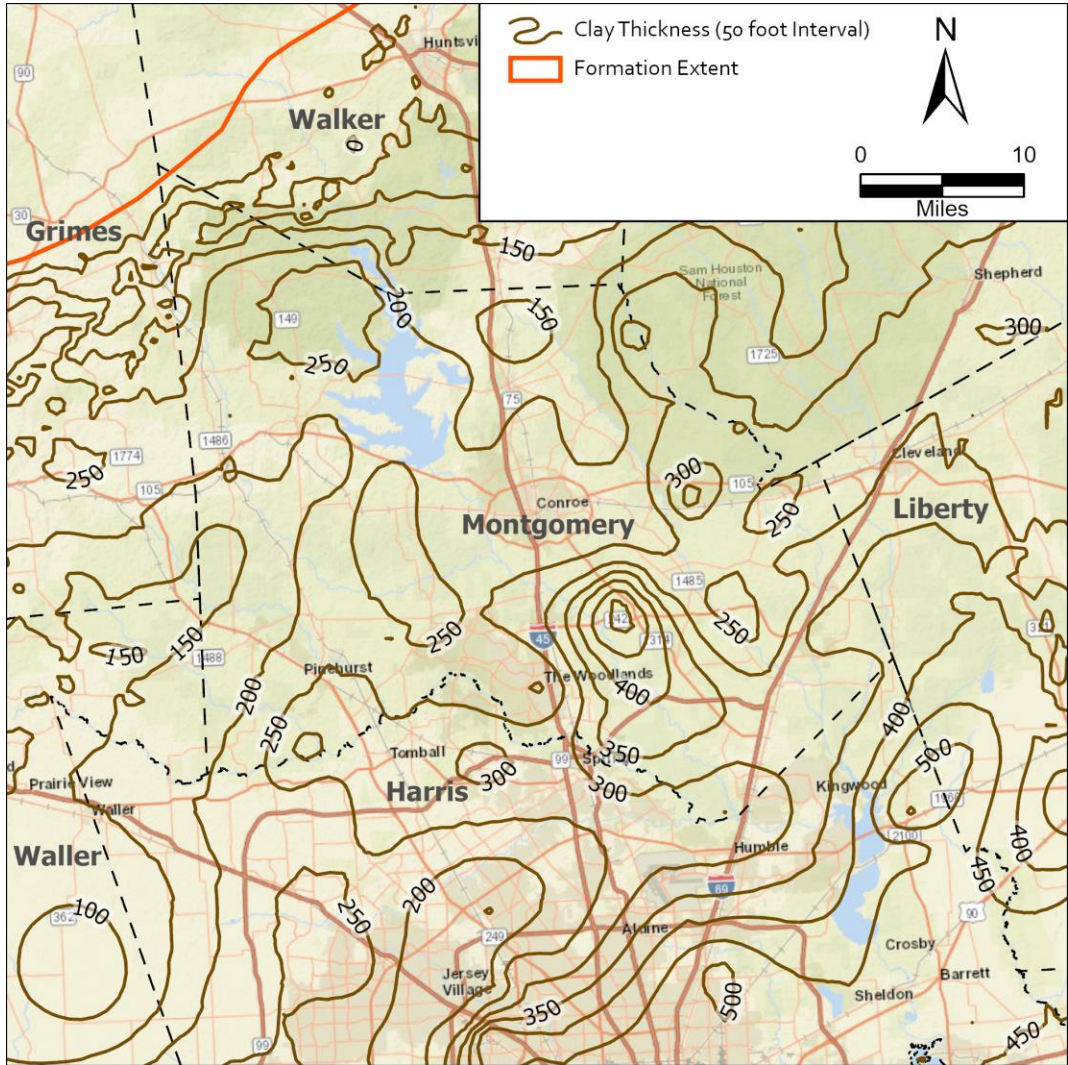


Figure 9. Clay thickness of the Oakville Formation. Clay thickness calculated by subtracting the sand thickness from the total thickness as provided in the data set by Young and others (2012).

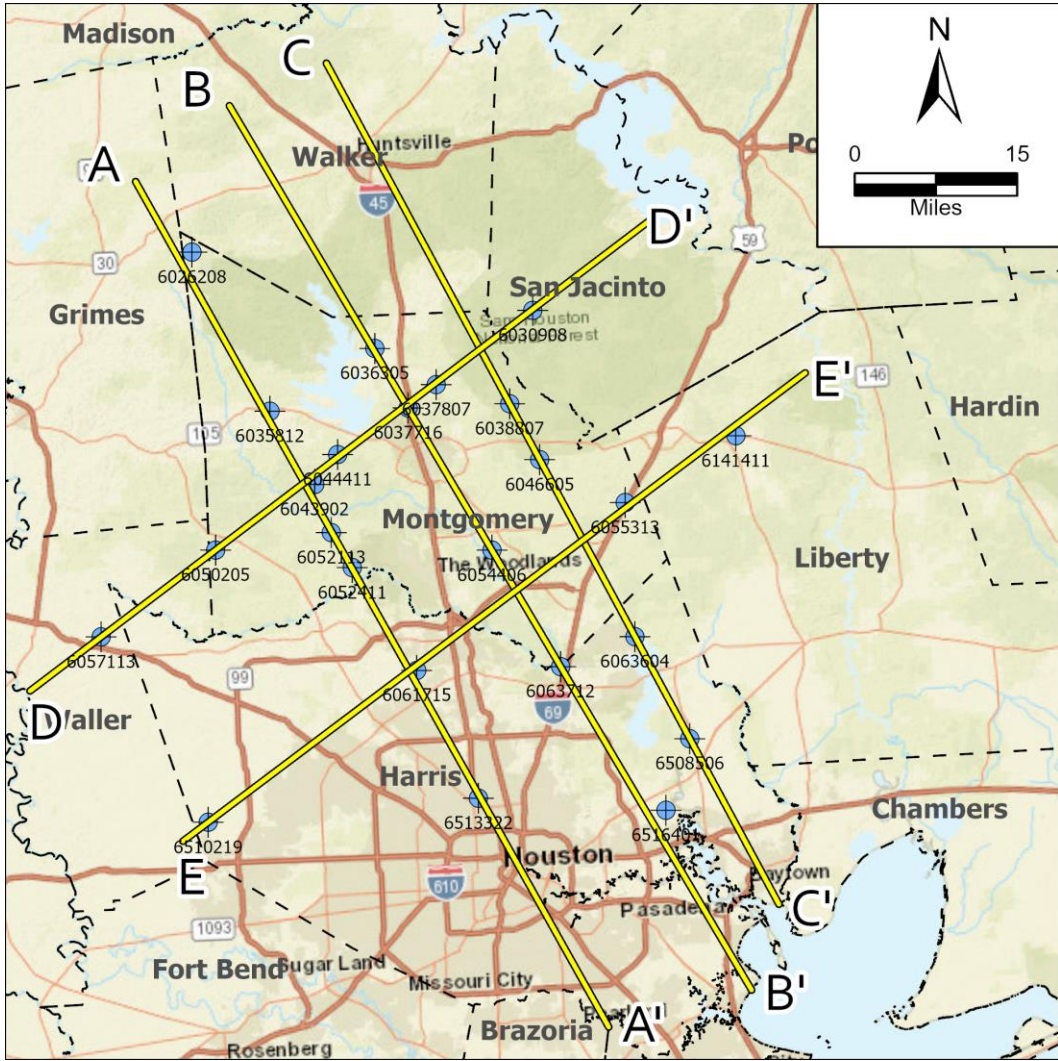


Figure 10. Location of cross-sections.

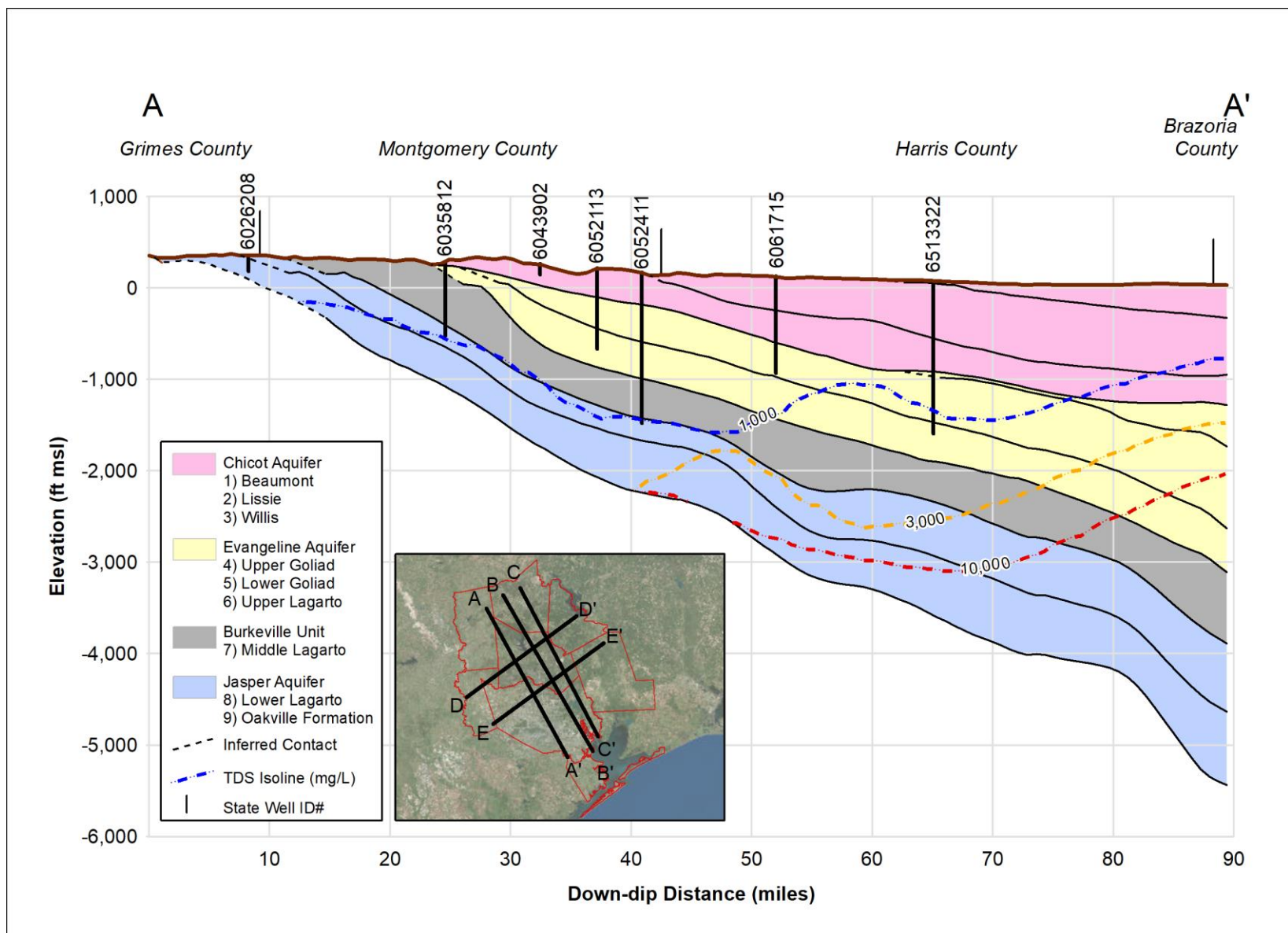


Figure 11. A-A' dip cross-section. Formation elevations from Young and others (2012). TDS isolines from Young and others (2016).

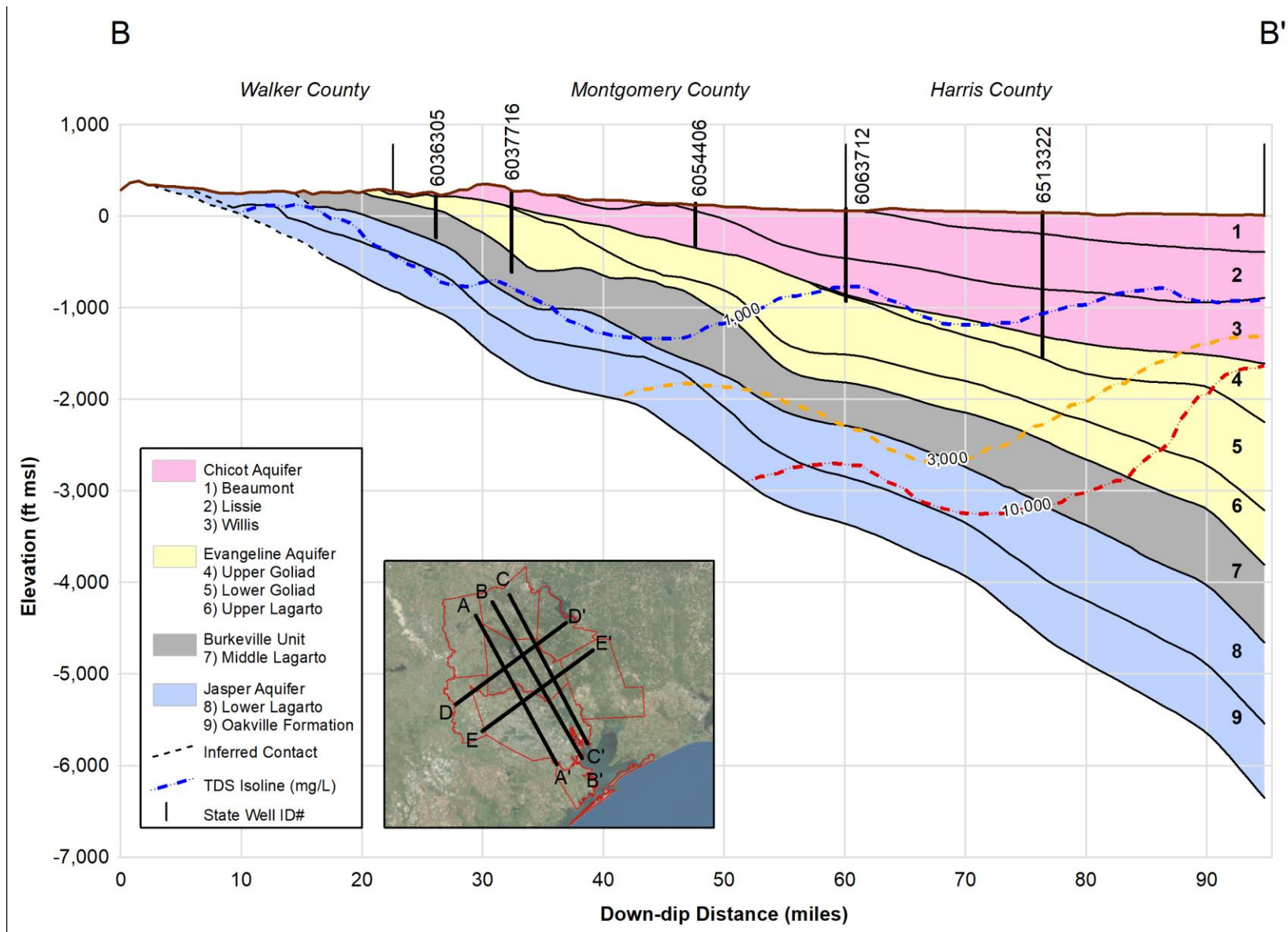


Figure 12. B-B' dip cross-section. Formation elevations from Young and others (2012). TDS isolines from Young and others (2016).

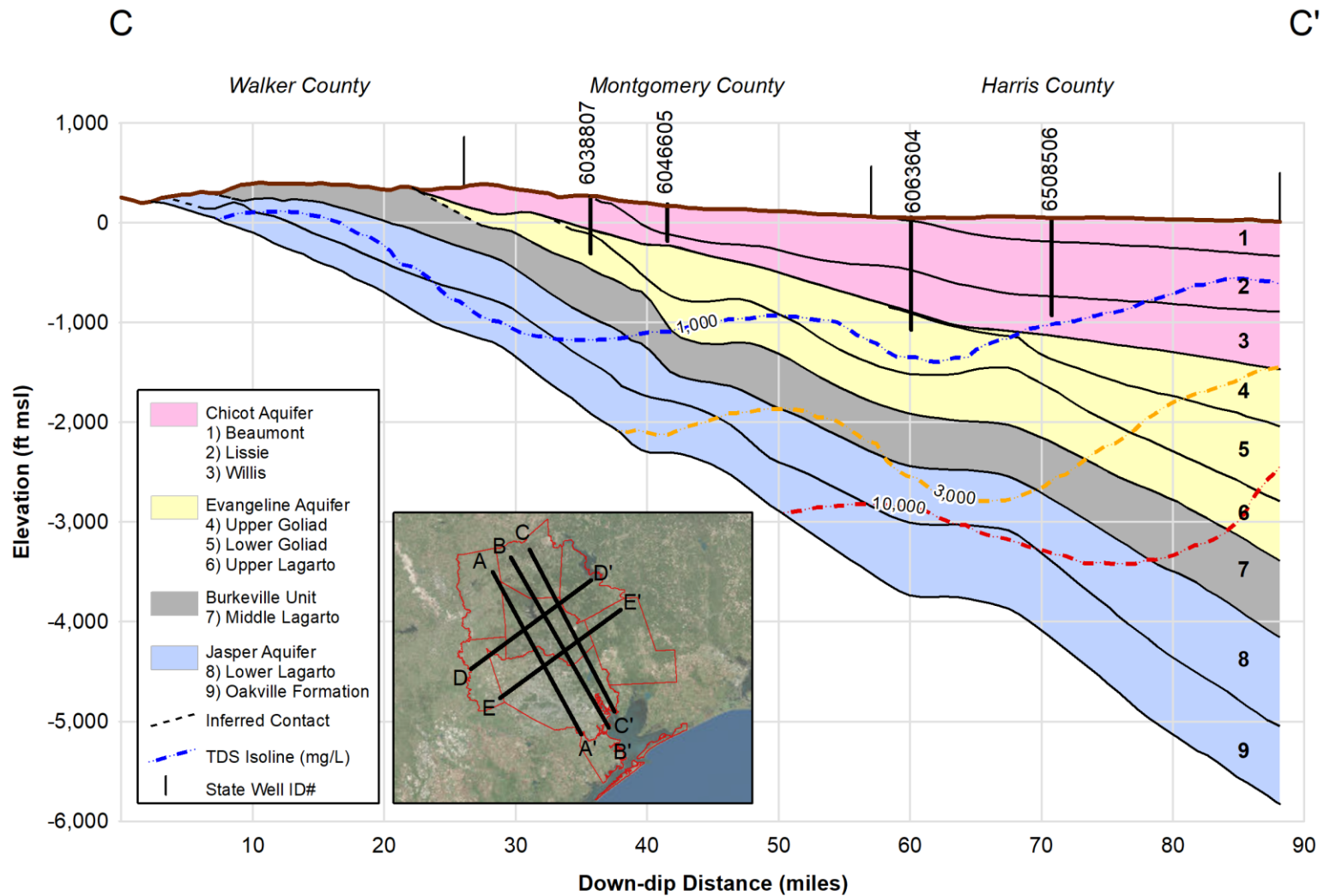


Figure 13. C-C' dip cross-section. Formation elevations from Young and others (2012). TDS isolines from Young and others (2016).

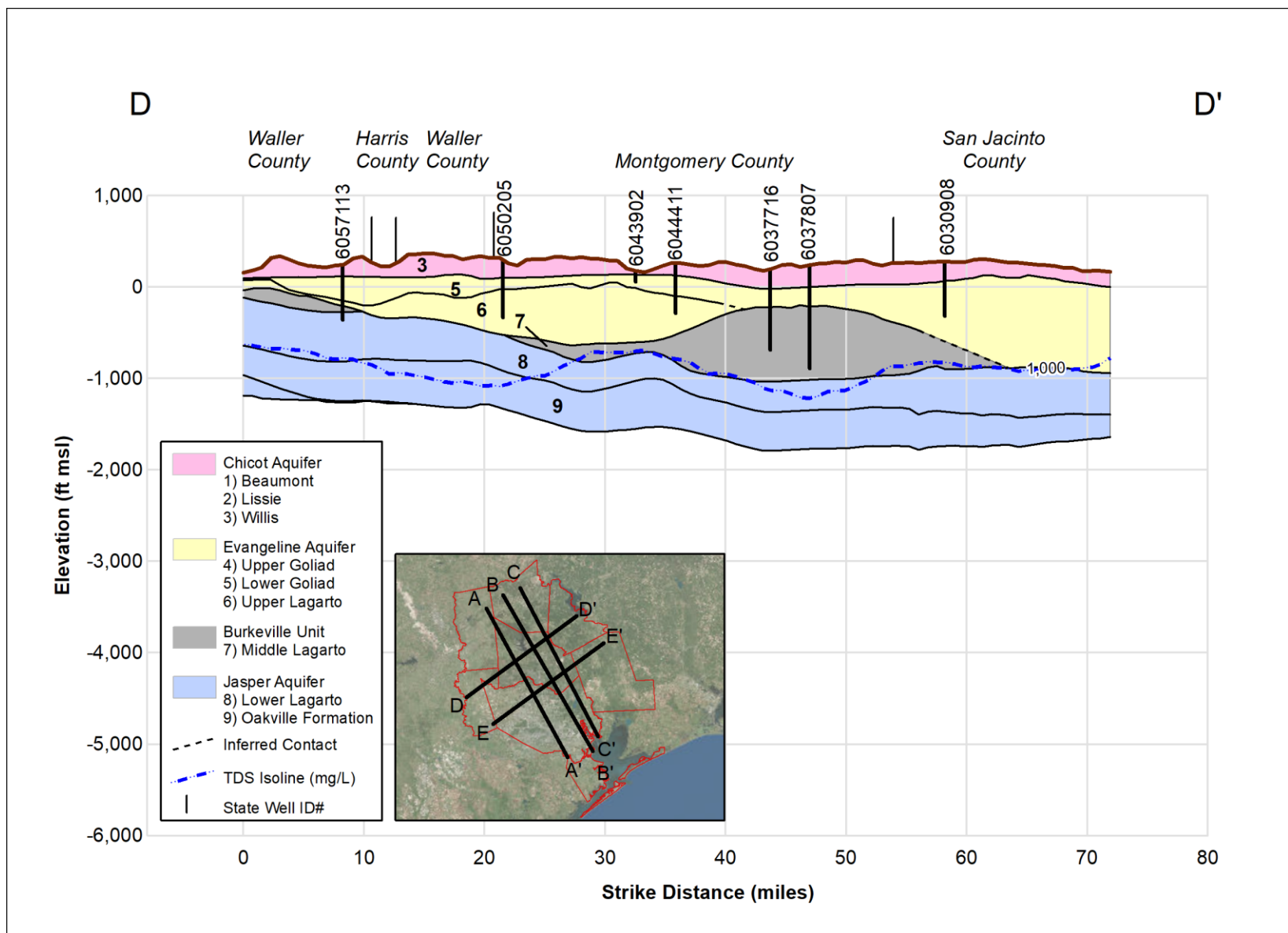


Figure 14. D-D' strike cross-section. Formation elevations from Young and others (2012). TDS isolines from Young and others (2016).

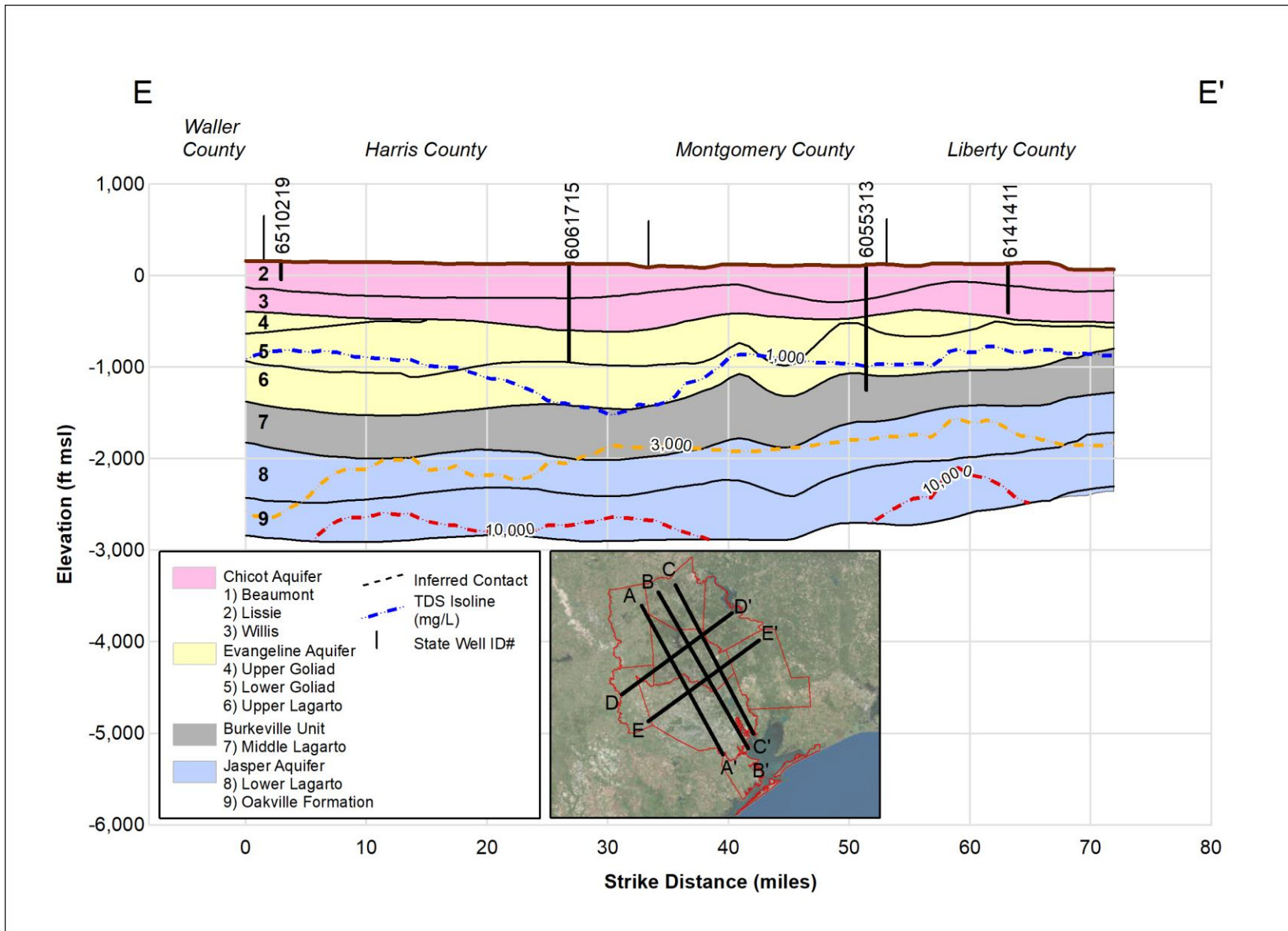


Figure 15. E-E' strike cross-section. Formation elevations from Young and others (2012). TDS isolines from Young and others (2016).

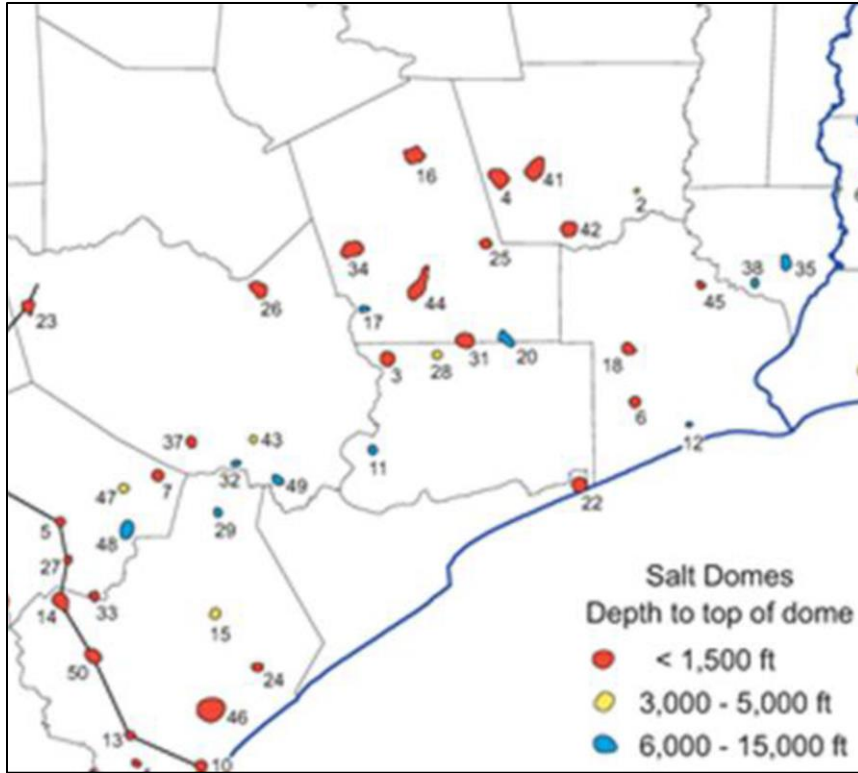


Figure 16. Salt domes in the Gulf Coast area. Reproduced from Young and others (2012).

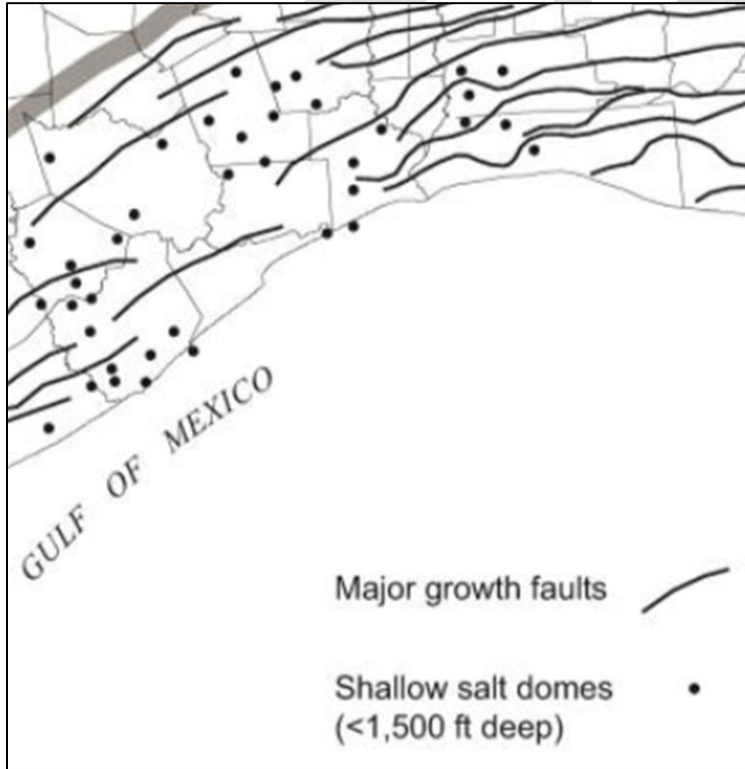


Figure 17. Illustration of major growth faults in the Gulf Coast area. Reproduced from Young and others (2012).

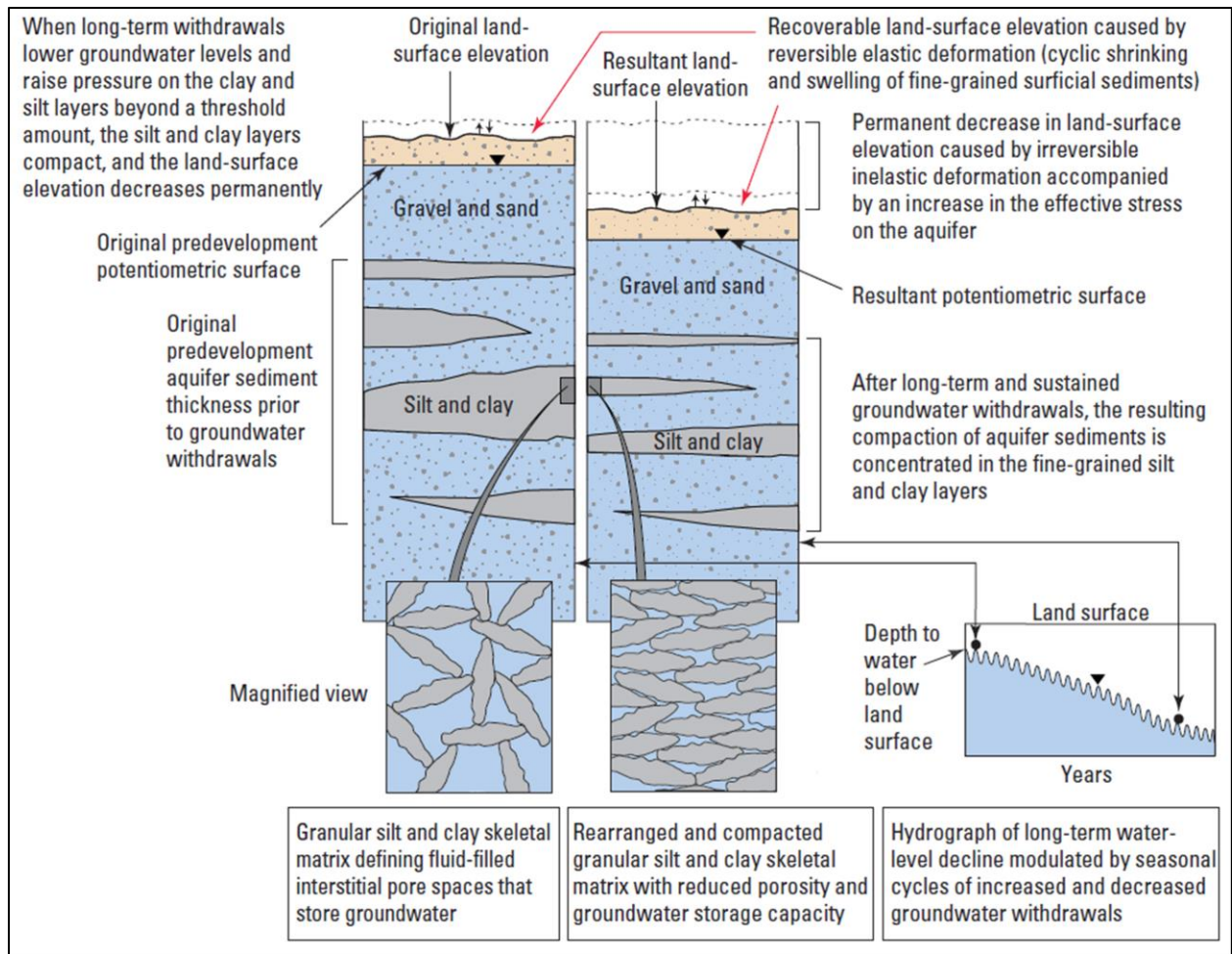


Figure 18. Illustration of subsidence due to reorientation of fine-grained aquifer sediments. Reproduced from Kasmarek and Ramage (2017).

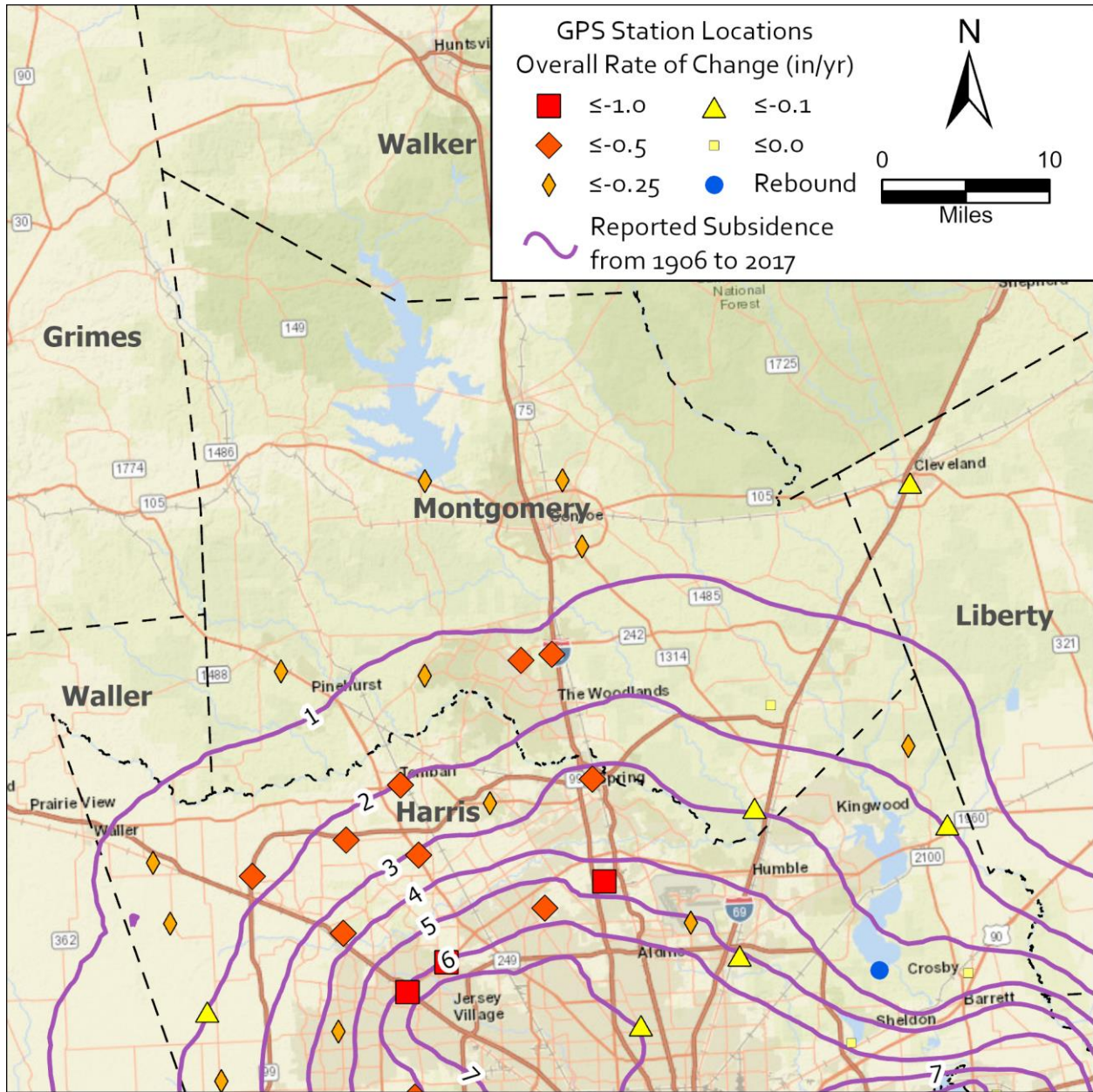


Figure 19. Subsidence rate at monitoring locations with a minimum of 5 year measurement history and reported land surface subsidence from 1906 through 2017.

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

Hydrostratigraphic 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

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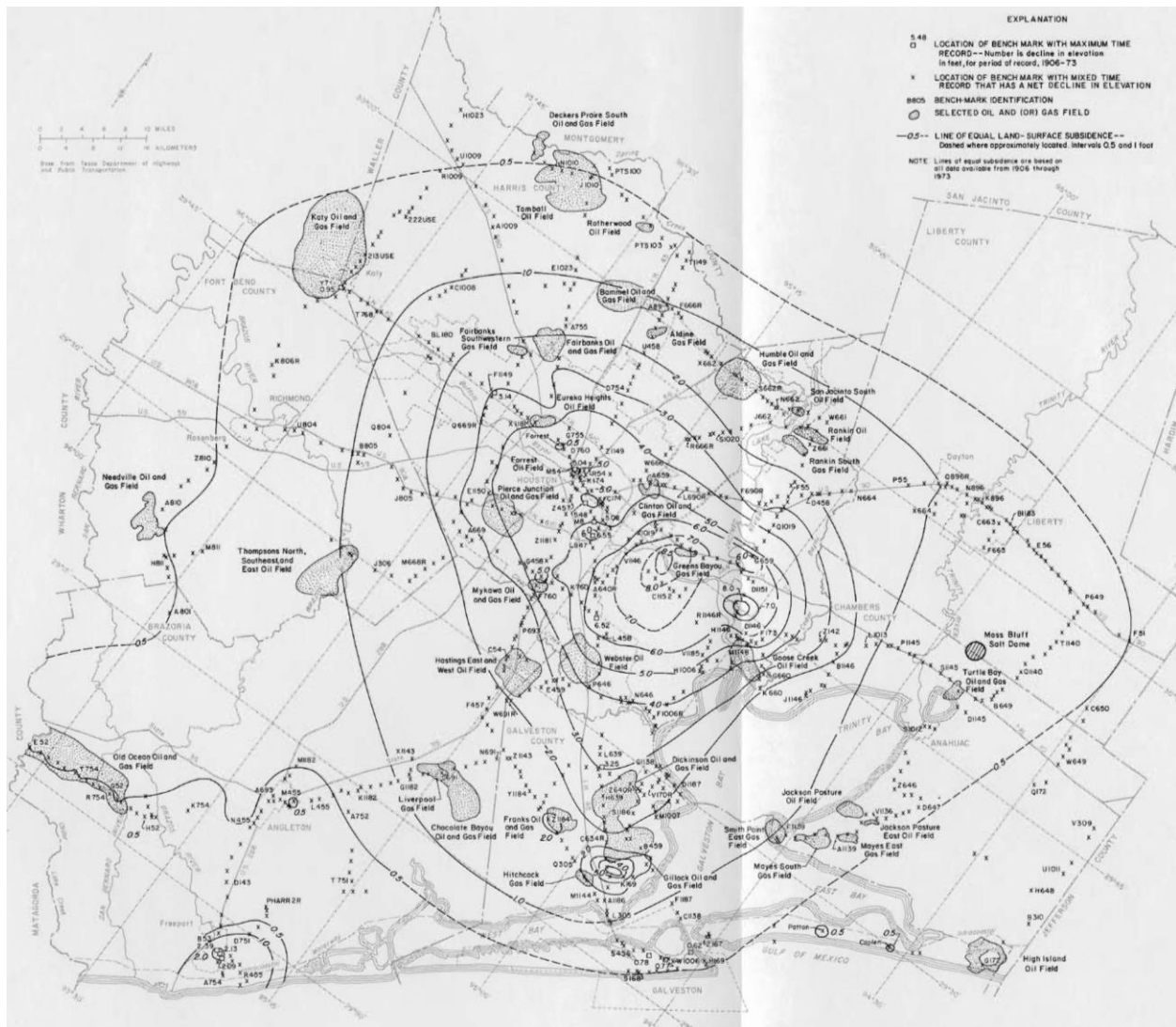


Figure 20. Land-surface subsidence in Subregion 2, 1906-1973, as calculated by Ratzlaff (1982). Reproduced without alteration from Figure 5 of Ratzlaff (1982).

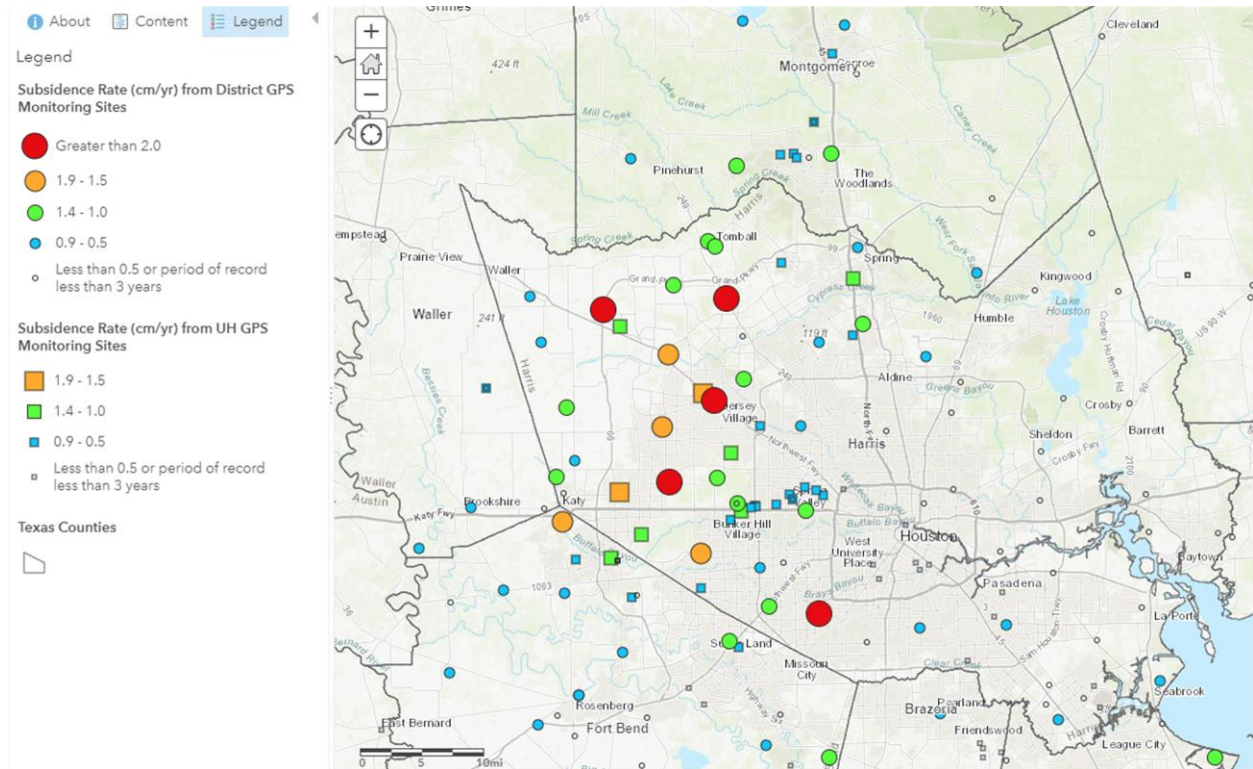


Figure 21. Rate of subsidence in the Houston area. Larger, warm color circles indicate a higher rate of subsidence (<https://www.arcgis.com/home/webmap/viewer.html?webmap=a3e7214071f6421fb745d9866e2d3985>).

PA13

Vertical Movement - Period of Record - Horizontal Reference Frame 16

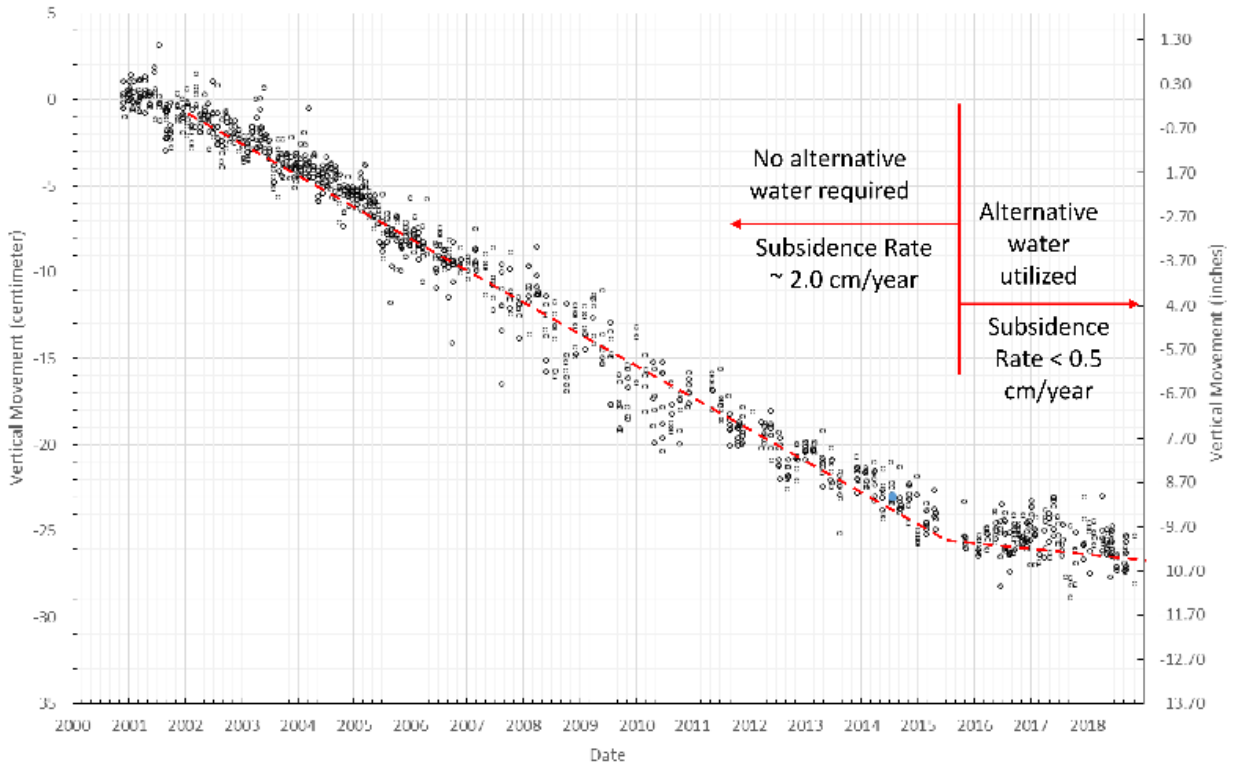


Figure 22. GPS measurements of the vertical change in land surface at PA13 site near The Woodlands.

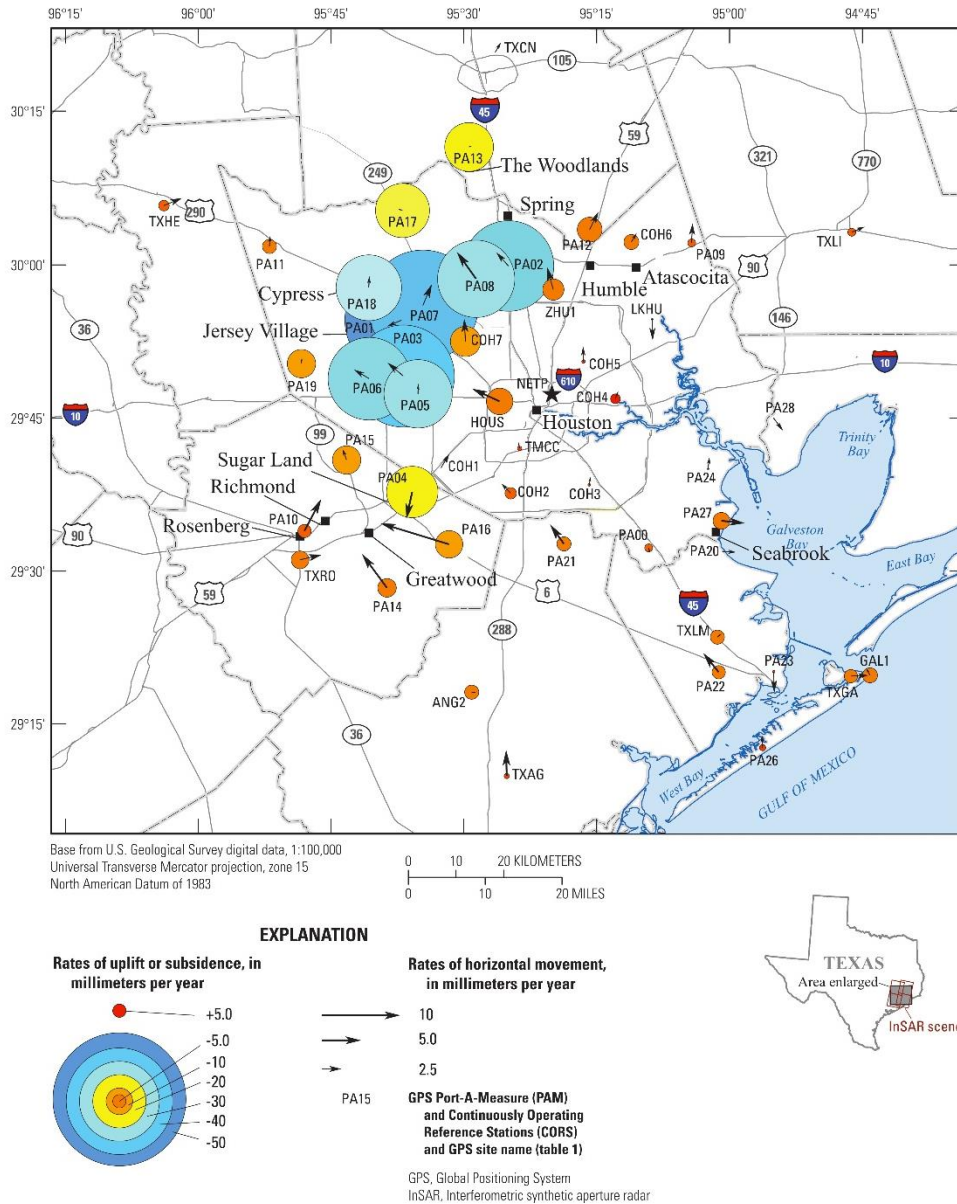


Figure 23. Map illustrating rates of subsidence from GPS readings (from Bawden, Johnson, Kasmarek, Brandt, and Middleton, 2012).

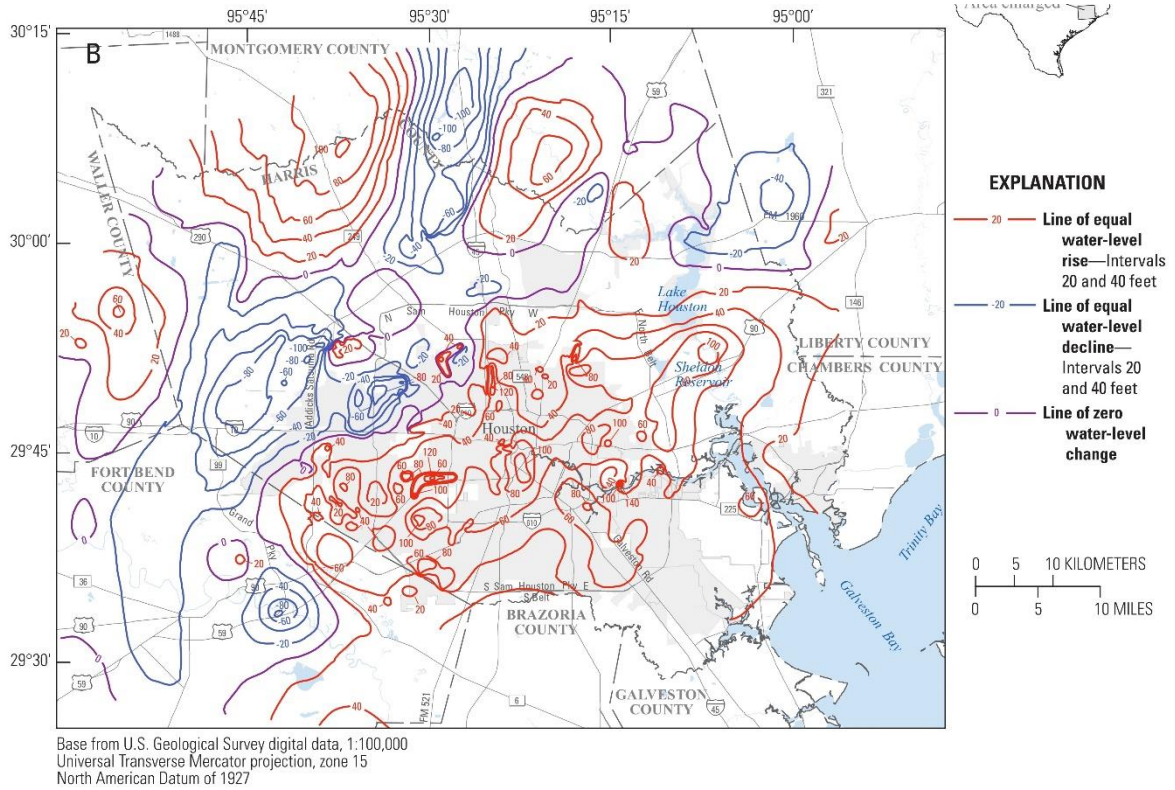


Figure 24. Map illustrating changes in water levels in the Evangeline aquifer between 1990 and 2003 (from Bawden, Johnson, Kasmarek, Brandt, and Middleton, 2012).

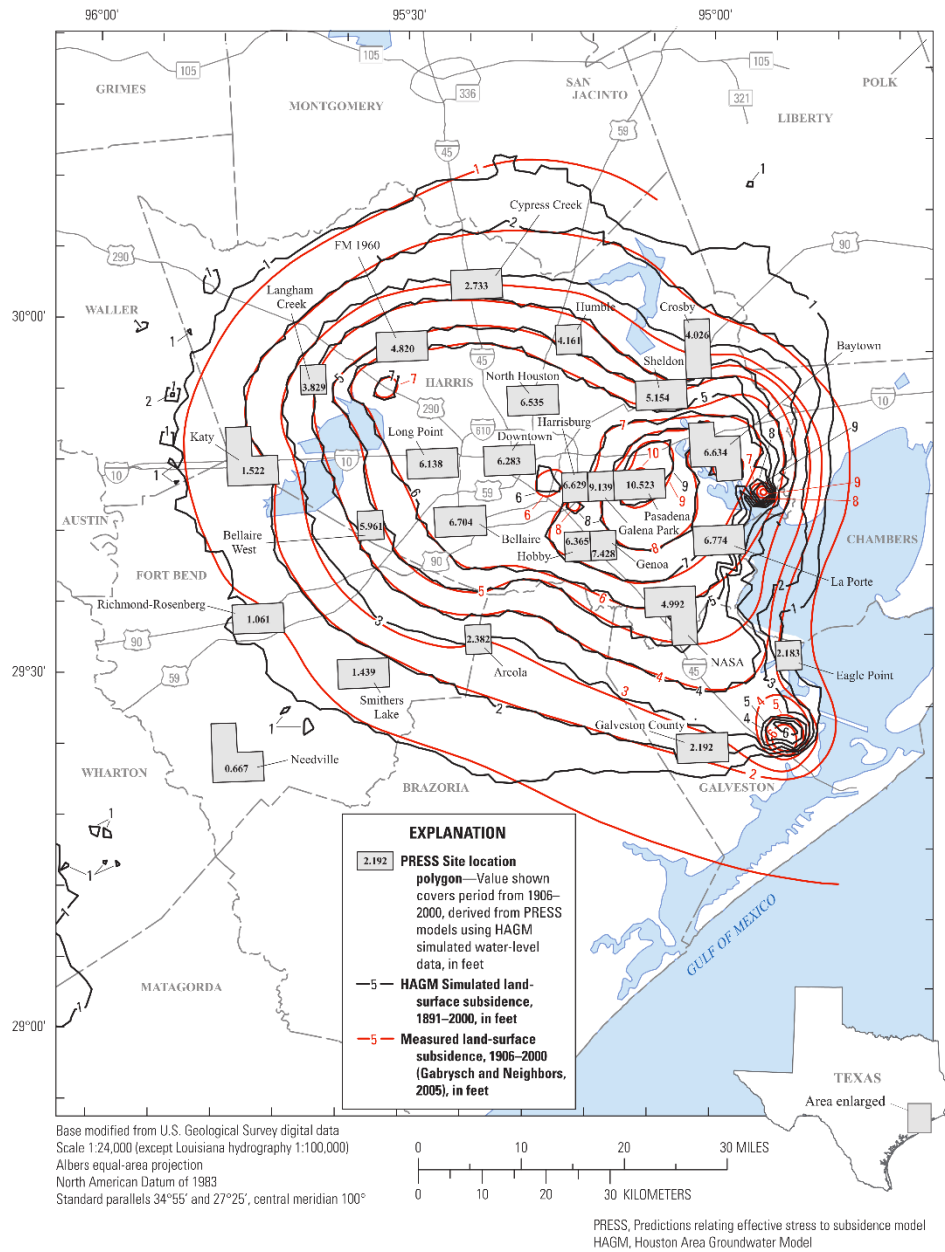


Figure 25. Map showing long-term subsidence values from PRESS models, HAGM simulations, and measurements (from Kasmarek, 2013).

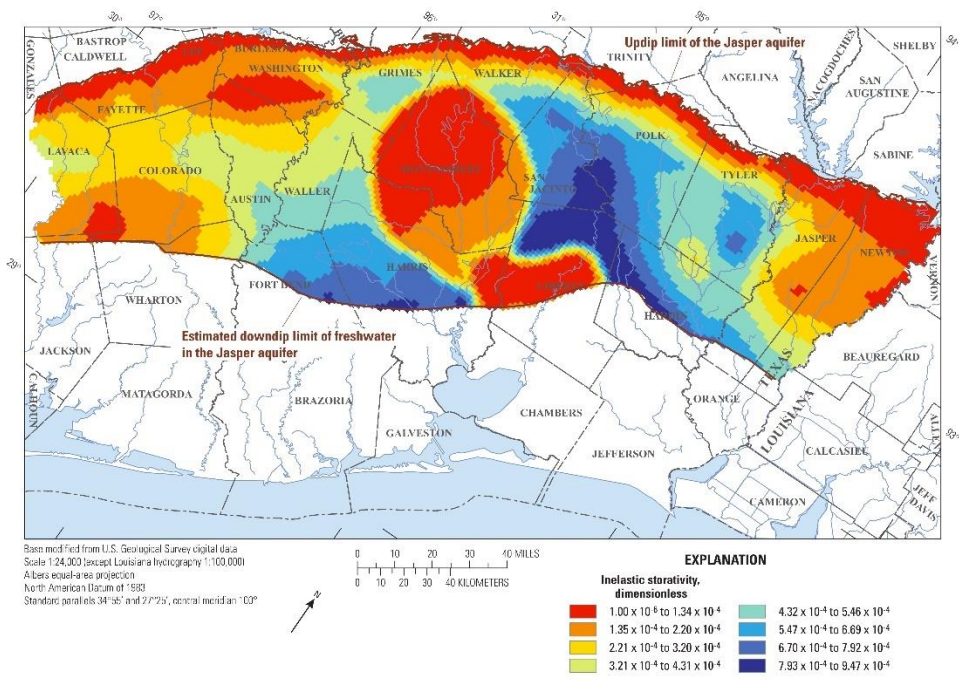
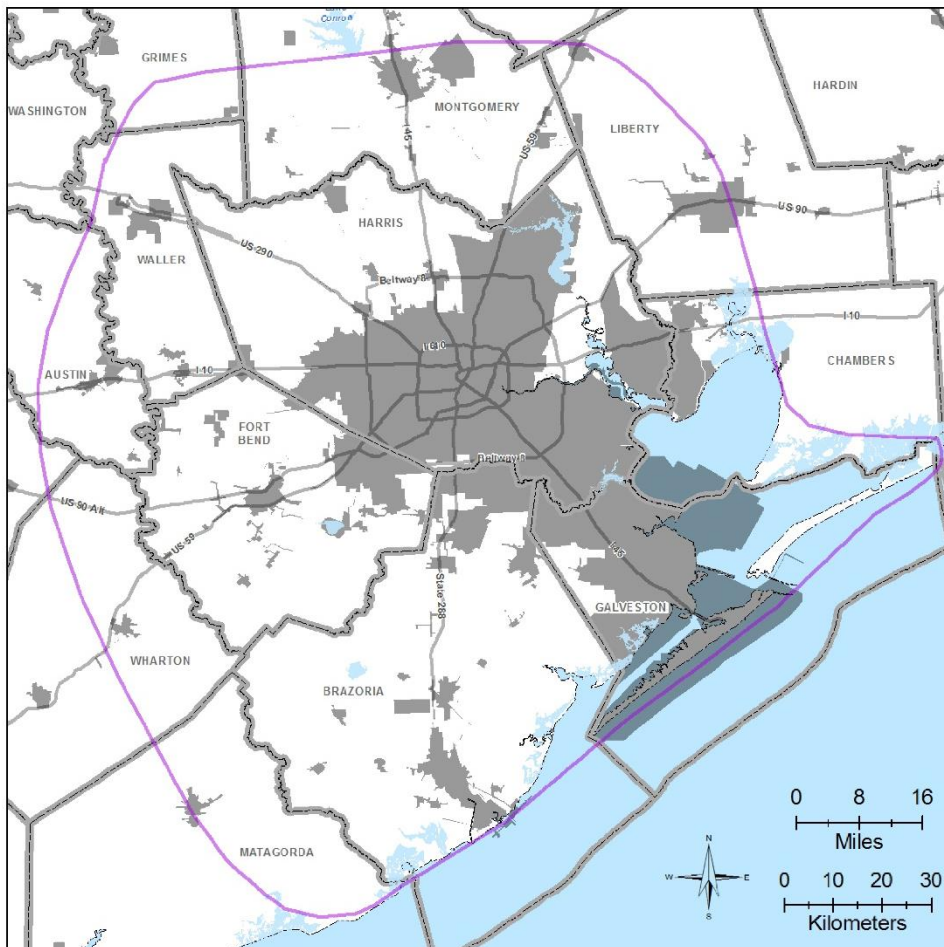






Figure 18. Simulated inelastic-clay storativity of the Jasper aquifer in the Houston Area Groundwater Model study area.

Figure 26. Map showing HAGM values for inelastic-clay storativity in the Jasper aquifer (from Kasmarek, 2013)



Legend

-  Study Area
-  County Lines
-  Major Highways
-  Municipalities



Map Location

Prepared for:



Prepared by:



Figure 27. Map showing the study area for INTERA's brackish Jasper aquifer subsidence risk assessment (from Kelley, Deeds, Young and Pinkard, 2018).

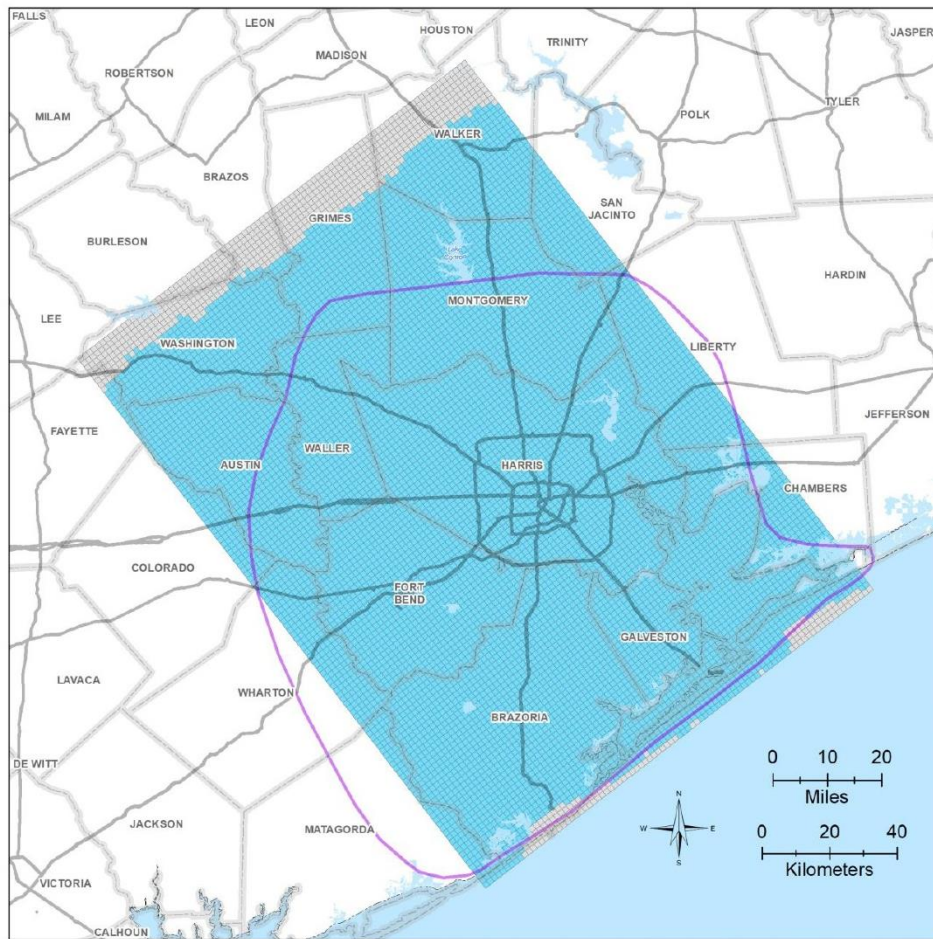


Figure 28. Map showing INTERA's model grid for its brackish Jasper aquifer subsidence risk assessment (from Kelley, Deeds, Young, and Pinkard, 2018).

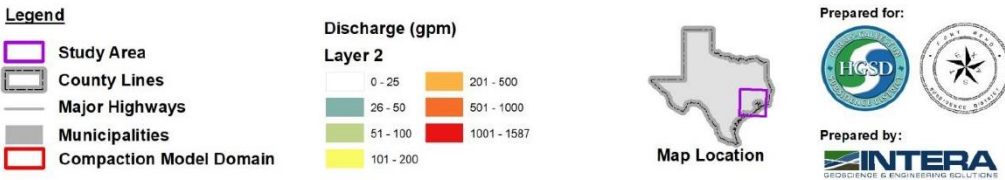
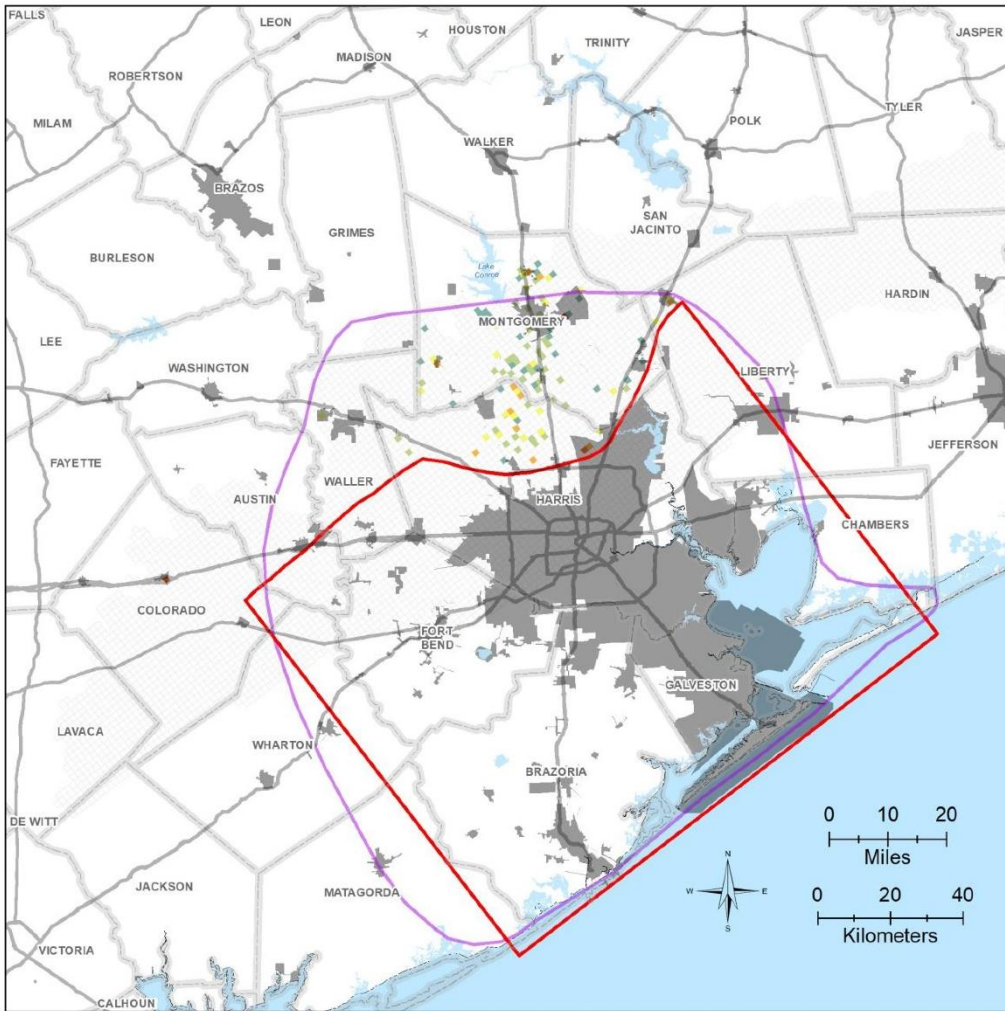


Figure 29. Map showing INTER's extent of Jasper compaction modeling domain (from Kelley, Deeds, young, and Pinkard, 2018)

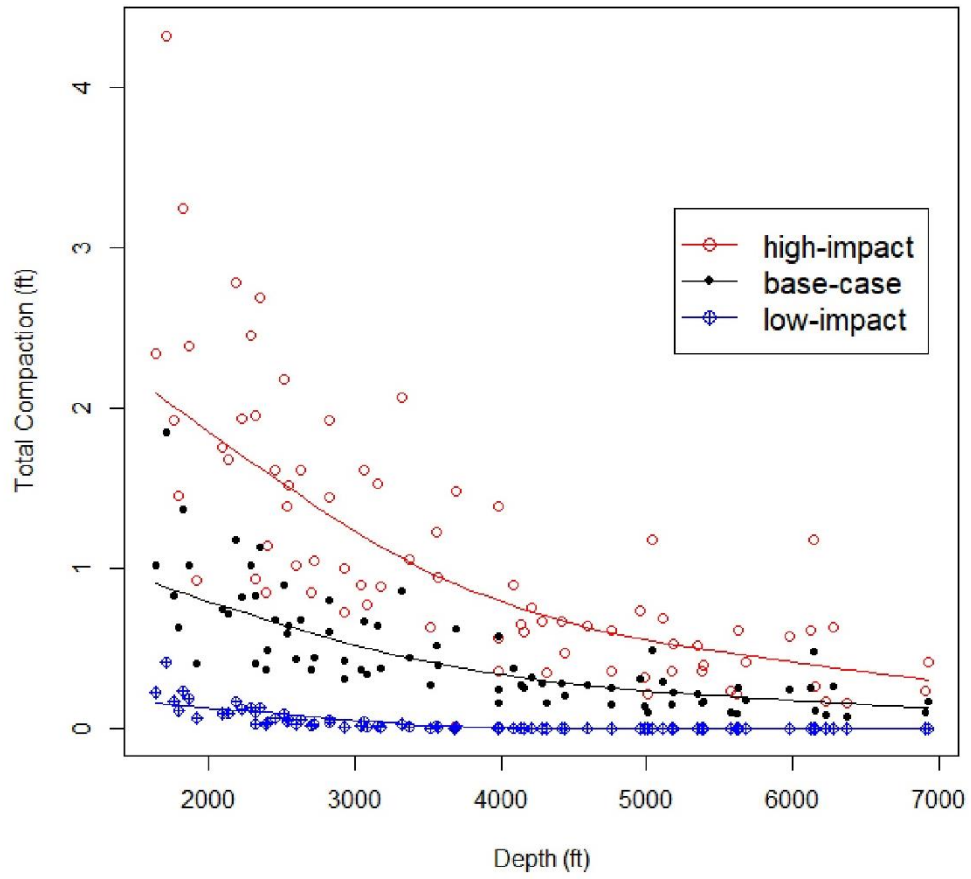


Figure 30. Chart showing INTERA's simulated variation of 10-year compaction with depth for three sensitivity cases – Jasper aquifer (from Kelley, Deeds, young, and Pinkard, 2018)

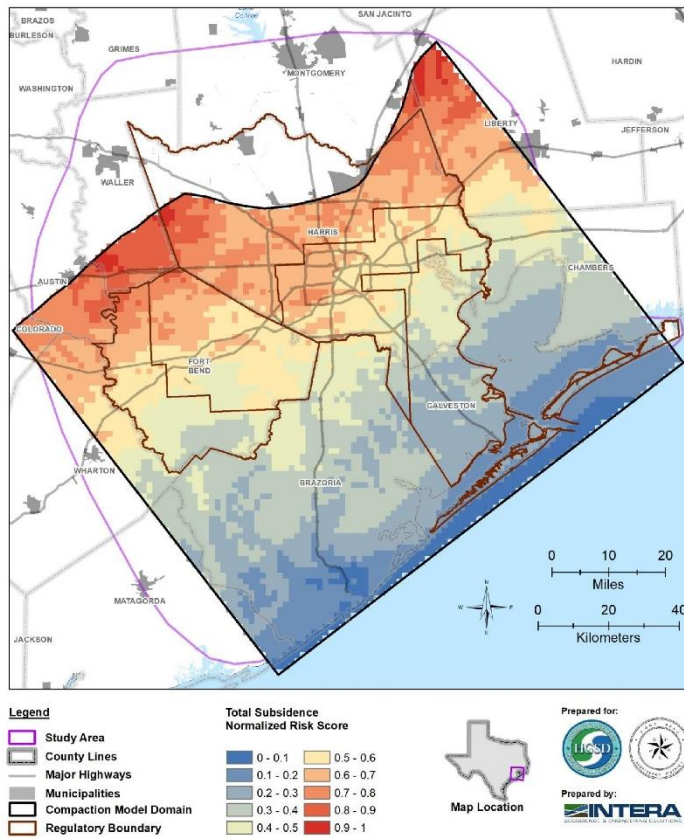


Figure 31. Map showing INTERA's Jasper aquifer total subsidence normalized risk score (from Kelley, Deeds, Young, and Pinkard, 2018)

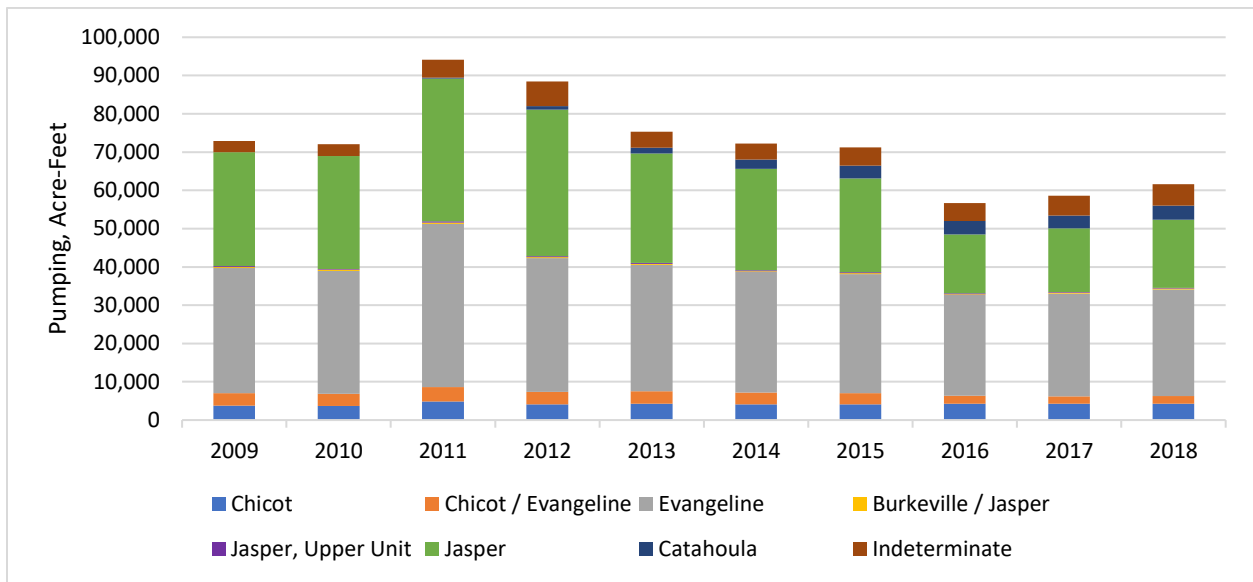


Figure 32. LSGCD reported pumping associated with permits by assigned aquifer.

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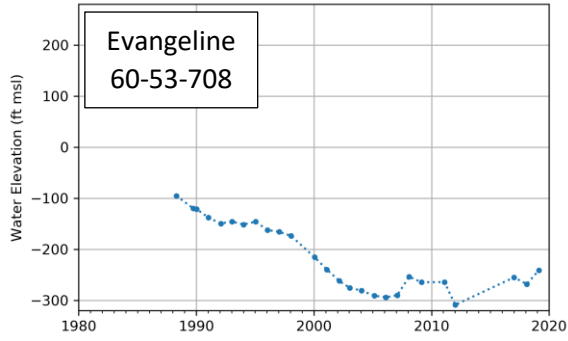
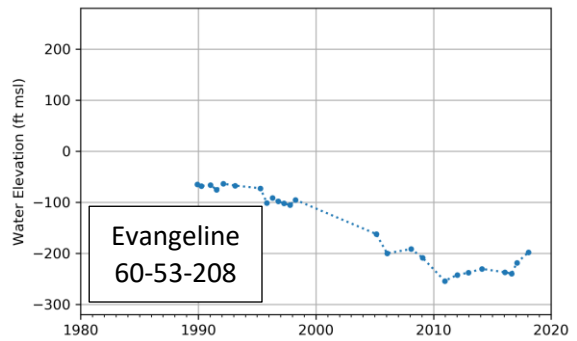
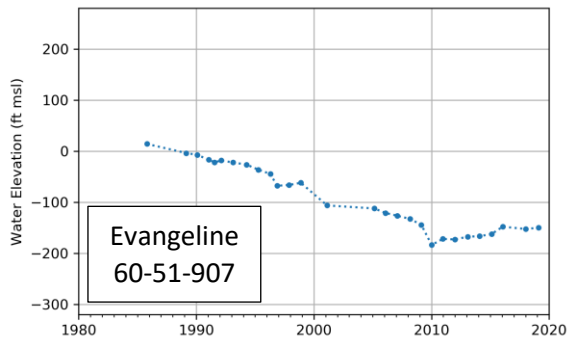
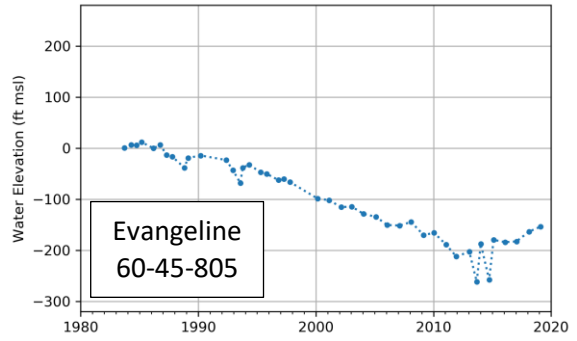
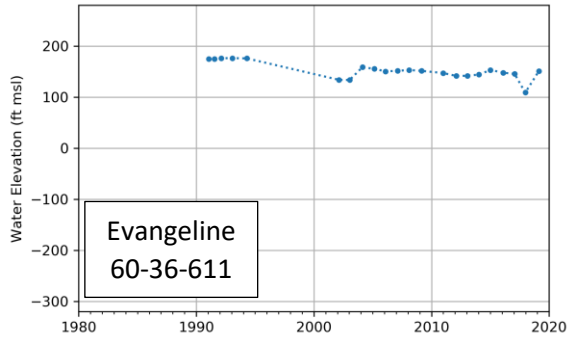
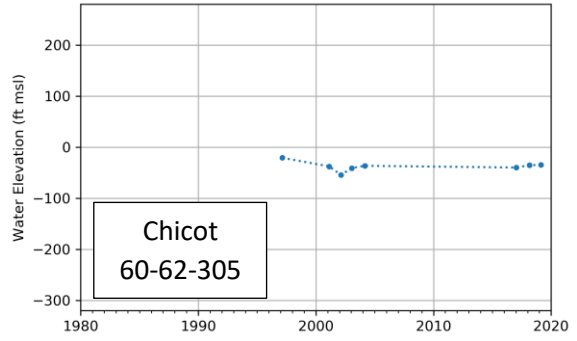
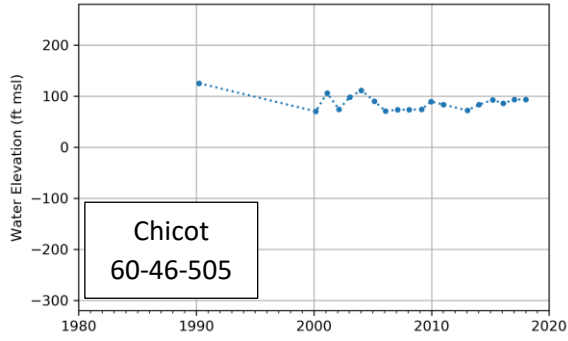


Figure 33. Reported water levels from the TWDB Groundwater Database (TWDB, 2020).

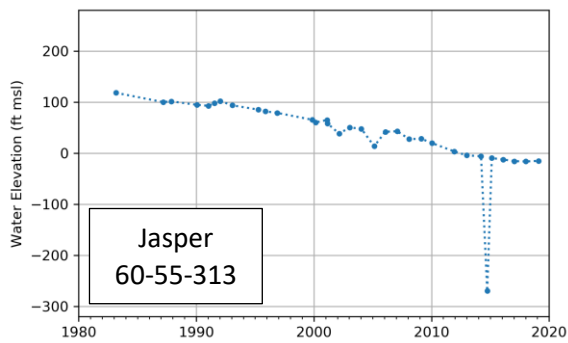
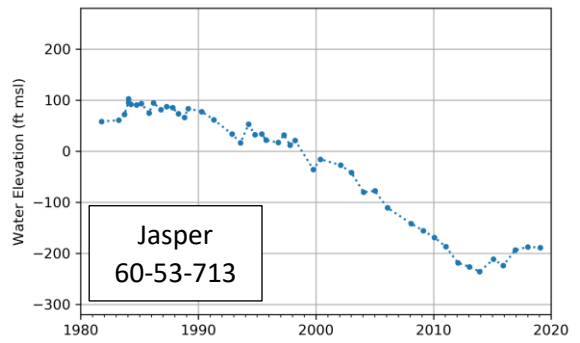
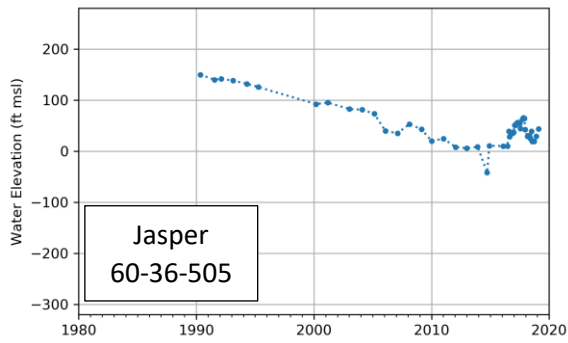
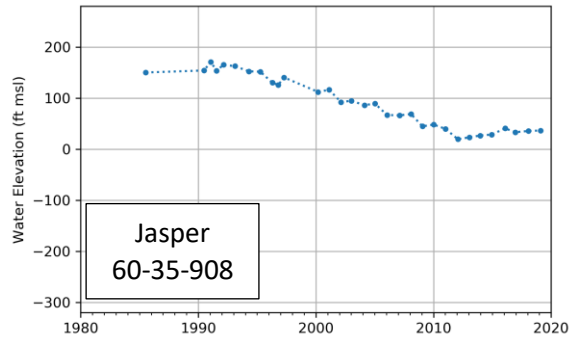
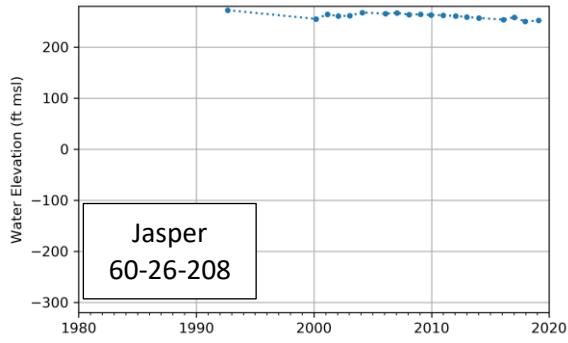
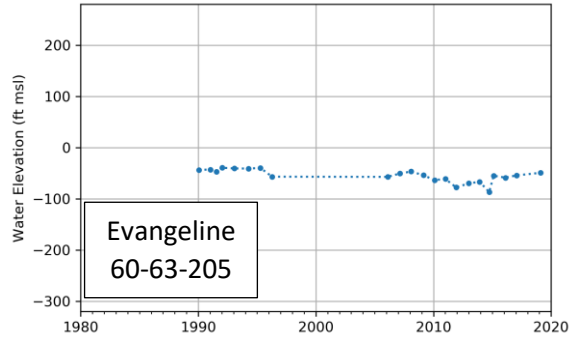
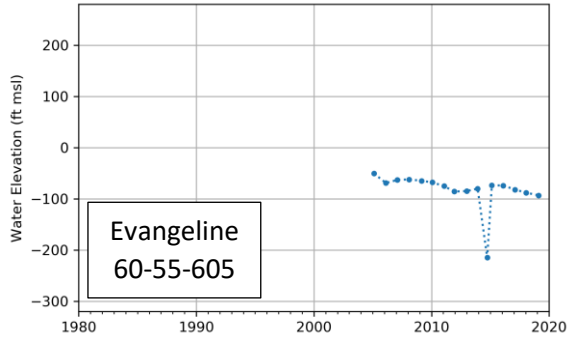


Figure 33. (continued) Reported water levels from the TWDB Groundwater Database (TWDB, 2020).

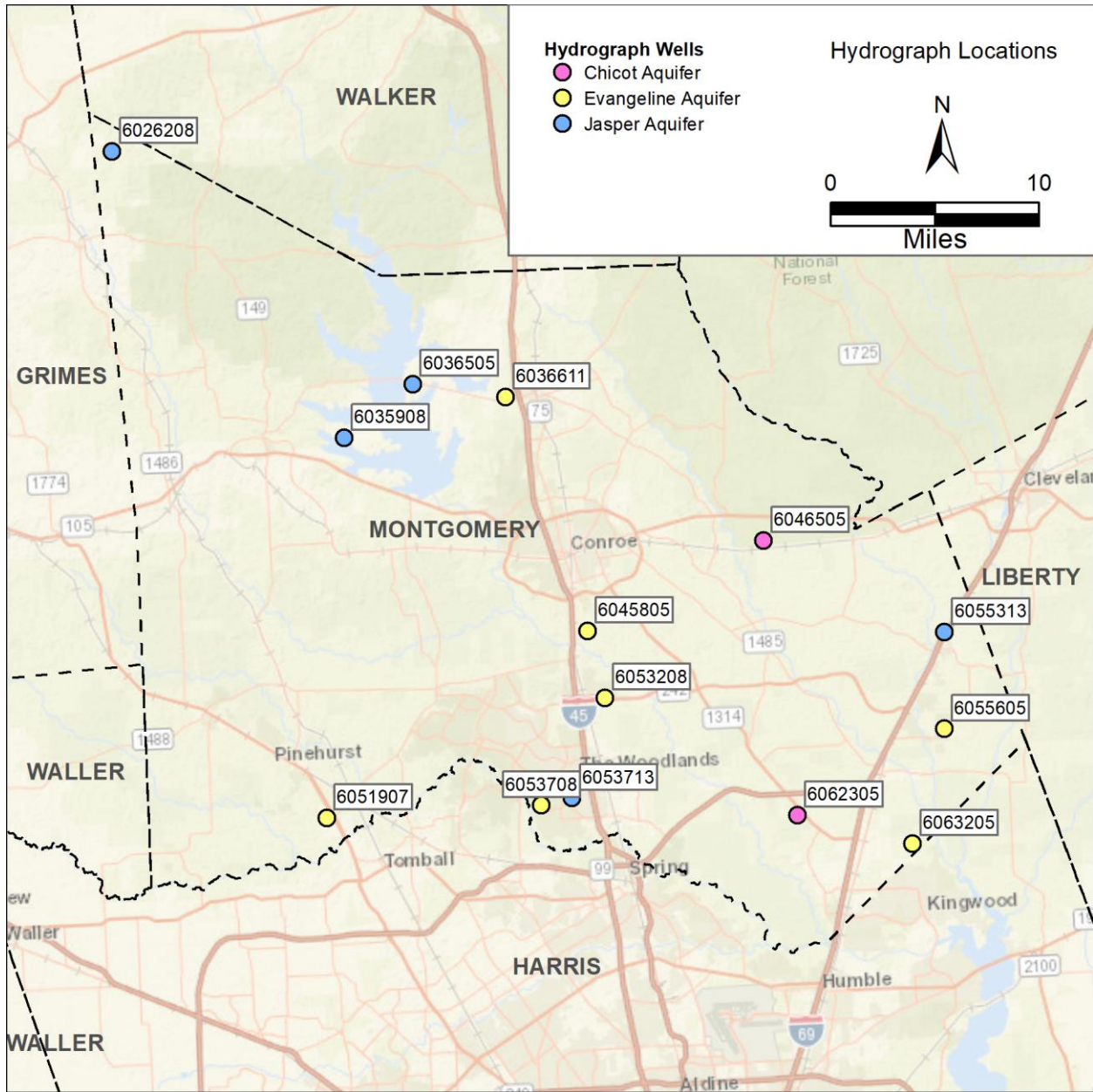


Figure 34. Map illustrating the location of the reported water levels from the TWDB Groundwater Database (TWDB, 2020).

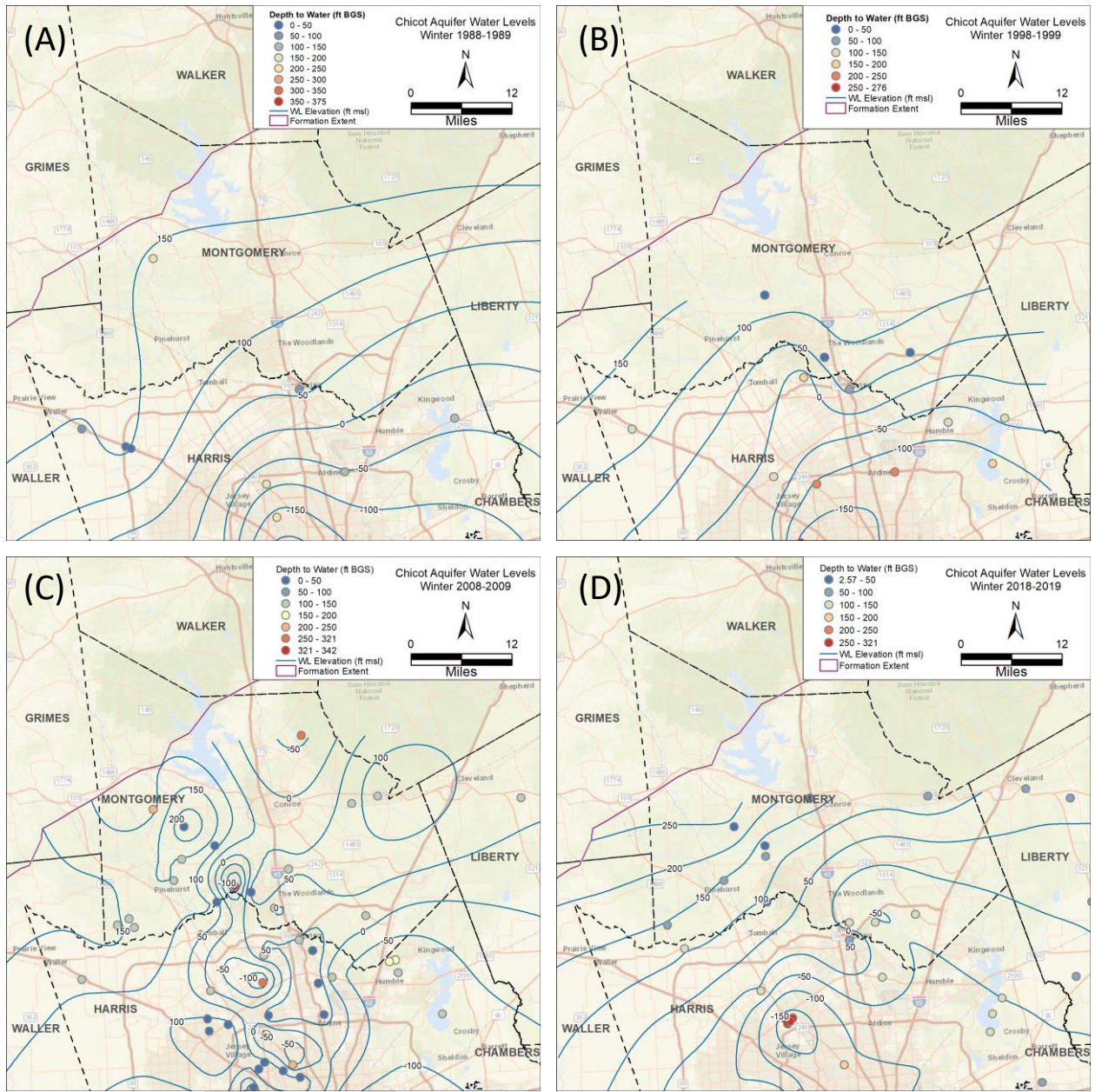
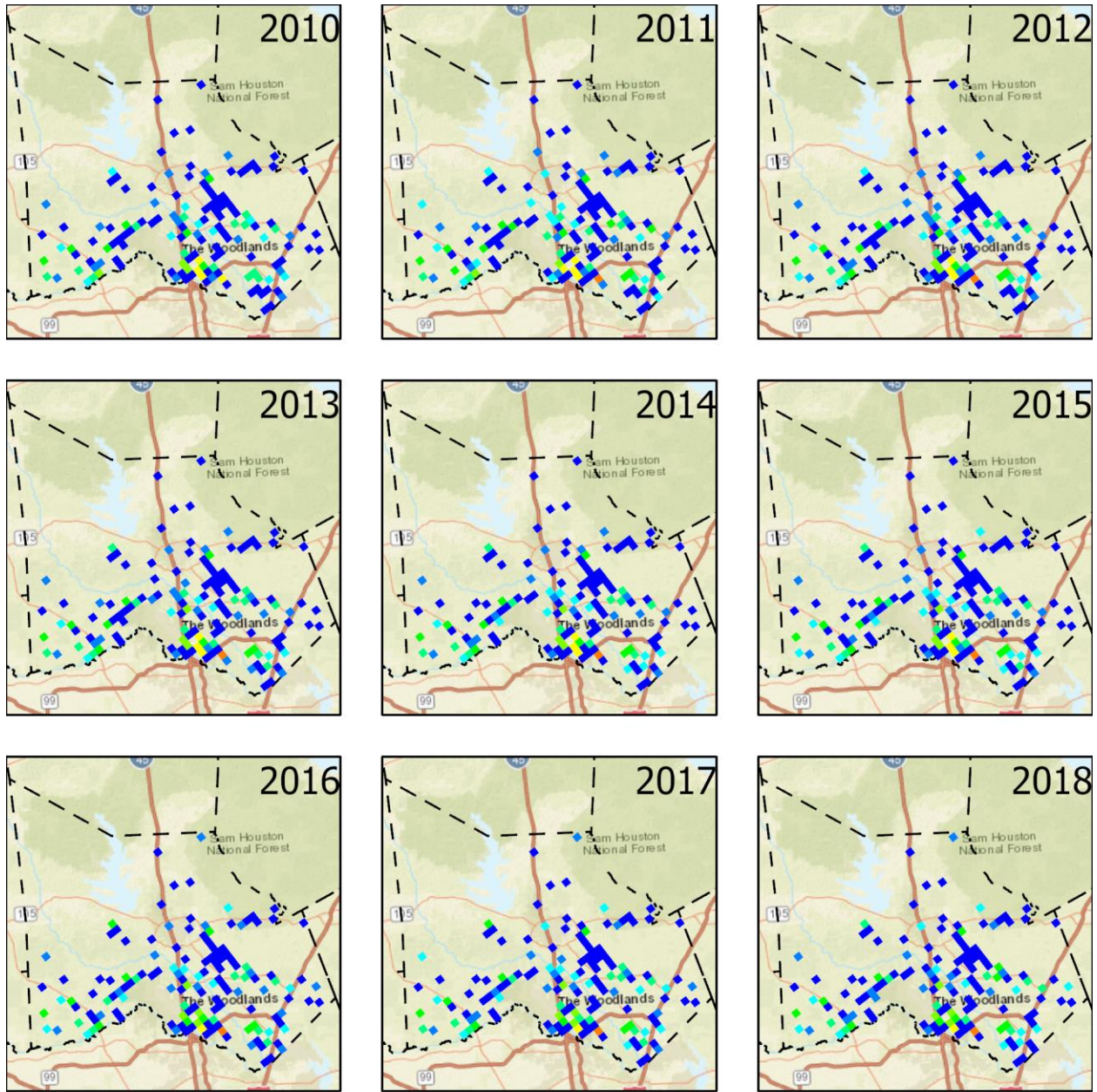


Figure 35. Estimated water levels in the Chicot Aquifer. Well locations, aquifer designation, and measured water level from the TWDB Groundwater Database (TWDB, 2020).



LSGCD Reported Annual Pumping, Acre-Feet

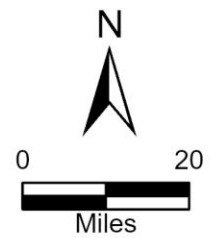
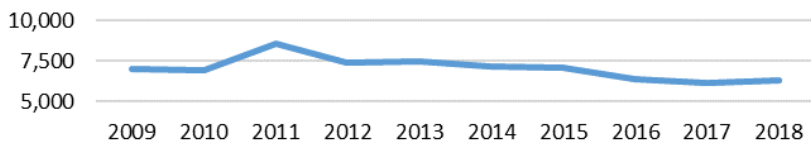
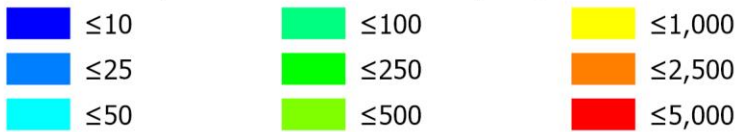


Figure 36. LSGCD reported pumping from permitted wells completed in the Chicot Aquifer.

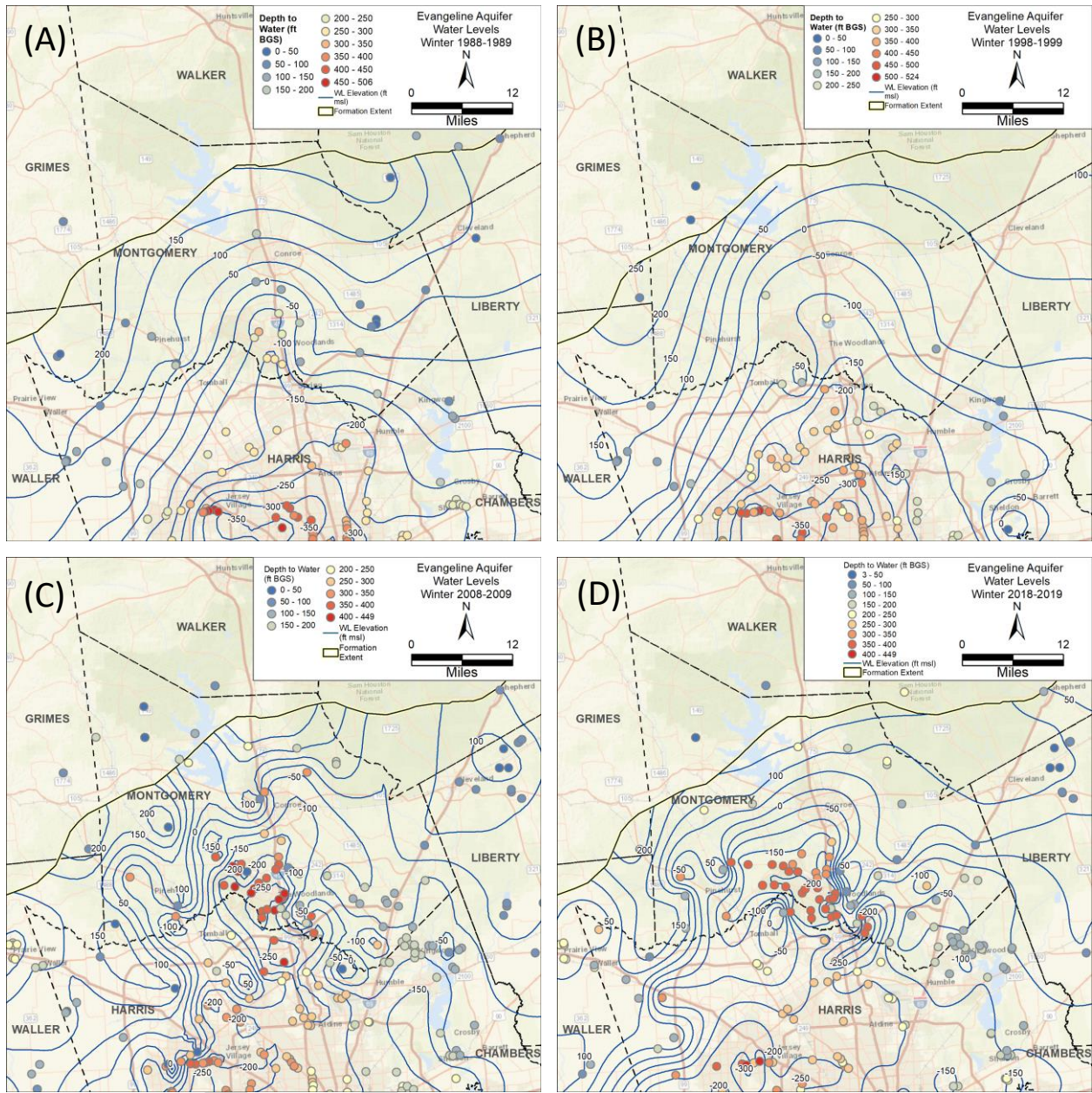
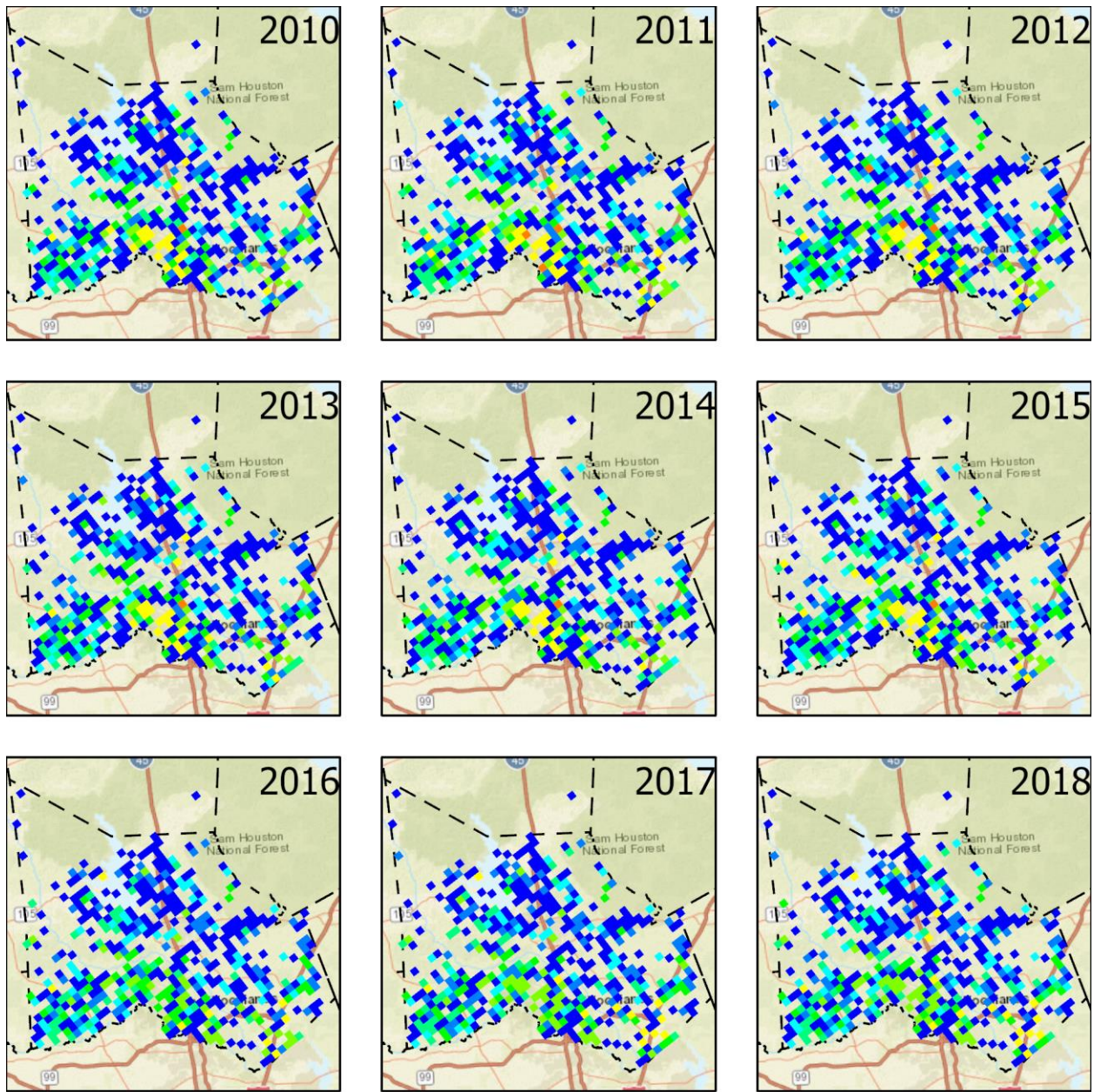


Figure 37. Estimated water levels in the Evangeline Aquifer. Well locations, aquifer designation, and measured water level from the TWDB Groundwater Database (TWDB, 2020).



LSGCD Reported Annual Pumping, Acre-Feet

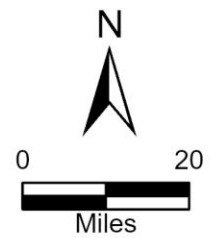
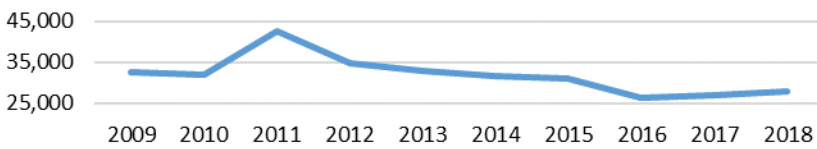
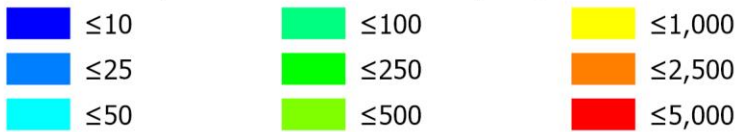


Figure 38. LSGCD reported pumping from permitted wells completed in the Evangeline Aquifer.

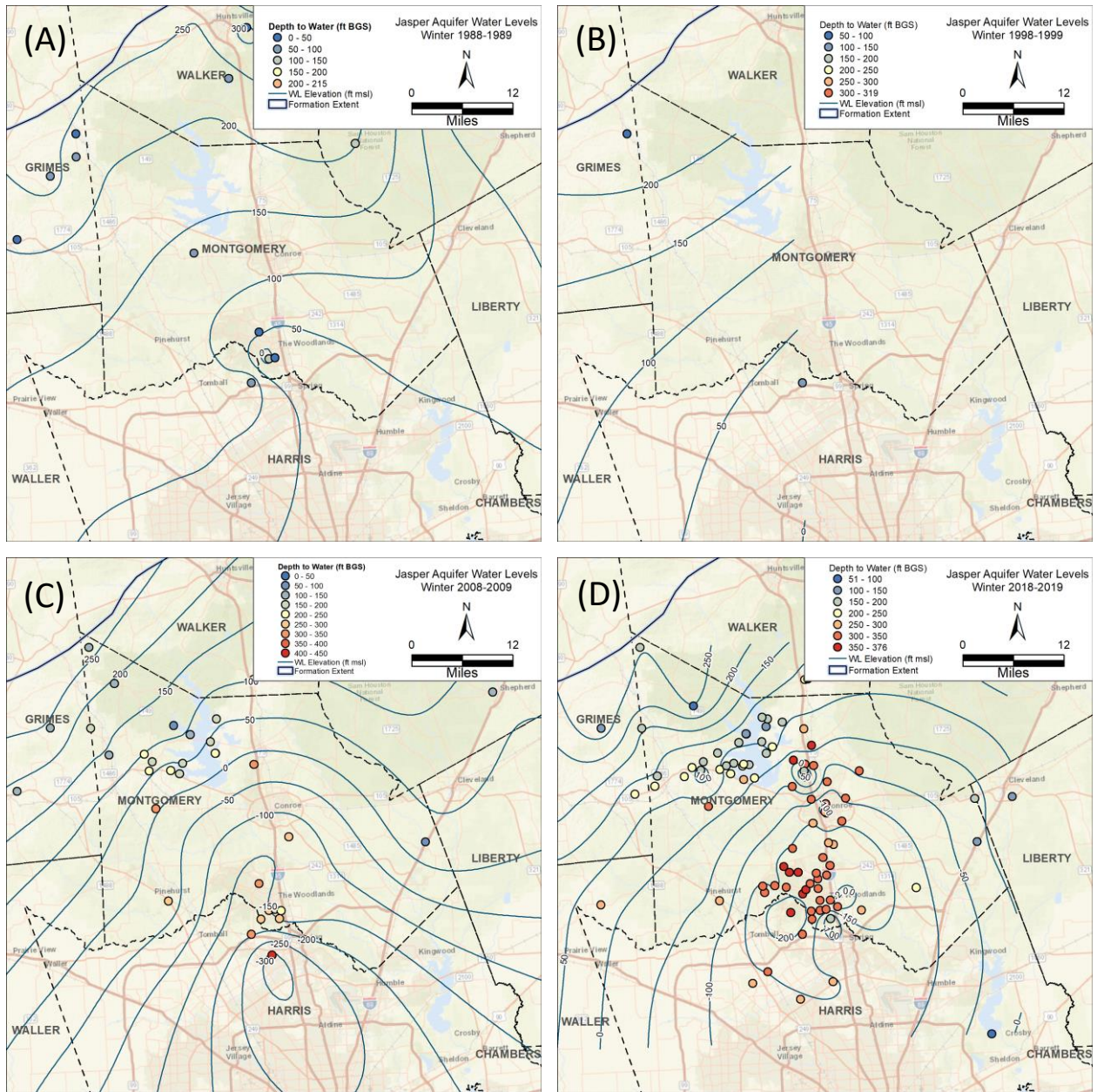
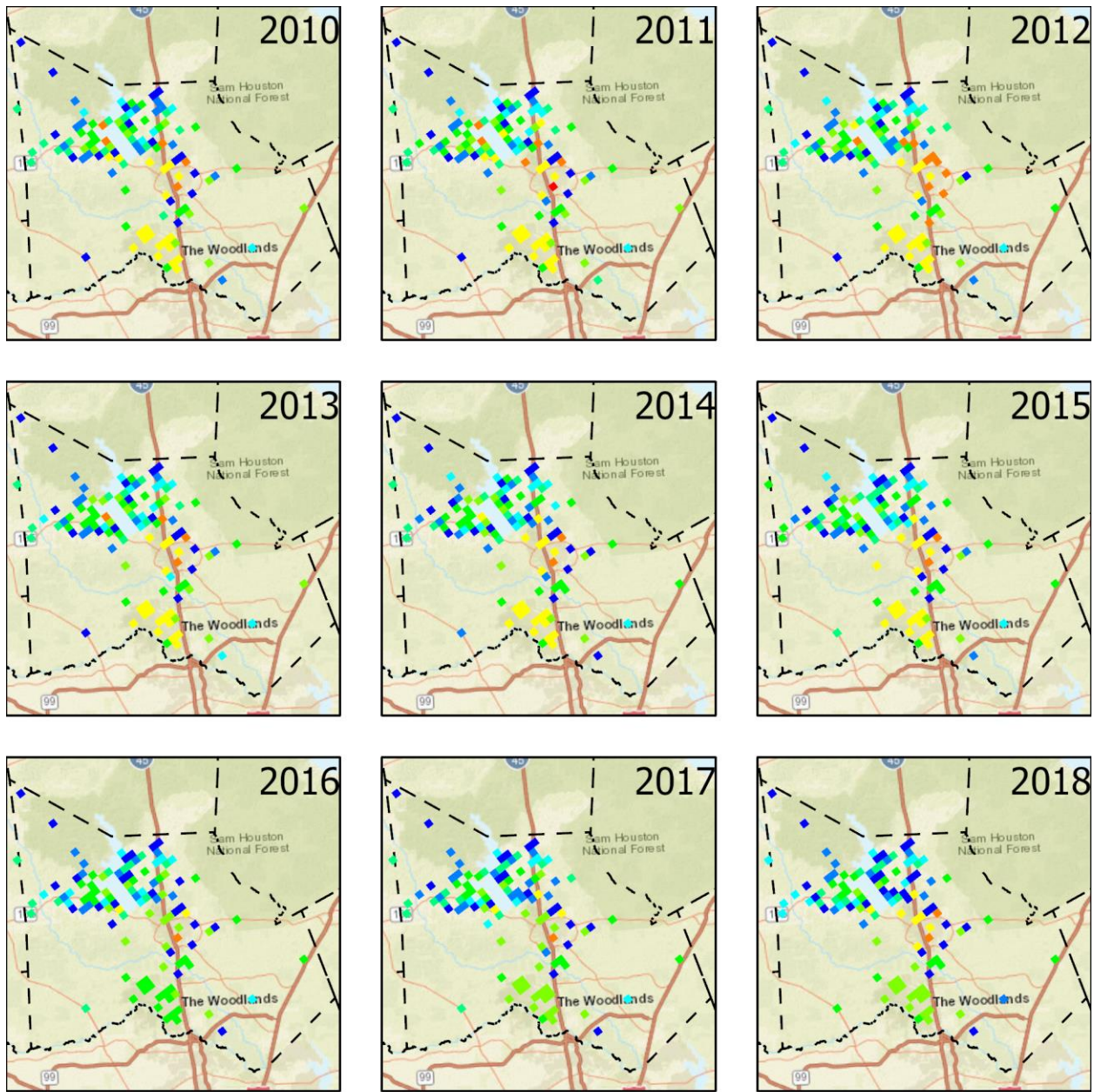


Figure 39. Estimated water levels in the Jasper Aquifer. Well locations, aquifer designation, and measured water level from the TWDB Groundwater Database (TWDB, 2020).



LSGCD Reported Annual Pumping, Acre-Feet

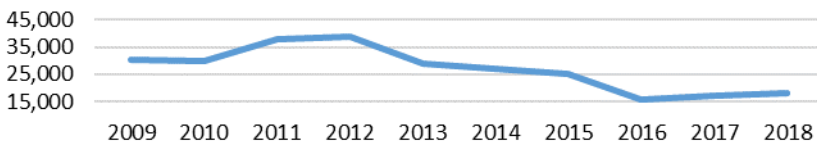
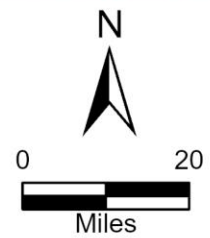
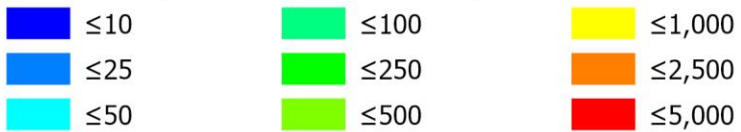
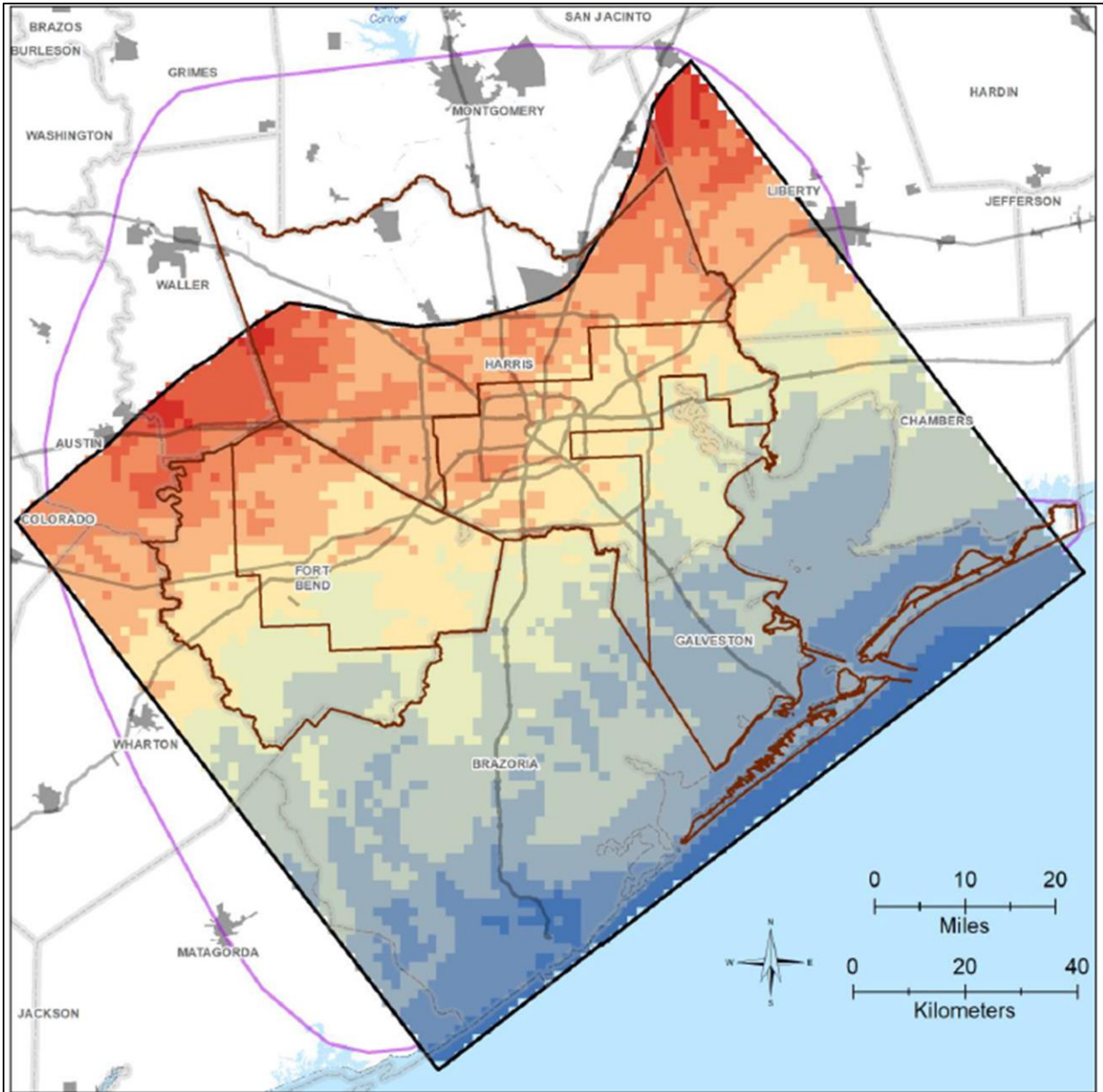












Figure 40. LSGCD reported pumping from permitted wells completed in the Jasper Aquifer.



Legend

-  Study Area
-  County Lines
-  Major Highways
-  Municipalities
-  Compaction Model Domain
-  Regulatory Boundary

Total Subsidence Normalized Risk Score

 0 - 0.1	 0.5 - 0.6
 0.1 - 0.2	 0.6 - 0.7
 0.2 - 0.3	 0.7 - 0.8
 0.3 - 0.4	 0.8 - 0.9
 0.4 - 0.5	 0.9 - 1



Map Location

Prepared for:



Prepared by:



Figure 41. 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.

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

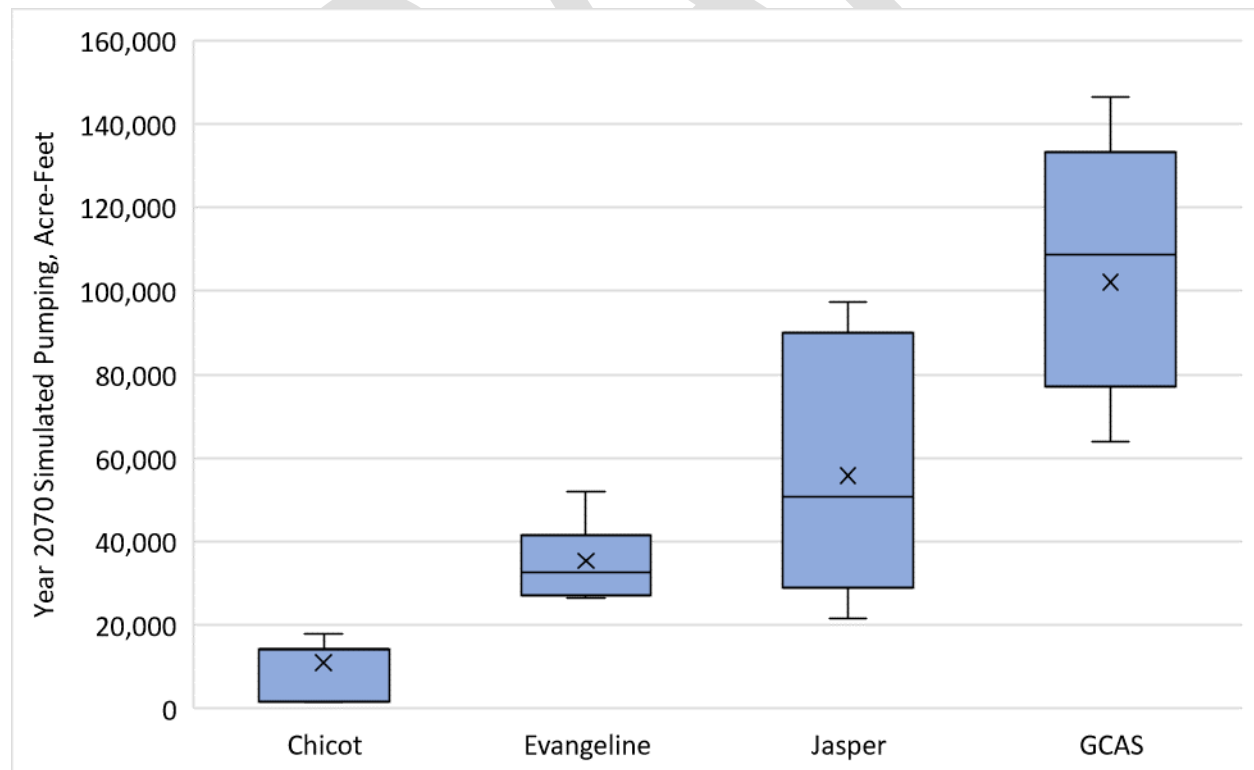


Figure 42. Box-and-whisker plot illustrating the distribution of simulated pumping within Montgomery County in each of the scenarios.

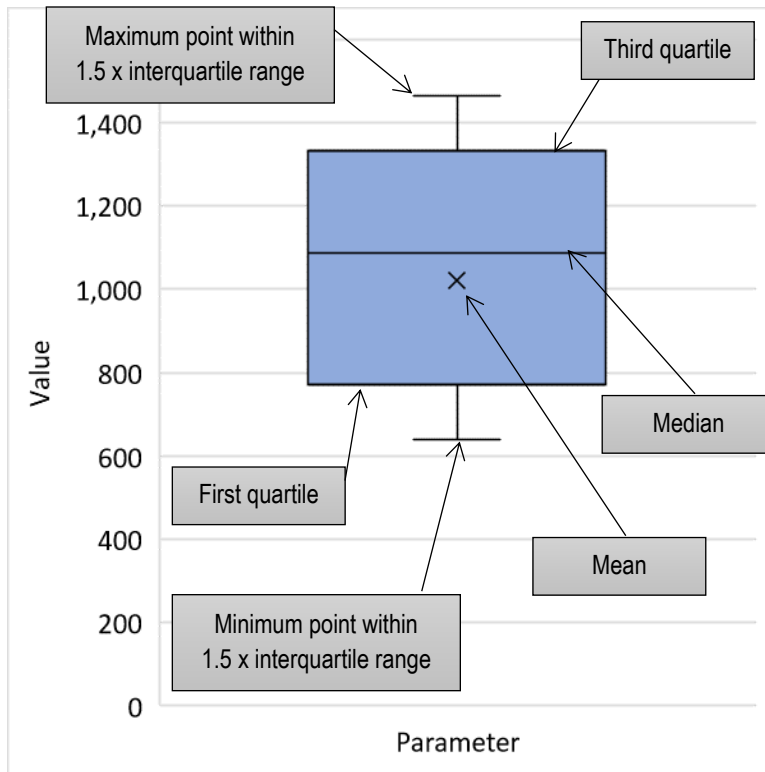


Figure43. Legend illustrating the parts of the box and whisker plot. Interquartile range is the difference between the third and first quartile. Outliers beyond the minimum and maximum extents are not shown.

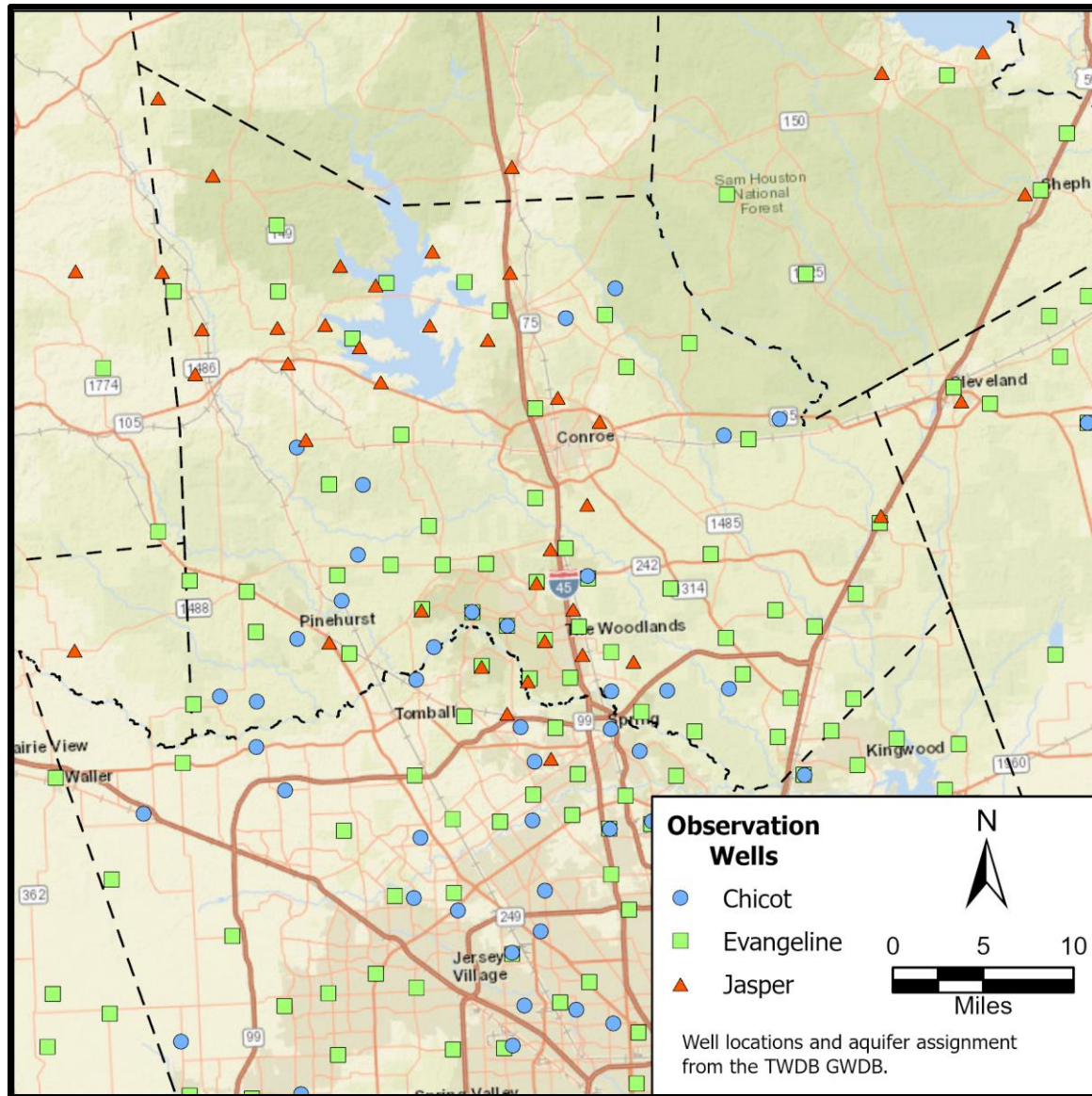


Figure 44. Location of monitoring wells used for analysis of model results within Montgomery County. Modified from Keester (2020).

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

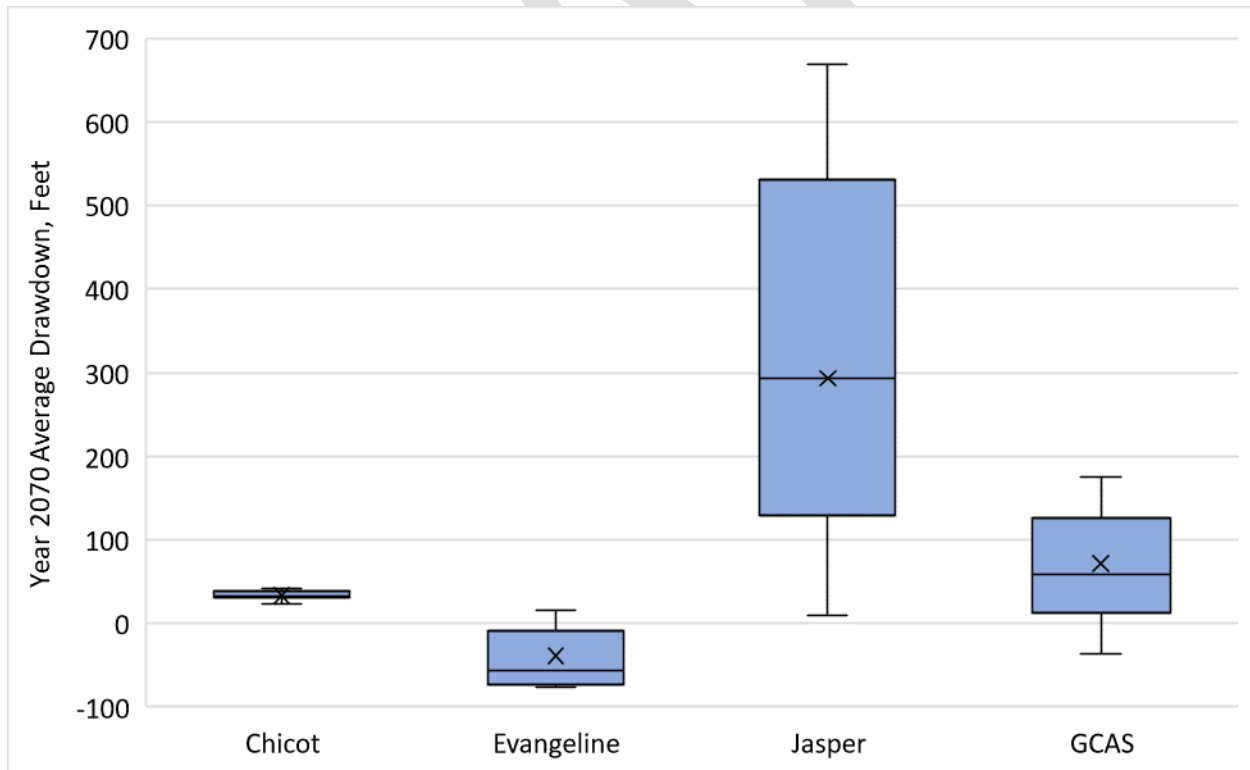


Figure 45. Box-and-whisker plot illustrating the distribution of average drawdown within Montgomery County in each of the scenarios. See Figure 2 for an explanation of the box-and-whisker plot.

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

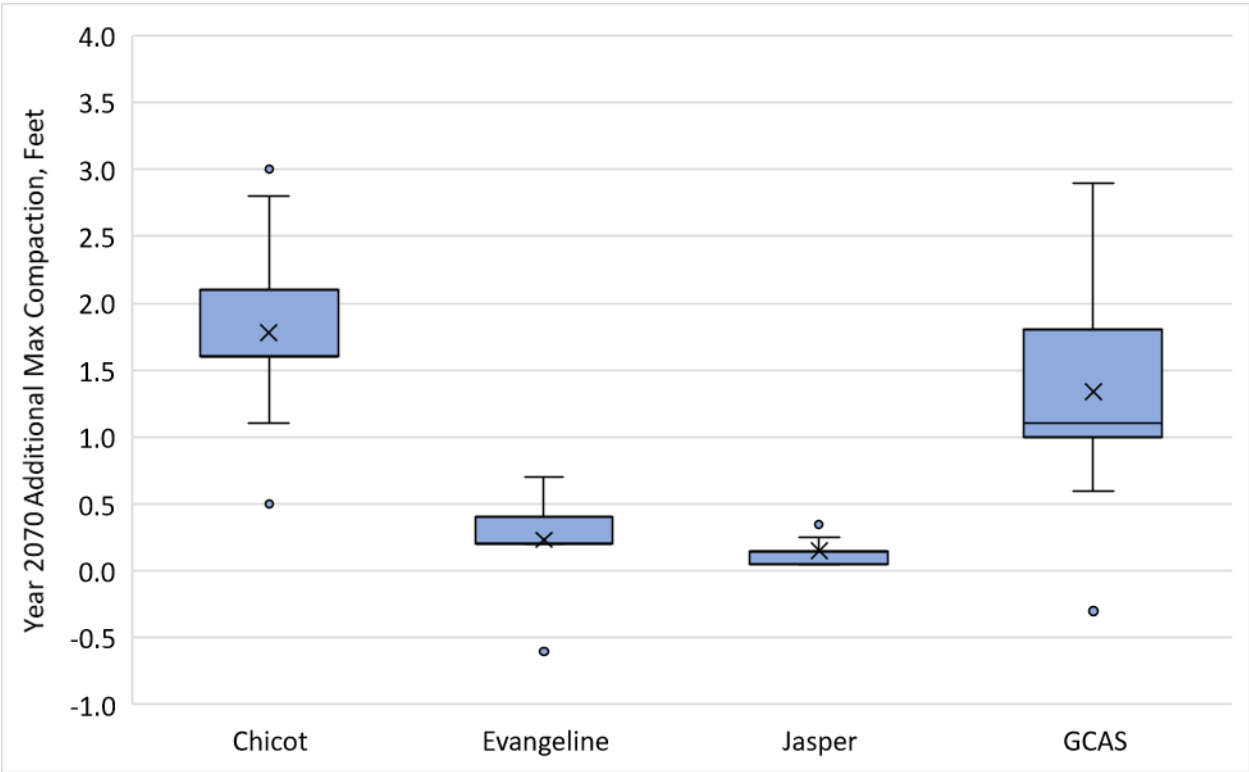


Figure 46. Box-and-whisker plot illustrating the distribution of maximum compaction within Montgomery County in each of the scenarios. The maximum compaction range for the GCAS represents land-surface subsidence.

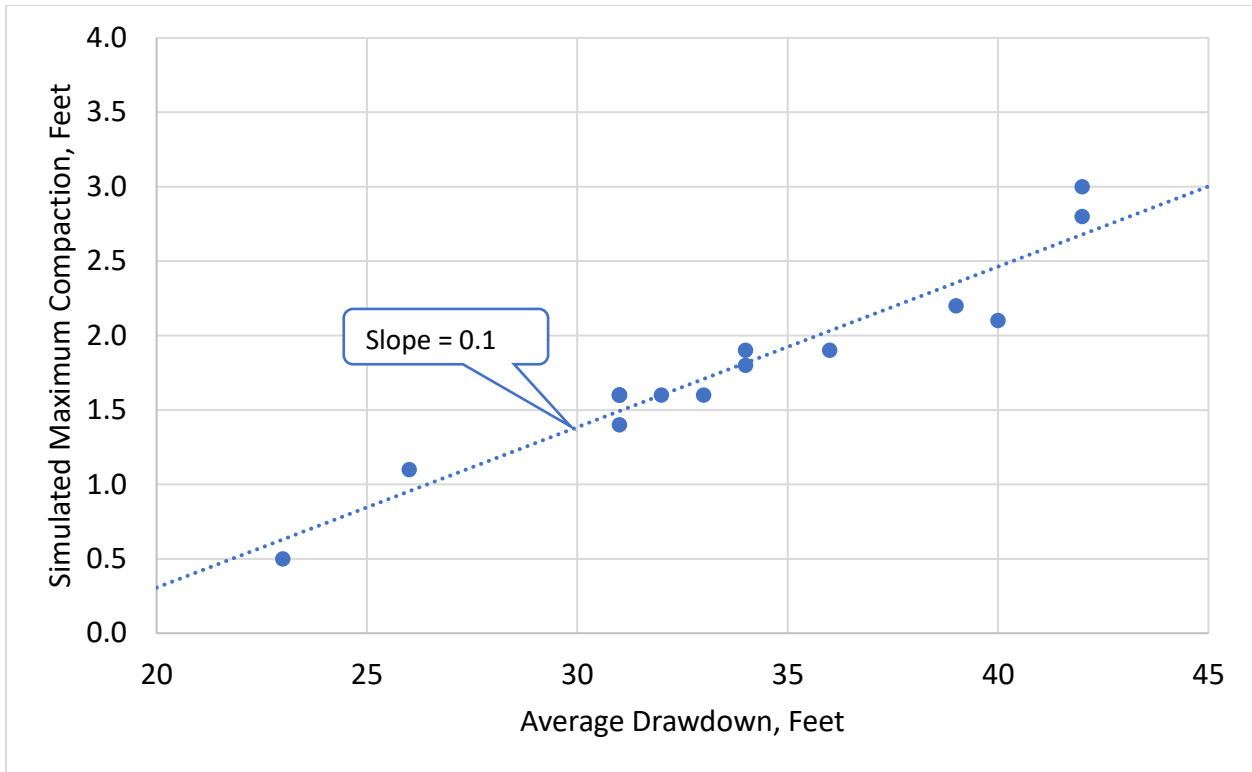


Figure 47. Comparison of simulation results for the Chicot Aquifer showing the relationship between average drawdown and maximum compaction.

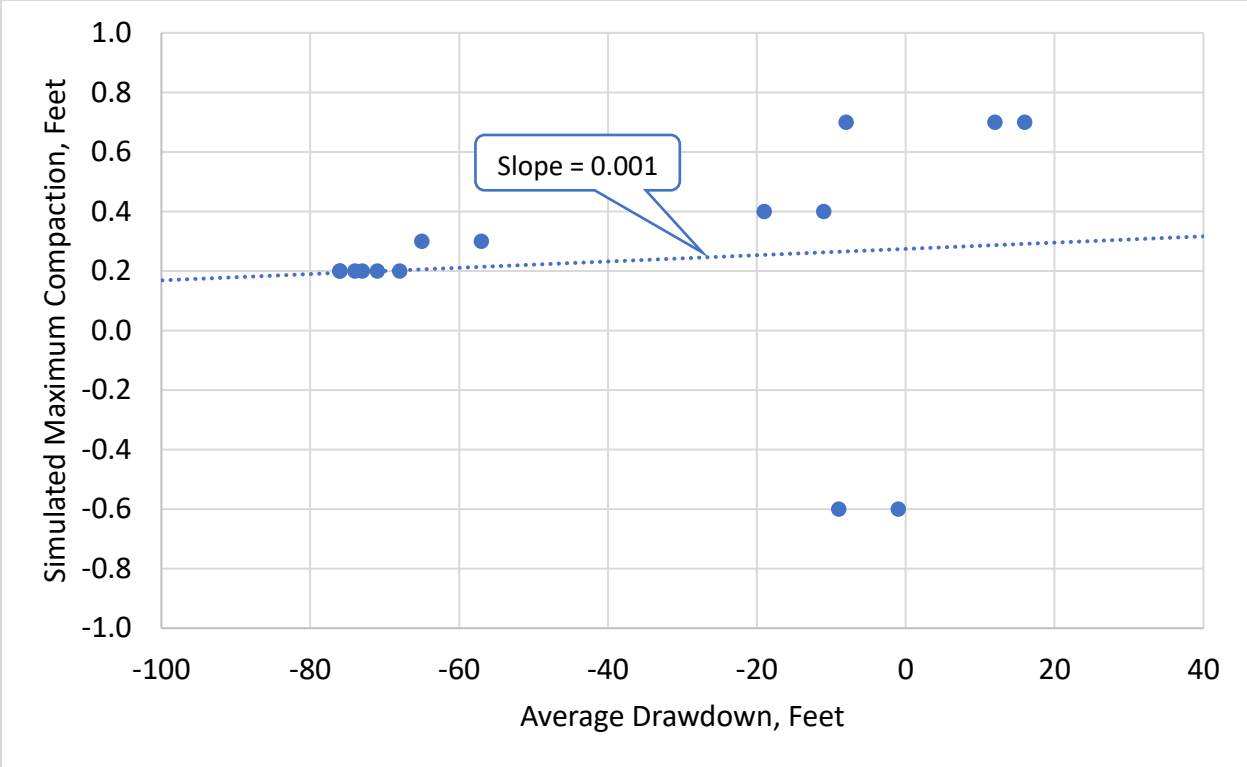


Figure 48. Comparison of simulation results for the Evangeline Aquifer showing the relationship between average drawdown and maximum compaction.

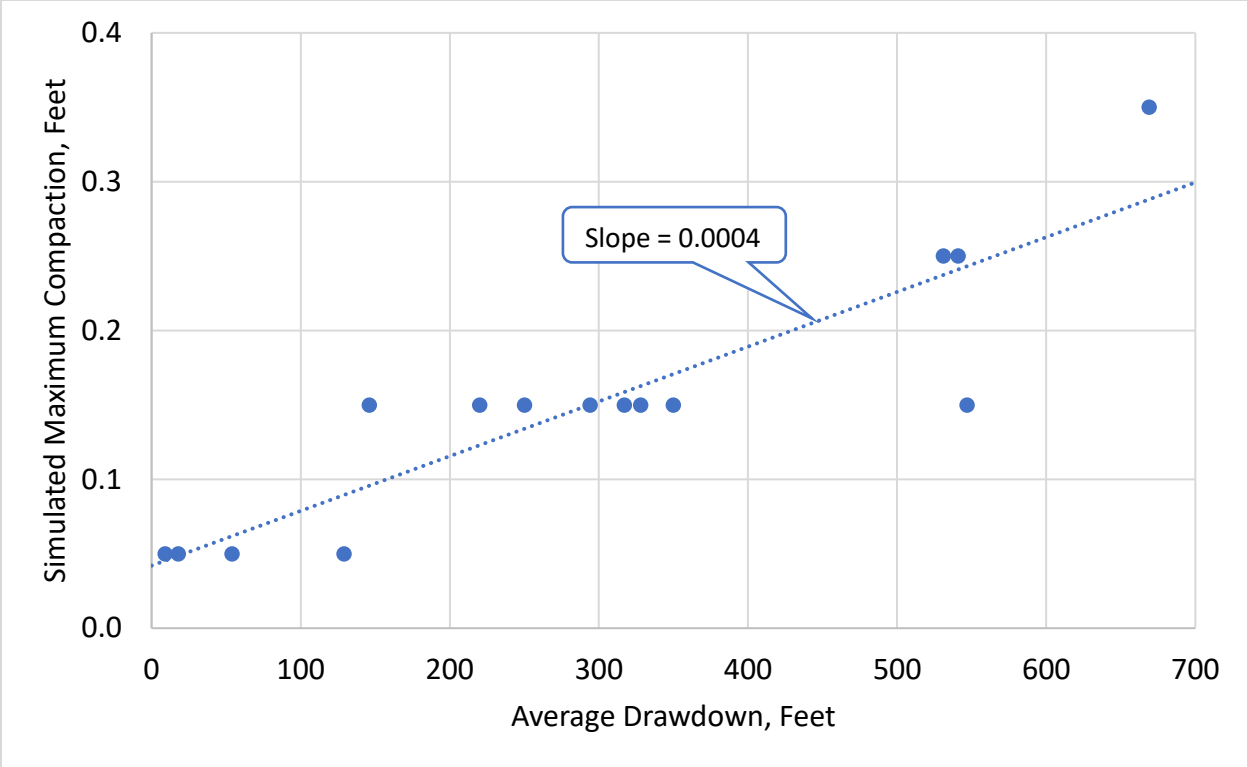


Figure 49. Comparison of simulation results for the Jasper Aquifer showing the relationship between average drawdown and maximum compaction.

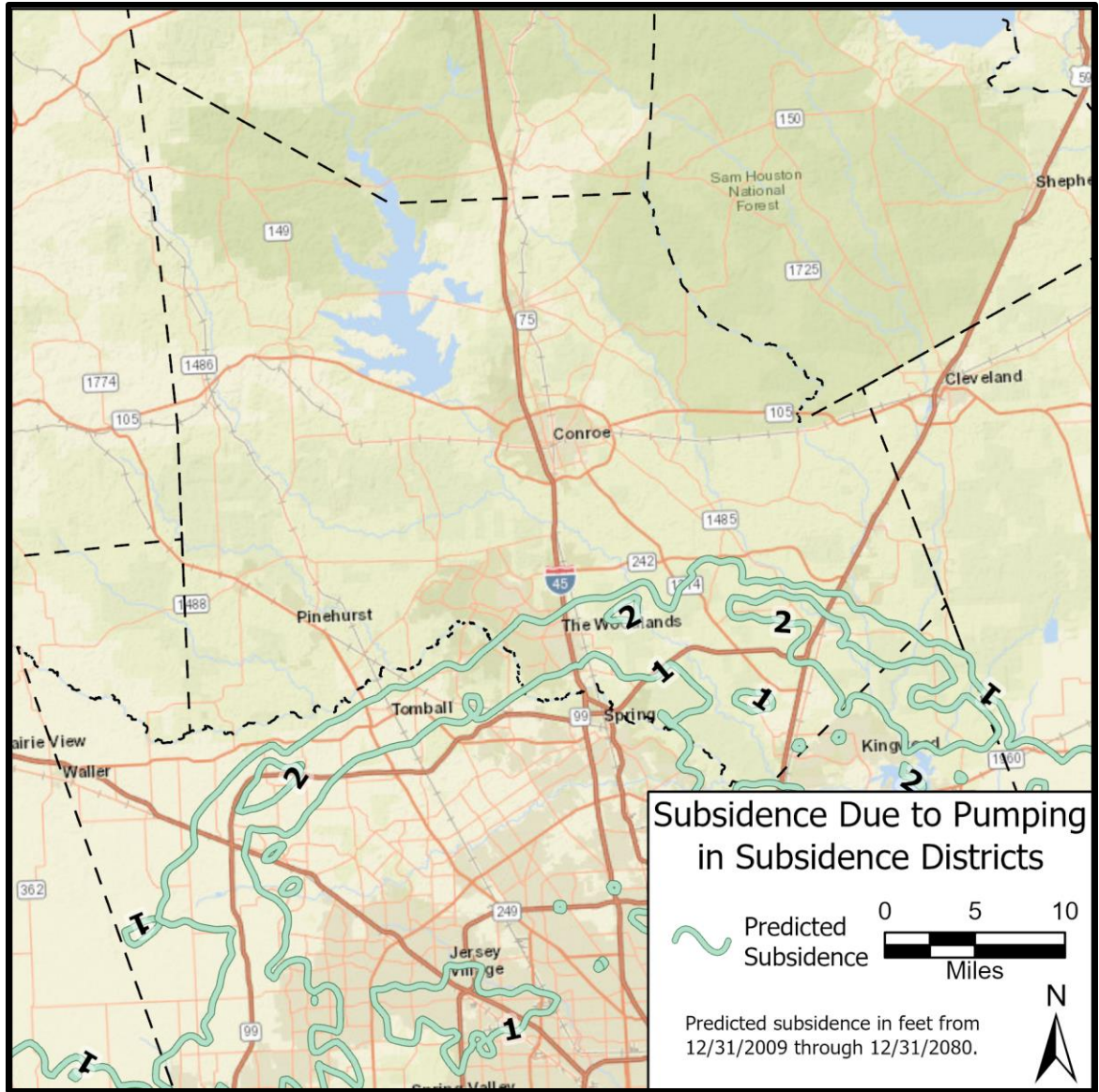


Figure 50. Calculated subsidence due to simulated pumping in the subsidence districts near Montgomery County (Keester, 2020).

5.0 Regulatory and Management Overview

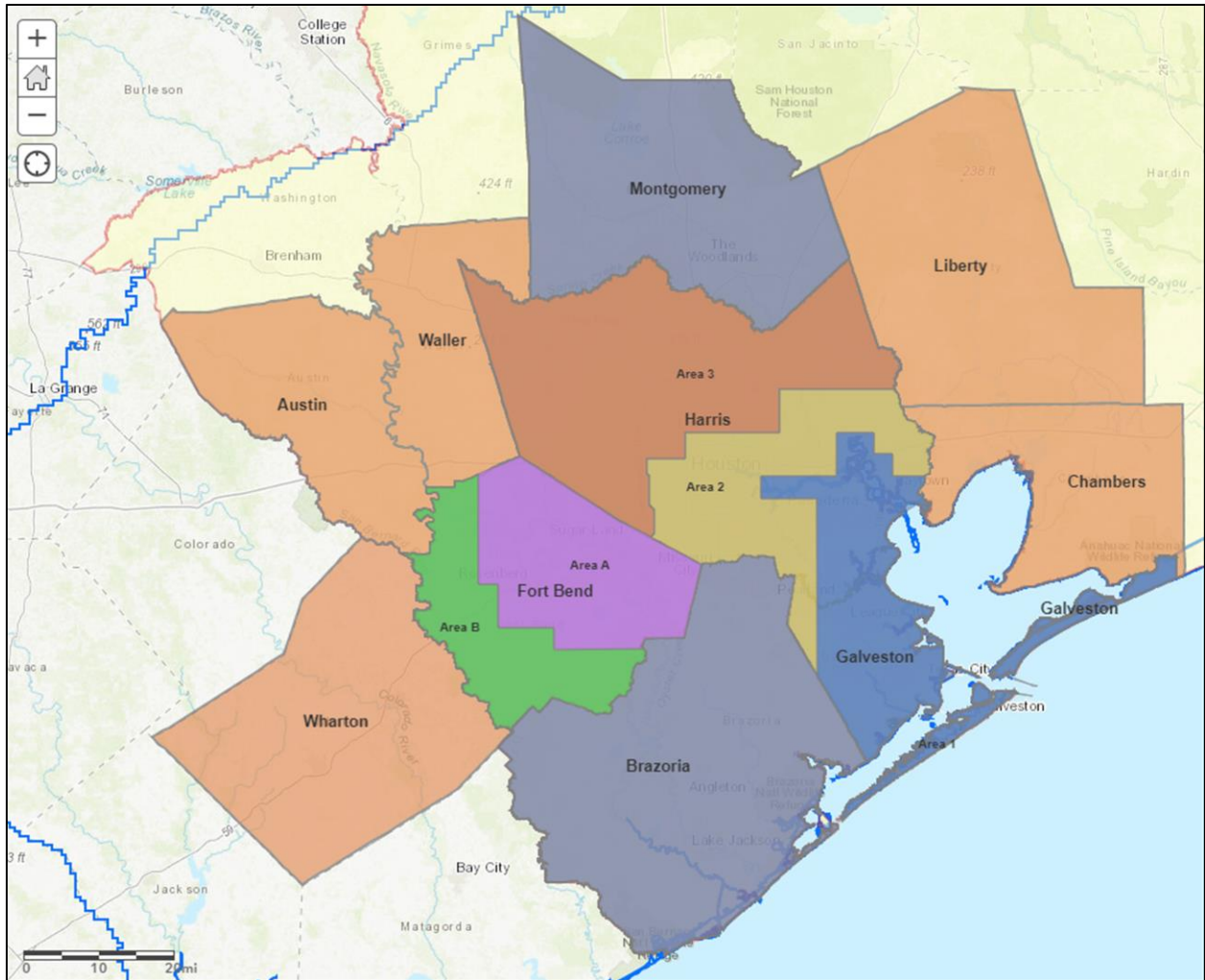


Figure 51. Regulatory areas in the HGSD and FBSD. Image from the HGSD Regulatory Plan Review web map accessed June 16, 2020 (<https://www.arcgis.com/home/item.html?id=5c534d3137d34c04b5460dee0813984f>).

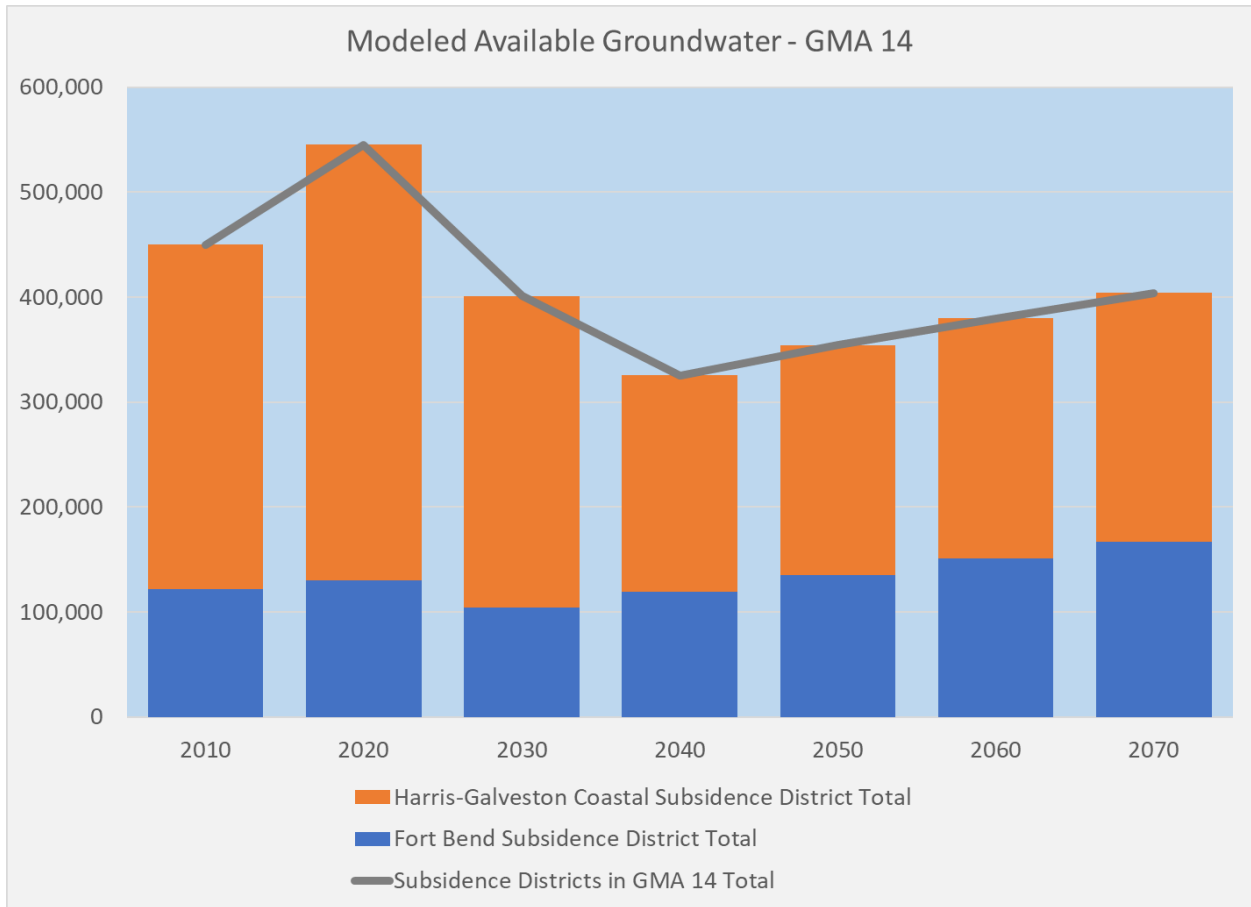


Figure 52. Projected total pumping in HGSD and FBSD through 2070 (Wade, 2016).

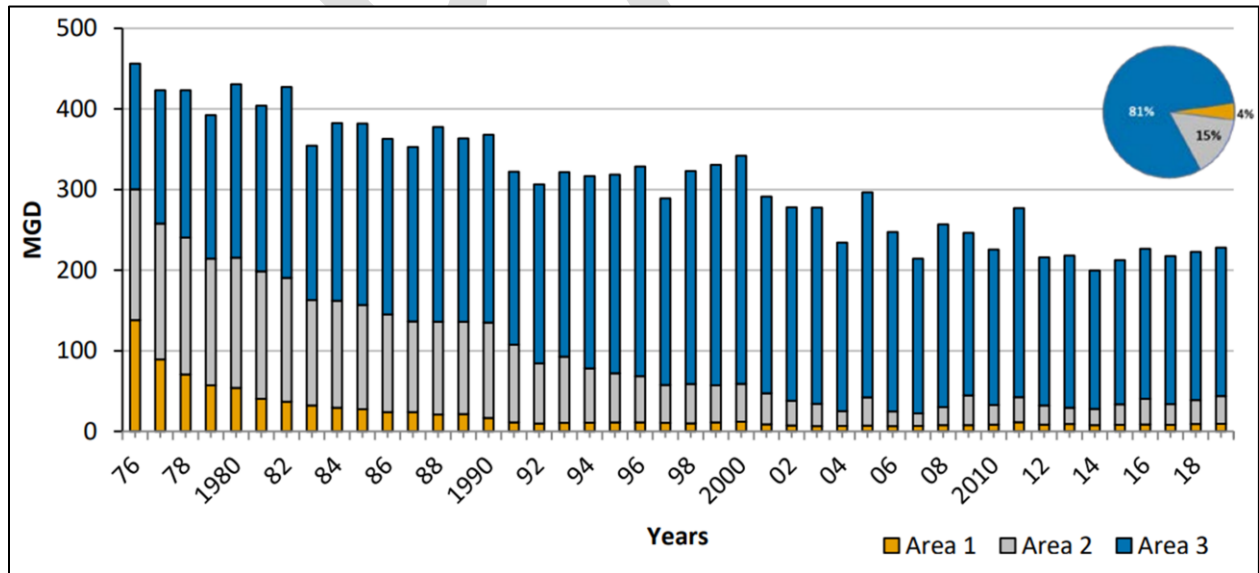


Figure 53. Historical pumping in HGSD (Petersen and others, 2020).

COMMENTS LSGCD STAKEHOLDERS MEETING

Thank You, my name is John Yoars, a resident of Grogan's Mill Village in the Woodlands. My comments today concern three topics that are outlined in the "Subsidence Investigations-Phase 1-Executive Summary". They are 1) the Texas Water Code Chapter 36, 2) Current Subsidence readings, And 3) LSGCD Management Plan.

Using your reference to the PM 13 data we see that since The Woodlands responsibly switched to integrating surface water into the water demand requirements, the subsidence has been arrested and the water table readings have recovered by some 50-75 feet both in the Evangeline and in the Jasper, showing that by the well pumping reductions of some 6 Million gallons a day is allowing the aquifers to recharge. That has been during a time of some development occurring within The Woodlands but not as much as on the East side of I-45. This is factual, readily available data not requiring a detailed historical literature search to determine current aquifer response habits. With the allowed subsidence proposed in the water table reductions in "Run D" that LSGCD asked GMA -14 to include in the next DFC considerations, I can see The Woodlands losing the use of their existing well pumps and switching to all surface water, and still see the water table under The Woodlands declining, as your Run D graph shows, and subsidence reoccurring. This would not comply with The Water Code section 36.002-part b1. Nearly all the woodlands wells become inoperable depriving those citizens their water rights as well as subsidence reoccurring caused by others negligently pumping the woodlands water.

I keep coming back to the point that subsidence and it being a major control point and a most important factor that must be clearly defined in any future LSGCD Ground Water Management Plan that his group issues. Subsidence, aquifer recharge, conservation, waste prevention, and efficient use of ground water are all linked and make up 5 of the 8 factors LSGCD must consider. The Texas Water code for conservation district's mention's subsidence 6 times in the sections cited in your summary. The Water Code also clearly states that

management plan includes and I quote, "coordination with surface water management entities" be included. The recent actual data shows that surface water avails will provide Montgomery County's water needs without irreparable damage to the aquifers and the citizens property. The Run D clearly exceeds the aquifers ability to recharge and therefore also not in compliance with the Water Code directives and Phase 2 of your study needs to focus more on current aquafer response habits than interpretation of literature studies and theoretical outcomes.

Thank You.

Lone Star Groundwater Conservation District Public Workshop
Phase 1 Subsidence Study
July 9, 2020

Good afternoon. My name is Ron Kelling and I am the Deputy General Manager of the San Jacinto River Authority (“SJRA”). We appreciate the opportunity to participate in this workshop for stakeholders.

The SJRA owns, operates and maintains 38 groundwater wells and is the single largest producer of groundwater in Montgomery County. As a key stakeholder in this process, we see at least two issues surrounding this report: an inadequate timetable for thorough technical review and your consultants’ mixed messages regarding the correlation of subsidence to compaction in the Jasper aquifer resulting from the pumping of groundwater.

The report “Subsidence Investigations – Phase 1, Assessment of Past and Current Investigations” prepared for the Lone Star Groundwater Conservation District (“Lone Star”) by Michael R. Thornhill, P.G. and Michael R. Keester, P.G. contains 31 pages of text, 53 figures, six tables of data and references to 53 different articles, studies, publications and other sources of information representing well over a year of effort by Lone Star’s consultants that included little transparency and inclusivity with area stakeholders.

We understand that Phase 1 was intended primarily to be a literature review, however it appears that the report also includes conclusions made by Lone Star’s consultants regarding the information that was obtained. Unfortunately, it is impossible for stakeholders to thoroughly review all of this information and provide a complete set of conclusions and comments regarding the work presented in this report in the 15 calendar days that the Lone Star provided to stakeholders since the posting of the full report. In particular, the full context of each reference must be thoroughly understood, rather than just reviewing a select sentence or two that may be extracted from a publication, which may or may not reflect the conclusion of each author. In any event, we will provide these preliminary comments within the minimal time allotted by Lone Star for the preparation of this workshop.

Mr. Thornhill and Mr. Keester appear to dispel any correlation of subsidence to compaction in the Jasper aquifer caused by removal of groundwater that is presented in research by others. Yet even though they dismiss correlations drawn by others, Mr. Thornhill and Mr. Keester appear to attempt to justify a substantial lowering of the water levels of the Jasper aquifer by specifically quantifying a small amount of potential compaction and resulting subsidence. In other words, they dismiss reports connecting water-level declines in the Jasper to subsidence, and then they claim to know with confidence that only 0.35 feet of subsidence will occur from massive drawdowns in the Jasper. The following statements from the report lead to this perception.

- On page 12 of the report, Mr. Thornhill and Mr. Keester appear to attempt to cast doubt on the findings of the research supported by NASA and the Shuler-Foscue Endowment at SMU and as reported in the article *Identify and Monitor Growth Faulting Using InSAR over Northern Greater Houston, Texas, USA*. The research was conducted by Feifei Qu, Ph.D. in Geodesy & Surveying Engineering and Postdoctoral Fellow at SMU, Zhong Lu, Ph.D. in Geophysics and Schuler-Foscue Professor of Earth Sciences at SMU, Jin-Woo Kim, Ph.D. in Geodetic Science and SAR/InSAR Research Scientist at SMU, and Weiyu

Zheng, Ph.D. student at SMU. All are associated with the SMU Radar Laboratory which conducts research involving the use of Interferometric synthetic aperture radar (“InSAR”). It is our understanding that the Harris Galveston Subsidence District (the “Subsidence District”) has also engaged the same team in conducting further research in this area. Did Mr. Thornhill and/or Mr. Keester utilize the professional relationship between Lone Star and the Subsidence District to reach out to these highly experienced and qualified experts at SMU to gain a more thorough understanding of the research conducted and to address their concerns regarding the correlation of pumping water from the Jasper aquifer and faulting? If not, we hope that they will during Phase 2 of the subsidence study.

- On page 16 of the report, Mr. Thornhill and Mr. Keester point out the “problematic issues with the HAGM” but also state “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 GCAS.”
- On page 17 of the report, Mr. Thornhill and Mr. Keester select specific sentences from the report *Subsidence Risk Assessment and Regulatory Considerations for the Brackish Jasper Aquifer – Harris-Galveston and Fort Bend Subsidence Districts* as prepared by Van Kelley and others to conclude “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).”
- On page 22 of the report, Mr. Thornhill and Mr. Keester state “...the HAGM has limitations...” and “Results from modeling simply must be interpreted within the model limitations.”
- On page 31 of the report, Mr. Thornhill and Mr. Keester conclude “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 conditions for Montgomery County that must be directly assessed in order to derive conclusive answer; and, Detailed correlating 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.”
- Yet on page 23 of the report, supported by the data presented in Tables 5 and 6 and Figures 45 and 46, Mr. Thornhill and Mr. Keester appear to insinuate that pumping large amounts of groundwater from the Jasper yield an average drawdown ranging from “nearly zero to almost 700 feet” which results in a “Year 2070 Additional Max Compaction” of only 0.05 to 0.35 feet.

How can Mr. Thornhill and Mr. Keester try to correlate removal of groundwater from the Jasper aquifer to such low amounts of additional long-term compaction with such specificity, when they devote time in their report attempting to disregard the correlation or at least raise concerns about the validity of such correlation? These messages appear to be contradictory.

If the Lone Star Board, staff and consultants are unconvinced as to the compactability of the Jasper aquifer due to overpumping of groundwater and the potentially devastating impacts of resulting subsidence and fault activation to the residents of Montgomery County, additional tools and resources are available to quantify compaction of the Jasper and correlate it to subsidence and fault movement with the needed specificity.

As a stakeholder in this process, we suggest that Lone Star aggressively develop and implement a plan to site, install, maintain and monitor a global positioning system network complete with Continuously Operating Reference Stations (CORS), Port-A-Measures (PAM) and extensometers in Montgomery County. Data obtained from this network in coordination and cooperation with the Subsidence District's maintenance and monitoring of their existing system, will provide the specific scientific information needed to address Lone Star's reservations.

The SJRA offers to be a part of the solution to enhance the current collection of scientific data regarding the correlation of pumping in the Jasper aquifer and resulting devastating and irreversible subsidence.

As an initial move, we offer to provide available land at our Lift Station No. 27 in The Woodlands as a site to place the combination of a CORS and an extensometer. The site is located (1) in far southern Montgomery County where subsidence is of concern due to the proximity to Spring Creek, (2) in an area where current and future pumping in the Jasper aquifer is a key to long-term water supplies in Montgomery County, (3) in an area where communication of data to satellites is available and (4) where easy access by the Subsidence District and Lone Star personnel is available. Additional information from the Subsidence District regarding this specific site is attached.

We offer any assistance necessary to facilitate the development of this site to accommodate the tools required to collect the necessary scientific data that will support decisions regarding groundwater management strategies in the future.

We also request that Phase 2 of the Lone Star subsidence study be conducted in a more transparent and inclusive manner with the stakeholders in Montgomery and surrounding counties.

Despite the short timetable available for thorough review as well as Lone Star's consultants' apparent conflicting information regarding the correlation of subsidence to compaction in the Jasper aquifer caused by groundwater removal, we appreciate the opportunity to make these remarks and stand ready to be part of successful groundwater management in Montgomery County.

Respectfully,

Ronald Kelling, P.E.
Deputy General Manager
San Jacinto River Authority

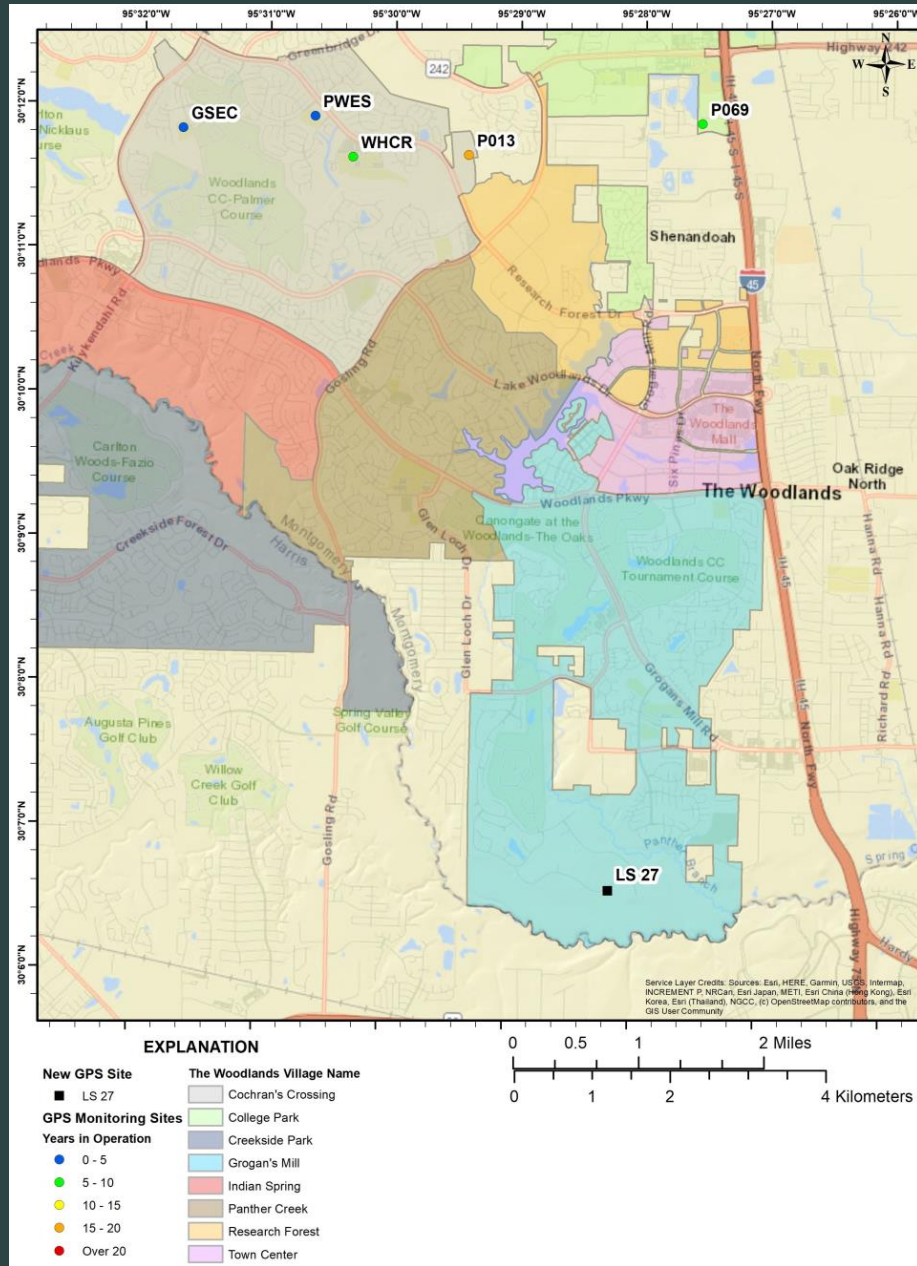


NEW GPS MONITORING SITE POTENTIAL LOCATION

Grogan's Mill Village

GPS Monitoring Sites

Potential location for new GPS monitoring site is the San Jacinto River Authority's Lift Station 27. LS 27 is within Grogan's Mill Village.





Lift Station 27

1. No additional fencing is required
2. Constant power source is available from 2 separate sources
3. Clear sky views with no close-by tree cover
4. No underground piping

Facing Northwest



Facing East



Facing South



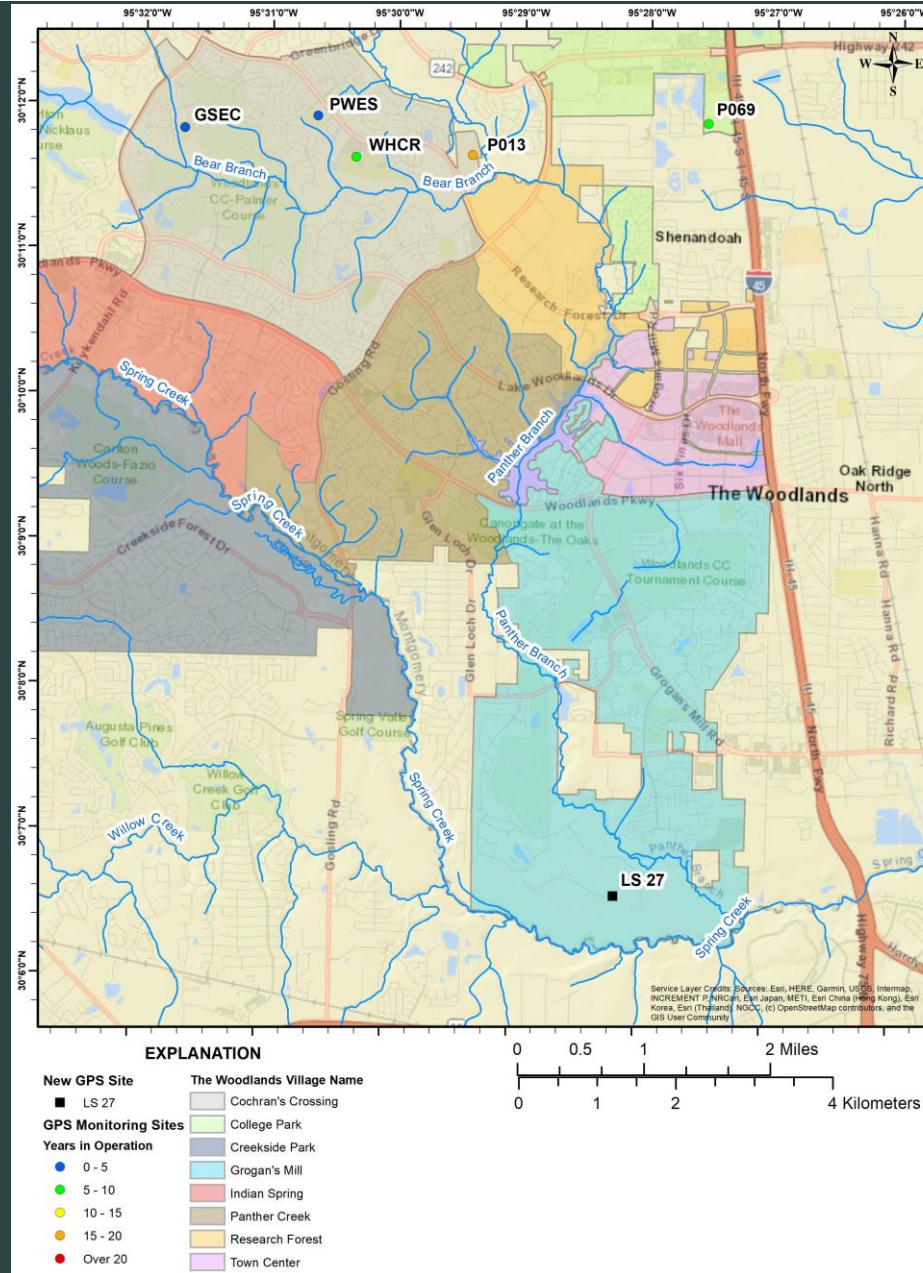
Site Observations

Desired location is approximately where the 2 men are standing in the picture.

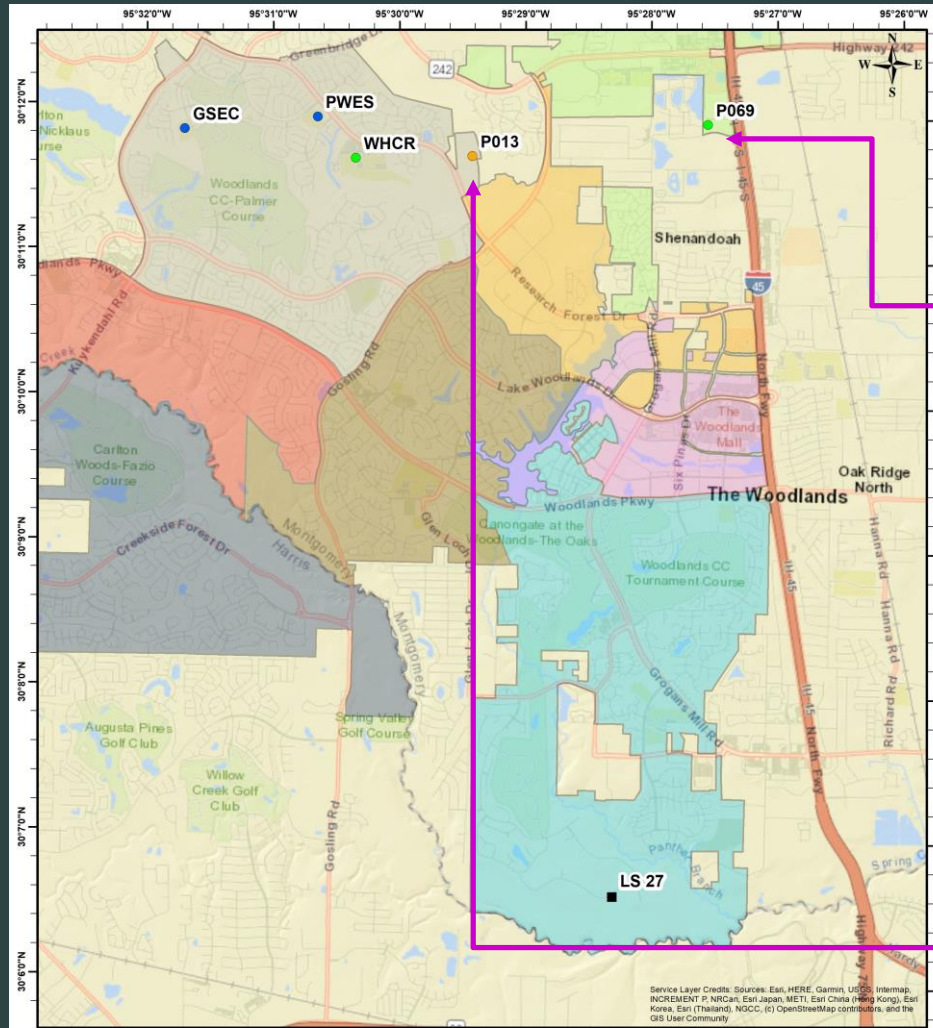
Additional Details - Waterbodies

LS 27 is approximately 0.38 miles due north of Spring Creek.

It offers coverage in an area close to the county border that doesn't have nearby GPS sites (closest one is P013, about 5.9 miles northwest)

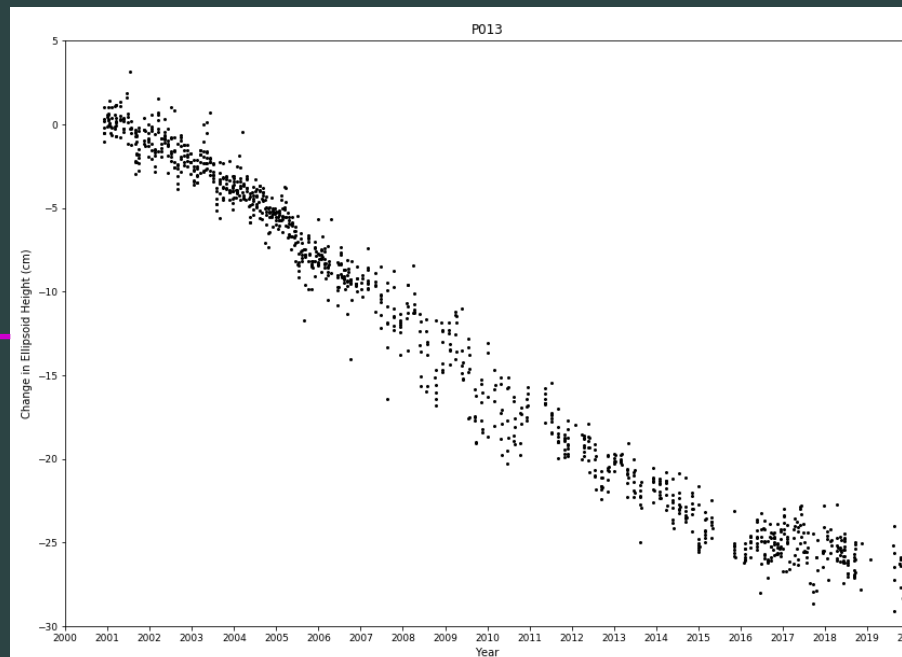
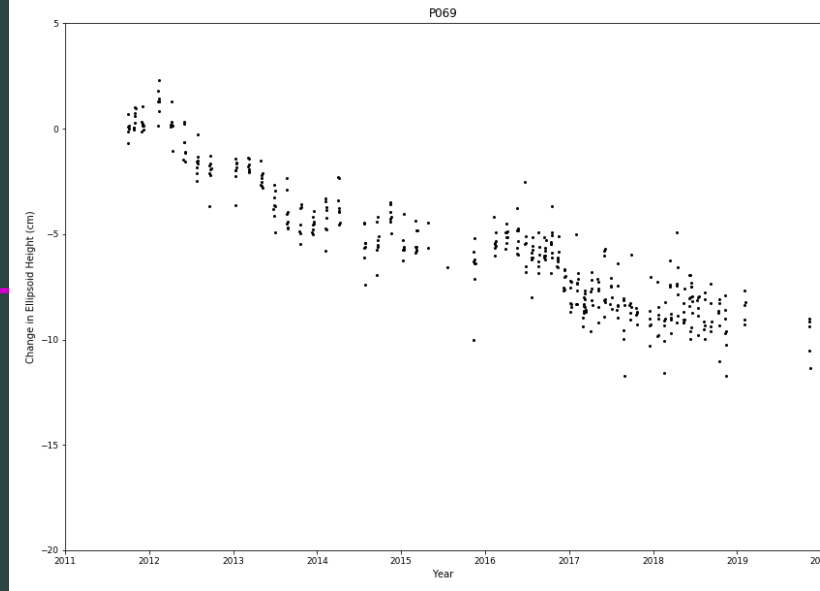
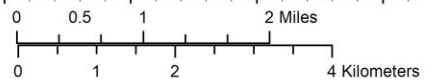


Period of Record Data



EXPLANATION

- | | |
|-----------------------------|-----------------------------------|
| New GPS Site | The Woodlands Village Name |
| ■ LS 27 | ■ Cochran's Crossing |
| GPS Monitoring Sites | ■ College Park |
| Years in Operation | ■ Creekside Park |
| ● 0 - 5 | ■ Grogan's Mill |
| ● 5 - 10 | ■ Indian Spring |
| ● 10 - 15 | ■ Panther Creek |
| ● 15 - 20 | ■ Research Forest |
| ● Over 20 | ■ Town Center |



Comments for LSGCD Phase 1 Workshop July 20, 2020

Thank you for the opportunity to make public comment on the Phase 1 report. I am Neil Gaynor, a resident of The Woodlands in Montgomery County.

A conclusion in the executive summary of the report states: "Montgomery County had experienced a considerable amount of the total currently observed subsidence in decades before pumping within the county was substantial;"

I want to review subsidence estimates where I-45 crosses Spring Creek. These estimates are extracted from several subsidence maps covering Harris and Montgomery Counties, including Figures 19, 20 and 25 in the draft report. All maps have 1906 as reference year. The progression of subsidence from 1973 to 2016 at the I-45 location is as follows:

Year	Subsidence ft
1973	0.5
1978	1
1987	~1
2000	~1.5
2005	2
2016	~3

Extrapolation of these numbers suggests a probable start of Montgomery County subsidence nearer to 1966 not 1906. A conclusion that considerable subsidence occurred in Montgomery County during earlier decades is not convincing.

I refer now to a subsidence dataset from The Woodlands GPS site PA13, shown in Figure 22 of the report.

From January 2001 to September 2015, PA13 data show 25 cm of subsidence at a rate of 1.7 cm/year. Over the same period, average static levels in nearby groundwater production wells declined by 90 ft and 230 ft in the Evangeline and Jasper aquifers, respectively.

However, between September 2015 and October 2019, the subsidence rate dropped 80% to 0.3 cm/year. Conjunctive use of surface water from SJRA's Lake Conroe treatment plant since September 2015 has decreased groundwater withdrawal in The Woodlands. This action has significantly reduced subsidence rates. Water levels have rebounded in the same wells 70 ft and 60 ft in the Evangeline and Jasper, respectively.

A 2000 National Research Council report recognizes that conjunctive use of surface water and groundwater is a best practice for water resource management. Integration of water sources will help steady the decline of aquifer water levels and limit impacts of subsidence due to groundwater pumping.

One consequence of continued subsidence is greater risk for property flooding near Spring Creek. A 1986 study on flooding in Harris County notes that the subsidence gradient and existing channel slope are two significant factors relating subsidence to inland flooding.

I ask that subsidence-related flood risk due to accelerated aquifer pumping be fully addressed during the Phase 2 study in partnership with the Houston-Galveston Subsidence District.

Thank you for your time.



Harris - Galveston Subsidence District

July 7, 2020

via email and USPS

Samantha Reiter - General Manager
Lone Star Groundwater Conservation District
655 Conroe Park North Drive
Conroe, TX, 77303
sreiter@lonestargcd.org

Dear Ms. Reiter,

Thank you for the opportunity to review the consultant stamped technical memorandum titled "Subsidence Investigations – Phase 1 Assessment of Past and Current Investigations" prepared by Michael Thornhill, P.G. with the Thornhill Group, Inc. and Michael Keester, P.G. with LRE Water. Although I would have liked to have been able to give this a more detailed review, due to the limited amount of time between the posting of the report (email dated June 25, 2020) and the stakeholder workshop, I have provided some initial thoughts of the work in this letter for your information. The comments included in this letter are not comprehensive. In the interest of brevity, I have included a few examples where the staff and Board of Directors of the Lone Star Groundwater Conservation District (LSGCD) should be cautious in utilizing the interpretations provided by the contract consultant team.

In section 2.1.2 and 2.3 the authors present data developed by other researchers related to the hydrostratigraphy and lithologic properties of the Gulf Coast Aquifer System and discuss the importance of these characteristics in the context of subsidence mechanics. It is mentioned that the primary considerations for subsidence are: 1) The amount of clay in the aquifer material; 2) Aquifer water-level changes; and 3) the lowest historical water level. Please be advised that the historical minimum is not as important as the duration and magnitude of the depressurization (water-level decline). Groundwater and subsidence data from the 2011 drought show this very clearly. Drought is not mentioned at all in the phase one report, but it is an important consideration since those are the times when water demand increases significantly. Recent droughts in the region resulted in large water-level declines and annual rates of subsidence.

Mr. Thornhill and Mr. Keester suggested in their presentation to the Board in June that the susceptibility of the Jasper was 1,000 times less than the Chicot aquifer according to the HAGM. Although the HAGM model is the model of record, HGSD/FBSD/USGS/TWDB are cooperating to update and revise the model to address known limitations which include the simulation of compaction in the Jasper aquifer. It is

BOARD OF DIRECTORS: Alan Petrov – **Chairman** (*Municipalities of West University Place, Southside Place, Bellaire, and Jacinto City*); Susan Baird – **Vice Chairman** (*City of Houston*); Alberto Gonzalez – **Secretary** (*City of Houston*); Lindall Murff (*Harris County Commissioners Court*); Joe Goins (*Harris County Commissioners Court*); Chris Canonico (*City of Houston*); Linn Smyth (*Harris County Commissioners Court*); William Latimer (*Galveston County Commissioners Court*); Pete Cote (*City of Baytown*); James Edwards (*Clear Lake Water Authority and the municipalities of Deer Park, Galena Park, La Porte, Nassau Bay, and Seabrook*); Pamela Puckett (*City of Houston*); Kyle Sears (*Municipalities of Humble, Piney Point Village, Hedvig Village, Bunker Hill Village, Hunters Creek Village, Hillshire Village, and Spring Valley*); Kathy Rogers (*Galveston County Commissioners Court*); Shaun Theriot-Smith (*City of Houston*); Shannon Lucas (*Municipalities of Galveston County*); Katherine Ostroff (*City of Houston*); Jason Long (*Municipalities of Galveston County*); Sarah Benavides (*City of Pasadena*); Ken Keller (*Galveston County Commissioners Court*)

GENERAL MANAGER: Michael J. Turco

important that Lone Star recognize that the current state of the science is that the Jasper can compact, particularly where it is shallow and used for municipal supply as in Northern Harris and Montgomery County.

As it relates to the compaction of the Jasper aquifer here are some considerations:

- It contains similar, in some cases more, clay as a percentage than the Evangeline Aquifer;
- It is developed over similar depth intervals as other sediments (Chicot/Evangeline) in Harris County (within about 2000 feet of land surface or less);
- It has concentrated areas of high groundwater use and drawdown in southern Montgomery County where subsidence has been measured;
- InSAR data and analysis published in a peer-reviewed journal by Southern Methodist University researchers funded by NASA attribute a portion of the subsidence in southern Montgomery County to "...exploitation of the Jasper aquifer;"
- Recent reductions in groundwater use in The Woodlands, mandated by LSGCD, resulted in increases in water-level in the Jasper aquifer, a significant decrease in the rate of subsidence, and a decrease in the velocity of fault movement in the Woodlands.

It is encouraging to see in your report that LSGCD is committed to a better understanding of compaction in the Jasper aquifer. Considering the reliance Montgomery County has had on the Jasper aquifer and the regulatory uncertainty of future groundwater withdrawals, the impacts of future increases in Jasper production should be well understood.

Although I don't think it was presented as part of the Special Board meeting, or included in the executive summary, the information in the report from a technical memorandum by Michael Keester delivered at the May GMA 14 meeting and shown in Figure 50 misrepresents the impact of groundwater withdrawal in Harris County on subsidence in Montgomery County. Having had the opportunity to review the technical memorandum associated with the figure, not only is it unrealistic, it is misleading to your Board, and the people of Montgomery County.

The most important piece of the report is the plan for future monitoring and research. Subsidence has been, and will continue to be, a policy-driving hazard in this area. Water planning in the context of subsidence requires a long-term approach. The responsibility to prevent or control subsidence in Montgomery County is yours. A robust monitoring plan that compiles and analyzes real data is important for the success of any future groundwater management program in Montgomery County. The type of data collection being proposed in this report will help you better understand the impact of Lone Star's regulatory plan on the future of Montgomery County.

As I have mentioned on several occasions to your staff and consultants, the Subsidence Districts are willing to assist LSGCD in the understanding of the breadth of previous research and data collection as well in the development of future focused science and research. I encourage you to meet with the Subsidence District so that collaboratively we can coordinate your efforts with on-going and future planned programs by the Subsidence District.

Sincerely,



Michael J. Turco – General Manager



From: melderbw@aol.com <melderbw@aol.com>

Sent: Thursday, July 9, 2020 9:14 PM

To: Samantha Reiter <sreiter@lonestargcd.org>; hhardman@gmail.com; JIM.SPIGENER@DEKRA.COM

Subject: WEBB MELDER's SUBSIDENCE COMMENTS FOR THE LSGCD SUBSIDENCE PHASE 1 STUDY REPORT

LSGCD SUBSIDENCE STUDY PHASE 1 Draft Report

Re: stakeholder input and public comments - July 9, 2020 3:00 p.m. - ZOOM meeting

Good afternoon Mr. President and Honorable Directors,

First, As you move forward addressing all issues LSGCD is charged with managing, I want to thank you for standing strong against the political pressures that surround you. This newly elected board is doing an outstanding job representing "The People" of Montgomery County. Please know the majority of citizens support you.

Second, the main purpose of today's meeting is to address the new Subsidence study phase 1 study report. There is an honest interest in "some parts" of the county to address this subject. An important fact is subsidence does not recognize county lines. It's no surprise the focal point of Montgomery county citizens interested in subsidence live in the Woodlands. This is because the largest groundwater pumper / producer in the county is SJRA ; they own ALL the water wells in the Woodlands and supply all the water to the Woodlands. This is an important fact because both SJRA and the WJPA (now the Woodlands Water Agency) both held directors positions on the old appointed lsgcd board for 17 + years.

My four questions are: **(1)** Over a 17 yr. period, what subsidence studies were done "solely" by the previous appointed LSGCD board ? **(2)** Has the SJRA provided LSGCD with any of their own subsidence studies since they have been, and remain the sole pumpers of groundwater to serve the Woodlands ; and are the largest pumper of groundwater in the county. ? **(3)** If SJRA is "just now" calling for the installation of extensometers in the Woodlands to address the subsidence effects of their (sjra) groundwater pumping, why have they not installed extensometers previously over the last 48 +/- years since they pump 100% of the groundwater in the Woodlands ? As the "sole pumper / provider of groundwater" to the Woodlands, SJRA should pay 100% of the cost for this. No one else pumps groundwater in the Woodlands except SJRA. **(4)** Since subsidence does not recognize county lines, what are your plans to reduce subsidence in certain areas of south Montgomery county caused by groundwater pumping in northern Harris county; be it that the aquifer does not recognize the county line either.

In closing, one subsidence shoe does not fit all subsidence feet, as each aquifer and the confining layers between them have their own characteristics.

On behalf of the citizens of Montgomery County, thanks again for your public service. Stay strong and keep the Faith.

Webb Melder