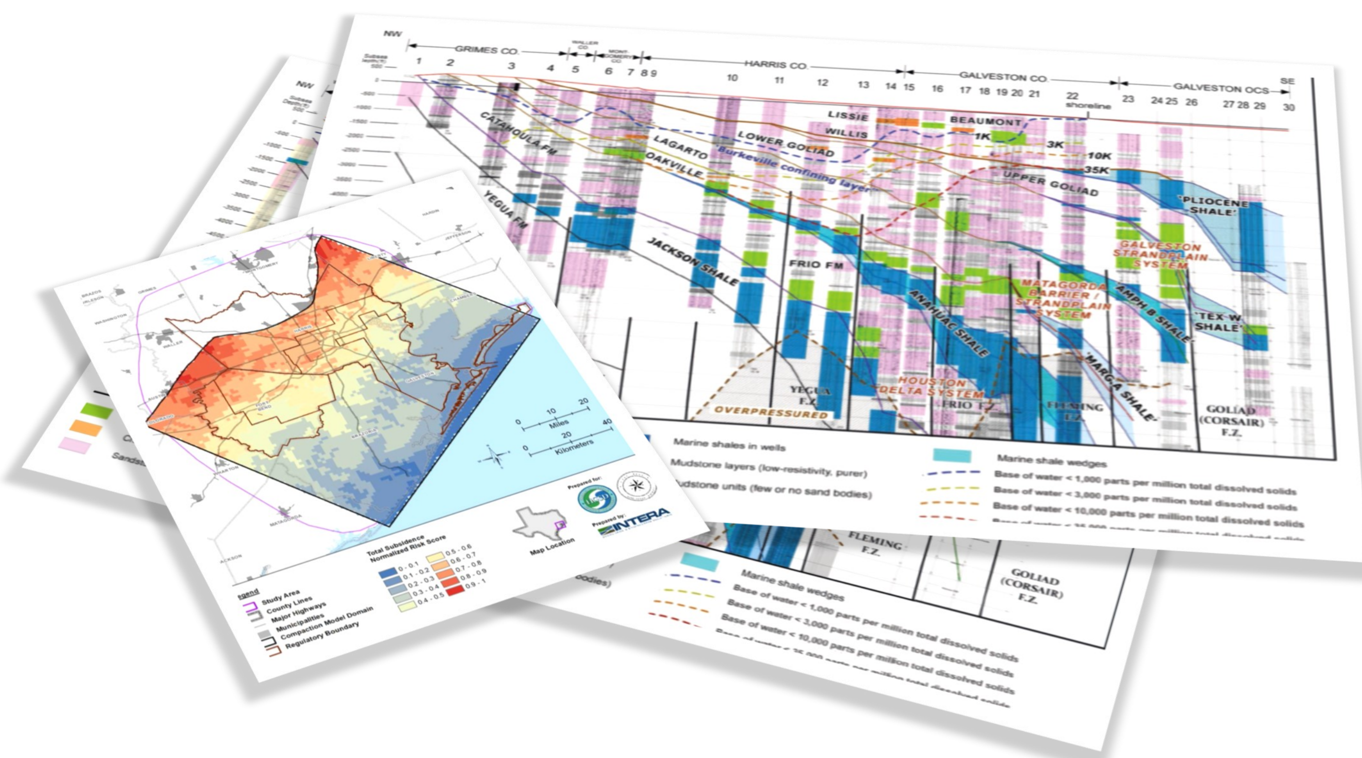
Investigation of the Brackish Groundwater Resources in the Gulf Coast Aquifer and the Determination of Potential Subsidence Risk Due to Resource Development

EXECUTIVE SUMMARY



HARRIS-GALVESTON SUBSIDENCE DISTRICT
FORT BEND SUBSIDENCE DISTRICT
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INVESTIGATION OF THE BRACKISH GROUNDWATER RESOURCES IN THE GULF COAST AQUIFER AND THE DETERMINATION OF POTENTIAL SUBSIDENCE RISK DUE TO RESOURCE DEVELOPMENT

ABSTRACT

The development of brackish groundwater resources has become a more common water management strategy in the State of Texas. Significant brackish groundwater resources exist within the Gulf Coast Aquifer System near Houston, Texas in Harris, Galveston, Fort Bend, and surrounding counties. Any future development of the brackish groundwater resources will require improved understanding of these historically undeveloped resources, their reaction to the stress of development, and any consequences associated with land surface subsidence.

The Harris-Galveston Subsidence District and the Fort Bend Subsidence District (hereafter referred to as the Districts) were created by the Texas Legislature in 1975 and 1989 respectively to regulate groundwater withdrawal from the Gulf Coast Aquifer to stop on-going and prevent future subsidence. Subsidence is the lowering of land surface elevation. In the Districts' region, this is caused by the lowering of groundwater-level in the aquifers (depressurization) and compaction of the many clay lenses in the subsurface. Subsidence caused by the compaction of the generally shallow and fresh-water portions of the aquifer is well understood and documented.

The Texas Water Development Board defines brackish groundwater as having a total dissolved solids concentration from 1,000 to 10,000 milligrams per liter. Recognizing the potential interest in brackish resources within the Districts, in 2018 a study was completed for the Districts which delineates the occurrence of brackish groundwater resources within the Districts and provides a detailed assessment of the stratigraphy, structure and lithology of the Gulf Coast Aquifer System. The purpose of this effort was to develop a higher resolution depiction of the hydrostratigraphy of the Gulf Coast Aquifer System, determine the occurrence and hydrogeologic characteristics of the brackish resources within the Districts' area, and determine the risk of subsidence should the brackish resources be developed.

Data were compiled and multiple hydrologic parameters were utilized to improve the understanding of the brackish resources within the study area. A total of nine stratigraphic cross-sections were created based on 209 geophysical logs to locally define aquifer stratigraphy. A total of 294 geophysical logs were used to interpret aquifer lithology in a binary classification of sand and clay. A total of 299 geophysical logs were used to estimate groundwater salinity of sands. Multiple datasets were created to better understand the hydrogeologic characteristics and large quantities of brackish groundwater were identified in the study area.

These data were used to develop a groundwater flow model capable of simulating subsidence to inform the subsidence risk of brackish development of the Jasper aquifer. The U.S. Geological Survey (USGS) MODFLOW-SUB model was used to simulate compaction in the Jasper aquifer. Compiled data detailing the total clay thickness, clay bed thickness, and clay bed location were input into the model along with a hypothetical stress to predict compaction within the Jasper aquifer across the area comprising the Districts while incorporating the observed heterogeneity in clay properties.

The results of this study confirm the potential for compaction in the Jasper aquifer and subsidence to occur from brackish groundwater development particularly in up-dip areas near where the Jasper is being used for freshwater supply. Using the results from the model simulations and two other risk performance measures, the total subsidence normalized risk score was estimated. The normalized risk score provides a means for the Districts to compare the relative risk of subsidence associated with the location of a future brackish Jasper Aquifer project. This study provides a basis for future research on subsidence in the Districts' area and can inform water managers and planners in the Houston area on the availability of brackish groundwater resources.

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DELINEATION OF FRESH, BRACKISH, AND SALINE GROUNDWATER RESOURCES BASED ON INTERPRETATION OF GEOPHYSICAL LOGS

Coordinating with work being completed by the Texas Water Development Board, the Districts conducted a study from 2016 through 2018 to determine the occurrence of fresh, brackish, and saline groundwater resources.

The Gulf Coast Aquifer System in the study area has been the primary water source for the region's municipal, industrial, and agricultural water supply. The Chicot, Evangeline, and Jasper aquifers are the three primary water bearing units of the aquifer system, with the Chicot being the shallowest and the Jasper being the deepest. Extensive development of these aquifers has resulted in the compaction of the aquifer and measured land surface subsidence. Land subsidence can contribute to infrastructure damage, coastal inundation, and inland flooding.

The distribution of major sand and clay-rich sequences within the aquifer system was determined to better understand the relation between aquifer lithology, stratigraphy, and salinity. Nine stratigraphic cross-sections were created based on 209 geophysical logs to locally define aquifer stratigraphy. A total of 294 geophysical logs were used to interpret aquifer lithology in a binary classification of sand and clay. A total of 299 geophysical logs were used to estimate groundwater salinity. The nine cross sections include aquifer structure boundaries, aquifer lithology and water salinity classification.

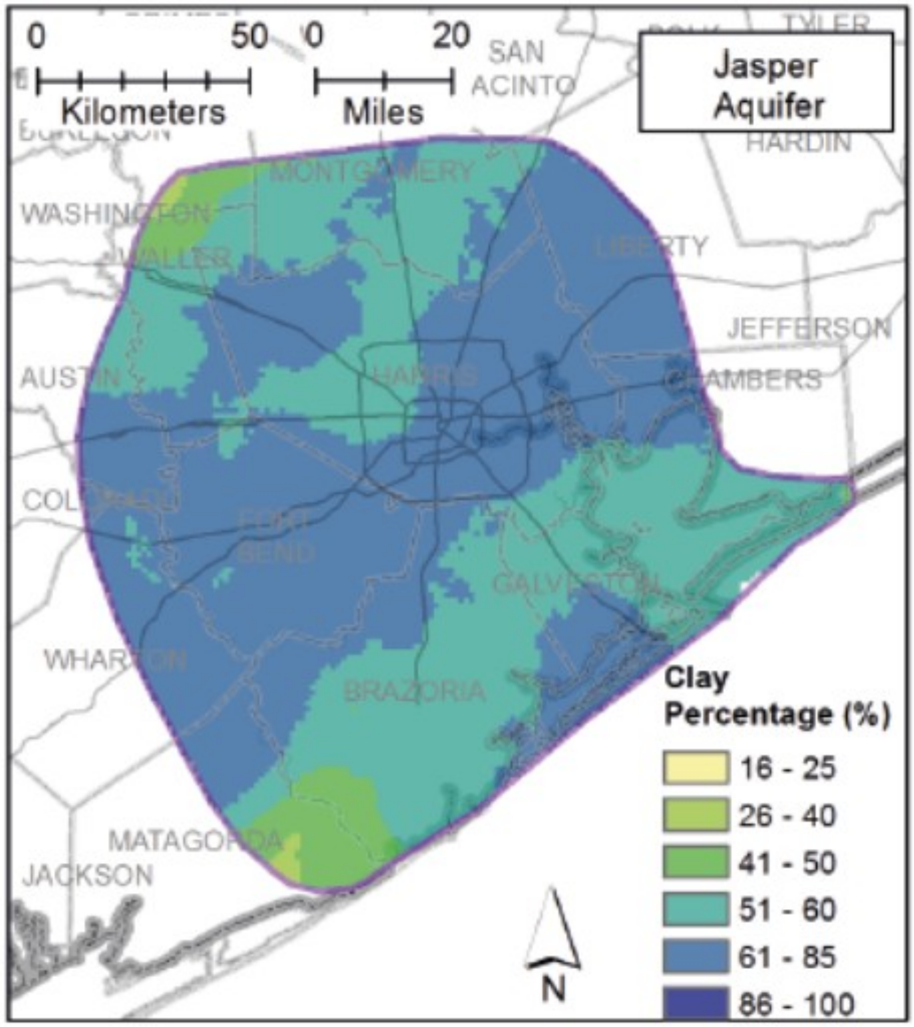

FIGURE 1. CLAY PERCENTAGE DETERMINED FROM GEOPHYSICAL LOG ANALYSIS, JASPER AQUIFER, TEXAS.

The primary consideration for the data analysis, particularly as it relates to aquifer compaction and subsidence, is to determine the distribution and ratio of sand and clay in the aquifer. The Jasper aquifer contains a higher percentage of clay than the other primary water bearing units of the Gulf Coast Aquifer System. The characteristics of the clay beds in an aquifer, thickness and content, is of direct importance to the compaction potential of an aquifer and are directly correlated with a higher potential for compaction that could result in land subsidence. Figure 1 shows clay percentage in the Jasper aquifer.

Analysis was completed to determine the base of the freshwater zones in the aquifer system and the distribution of the slightly saline, moderately saline, and very saline groundwater in the aquifer. Total dissolved solids (TDS) is the customary measure of the salinity level in water. TDS values greater than 1,000 mg/L are typically referred to as being brackish with values above 10,000

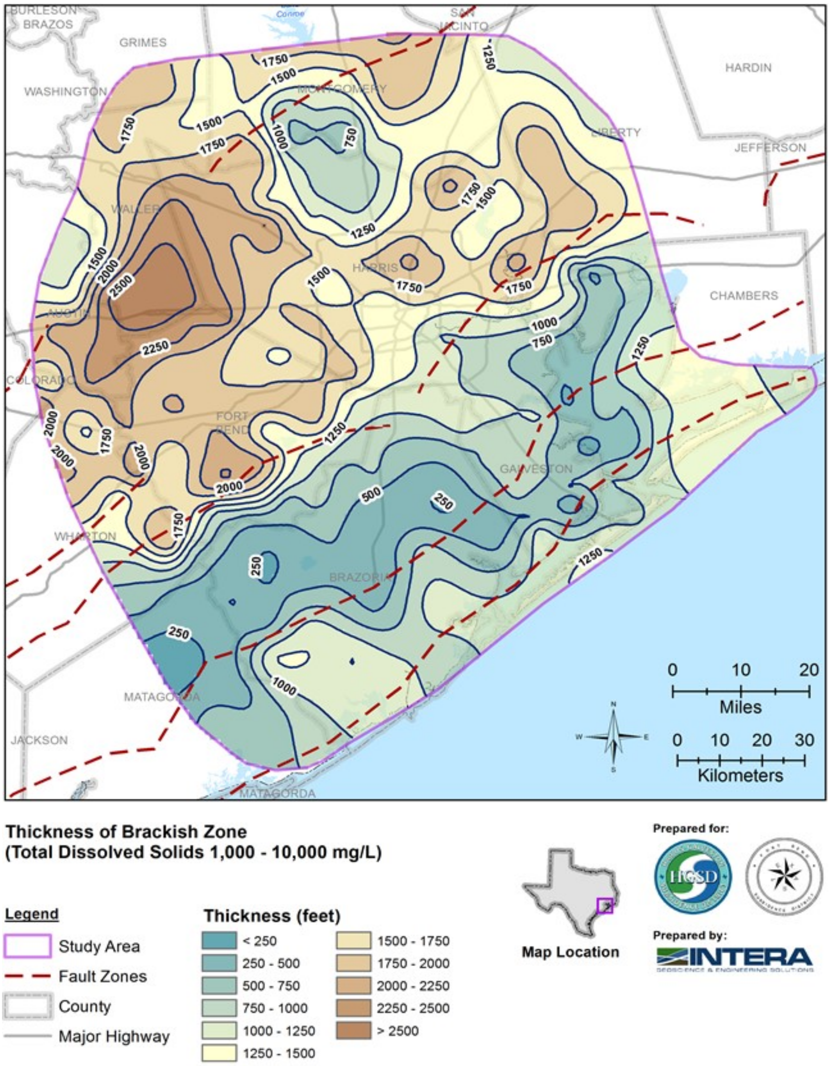

FIGURE 2. ESTIMATED THICKNESS OF THE BRACKISH ZONE IN THE GULF COAST AQUIFER SYSTEM, TEXAS.

mg/L referred to as saline. The base of the freshwater zone is the deepest between the coast and the updip regions of the study area parallel to the Texas coast and can reach over 2,000 feet in depth. Fault zones and other structural features in the aquifer, such as salt domes, can influence the depth of the freshwater zone and may have significant impact on water quality at the local scale.

The brackish groundwater zones were delineated for the Chicot, Evangeline, and Jasper aquifers. Shallow brackish zones are the thickest near the coast in the Chicot aquifer. The thickest regions of the Evangeline aquifer brackish zones occur in southern Fort Bend and Harris counties, with an average thickness of about 1,300 feet. Brackish groundwater occurs in most of the Jasper Aquifer across Harris and Fort Bend counties, with the thickest brackish zone in Fort Bend County averaging 1,200 feet thick. Figure 2 plots a map of the estimated thickness of the brackish (1,000 to 10,000 mg/L TDS) in the Gulf Coast Aquifer System.

The distribution and occurrence of brackish waters determined in this study provides a framework for additional local studies of brackish and saline groundwater within the Districts and provides key lithologic and water salinity data needed to evaluate the risk of future subsidence should brackish and saline groundwater development occur. Additionally, this information has provided keen insight into the potential for compaction in the Jasper aquifer.

SUBSIDENCE RISK ASSESSMENT FOR THE BRACKISH JASPER AQUIFER

Brackish groundwater occurs in most of the Jasper Aquifer across Harris and Fort Bend counties, with the thickest brackish zone in Fort Bend County averaging 1,200 feet thick.

The Districts conducted a study from 2016 to 2018 to determine the risk and potential for subsidence resulting from Jasper Aquifer brackish groundwater development. The majority of the freshwater pumped from the Gulf Coast Aquifer System in the Districts is from the Chicot and Evangeline aquifers. This study focused on determining the risk in the Jasper aquifer because; (1) significant volumes of brackish groundwater exist in storage in the Jasper, (2) additional fresh groundwater development in the Gulf Coast Aquifer System is limited by the regulatory policies within the Districts, (3) there is current interest in development of brackish groundwater in the Jasper Aquifer, (4) the risk of subsidence in the shallower Chicot and Evangeline, regardless of salinity, is well understood and documented and (5) little is known regarding the potential for compaction and resulting subsidence from the development of the Jasper Aquifer.

compaction in the Jasper aquifer and subsidence

The Gulf Coast Aquifer System is composed of a complex sequence of interbedded sands and clays. Compaction and resulting subsidence in the Gulf Coast aquifer in the study area is caused by

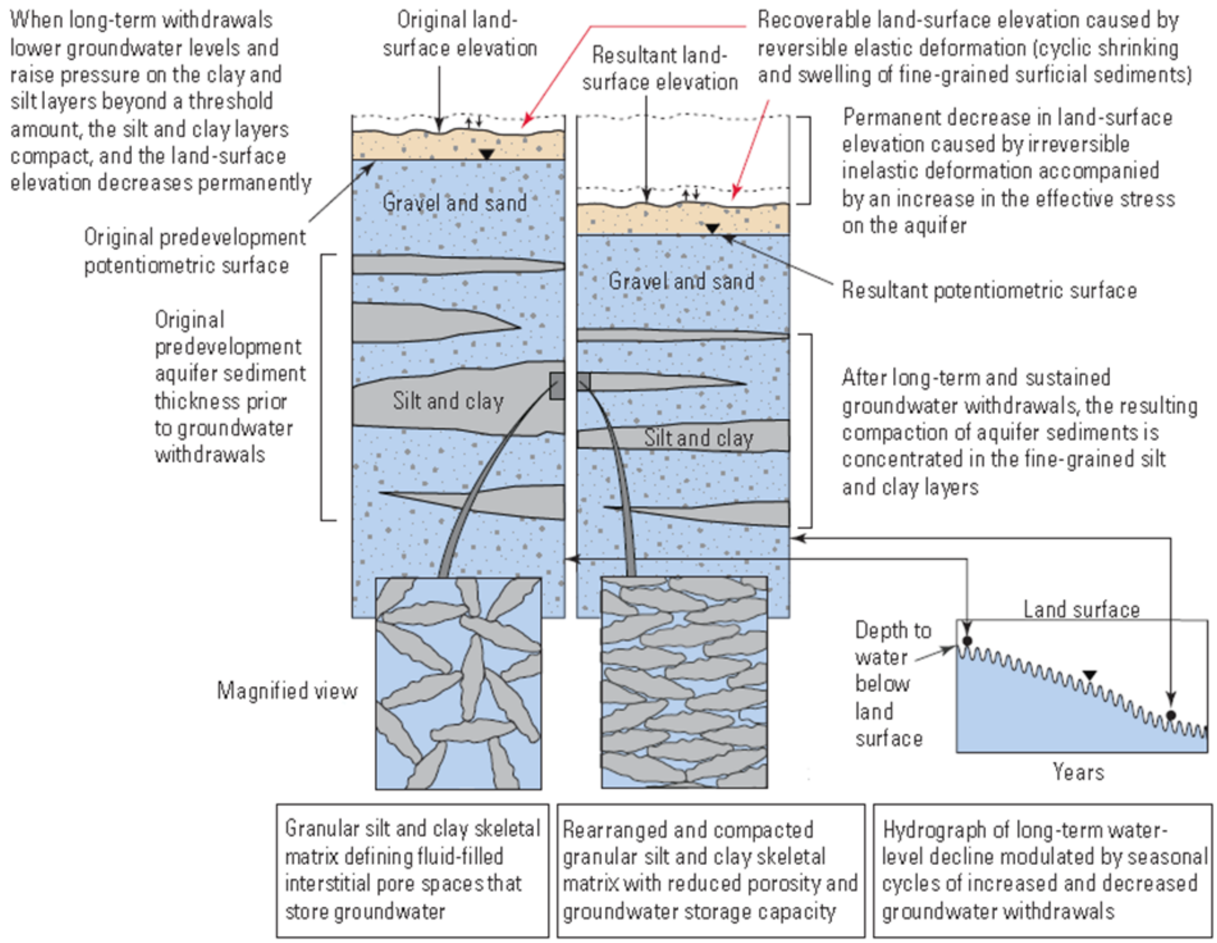

FIGURE 3. MECHANISM OF SUBSIDENCE CAUSED BY WATER LEVEL DECLINES INDUCED BY GROUNDWATER PUMPING (SOURCE: THE UNITED STATES GEOLOGICAL SURVEY).

the reduction of the pore pressure in the clay beds as a result of groundwater pumping. When water-levels decline as a result of groundwater withdrawal, the pressure within the aquifers decline which leads to a decrease in pore pressure within the numerous clay lenses which then begin to compact. The decrease of the pore pressure in the aquifer is observed through the measurement of water level declines in a well. There are two components to compaction: elastic and inelastic compaction. The shrink-swell behavior we observe in surficial clays which create cracks in sidewalks and foundations is referred to as elastic compaction. Inelastic compaction, caused by groundwater withdrawal, occurs at depth and is the largest contributor to land subsidence throughout the region. Although elastic compaction can rebound over time under the right conditions, inelastic compaction does not rebound. (see Figure 3).

Subsidence is measured as a lowering of ground surface elevation and is the surface manifestation of compaction at depth. Inelastic compaction occurs preferentially in the clays because they are more deformable than sand grains under increased stress. The maximum amount of compaction that can theoretically occur under a given amount of drawdown is a product of the thickness of the clay beds in the aquifer and the clay inelastic storativity. Compaction can be a slow process and the time it takes for compaction to occur within a clay bed is a function of the clay bed properties and the clay bed thickness.

Some physical properties of clays that are important to prediction of compaction are not easily determined and generally require specialized laboratory testing. These include the clay vertical

Subsidence observed at well head located in Baytown, TX.

hydraulic conductivity, which determines how fast a clay will depressurize, and the inelastic clay specific storage which determines how much a clay will compact under a given increase in drawdown. Both the clay vertical hydraulic conductivity and clay inelastic specific storage are observed to be strongly correlated with depth of burial. That is, the deeper the depth of burial, the smaller the value, and the lesser the risk for compaction induced subsidence. Because no measurements of compaction or measurements of clay properties controlling compaction were available for the Jasper Aquifer, this study provides the foundation for future studies or modeling of subsidence in the Jasper Aquifer. Additionally, this study uses laboratory measurements based upon data collected in the Chicot and Evangeline Aquifers, which has broad applicability for the estimation of clay compaction properties in those aquifers.

NUMERICAL SIMULATION OF JASPER COMPACTION

A numerical groundwater flow model was developed to estimate compaction in the Jasper Aquifer in the study area based upon a hypothetical brackish groundwater development project. Groundwater flow models are numerical tools used to estimate a physical process under a defined set of conditions and represent a simplified version of reality. A numerical model was used to simulate compaction in the Jasper Aquifer because it allows the flexibility to include the spatial variability in clay bed occurrence and thickness in the study area and can efficiently predict both the timing and the amount of compaction that could occur. The numerical model was developed using the United States Geological Survey code MODFLOW SUB which is the standard code used in the hydrogeologic community to predict compaction and subsidence and is the code that was used in the development of the Houston Area Groundwater Model. The model developed for this study is called the Jasper Compaction Model (JCM).

The JCM accounts for the variability in clay properties and aquifer depth of burial across the study area, where the occurrence of clay beds was based upon the nearest geophysical log. To analyze the effects of brackish production at different locations in the study area, a grid was constructed consisting of 9- by 9-mile square cells, with a hypothetical representative brackish groundwater production project at the center of each area. This resulted in 117 different

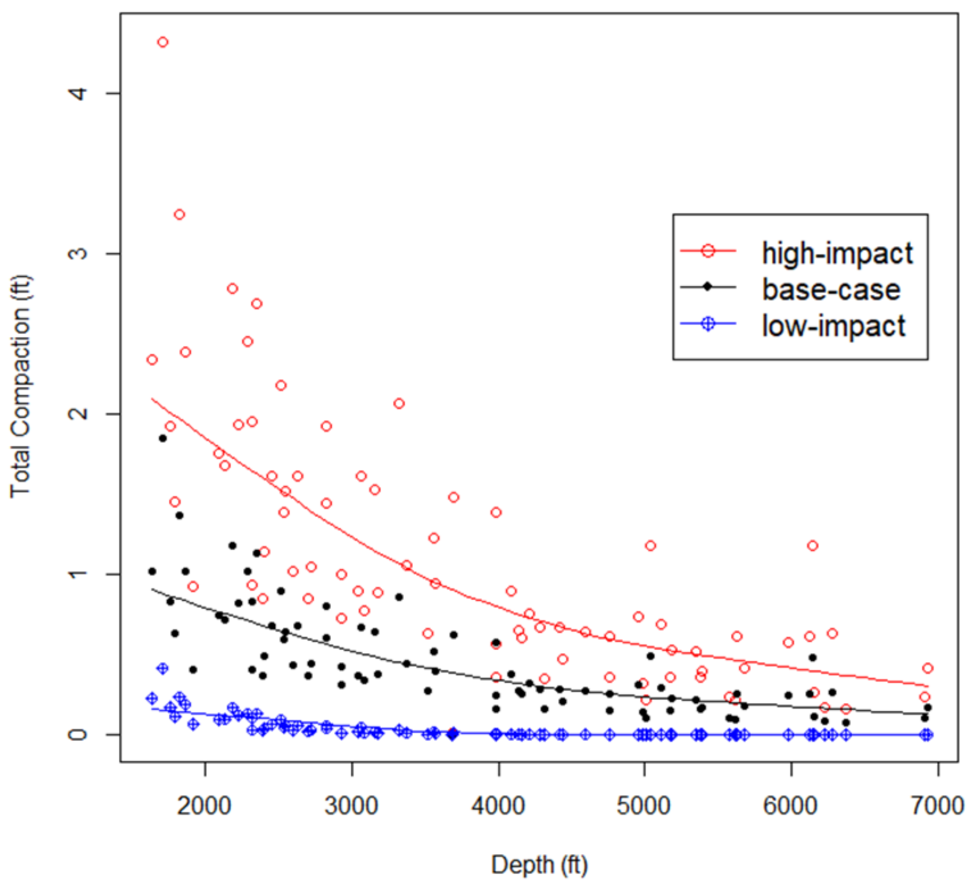

FIGURE 4. SIMULATED VARIATION OF 10-YEAR COMPACTION WITH DEPTH FOR THREE PARAMETER SENSITIVITY CASES.

models to simulate each of the representative project locations. Because compaction is dependent on drawdown and not production rate, each hypothetical project was assumed to have an equal drawdown of 500 feet.

Because of a lack of measurements of compaction and clay properties in the Jasper Aquifer, there is uncertainty associated with the best estimate parameters controlling compaction. Two additional model scenarios, a low impact and a high impact, were developed to explore the sensitivity of the model results to variations in the model input parameters (Figure 4). The low-impact simulation assumed parameter values within the range of possibility that minimized the potential for compaction to occur. The high-impact simulation assumed parameter values within the range possibility that maximized the potential for compaction to occur. The results of all three scenarios (Low, Base, and High) in the Jasper Aquifer are presented in Figure 4 as predicted compaction after 10 years of brackish production versus the depth of production. At shallower depths (less than 2,000 feet), an average of about 1 foot of cumulative compaction will occur over 10 years (0.1 feet/year) for the base case. Alternatively, at those same depths, about 2.0 feet and 0.2 feet of compaction will occur over the 10 years of production for the high and low impact scenarios respectively. While not the focus of this study, it is clear from a review of Figure 4 that areas shallower than approximately 2,000 ft. below ground surface in the Jasper Aquifer have a higher risk of compaction as compared to the deeper brackish portions of the aquifer.

A review of the results of the groundwater water flow model created for this study show that areas shallower than approximately 2,000 feet below land surface in the Jasper Aquifer have a higher risk of compaction as compared to the deeper brackish portions of the aquifer

RISK OF SUBSIDENCE INDUCED BY COMPACTION OF THE JASPER AQUIFER DUE TO INCREASED DEVELOPMENT

The objective of the Jasper Aquifer subsidence risk assessment is to develop a relative measure of risk of subsidence associated with pumping brackish groundwater in the Jasper Aquifer. It is understood that, due to lack of data in the brackish portions of the Jasper Aquifer, absolute estimates of compaction are uncertain. However, the available data from shallower aquifers and the theoretical and conceptual relationships that have been used to simulate compaction in the Jasper Aquifer provide adequate knowledge for developing measures of relative risk.

The calculated normalized risk, assuming the hypothetical development of the Jasper brackish aquifer, was determined based on three risk categories; Jasper aquifer predicted compaction, land subsidence and consequence from subsidence. The performance measures for each risk category are, respectively: Jasper Compaction Model predicted cumulative compaction at 50 years, (2) depth to the top of the Jasper aquifer, and (3) the presence of the FEMA 100-year flood plain. A combined Total Subsidence Normalized Risk Score (TSNRS) was calculated based on the performance measures throughout the model on a one-mile risk grid. The TSNRS ranges from zero to 1.0 with 1.0 being the maximum relative risk of subsidence and zero being the minimum relative risk of subsidence.

The TSNRS was determined across the entire study area, results for the brackish resources of the Jasper aquifer are included in Figure 5. The boundary was developed based upon both Jasper aquifer groundwater quality and the location of Jasper aquifer fresh groundwater production wells. Generally, development of groundwater in the shallower areas of the Jasper aquifer is at a higher risk of causing subsidence. Areas of high risk include southern Waller County, Northern Harris County, and Southern Montgomery County.

The relative risk of subsidence induced from development of brackish water from the Jasper Aquifer decreases from the highest risk in northern Harris County and Southern Waller County to lowest risk near the Texas Coast.

The TSNRS map was developed to provide a means of estimating the relative risk of subsidence from a Jasper Aquifer brackish groundwater development project being developed in one location versus another location. The results have not been presented in an absolute context because of the uncertainty in predicting the potential compaction that may occur within the brackish portions of

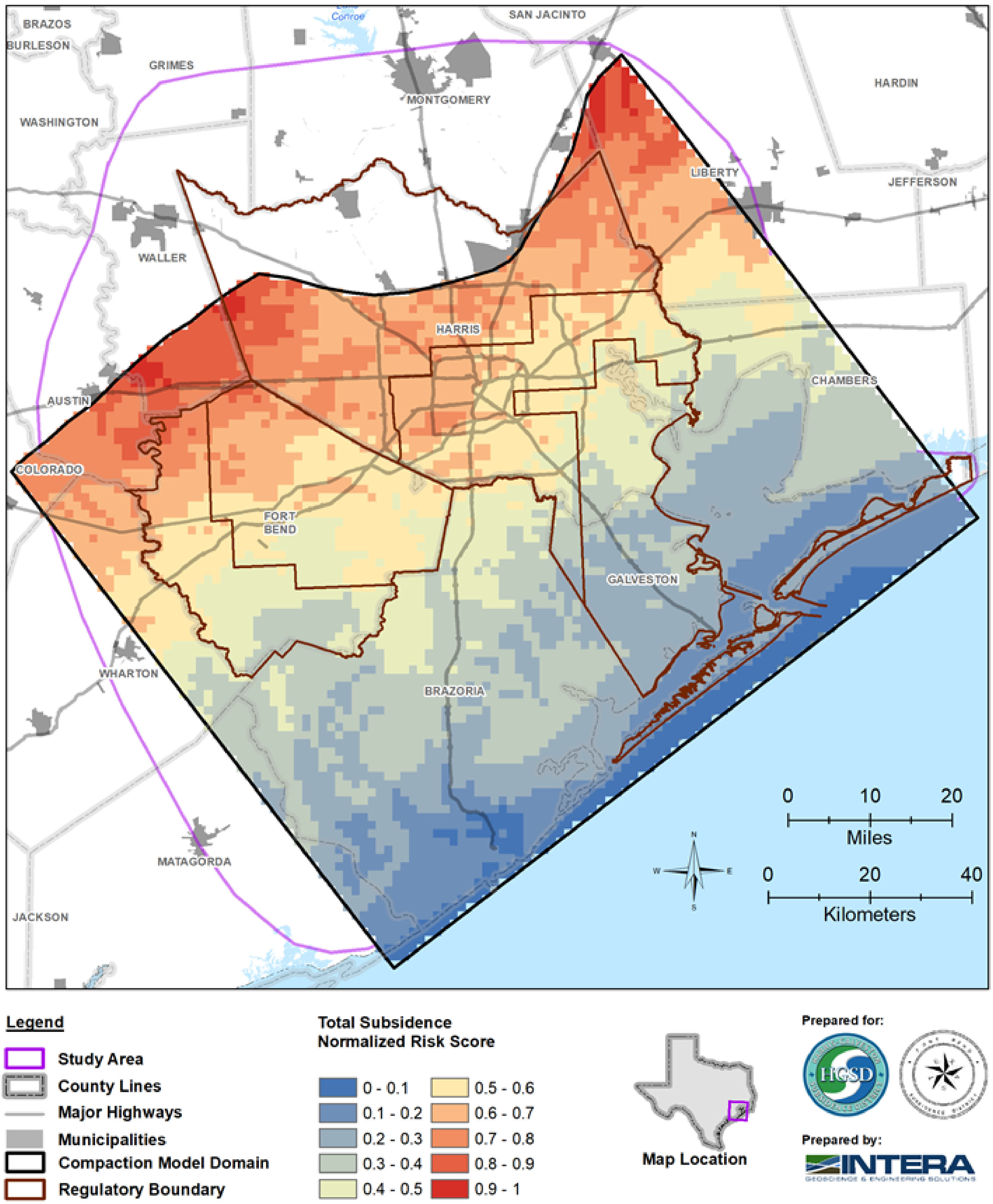

FIGURE 5. MAP OF THE JASPER AQUIFER TOTAL SUBSIDENCE NORMALIZED RISK SCORE.

the Jasper Aquifer. However, the study results provide a basis for the Districts to inform regulation of brackish groundwater production within the Jasper Aquifer and to communicate relative risks of such development at one location versus another.

As is the case for any predictive modeling application, there are limitations to this risk assessment of the brackish Jasper aquifer groundwater development presented in this report. Although these limitations do not undermine the conclusions of this study, they should be considered when evaluating the results. Key limitations include:

- Parameter values associated with the clay compaction properties of the Jasper Aquifer were estimated based on a review of the available data from other portions of Gulf Coast Aquifer. Parameter values used in this study are consistent with the available data and data trends measured in the shallow aquifers.

- The compounding effects of wide-spread development of the resources was not simulated in the Jasper Compaction Model. Each well field was modeled independently which does not account for the potential for drawdown in the freshwater section propagating downdip into the brackish portions of the aquifer, increasing the drawdown and potential compaction.

- Published literature indicates that subsidence resulting from compaction at depth is a function of both the lateral extent of drawdown and the depth of burial. This study uses a simple proxy of depth to the top of the Jasper Aquifer to inform this relationship between compaction and subsidence.

- The impact of compaction in the overlying sediments on the occurrence of subsidence due to compaction in deeper sediments was not explicitly explored in this study.

RELEVANCE AND POTENTIAL IMPACT ON FUTURE REGULATIONS

This study is the first District-wide study of the potential for subsidence from brackish groundwater development in the Jasper aquifer. The study indicates that compaction and resulting subsidence is likely to occur from significant Jasper groundwater development. This study provides new insight to the conceptual model of how compaction and subsidence may be impacted by the development of the shallow Jasper aquifer.

The results of this study have led to the development of recommendations for future data and research requirements for brackish groundwater development projects. Recommendations are based upon the need for data collection and research to better understand aquifer performance and to better manage subsidence risk.

A two-tiered system of data collection and research activities were recommended to provide additional information for potential future brackish groundwater development projects (Table 1). Tier 1 and Tier 2 activities are consistent with the mission of the Districts and are considered reasonable given the need for basic data in the brackish Jasper Aquifer. Tier 2 activities may be considered by the Districts when a project is considered of higher risk.

This risk assessment provides a context for the Districts as they consider the potential regulation of brackish groundwater development. The risk analysis and the recommendations related to data collection and research may be evaluated and included in future regulatory plans. As brackish resources become viable for development within the Districts, additional data collection and research of the aquifer below 2,000 feet will be necessary.

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Table 1. List of Tier 1 and Tier 2 data research activities recommended to be included in brackish groundwater development projects.

Category	Tier One Recommendations	Tier Two Recommendations
Well Design and Completion Documentation	Well Design Engineering Drawings Well Testing Plan Well Completion Report	*No Additional Recommendations Beyond Tier One Requirements*
Geophysical Logs	Caliper Density (Gamma Gamma) Temperature, Resistivity, Induction, Spontaneous Potential Porosity Cement-Bond	Acoustic Dipole Magnetic Resonance, Natural Gamma Spectroscopy, Elemental Capture Spectroscopy
Hydraulic Data	36-hour Aquifer Test Static Water-level	Installations of monitoring well(s) near wellhead
Geochemical Data	Water Quality Samples Water Quality Estimated from logs at Specific Depth Intervals Depth Dependent Water Quality Samples	Interval Specific Water Sampling
Geotechnical Core Data	*No Recommendation*	Clay Compressibility Clay Vertical Hydraulic Conductivity Clay Mineralogy
Modeling	Modeled drawdowns and radius of influence	Compaction model using District parameters and tools
Monitoring	Monthly Water Level Measurements Surface Land Subsidence Monitoring Station (PAM) Installation	Continuous water-level monitoring Extensometer Installation Maximum allowable drawdown
Subsidence Management Plan	Estimate potential subsidence over expected project timeline Establish protocol for monitoring and reporting subsidence Develop a plan to address measured subsidence	*No Additional Recommendations Beyond Tier One Requirements*

PUBLICATIONS

Young, S.C., Kelley, V., Deeds, N., Hudson, C., and Piemonti, D., 2017. Report on the Delineation of Fresh, Brackish, and Saline Groundwater Resources Based on Interpretation of Geophysical Logs, Harris-Galveston Subsidence District Consulting Report 2017-001, 216p.

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Kelley, V., Deeds, N., Young, S.C., and Pinkard, J., 2018. Subsidence Risk Assessment and Regulatory Considerations for the Brackish Jasper Aquifer, Harris-Galveston Subsidence District Consulting Report, 2018-001, 69 p.