SUBSIDENCE RISK ASSESSMENT AND REGULATORY CONSIDERATIONS FOR THE BRACKISH JASPER AQUIFER

Harris-Galveston and Fort Bend Subsidence Districts

Final Report

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May 2018

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Van A. Kelley (P.G. 4923) was the Project Manager and Principal Investigator for this study. All work performed was under the direct supervision of Van A. Kelley. It is not to be used for construction, bidding or any other purposes not specifically sanctioned by the authors.

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Neil Deeds was (P.E. 92741) was the technical lead for development of the Jasper Risk Model and he supervised all modeling associated with this report. Dr. Deeds also participated in the development of the conceptual model for prediction of compaction in the Jasper Aquifer.

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Steve C. Young (P.G. 231) was the technical lead for the development of the conceptual model for prediction of compaction in the Jasper Aquifer and in that role Dr. Young reviewed available geotechnical data from cores taken from USGS boreholes in the Houston area in the Gulf Coast Aquifer.

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Zhuping Sheng (P.E. 87496) provided peer technical review for the study. Dr. Sheng supported the interpretation of geotechnical core analyses in the literature. Dr. Sheng also reviewed the conceptual model for prediction of compaction in the Jasper Aquifer and provided comment on the risk assessment and the relevant limitations and assumptions.

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Acknowledgments:

The authors would like to acknowledge John Seifert (WSP) for improvement in our understanding of the Jasper Aquifer through his contribution of hydrogeologic data for the Jasper Aquifer and his review of the Jasper Risk Assessment Model. We would also like to acknowledge Scott Marr (HDR) for his support in understanding the historical application of PRESS in the Houston area to model compaction and for his review of the conceptual model for prediction of compaction in the Jasper Aquifer. Finally, we would like to thank Mike Turco (Harris-Galveston and Fort Bend Subsidence Districts) and his staff for supporting this project and providing feedback as the study progressed. We would finally like to thank Bill Mullican of Mullican and Associates who provided third party review during this project on behalf of the Harris-Galveston Subsidence District. The report has been much improved with these contributions.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACROYNMS AND ABBREVIATIONS

%	percent
amsl	above mean sea level
bgs	below ground surface
CORS	Continuously Operating Reference Stations
FEMA	Federal Emergency Management Agency
FBSD	Fort Bend Subsidence District
ft	feet
GPS	global positioning system
gpm	gallons per minute
GRP	Groundwater Reduction Plan
HGSD	Harris-Galveston Subsidence District
HAGM	Houston Area Groundwater Model
JCM	Jasper Compaction Model
mg/L	milligrams per liter
MGD	million gallons per day
MRI	magnetic resonance image
MUD	municipal utility district
NRS	normalized risk score
PAM	Port-A-Measure
psi	pounds per square inch
SDR	Submitted Drillers Reports
SUB	MODFLOW subsidence
TCEQ	Texas Commission of Environmental Quality
TDLR	Texas Department of Licensing and Regulation
TDS	total dissolved solids
TSNRS	Total Subsidence Normalized Risk Score
TSRS	Total Subsidence Risk Score
TWDB	Texas Water Development Board
USGS	United States Geological Survey

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1.0 INTRODUCTION

Recently, in Texas, there has been significant interest in brackish groundwater resources as a water supply alternative to fresh groundwater and surface water. The Texas Water Development Board (TWDB) defines brackish groundwater as having a total dissolved solids (TDS) concentration from 1,000 to 10,000 milligrams per liter (mg/L). Significant brackish groundwater resources exist in the Gulf Coast Aquifer System within the boundaries of the Harris-Galveston and Fort Bend Subsidence Districts (the Districts). Recently, projects have been proposed, and in some cases been implemented, to produce brackish groundwater in both Districts from the Jasper Aquifer.

This report estimates the relative risk of subsidence associated with development of brackish groundwater in the Jasper Aquifer of the Gulf Coast Aquifer System within the Districts. The study area extends past the District's boundaries (**Figure 1-1**). This section of the report provides the study background and a statement of study objectives.

In 2015, both Districts adopted Science and Research Plans to define the strategic direction for science and research they conducted or supported (Turco, 2015a; 2015b). In response to interest in brackish groundwater resource development, the Districts' respective Science and Research Plans identified that research should be performed to:

- Develop a more vertically and horizontally resolute depiction of the hydrostratigraphy of the Districts and surrounding areas; and
- Determine the occurrence and hydrogeologic characteristics of the brackish resources within the Districts and surrounding areas.

Young and others (2017) completed a report documenting the detailed hydrostratigraphy and occurrence of brackish groundwater resources within the study area defined in Figure 1-1 was completed for the Districts in 2017. Their results provide the necessary detailed lithologic and water quality data to perform the Jasper Aquifer brackish groundwater development risk assessment. The objectives of this risk assessment are to:

- Assess potential risk of subsidence that may result from development of brackish groundwater resources in the Jasper Aquifer within the Districts; and
- Provide the Districts with guidance regarding the types of activities and data that would benefit the consideration as special provisions to Jasper Aquifer brackish production permits.

The Jasper Aquifer brackish groundwater development risk assessment scope of work documented in this report was performed for the Districts, Contract HGSD-2016-001 and Contract FBSD-2016-001, respectively.

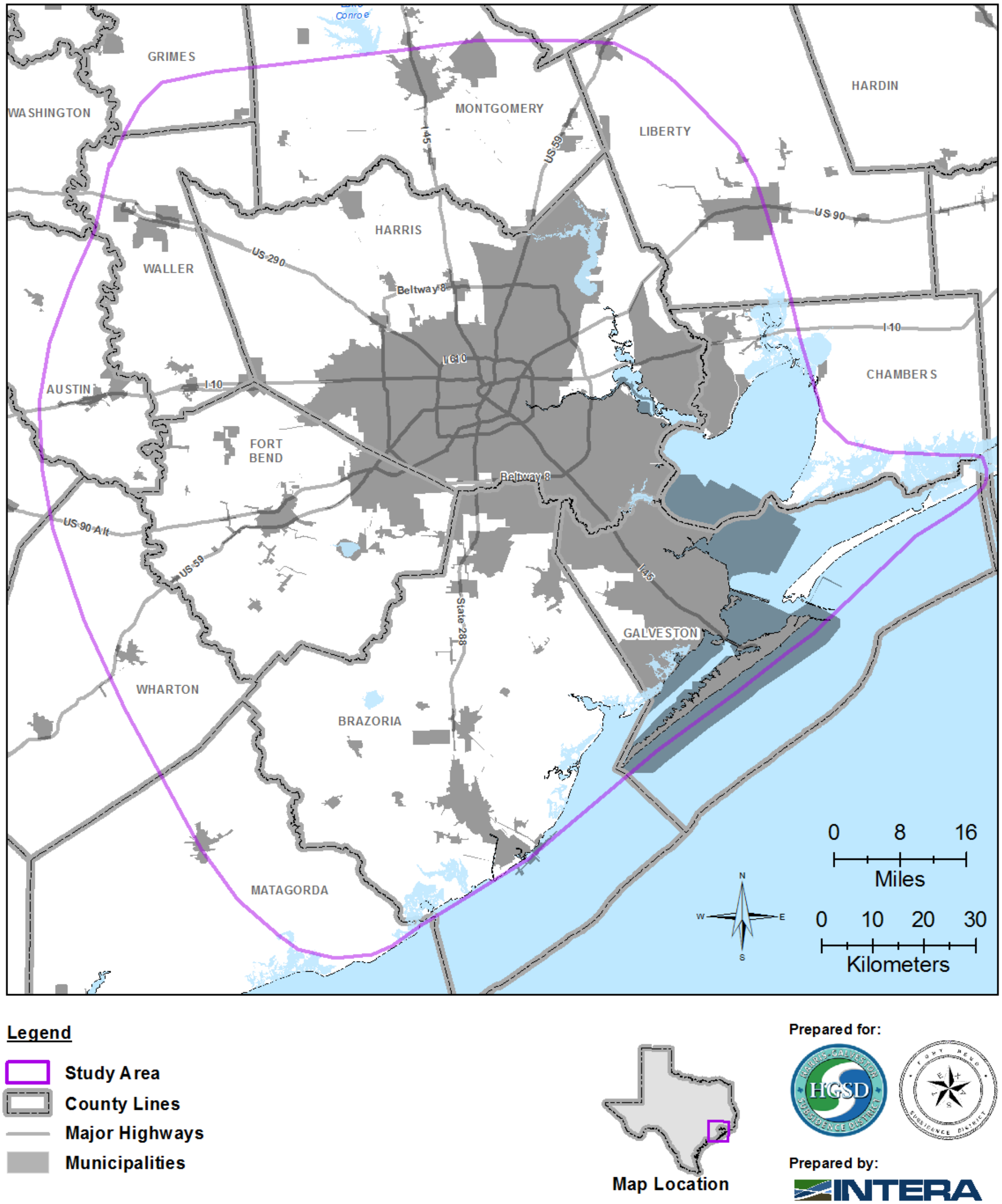


Figure 1-1 Boundary defining the study area

2.0 CONCEPTUAL MODEL FOR PREDICTION OF COMPACTION IN THE JASPER AQUIFER

This section introduces the concepts of compaction and subsidence, discusses the underlying properties and relationships used to characterize and predict subsurface compaction in the Jasper Aquifer, and reviews the available data for estimating the properties governing compaction. The section ends by summarizing our current conceptual understanding of compaction in the Jasper Aquifer as well as the parameterization of the properties governing compaction used in the remainder of this report to assess the relative risk of subsidence from brackish groundwater development in the Jasper Aquifer.

2.1 Introduction to Compaction and Subsidence

Jacob (1940) concluded that, when a confined aquifer is pumped, pressure decreases, and the compression of the aquifer matrix causes groundwater to be derived from the expansion of water. Jacob (1940) also concluded that most of the groundwater released from storage from aquifer compression was derived from fine-grained deposits (clays) within and surrounding the aquifer matrix. These fine-grained deposits are orders of magnitude more susceptible to compression than sands (Freeze and Cherry, 1979; Domenico and Schwartz, 1990). The fine-grained materials are generally referred to as interbeds. If pumping is significant, and the aquifer interbeds are underconsolidated, then irreversible compaction of the interbeds can occur.

When subsurface compaction occurs, this decrease in interbed thickness may propagate upward and result in the lowering of the land surface, which is termed "land subsidence." **Figure 2-1** shows the mechanism of compaction caused by a reduction in the aquifer pore-fluid pressure from groundwater withdrawal (Galloway and others, 1999; Kasmarek and others, 2016). The figure shows the thickness of the clayey aquifer before and after pumping. Before and after pumping, the total stress, or geostatic pressure, on the aquifer is the same.

In response to the reduction of pore-fluid pressure in the interstitial pores by pumping, the effective stress on the clay particles in the clay interbeds is increased by the same amount of pressure that that pore-fluid has is decreased. For both situations, before and after pumping, the total stress on the clayey aquifer from above is balanced by the pore-fluid pressure and effective stress on the clay particles in the clayey aquifer. The increase in the effective stress on the clay particles caused by the depressurization of groundwater in the aquifer causes the clay grains to reorient and shift position, which leads to consolidation of the aquifer (Galloway and others, 1999; Kasmarek and others, 2016).

Figure 2-1 shows a simplified version of reality, with all the subsurface compaction manifesting as subsidence at land surface. Subsidence may be attenuated compared to compaction, depending on the depth at which compaction occurs, the area over which compaction occurs, and the geomechanical characteristics of the overlying sediments. Rigorous consideration and quantification of the relationship between compaction and subsidence is beyond the scope of the current study. The remainder of Section 2 considers factors governing compaction. However, the relationship between compaction and subsidence is discussed in Section 4 when considering factors that drive the overall risk of subsidence due to groundwater withdrawals from the Jasper Aquifer.

2.2 Properties that Govern Compaction

In this subsection, we first discuss the physical process of one-dimensional compaction, which quantifies the ultimate compaction that will occur under steady-state conditions, and describe the key properties underlying this process. Second, we discuss the process of delayed compaction, and which properties can govern the rate at which compaction occurs. Finally, we discuss the concept of preconsolidation stress, which determines the stress conditions under which compaction will begin to occur.

2.2.1 Ultimate Compaction: Overall Bed Thickness and Compressibility

Terzaghi (1925; Terzaghi and Peck, 1967) developed the theory for one-dimensional consolidation of clays that has served as the basis for the mathematical equations describing most practical soil mechanics and land subsidence problems for the past half century. This theory is commonly used to estimate the magnitude and rate of settlement or compaction that will occur in aquifers under a given change in load (stress). The change in load can be caused by adding weight on the ground, such as the construction of a large building, or by reducing fluid pore-pressure in an aquifer, such as by pumping groundwater.

In developing his consolidation theory in 1925, Terzaghi introduced the basic principle of effective stress, σ', which is defined as:

$$\sigma' = \sigma - P \qquad \text{(Equation 2-1)}$$

where:

- σ' = effective stress or intergranular stress (effective stress, or pressure, at the grain-to-grain contact points in a deposit)
- σ = total stress on the deposit (geostatic pressure on the deposit caused by the weight of the overlying water and subsurface material above a deposit)
- P = pore-fluid pressure (hydraulic head in the interstitial pores of a deposit)

In a confined aquifer system, the change in effective stress at any point in an aquifer is equivalent to the change in pore-fluid pressure (Poland and Davis, 1969).

$$d\sigma' = dP \qquad \text{(Equation 2-2)}$$

The change in aquifer level is directly related to this change in pore-fluid pressure:

$$\Delta h = dP / \rho g \qquad \text{(Equation 2-3)}$$

where:

- ρ = water fluid density
- g = gravitational constant
- Δh = change in hydraulic head
- d = delta operator

In a confined system, under assumptions that incremental changes in effective stress are small, compaction can be related directly to this change in hydraulic head:

$$\Delta b = \Delta h b Ss \qquad \text{(Equation 2-4)}$$

where:

Δb = change in thickness of sediment layer (compaction)

b = overall thickness of sediment layer

Ss = specific storage

The key properties that drive ultimate compaction are the change in stress (drawdown), the overall thickness of the fine-grained sediments, and the specific storage. Because nearly all compaction occurs in the clay beds, we will focus on parameterizing the overall thickness and specific storage of the clay beds.

2.2.2 Rate of Compaction: Individual Clay Bed Thickness and Vertical Conductivity

Compaction occurs due to the change in pore pressure in the clay beds in an aquifer. The change in stress originates where the water is withdrawn (mostly the sand layers). It takes time for the pressure change in the sands to propagate into the clays to the point where the pressure in the clays has equilibrated and ultimate compaction has occurred.

Figure 2-2, reproduced from Leake and Prudic (1991) and Hoffman and others (2003), illustrates this concept. Figure 2-2A shows a clay-rich interbed that lies between two layers of aquifer sediments (more coarse-grained sediments). When pressure decreases in the aquifer due to pumping, water will move from the interbed's center to the aquifer. The pressure in the interbed where it interfaces with the aquifer will change immediately, and compaction will begin. As more water moves from the interbed's center, the change in pressure propagates towards the center, and compaction occurs deeper in the interior of the interbed. Figure 2-2B shows the effect of this delay, as compaction occurs fastest when the pressure change first occurs, but then the rate of compaction slows as compaction nears its ultimate compaction value.

The time constant τ_0, at which about 93 percent (%) of the ultimate compaction will occur, can be expressed as (Hoffman and others, 2003):

$$\tau_0 = \frac{\left(\frac{b_0}{2}\right)^2 S_s}{K_v} \qquad \text{(Equation 2-5)}$$

where

b_0 = the thickness of the clay interbed

S_s = the specific storage of the clay interbed

K_v = the vertical conductivity of the clay interbed

So, while the specific storage is important to both the ultimate compaction (Equation 2-4) and the rate at which compaction occurs, the rate is also governed by the thickness and vertical hydraulic conductivity of the individual clay interbeds.

2.2.3 Stress at Which Compaction Begins: Drawdown at Preconsolidation Stress

An aquifer has typically experienced many different stress regimes since initial deposition of the sediments, and an overburden has developed. Preconsolidation stress is the maximum effective stress that an aquifer has sustained in the past. An aquifer may be currently experiencing this maximum effective stress, in which case it is termed "normally consolidated." If the current stress is less than the preconsolidation stress, then the aquifer is termed "overconsolidated." An overconsolidated aquifer can experience additional stress (drawdown) without compaction occurring because the clays in the aquifer had been previously compacted under a higher stress regime. This assumes that the clays reached ultimate compaction under the preconsolidation stress.

If effective stress is less than preconsolidation stress, then changes in stress will result in *elastic* (reversible) compression of both the sands and clays in the aquifer. When stress exceeds the preconsolidation stress, then the clays in the aquifer will begin to experience *inelastic* (irreversible) compression. In both cases, Equation 2-4 can be applied, but the specific storage (S_s) is different depending on whether the compression is elastic or inelastic. The elastic specific storage is typically much smaller than the inelastic specific storage.

The drawdown stress that creates an effective stress condition that is equal to the preconsolidation stress is called “drawdown at preconsolidation stress.” When current drawdown is less than the drawdown at preconsolidation stress, then the elastic specific storage will apply. When current drawdown exceeds the drawdown at preconsolidation stress, then inelastic specific storage will apply, and compaction will begin to occur (Hoffman and others, 2003).

2.3 Compaction Properties in the Gulf Coast Aquifer System

In the previous subsection, we detailed the properties that were important for developing a conceptual model of compaction in the Jasper Aquifer. They are the specific storage, the thickness of clay beds, the vertical hydraulic conductivity of the clays, and the drawdown at preconsolidation stress. In this subsection, we discuss the available data and our approach to characterization of these properties in the Gulf Coast Aquifer System. It is important to note that none of the physical measurements presented in this subsection have been collected at depths representative of the brackish Jasper Aquifer in the Districts. As a result, trends determined from the available data and prior subsidence modeling will be used to inform trends in deeper portions of the Gulf Coast Aquifer System. Properties controlling compaction of the brackish Jasper Aquifer should be considered uncertain.

2.3.1 Inelastic and Elastic Specific Storage

Specific storage is not directly measured in a laboratory but can be related to porosity and compressibility, which can be measured in core samples. Laboratory measurements of porosity and compressibility are reported by the United States Geological Survey (USGS) for three study areas near Houston, Texas (Gabrysch and Bonnet; 1974, 1976a, 1976b). The clay samples were obtained from cores of the Gulf Coast Aquifer System from three sites: Seabrook, Moses Lake, and near Baytown. The clay samples were collected at regular depth intervals to a maximum depth of 1,700 feet (ft). Consolidometer testing was performed on each clay sample using a sequence of increasing confining pressures.

INTERA used the consolidometer test data to generate relationships between porosity and compressibility of clays with effective depth of burial. INTERA developed these relationships using only measurements made on the clay samples where the applied pressure was greater than the pressure the clay sample is calculated to have experienced in-situ. The effective depth of burial is calculated by dividing the pressure applied to the core sample by a geostatic gradient of 0.467 pounds per square inch (psi) per foot of burial depth. Thus, an applied pressure of 100 psi would represent a burial depth of

214 ft. **Figure 2-3** shows porosity plotted as a function of effective depth of burial. The data exhibit a significant decrease in clay porosity with depth of burial.

The regression equation in Figure 2-3 and defined below (Equation 2-6) was used to generate porosity values (n) in **Table 2-1**.

$$n = 1.4485D^{-0.233} \qquad \text{(Equation 2-6)}$$

Where:

D = depth below ground surface

n = porosity

Equation 2-6 produces a 50% decrease in porosity from a depth of 100 to 3,000 ft. This relationship is derived from core collected from clay interbeds. Porosity changes as a function of depth for sand dominated beds is much less than for clay interbeds.

Figure 2-4 plots the compressibility coefficient of clay (α) as a function of effective depth of burial, based on the same clay consolidation dataset. This figure shows that clay compressibility decreases as a function of effective depth of burial. The regression equation in Figure 2-4 for inelastic compressibility of clay is:

$$\alpha = 3.0x10^{-6}D^{-0.703} \qquad \text{(Equation 2-7)}$$

Where:

α = clay compressibility coefficient

Application of Equation 2-7 produces a ten-fold decrease in the compressibility coefficient of clay for an increase in effective depth of burial from 100 to 3,000 ft (Table 2-1). The calculated inelastic compressibility coefficients were used to define values for elastic compressibility of clay. In Table 2-1, values for elastic compressibility are generated by dividing the inelastic compressibility by a factor of 100. A factor of 100 is based on results presented by Holzer (1981) and Kasmarek (2013) for the Texas Gulf Coast Aquifer System near Houston, Texas. Elastic compression is generally a linear process while inelastic compression is non-linear. The relationship between elastic and inelastic compressibility is worthy of future study in the study area.

The clay compressibility values are converted to a specific storage using Equation 2-8, the porosity values in Table 2-1, and a compressibility coefficient of 4.4E-10 meters squared per Newton (m^2/N) for water.

$$Ss = \rho g(\alpha + n\beta) \qquad \text{(Equation 2-8)}$$

Where:

Ss = specific storage

ρ = density of water

g = acceleration of gravity

α = clay compressibility coefficient

n = porosity

β = water compressibility coefficient

In Table 2-1, clay specific compressibility is equal to (ρgα).

2.3.2 Thickness of the Clay Beds

Young and others (2017) included a detailed lithologic analysis of 294 geophysical logs in the study area. Each log has the sand and clay intervals identified for the formations that comprise the Gulf Coast Aquifer System. The variation in the number and thickness of clay beds is known at each log location. **Figure 2-5** shows a histogram of the clay bed thicknesses in the study area, grouped by aquifer. The average clay bed thickness increases with depth of aquifer, with the Jasper Aquifer consisting of about 5% beds greater than 160 ft thick, compared to <1% of the beds in the Chicot Aquifer. The 294 geophysical logs with lithology data will be used to characterize directly local clay bed counts and thicknesses at any point in the study area.

2.3.3 Vertical Hydraulic Conductivity of Clays

The vertical hydraulic conductivity assigned to clays can be based on measurements performed by the USGS on cores collected near Baytown, TX (Gabrysch and Bonnet, 1974) and on values extracted from calibrated PRESS models for 26 sites in Fort Bend, Harris, and Galveston counties (Fugro, Inc., 2013). PRESS is a code that was developed to simulate one-dimensional subsidence and is discussed in more detail in Section 3.1.

The USGS (Gabrysch and Bonnet, 1974) used consolidometers to measure hydraulic conductivity on clay samples exposed to different loads (confining pressure). **Figure 2-6** shows measured vertical hydraulic conductivity plotted as a function of effective-burial depth. Figure 2-6 only plots results from core vertical hydraulic conductivity measurements made on clay samples where the applied pressure was greater than the pressure the clay sample is calculated to have experienced in-situ. The data in Figure 2-6 support a log-log relationship between vertical hydraulic conductivity and depth that is expressed in the regression equation in Figure 2-6.

Investigators in the Houston region have been modeling subsidence using a one-dimensional compaction code called PRESS since the 1980s (Espey, Huston and Associates, Inc., 1982; Fugro, Inc, 2013). Estimation of vertical hydraulic conductivity of clay in the PRESS models is based on a depth relationship. **Figure 2-7** shows the relationship of vertical hydraulic conductivity versus depth as extracted from the inputs to the 26 PRESS models (Fugro, Inc., 2013). For this plot, depth represents the depth of midpoint of the clay layer in the PRESS model.

Our best estimate of a lower and upper bound for clay bed vertical hydraulic conductivity are derived from the best-fit lines shown on Figures 2-6 and 2-7, derived from the two data sources (Gabrysch and Bonnet, 1974; Fugro, Inc, 2013):

$$k_{v,lower} = 1.02x10^{-5}e^{-2.55x10^{-3}\,D} \quad \text{(Equation 2-9)}$$

$$k_{v,upper} = 0.0342D^{-1.321} \quad \text{(Equation 2-10)}$$

Where $k_{v,lower}$ is considered a lower bound estimate, and $k_{v,upper}$ is considered an upper bound estimate. An average of the two is considered the best estimate.

The regressions shown in Figures 2-6 and 2-7 are used to create the clay vertical hydraulic conductivity values for depths between 100 and 3,000 ft in **Table 2-2**. The difference between the two sets of tabulated values is about a factor 10 at a depth of 100 ft; the difference decreases to a depth of 1,000 ft and diverges to greater than an order of magnitude at depths greater than 1,000 ft.

2.3.4 Drawdown at Preconsolidation Stress

Drawdown at preconsolidation stress can be estimated based on the analysis of the same core data used to estimate compressibility (Gabrysch and Bonnet, 1974; 1976a; 1976b). For each core consolidation test, we applied the Casagrande method (Casagrande, 1936) to estimate the preconsolidation stress (reported as equivalent freshwater head). Our analysis includes 12 estimates of preconsolidation head for only the consolidometer tests where the consolidation curve provides a clear inflection point required for the interpretation methodology.

Figure 2-8 shows the preconsolidation stress (expressed as equivalent freshwater head) as a function of the burial depth for 12 clay samples. For example, two of the twelve clay samples were obtained at a depth of about 500 ft. Of these, one sample has a preconsolidation stress of 69 psi, which is equivalent to 160 ft of freshwater head, and the other sample has a preconsolidation stress of 208 psi, which is equivalent to 481 ft of freshwater head. A linear regression of the data from the 12 clay samples is shown as the green dotted line. The blue dotted line represents the net effective stress (expressed as freshwater head) as a function of burial depth. The blue dotted line was created by using an effective stress gradient of 0.467 psi/ft which accounts for the weight or overlying sediments and groundwater.

In our conceptual model, the drawdown amount that causes a transition from elastic compaction to inelastic compaction decreases as a function of depth. Using the data in Figure 2-8, the difference between the estimated effective stress, represented by the blue dotted line, and the preconsolidation stress, represented by the green dotted line, provide an estimate of the drawdown required before compaction occurs as an inelastic process, or drawdown at preconsolidation stress. In Figure 2-8, the drawdown at preconsolidation stress is 104 and zero ft at burial depths of zero (ground surface) and 423 ft, respectively. For depths shallower than 423 ft, both inelastic and elastic compaction can occur. Based upon this analysis using a limited data set, inelastic compaction occurs with the initiation of any drawdown at depths greater than 423 ft.

Drawdown at preconsolidation stress is conceptualized as being greatest at shallower depths and decreasing with depth. This means that, at shallow depths, some amount of drawdown can occur under elastic conditions. At deeper depths, inelastic compaction will occur immediately. Our two estimates at approximately what depth this occurs are 423 and 870 ft, from the laboratory core data and PRESS modeling, respectively.

Given the limited core dataset and the large amount of scatter among the data from the trendline used to estimate of 423 ft, we conceptualize the depth cutoff to be 870 ft. Again, because of the limited and uncertain core data set presented in Figure 2-8, we assumed the best estimate of drawdown at preconsolidation stress at ground surface is 75 ft, consistent with the average value used in the Houston Area Groundwater Model (HAGM; Kasmarek, 2003). Our conceptualization is that this value decreases linearly with depth until it reaches zero at 870 ft below ground surface (bgs).

Our conceptualization assumes that the drawdown at preconsolidation is at a maximum value at shallowest depths and decreasing to zero at some depth. This conceptualization is consistent with the parameterization of the current PRESS models. The 90th percentile depth value where preconsolidation drawdown is zero in the PRESS models is 870 ft using calibrated parameters from all 26 site models (Fugro, Inc., 2013). However, the relationship describing drawdown at preconsolidation stress is very uncertain. The conceptual approach for modeling drawdown at preconsolidation stress is conservative considering the depths of the brackish Jasper Aquifer.

Table 2-1 Estimated porosity, specific compressibility, and specific storage of clay beds as a function of depth of burial

Depth of Burial (ft)	Porosity Based on Regression in Figure 2-3	Clay Compressibility Coefficient (m²/N) based on Regression in Figure 2-4	Clay Specific Compressibility (1/feet)		Clay Specific Storage (1/feet)	
			Inelastic	Elastic	Inelastic	Elastic
100	0.50	1.2E-07	3.5E-04	3.5E-06	3.5E-04	4.2E-06
250	0.40	6.2E-08	1.8E-04	1.8E-06	1.9E-04	2.4E-06
500	0.34	3.8E-08	1.1E-04	1.1E-06	1.1E-04	1.6E-06
750	0.31	2.9E-08	8.5E-05	8.5E-07	8.6E-05	1.3E-06
1,000	0.29	2.3E-08	7.0E-05	7.0E-07	7.0E-05	1.1E-06
1,500	0.26	1.8E-08	5.2E-05	5.2E-07	5.3E-05	8.7E-07
2,000	0.25	1.4E-08	4.3E-05	4.3E-07	4.3E-05	7.5E-07
2,500	0.23	1.2E-08	3.7E-05	3.7E-07	3.7E-05	6.7E-07
3,000	0.22	1.1E-08	3.2E-05	3.2E-07	3.3E-05	6.2E-07

Table 2-2 Estimated vertical hydraulic conductivity of clay beds as a function of depth of burial

Depth (ft)	Vertical Hydraulic Conductivity (feet/day)		
	Based on Regression in Figure 2-6 from USGS Lab Measurements	Based on Regression in Figure 2-7 from K_v Values Extracted from PRESS Models	Average of Values from USGS Lab Measurements and PRESS Models
100	7.80E-05	7.90E-06	4.29E-05
250	2.32E-05	5.39E-06	1.43E-05
500	9.30E-06	2.85E-06	6.08E-06
750	5.45E-06	1.51E-06	3.48E-06
1,000	3.72E-06	7.96E-07	2.26E-06
1,500	2.18E-06	2.23E-07	1.20E-06
2,000	1.49E-06	6.22E-08	7.76E-07
2,500	1.11E-06	1.74E-08	5.64E-07
3,000	8.72E-07	4.86E-09	4.39E-07

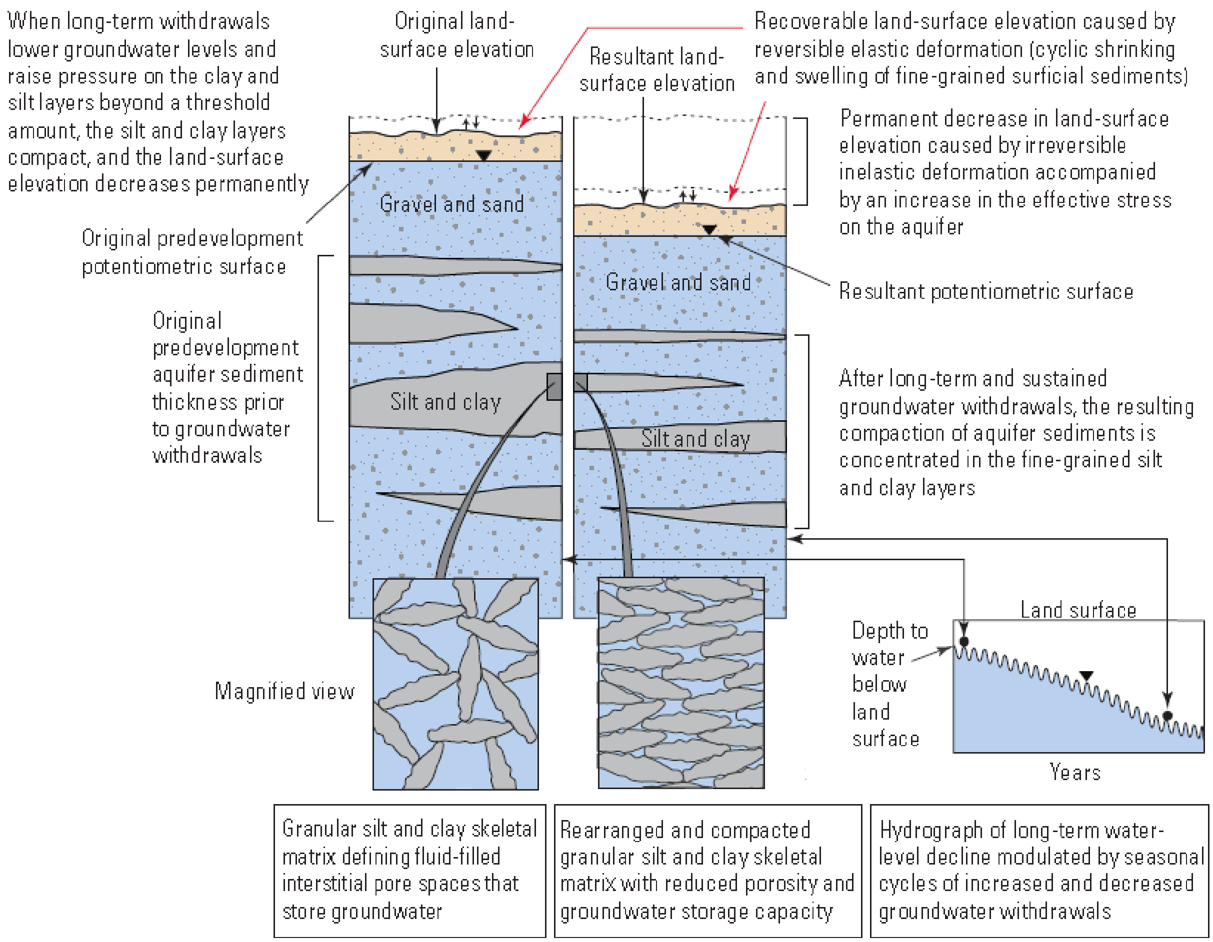
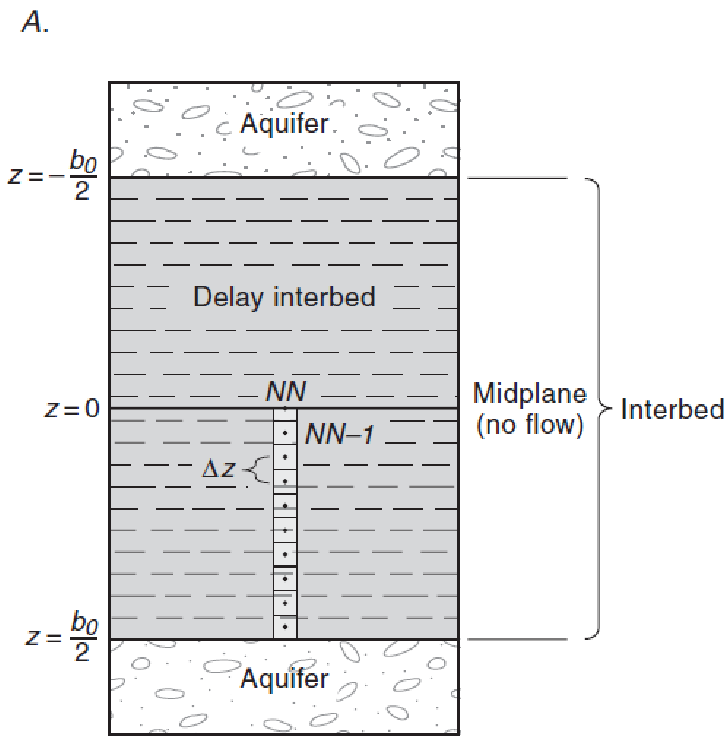


Figure 2-1 Mechanism of subsidence caused by potentiometric surface (pore-fluid pressure) declines induced from groundwater withdrawals in an aquifer composed of gravel, sand, silt and clay (Galloway and others, 1999; Kasmarek and others, 2016).



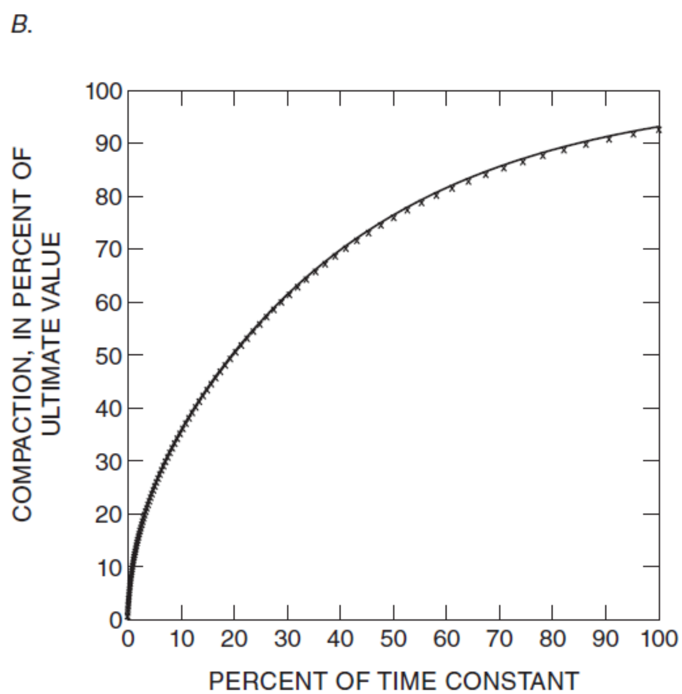


Figure 2-2 Illustration of the relationship between the aquifer layers and the clay-rich interbed layers (A) and the resulting delay in ultimate compaction that occurs (B) due to the time required for water to drain from the interbed and pressure to equilibrate between the aquifer and the interbed layers (Hoffman and others, 2003).

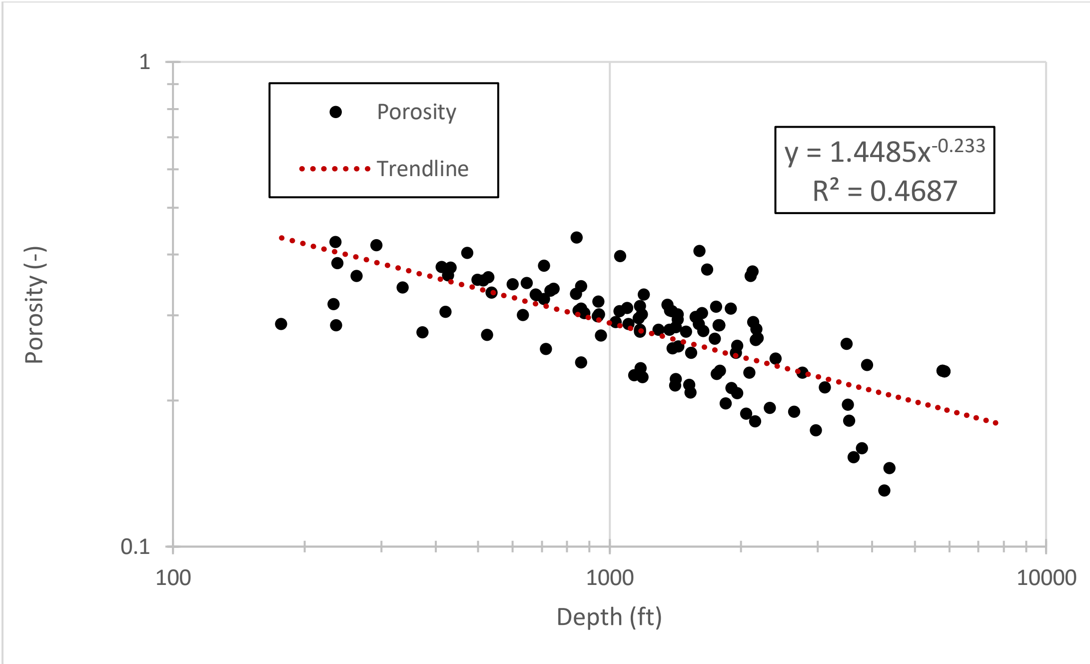


Figure 2-3 Porosity values as a function of depth for clay samples collected in the vicinity of Houston, Texas, and tested using a consolidometer Gabrysch and Bonnet, 1974, 1976a, 1976b)

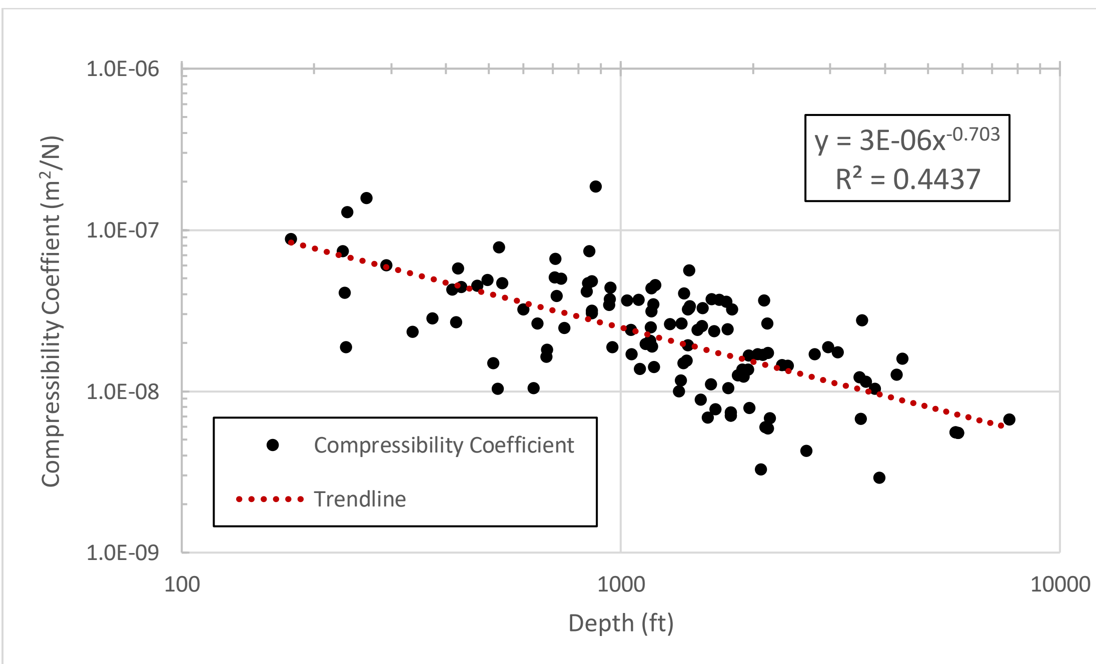


Figure 2-4 Compressibility coefficients as a function of depth for clay samples collected in the vicinity of Houston, Texas, and tested using a consolidometer (Gabrysch and Bonnet, 1974, 1976a, 1976b)

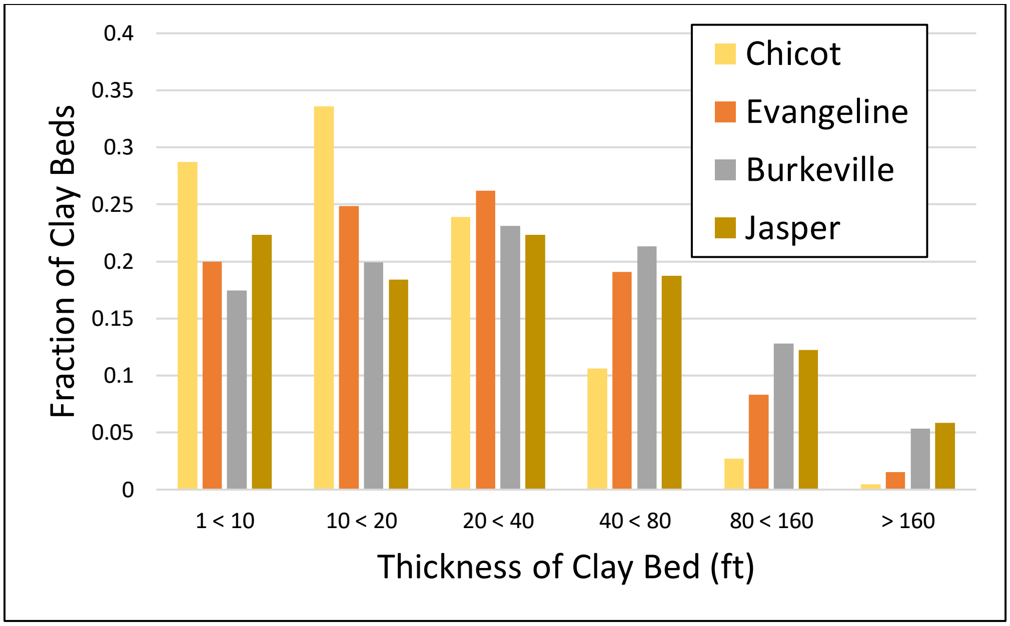


Figure 2-5 Distribution of clay bed thicknesses in the Gulf Coast Aquifer System based on geophysical log analyses in the study area

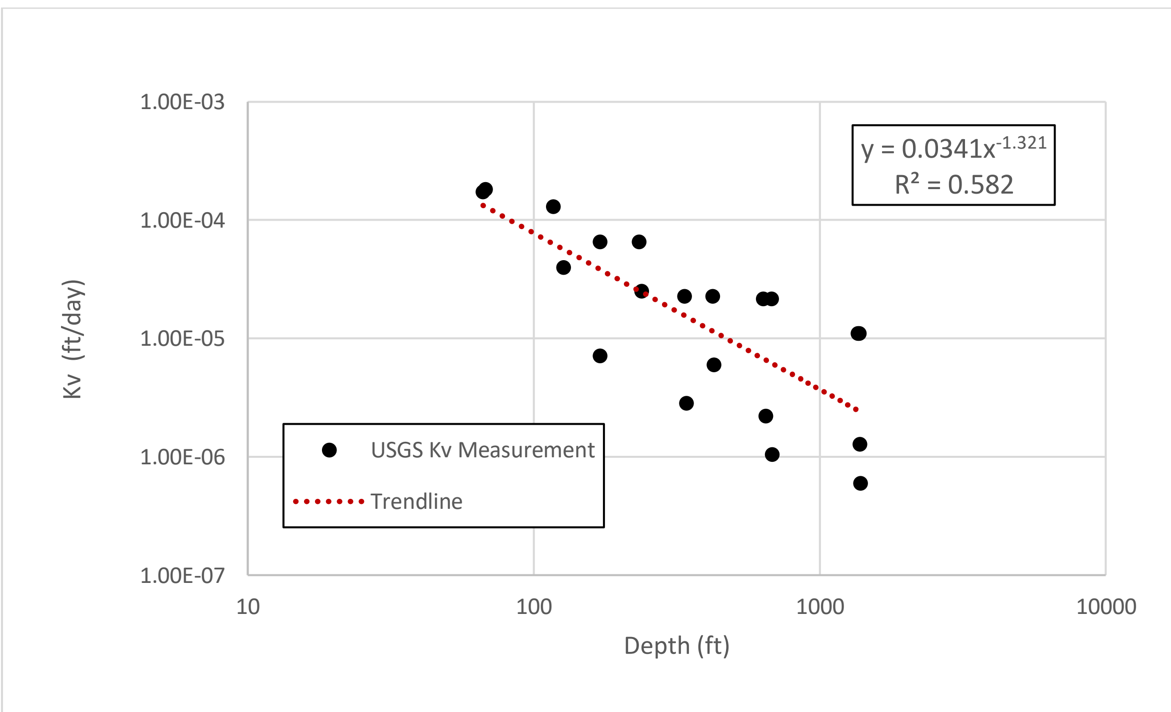


Figure 2-6 Measured vertical hydraulic conductivity performed by the USGS on clay core samples reported by Gabrysch and Bonnet (1974) near Baytown

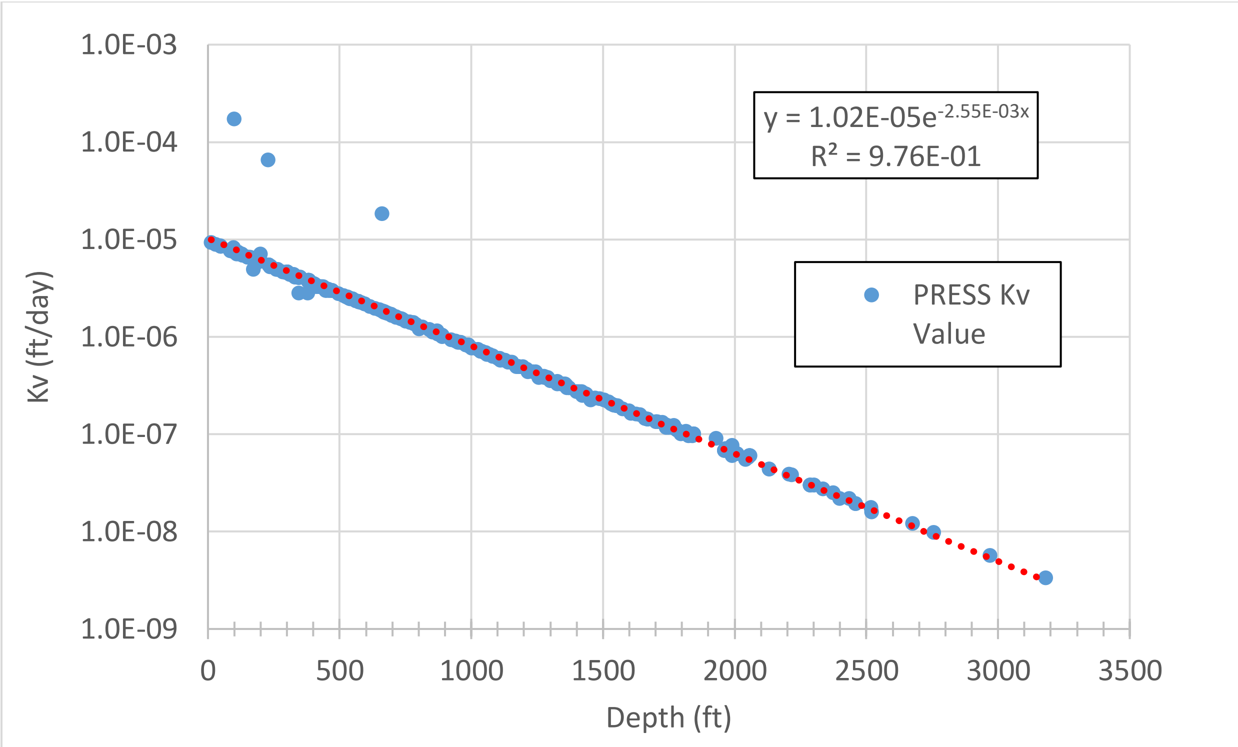


Figure 2-7 Vertical hydraulic conductivity for clay extracted from PRESS models for 26 PRESS Sites in the vicinity of Houston, Texas (Fugro, Inc., 2013)

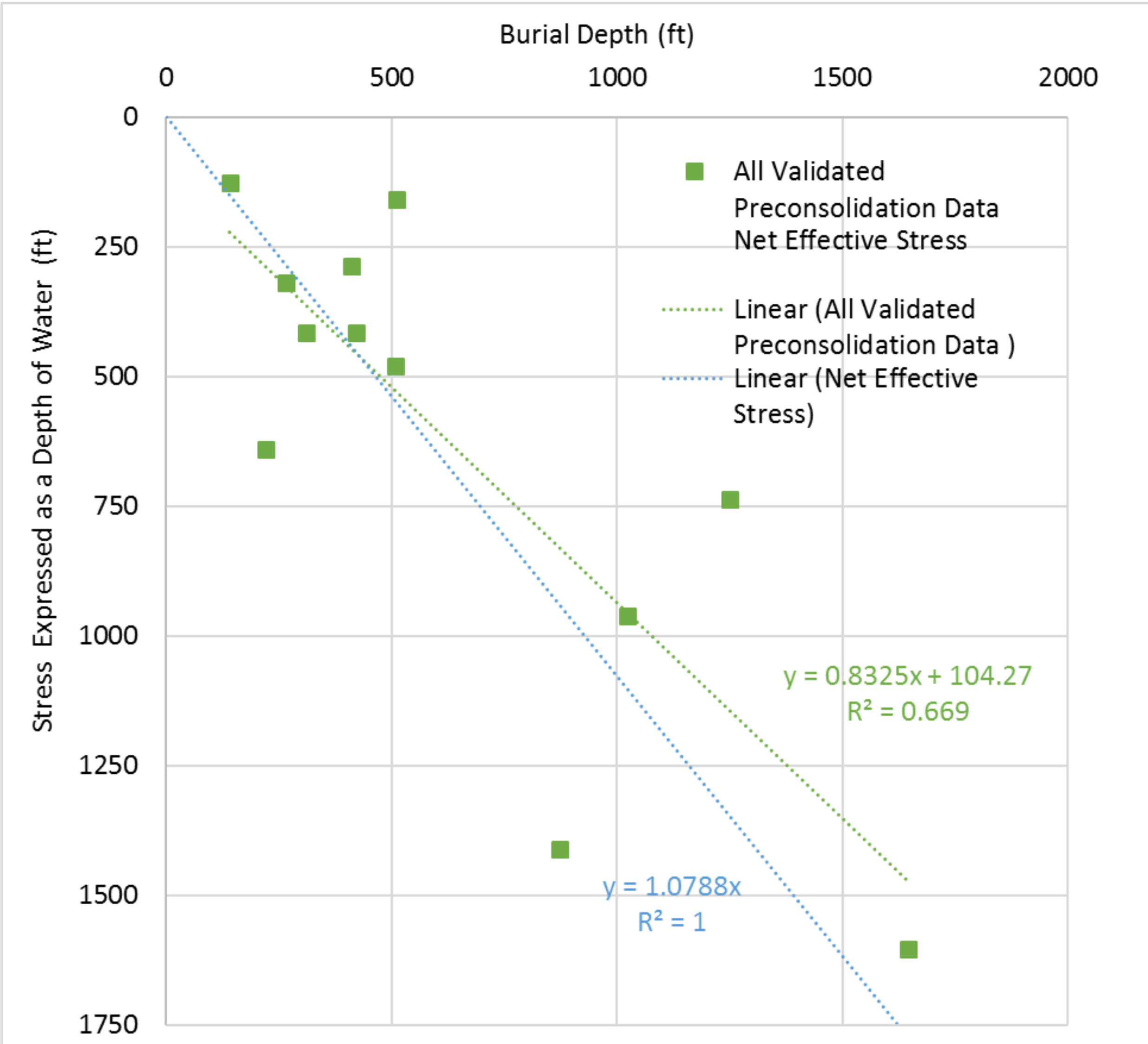


Figure 2-8 Preconsolidation stress calculated from consolidometer tests reported by the USGS and net effective stress plotted as a function of depth of burial

3.0 NUMERICAL MODEL FOR PREDICTION OF COMPACTION IN THE JASPER AQUIFER

This section describes the development of a numerical model for prediction of compaction in the Jasper Aquifer. This includes the selection of a code, hydraulic model construction, compaction model parameterization, and predictive simulations.

3.1 Code Selection

The code(s) selected for the study must simulate two primary processes: change in hydraulic head (drawdown or recovery of water levels) and the compaction that results from this change in effective stress. Historically, the Harris-Galveston Subsidence District (HGSD) has used MODFLOW (Leake and Prudic, 1991; Hoffman and others, 2003) to simulate both historical and predicted future hydraulic heads. The most recent model of the Gulf Coast Aquifer System used by HGSD for this purpose is the HAGM (Kasmarek, 2013).

For simulation of compaction, HGSD has used two different codes: PRESS (Espey, Huston and Associates, Inc., 1982; Fugro, Inc, 2013) and the MODFLOW subsidence (SUB) package (Hoffman and others, 2003). We discuss these two codes and our selection of the MODFLOW SUB package in the following two subsections.

3.1.1 PRESS

PRESS has historically been used to simulate subsidence at 26 Sites located across Harris, Galveston and Fort Bend counties. Each PRESS Site corresponds to a defined area over which the PRESS model results are considered to be representative. Six of the 13 extensometers in the region are coincident with a PRESS Site. PRESS simulates compaction as a one-dimensional process and allows parameterization on that basis (i.e., one PRESS model can simulate a single vertical profile in the subsurface.)

PRESS does not simulate change in hydraulic head. The transient variation in head is an input to a PRESS model. PRESS can simulate one or two aquifers. In the two-aquifer case, head is specified independently for the upper and lower aquifers. Head is linearly interpolated from a datum at land surface to the specified head in the first aquifer, then linearly interpolated to the specified head in the second aquifer. For depths below the second aquifer, head is linearly interpolated to another reference head at the lowermost extent of compaction (termed the base of compaction). PRESS Documentation Figure B-9 (Espey, Huston and Associates, Inc., 1982) provides a conceptual figure of how PRESS interpolates drawdown.

PRESS simulates the time-dependence of compaction described in Section 2.2.2 and requires input of all the parameters described in Section 2: clay bed thicknesses, vertical hydraulic conductivity of the clays, elastic and inelastic specific storage, and drawdown at preconsolidation stress.

3.1.2 MODFLOW-SUB

The SUB package in MODFLOW takes a similar approach to the simulation of time-dependent subsidence as PRESS. Compaction is simulated as a one-dimensional process, and the key compaction parameters described in Section 2 are required as inputs. However, there are several key differences that make the MODFLOW-SUB package a better choice for this application of assessing the risk of subsidence in the Jasper Aquifer.

First, because MODFLOW-SUB is coupled with MODFLOW, hydraulic head is simulated simultaneously at each grid cell along with compaction, and the groundwater released from storage due to depressurization of the clays is correctly accounted for in the water budget. The difference in hydraulic head response due to pumping under elastic and inelastic storage conditions can be significant, so accounting for this difference increases the accuracy of the result.

Second, although MODFLOW-SUB also simulates one-dimensional subsidence, compaction properties can be varied laterally within a single model. So, while multiple PRESS models would have to be developed to represent the varying compaction properties throughout the study area, a single MODFLOW-SUB based model can be developed that allows this variation. This adds simplicity to the implementation process.

Finally, because MODFLOW-SUB is the basis for the HAGM, we are using a consistent code for developing a sub-regional model of the study area. PRESS is more appropriate for local-scale simulation of subsidence at a single location.

For these reasons, we selected MODFLOW-SUB as the code to use as the basis for the numerical implementation of the conceptual model of compaction described in Section 2.

3.2 Model Construction

In this subsection, we discuss the construction of the Jasper Compaction Model (JCM), which is the implementation in a numerical model of the conceptualization and parameterization for compaction described in Section 2. The code used for the JCM to simulate compaction in the Jasper Aquifer is MODFLOW with the SUB package (Hoffman and others, 2003).

3.2.1 Extent and Grid

The model extent was chosen to capture the study area, and the extent of the Jasper Aquifer based on the updated stratigraphy used by the TWDB (Young and others, 2012) of the Lower Lagarto and Oakville formations. **Figure 3-1** shows the horizontal extent of the JCM grid. The active model area includes both Districts. The updip extent is based on the HAGM grid, with the active updip extent defined by the Jasper outcrop. The downdip extent is defined by the downdip extent of the available stratigraphy, which extends approximately to the Gulf of Mexico.

The horizontal resolution of the model grid was set to be identical to the HAGM, and, where the models overlap, the JCM grid cells are coincident with grid cells in the HAGM. This allows easy translation of hydraulic properties from the HAGM to the JCM.

Three formations were simulated in the model: the Middle Lagarto, the Lower Lagarto, and the Oakville. A stratigraphic column is shown in **Figure 3-2**. The Middle Lagarto corresponds to the Burkeville, while the Lower Lagarto and Oakville combine to form the Jasper Aquifer. We initially implemented each of the formations as one layer, and then further subdivided the Lower Lagarto into a shallow and deep layer, with the thickness of the shallow layer limited to 300 ft maximum. This subdivision allowed the more accurate representation of a well screen in the shallowest portion of the Jasper Aquifer.

Figure 3-2 includes a representative cross section for the JCM. Note that the shallow Jasper Aquifer layer is a constant 300 ft downdip but eventually thins updip as the overall thickness of the Jasper Aquifer decreases below 300 ft.

3.2.2 Boundary Conditions

The top of the model, where confined (i.e., downdip of the Jasper Aquifer outcrop), the bottom of the model (bottom of the Jasper Aquifer), and the lateral boundaries along dip (the "sides") are represented as no-flow boundaries. General head boundaries were considered for representing the younger sediments above the Burkeville; however, an investigation of the flow balance in the HAGM indicated that very little groundwater was exchanged between the Burkeville and shallower units, so a no-flow boundary was implemented.

General head boundaries were applied in the outcrop (to simulate surficial interaction with the groundwater system, including recharge) with heads set to 25 ft bgs. This approach to representing the surficial system is similar to the HAGM (Kasmarek, 2013). Because brackish pumping is located significantly downdip of the outcrop, there will be no interaction between these general head boundaries and any simulated pumping wells.

The downdip extent of the model was also simulated with general head boundaries, with the heads set at an elevation of zero ft above mean sea level (amsl). These general head boundaries allowed groundwater to flow downdip and exit the model.

3.2.3 Parameterization

In this subsection, we discuss the parameterization of the JCM, the two hydraulic properties that govern water level response to pumping stresses, and the compaction properties that govern the timing and magnitude of compaction that occurs due to the change in water levels.

3.2.3.1 Hydraulic Properties

Horizontal hydraulic conductivity is based on hydraulic conductivity in the HAGM where the Jasper Aquifer is active (modeled). For the Burkeville layer in the JCM, the HAGM properties are used throughout. The active portion of the Jasper Aquifer in the HAGM is mostly limited to the fresh water portion, so it does not extend downdip to the coastline. In areas where the HAGM is not active, an average hydraulic conductivity was estimated at the downdip limit and extended throughout the rest of the active JCM. In addition, a decrease in hydraulic conductivity with depth was applied, consistent with Young and others (2009). The same initial horizontal hydraulic conductivity was applied to JCM layers 2 through 4, with the depth trend applied based on the midpoint depth of each layer.

Figure 3-3 shows the resulting horizontal hydraulic conductivity distribution for the shallow Jasper Aquifer layer (Layer 2) in the JCM. In general, where the HAGM is active, the JCM has the HAGM horizontal hydraulic conductivity but with a decreasing trend with depth, especially moving into the more brackish portions of the Jasper Aquifer.

The vertical hydraulic conductivity could not be based directly on properties from the HAGM because the HAGM uses vertical conductance as input, which is the thickness-weighted harmonic average of the vertical hydraulic conductivities of two adjacent layers. Given this average value, the original input vertical hydraulic conductivities cannot be uniquely determined. However, by assuming an anisotropy ratio, possible combined distributions of vertical conductivity can be produced that can approximately match the simulated vertical conductance. We took this approach but set the lower limit to vertical conductivity at $1x10^{-4}$ ft/day, because there were areas in the model where the approach was producing unreasonably low values of vertical hydraulic conductivity. The final estimates of vertical hydraulic conductivity ranged from about $1x10^{-3}$ to $1x10^{-4}$ ft/day, which are reasonable for a regional model of the Gulf Coast Aquifer System (Young and others, 2009).

As for horizontal hydraulic conductivity, specific storage was used from the HAGM where the active portions of the models overlapped. Downdip where the HAGM is not active, we extended the estimate using an average value from the downdip limit of the HAGM. Values for specific storage typically range from $1x10^{-5}$ to $1x10^{-6}$ ft/day.

3.2.3.2 Compaction Properties

Compaction properties were implemented using the depth-dependent relationships summarized in Section 2.3. **Figure 3-4** shows the depth to the midpoint of JCM layer 2, which represents the shallow Jasper Aquifer. Because one of the key parameters governing compaction is the number and thickness of clay beds, the implementation is based upon the geophysical logs for which lithology was defined in the District's brackish groundwater characterization report (Young and others, 2017). For each cell on the JCM grid, the nearest geophysical log was identified and associated. All cells associated with a particular geophysical log shared the same compaction properties. The properties discussed in this section are for the best estimate case. Other sensitivity cases will be discussed in Section 3.3.4.

Figure 3-5 shows the parameterization of inelastic specific storage for JCM layer 2. In the shallowest portions of the model, where the geophysical log coverage can be sparse, there is less refinement in the parameterization. This does not impact the overall modeling objectives because compaction risk is assessed only in the brackish portion of the Jasper Aquifer, which starts further downdip. This boundary in the risk domain is discussed in Section 3.3.2.

The clay bed thickness and counts are available at each geophysical log. Because the MODFLOW-SUB package input requires a full grid array to be input for each set of clay beds with unique properties (regardless of their actual horizontal extent), explicit representation of each clay bed was not tenable. The MODFLOW-SUB documentation (Hoffman and others, 2003) proposes a strategy for creating a composite representation of clay beds based on the following two equations from Helm (1975):

$$b_{equiv} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} b_i^2} \qquad \text{(Equation 3-1)}$$

$$n_{equiv} = \sqrt{\frac{\sum_{i=1} b_i}{b_{equiv}}} \qquad \text{(Equation 3-2)}$$

Where N is the number of clay beds, b_i is the thickness of an individual clay bed, and b_{equiv} and n_{equiv} are the equivalent thickness and number of beds, respectively. We tested whether this composite representation of the clay beds produced a similar compaction response to an explicit representation of clay beds, with as many as 10 beds varying in thickness from 10 to 100 ft. The explicit and composite representations compared favorably, so the composite strategy was considered acceptable for the modeling. Both the explicit and the composite methods for modeling the interbeds require the detailed lithologic data developed earlier on this contract for the Districts. The composite method is more practical numerically.

Figure 3-6 shows the parameterization of the clay vertical hydraulic conductivity for JCM layer 2. The trend with depth is clear, with a range of about 3.5×10^{-6} ft/day in shallow outcrop decreasing to 1.5×10^{-7} ft/day in the deepest portion along the coast.

3.3 Compaction Simulation Approach

In this section, we discuss how the JCM is used to simulate potential compaction and to investigate the sensitivity of compaction to a range in input parameters.

3.3.1 Initial Conditions

The JCM fundamentally simulates changing conditions (i.e., potential future compaction caused by potential future drawdown in water levels). We did not attempt to calibrate the JCM to historical head conditions. For a confined aquifer system, like the brackish portion of the Jasper Aquifer, drawdown response to pumping will be independent of the initial water levels, so our goal was to create an initial condition that was approximately representative of actual conditions in the aquifer. This approach is acceptable because compaction is dependent upon drawdown from a baseline aquifer head. The approach is basically the same principle applied in superposition models (Reilly, Franke and Bennett, 1987), which have proven to be powerful administrative tools in the regulation of groundwater for decades.

We initialized the water levels in the model by running a steady-state stress period. This created an equilibrated water level surface and water balance, which is the best starting point for then simulating potential impacts of future stresses on the aquifer. **Figure 3-7** shows the steady-state water level surface that served as the initial condition for the simulations of future drawdown and compaction. The water levels follow topography, with the gradient generally towards the coast, as expected.

3.3.2 Project Grid Domain

To help assess the spatial variation in the potential for compaction, we divided the model area into a coarse grid of 9- by 9-mile square cells. The strategy was to assess the potential for compaction in each of these cells individually by simulating a representative brackish groundwater development project at that location, and then create a final composite of the individual results that would demonstrate that spatial variation.

Figure 3-8 shows the “project grid” of 9- by 9-mile square cells. While the entire model grid is represented by the initial project grid, the study objectives focus on the brackish portion of the Jasper Aquifer. We created a boundary that reflected these objectives based on the results of the brackish groundwater study (Young and others, 2017), the existing fresh water wells in the Jasper Aquifer (extracted from the HAGM pumping file) and observed water quality. **Figure 3-9** shows this boundary with HAGM Jasper Aquifer active layer grid extent and the cells where pumping is occurring in the current joint-planning predictive simulation.

3.3.3 Representative Jasper Aquifer Project

To assess the potential for compaction at one of the project grid cells, we created a representative brackish groundwater development project. Considerable uncertainty exists about the target production rate of any future project. For any given production rate, more drawdown would occur in lower transmissivity locations compared to higher transmissivity locations. Because compaction is dependent on the amount of drawdown, not on the production rate, we chose to take a “fixed drawdown” approach to the representative project.

The magnitude of fixed drawdown was set to 500 ft below the initial water level. This amount of drawdown was applied to the center of each project grid cell in the model layer representing the upper 300 ft of the Jasper Aquifer. The drawdown was simulated to occur for 50 years. Each project was simulated independently (i.e., only one project was simulated per model run). Note that the 500 ft of drawdown was applied in a one-mile square numerical grid cell, so it represents a well or wellfield that experiences more than 500 ft of drawdown at the wellhead.

A drawdown of 500 ft is significantly larger than the typical Chicot or Evangeline well in the freshwater portions of the Gulf Coast Aquifer System. However, the Jasper Aquifer in the brackish section is generally less transmissive that is seen in the Chicot or upper Evangeline aquifers. Also, some of the brackish wells could be 4,000 ft or deeper, allowing for significant available drawdown. Permittees could move to staged pump systems or oil-field lift technology, which would allow for significant drawdown to increase production. We assumed that 500 ft of drawdown would be a good representative maximum drawdown that standard water well methods could attain. The range of drawdown from 200 to 500 ft would not significantly change the risk assessment results.

3.3.4 Compaction Simulation Sensitivity Cases

The model parameterization of compaction properties discussed in Section 3.2.3.2 focused on the best estimates of those properties. Because of the uncertainty associated with the best estimates, we explored the sensitivity of the simulated compaction to changes in these parameters by developing lower and higher impact scenarios. The direction of variation from the best estimate case is summarized in **Table 3-1**. Table 3-1 provides the compaction parameter ranges associated with each of the modeled scenarios: Low, Base (Average), and High Impact. The parameter values associated with these ranges are described below.

For inelastic storativity, an increasing value will result in increasing compaction, as can be seen in Equation 2-4. For the sensitivity cases, the low value of inelastic storativity corresponds to 0.3 multiplied by the best estimate at a given depth, while the high value of inelastic storativity corresponds to 3.0 multiplied by the best estimate. This half order-of-magnitude range is based on the observed scatter in the correlation of compressibility with depth (Figure 2-4).

Table 3-1 Summary of direction of parameter variation for sensitivity scenarios

Scenario	Vertical Hydraulic Conductivity	Inelastic Storativity	Drawdown at Preconsolidation Stress
Low Impact	Low	Low	High
Base (Average)	Average	Average	Average
High Impact	High	High	Low

For vertical hydraulic conductivity, an increased value corresponds to more compaction for a given time interval, as the delay in depressurization of the clays is decreased and ultimate compaction is reached more quickly. For the sensitivity cases, the high values correspond to the measurements by the USGS (Gabrysch and Bonnet, 1974) (Table 2-2), while the low values correspond to the calibrated values from the PRESS models (Table 2-2).

Finally, in the case of drawdown at preconsolidation stress, an increasing value will result in a decrease in predicted compaction, because more drawdown will need to occur before inelastic compaction begins. For the sensitivity cases, we will vary the shallow drawdown at preconsolidation stress between a low of 30 ft and a high of 150 ft, which corresponds to the range currently parameterized in the HAGM in the Chicot and Evangeline aquifers (15 to 128 ft). The HAGM Jasper Aquifer drawdown at preconsolidation stress ranges as high as 294 ft, with an average of 192 ft.

3.4 Compaction Simulation Results

In this section, we discuss the results of the simulations, where a drawdown of 500 ft was simulated at the center of each project grid cell, and the resulting compaction was assessed through a 50-year period.

3.4.1 Variation in Flow Rate

For a given amount of average drawdown, the corresponding rate of groundwater production will vary with varying hydraulic properties. The flow rate will be primarily dependent on the horizontal transmissivity in the region where the production occurs, with secondary dependence on vertical hydraulic conductivity and storativity. Because transmissivity is conceptualized to decrease with depth, the production rate that occurs for a drawdown of 500 ft will also decrease with depth. **Figure 3-10** shows this variation in production rate with depth. Flow rates range from over 1,000 gallons per minute (gpm) to just over 200 gpm over the range in depths from shallow to deep. At each of these project grid locations, if a higher production rate were achieved than is shown in Figure 3-10, then more than 500 ft of average drawdown would occur, resulting in more compaction than is simulated.

3.4.2 Rate of Compaction

In Section 2.2.2, we discussed how the time required to reach ultimate compaction varies with the thickness, frequency, and vertical conductivity of the clay beds. **Figure 3-11** shows the simulated compaction through time for project grid location #59 (Figure 3-8) near the center of Harris County. At this location, the equivalent interbed thickness (Equation 2-10) is 21 ft, and the equivalent number of interbeds (Equation 2-11) is 4.5. The vertical hydraulic conductivity of the clay beds is 5.7×10^{-7} ft/day.

The greatest compaction occurs in the pumped layer (the uppermost 300 ft of the Jasper Aquifer), with less compaction in the remaining Jasper Aquifer. After 10 years, about 20% of the compaction has occurred that is simulated at 100 years. Even after 100 years, the compaction is still increasing (i.e., ultimate compaction has not occurred under these conditions).

3.4.3 Sensitivity Cases

The parameterization of the low-impact, base-case, and high-impact scenarios was discussed in Section 3.3.4. **Figure 3-12** shows a summary of the results of these three scenarios in the form of 10-year compaction versus depth in the Jasper Aquifer. Smoothed lines are plotted through the results of the three cases to help show the decreasing trend in compaction with depth. At shallower depths (less than 2,000 ft), an average of about 2 ft of compaction has occurred over 10 years (0.2 ft/year) for the high-impact case. At those same depths, about 1 ft of compaction has occurred over 10 years, or about 0.1 ft/year, for the base-case scenario. Finally, for the low-impact scenario only about 0.2 ft of compaction has occurred over 10 years, or about 0.02 ft/year. At 4,000 ft depth, about half as much compaction has occurred for the high-impact and base-case scenarios, compared to the shallower depth. For the low-impact case, minimal compaction is occurring at depths exceeding 3,500 ft.

While not the focus of this study, it is clear from a review of Figure 3-12 that areas of shallower than approximately 2,000 ft bgs in the Jasper Aquifer have a higher risk of compaction as compared to the deeper brackish portions of the aquifer, which are the focus of this study.

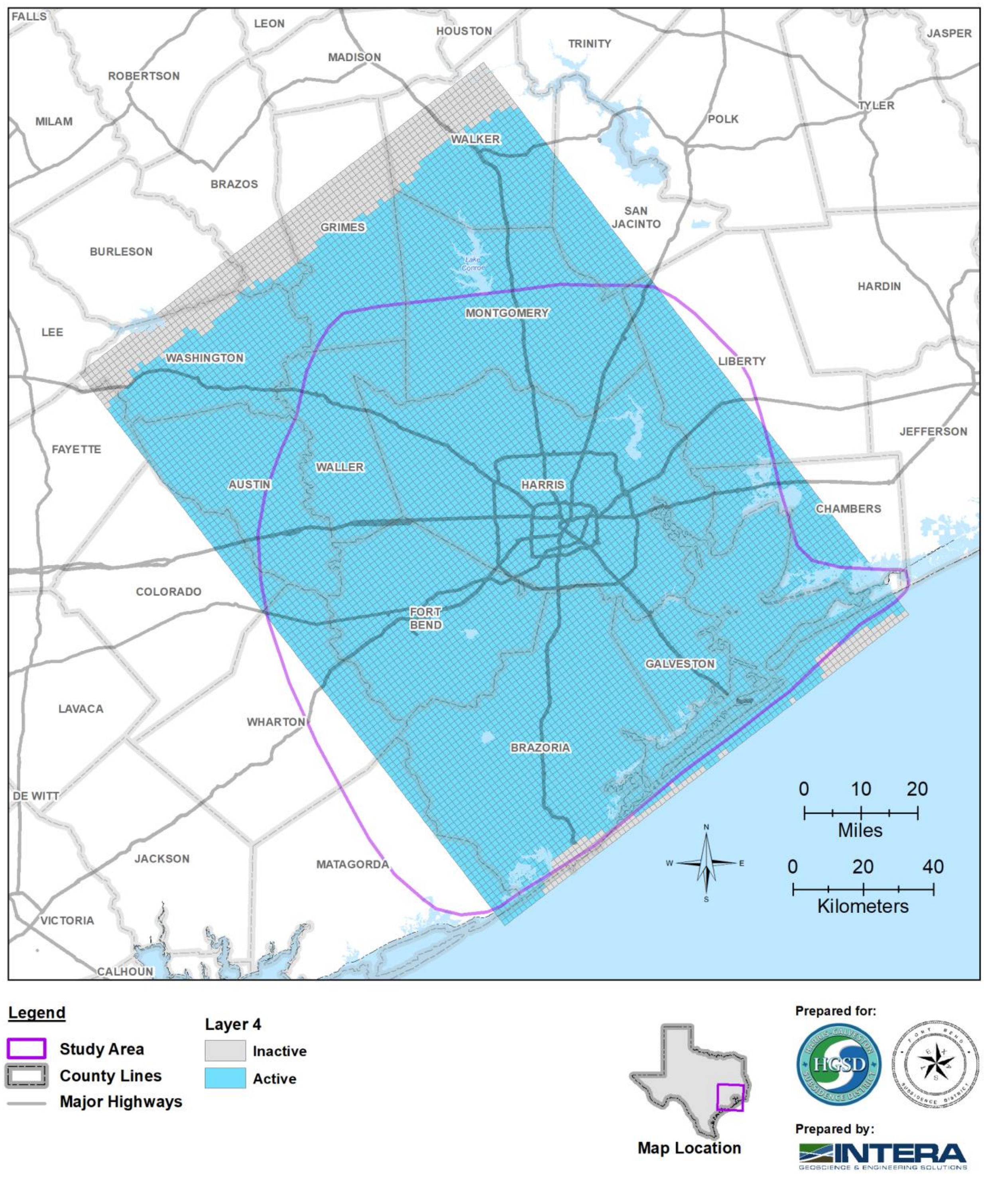


Figure 3-1 Jasper compaction risk model grid

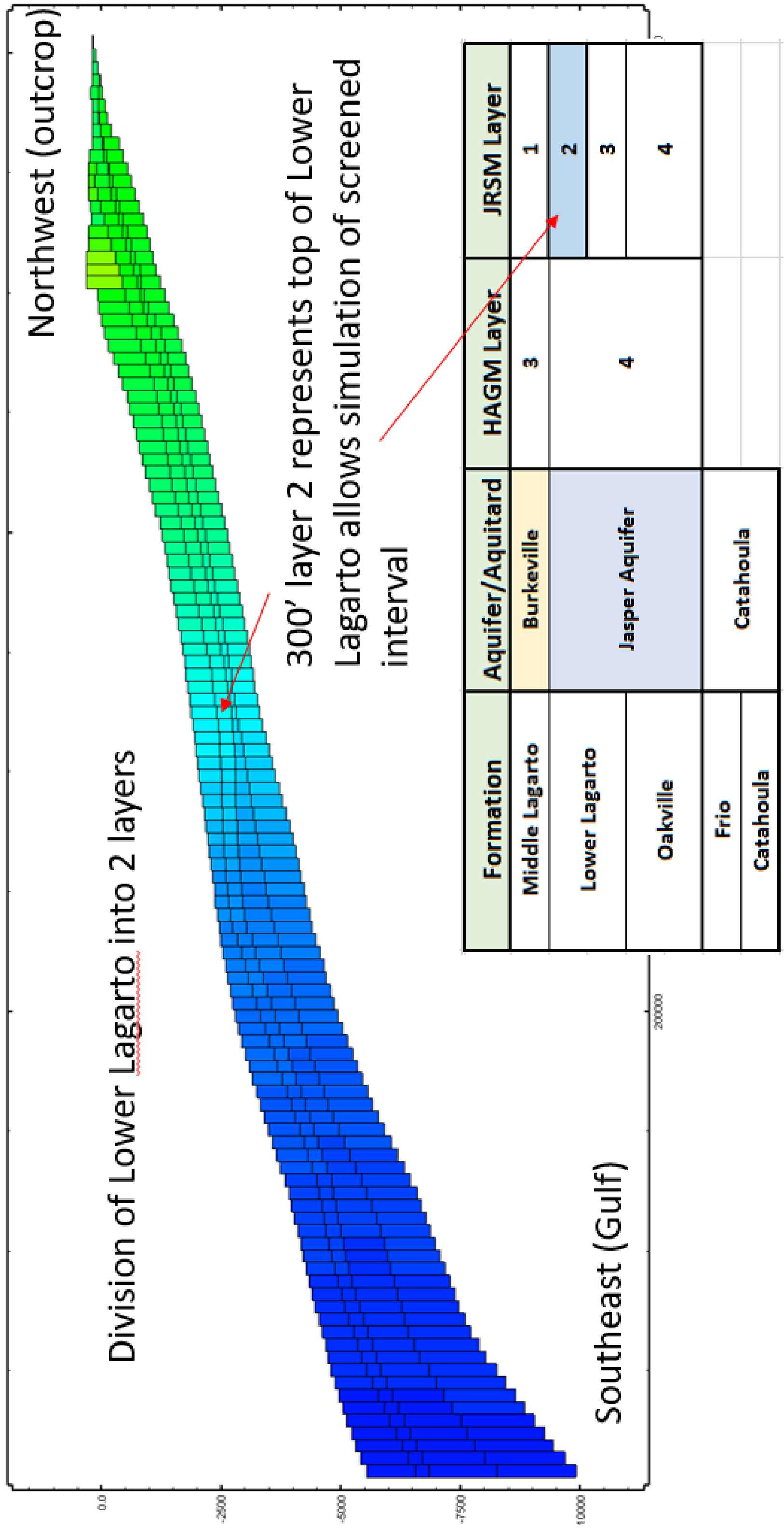


Figure 3-2 Stratigraphic column and dip section showing the vertical layering in the JCM

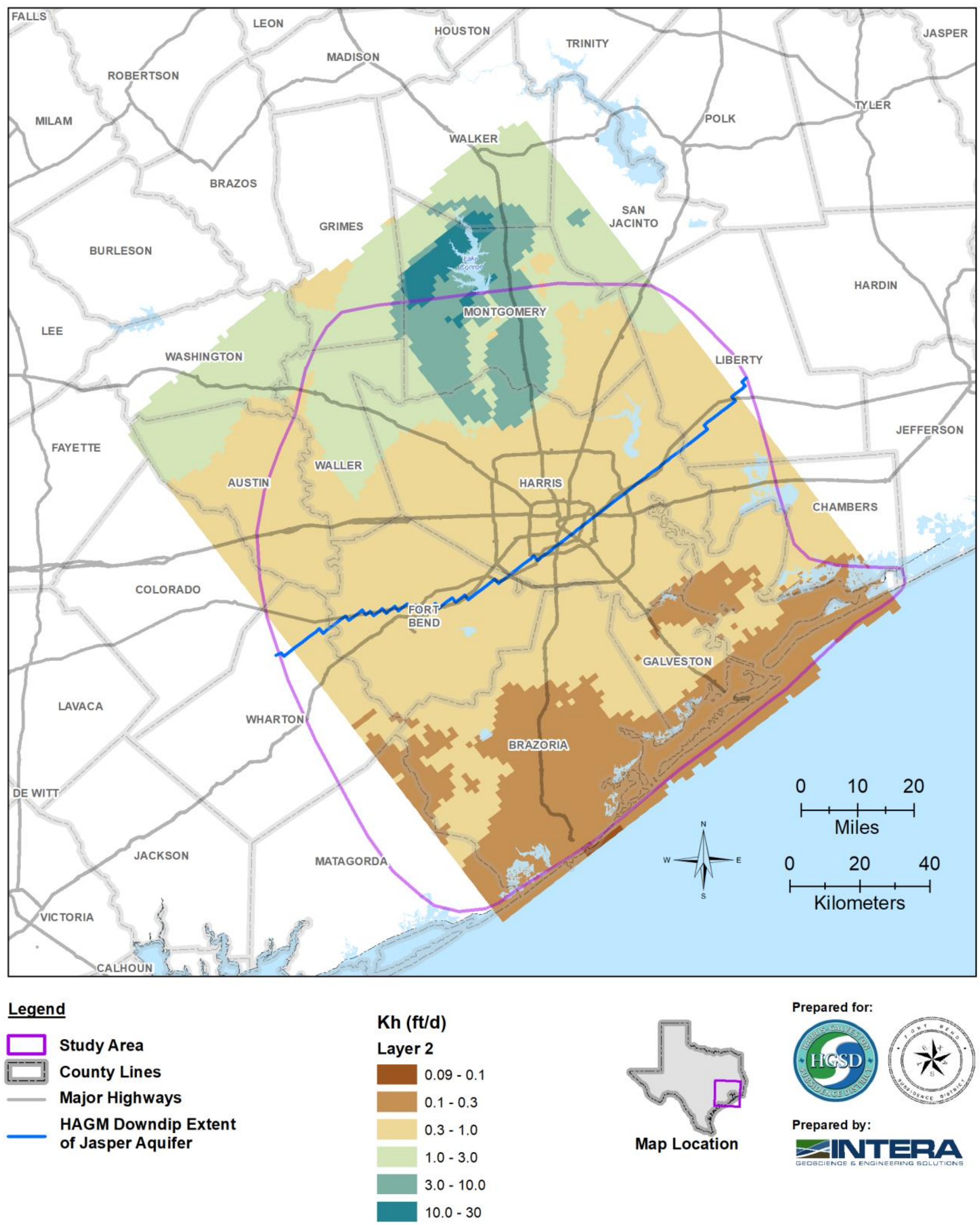


Figure 3-3 Horizontal hydraulic conductivity in model Layer 2, which represents the shallow Lower Lagarto Formation of the Jasper Aquifer

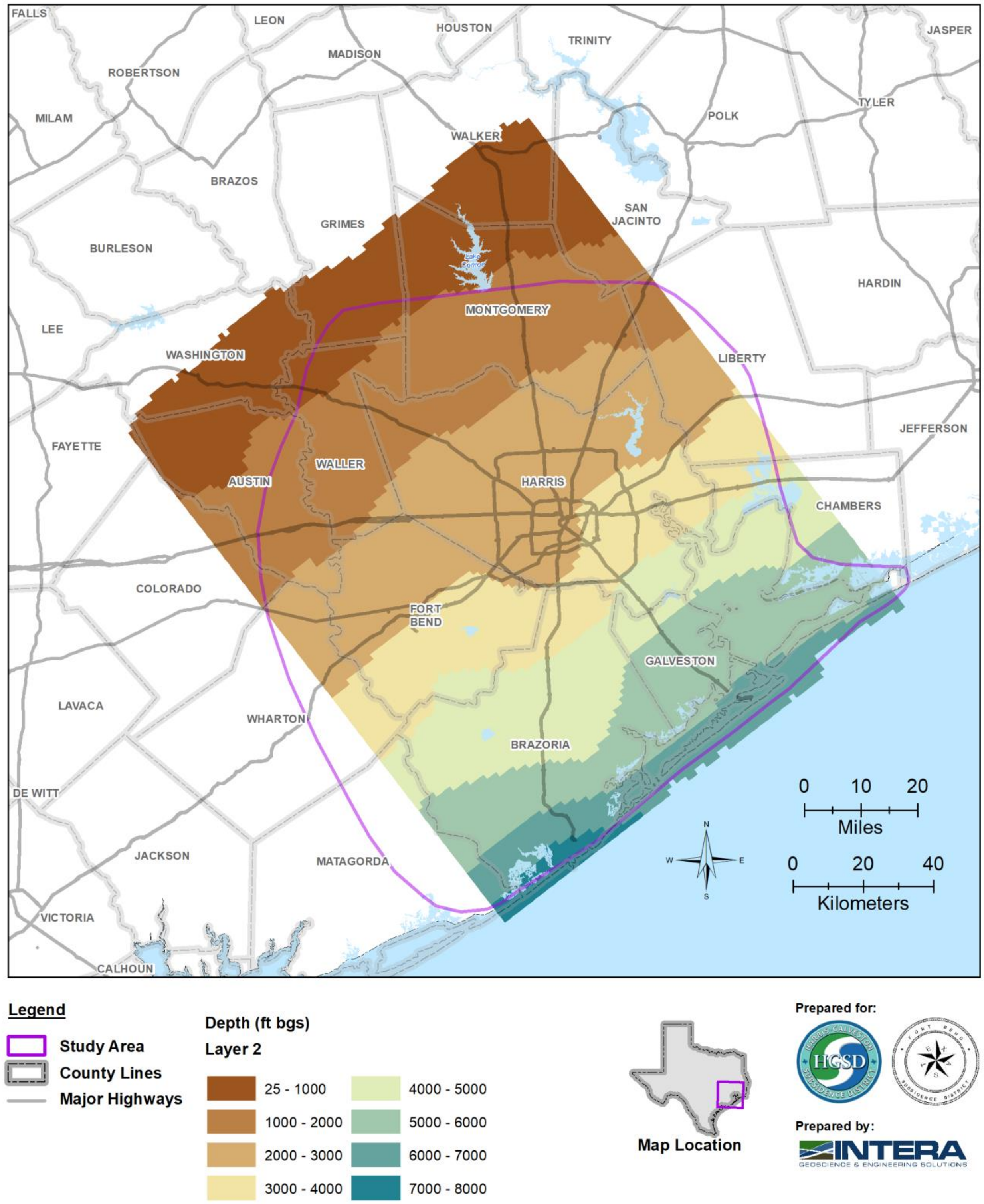


Figure 3-4 Depth to the midpoint of model Layer 2, which represents the shallow Lower Lagarto Formation of the Jasper Aquifer

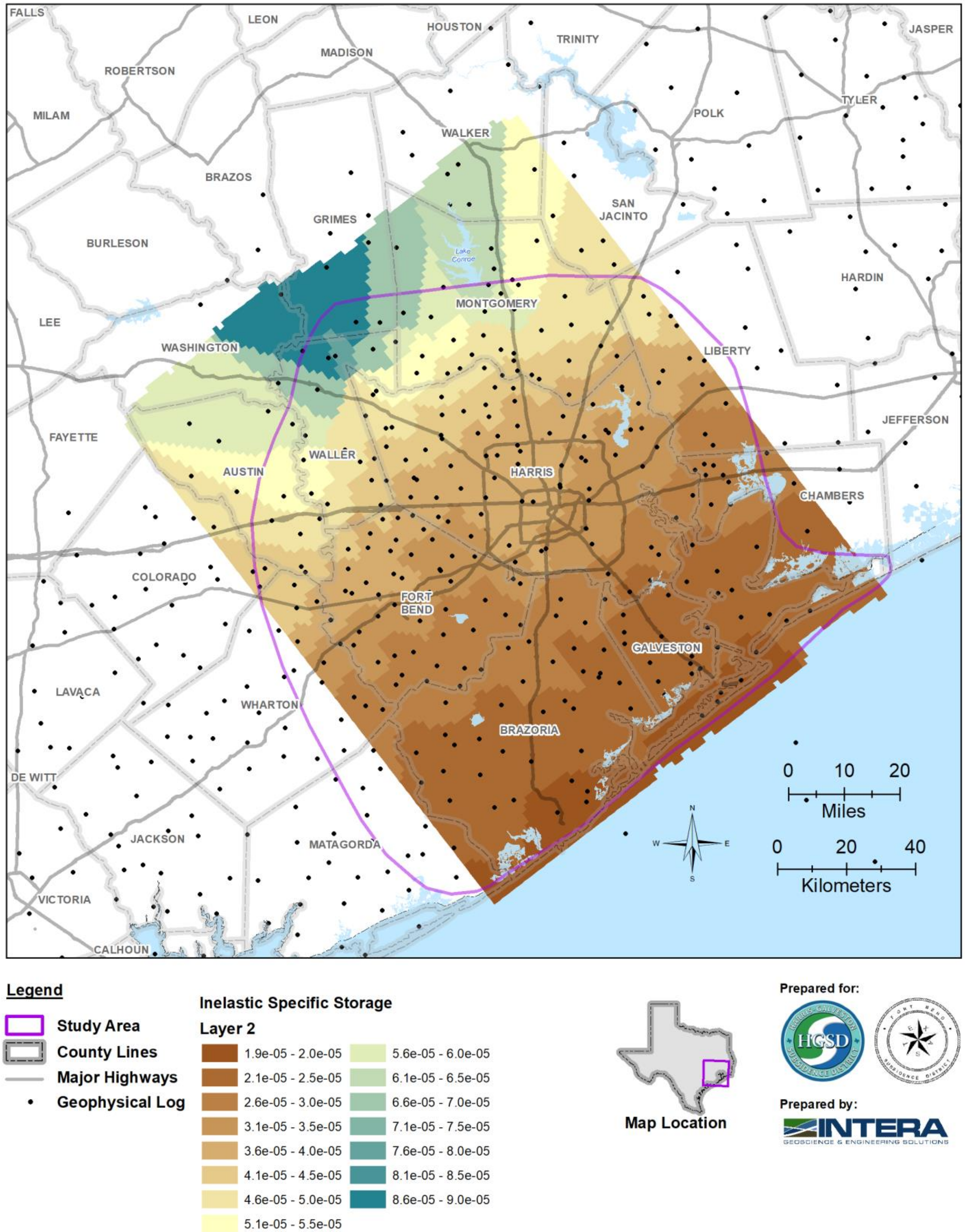


Figure 3-5 Inelastic specific storage in model Layer 2, which represents the shallow Lower Lagarto Formation of the Jasper Aquifer

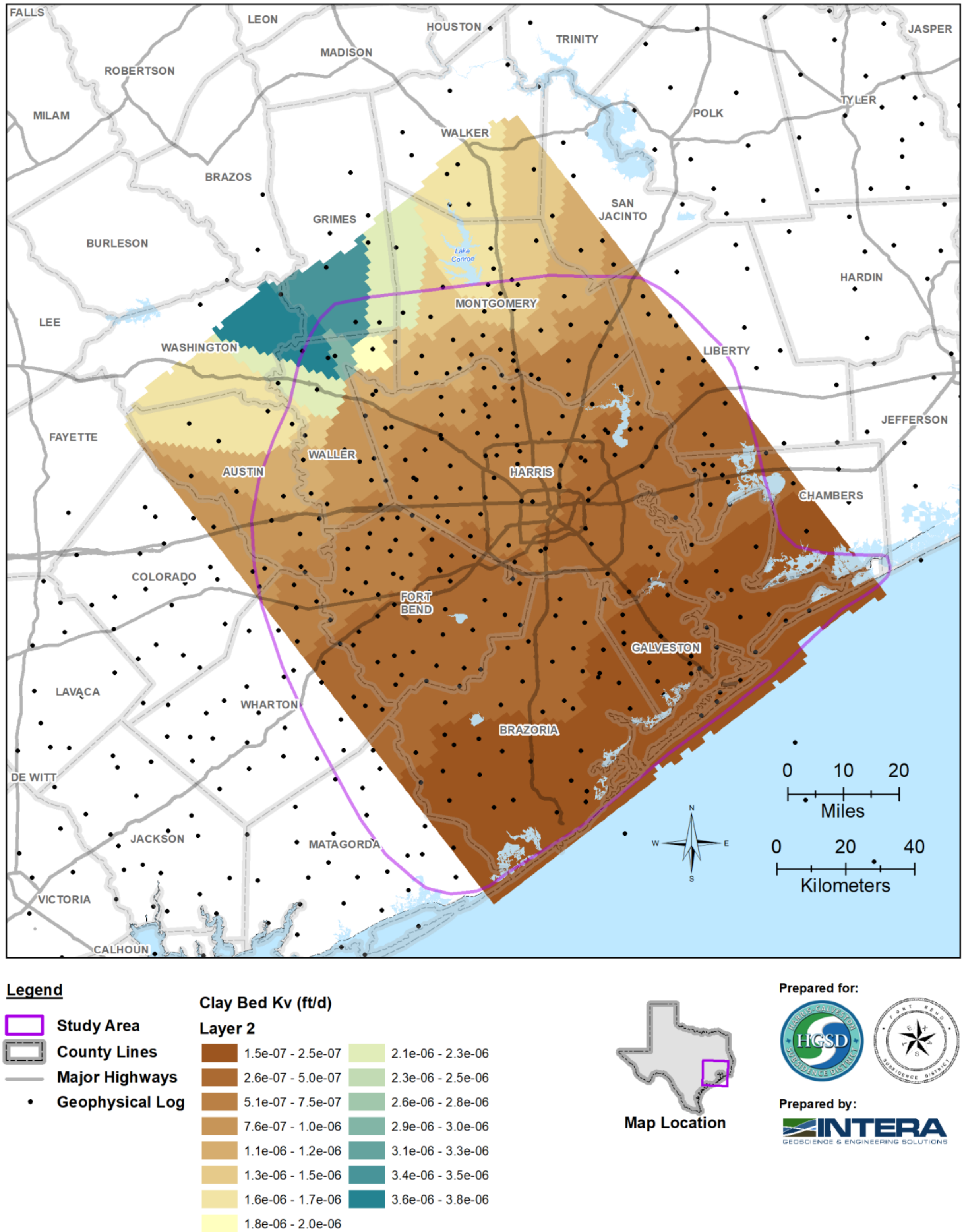


Figure 3-6 Clay bed vertical hydraulic conductivity model Layer 2, which represents the shallow Lower Lagarto Formation of the Jasper Aquifer

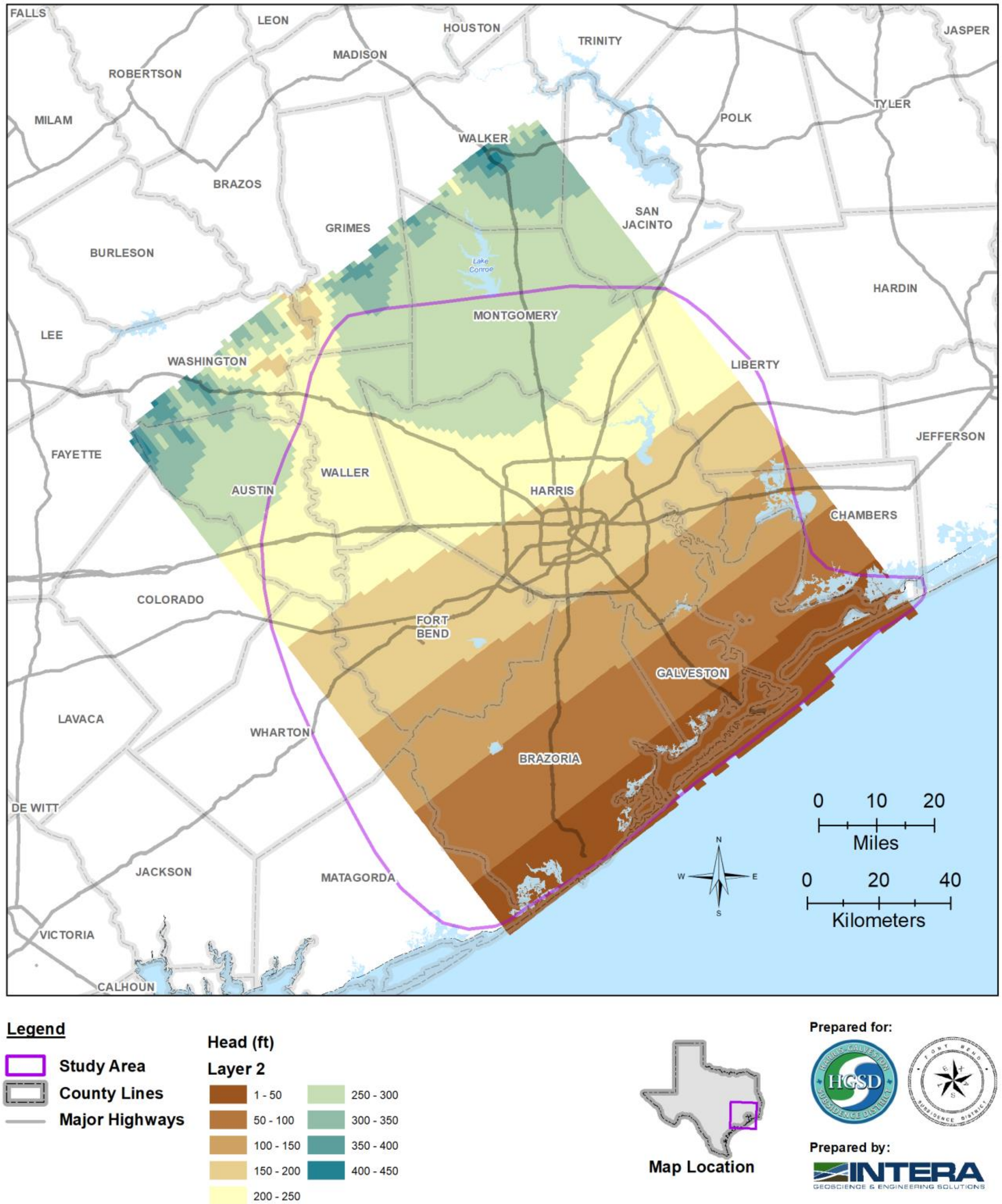


Figure 3-7 Simulated steady-state water levels in model Layer 2, which represents the shallow Lower Lagarto Formation of the Jasper Aquifer

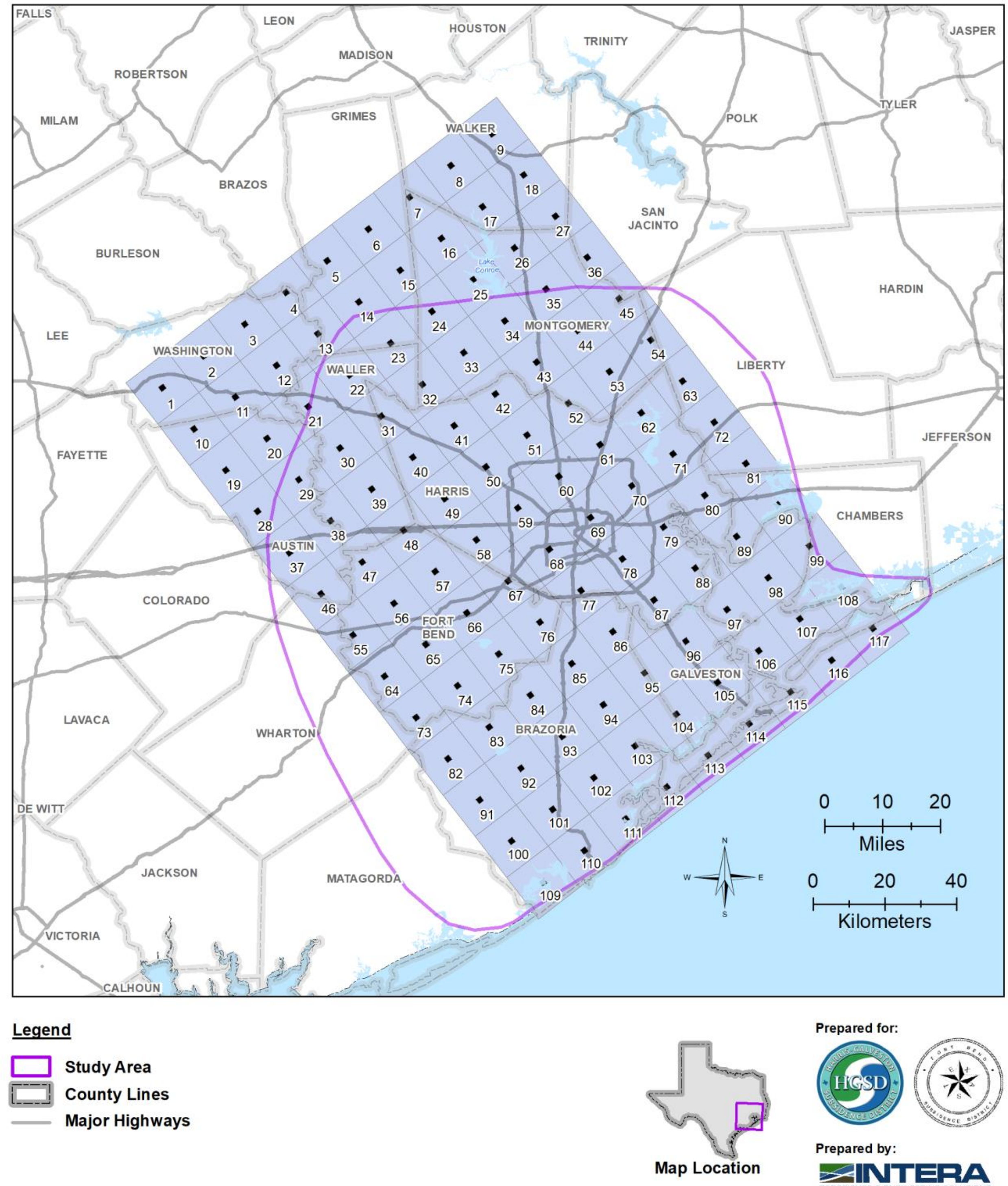


Figure 3-8 Jasper compaction simulation project grid

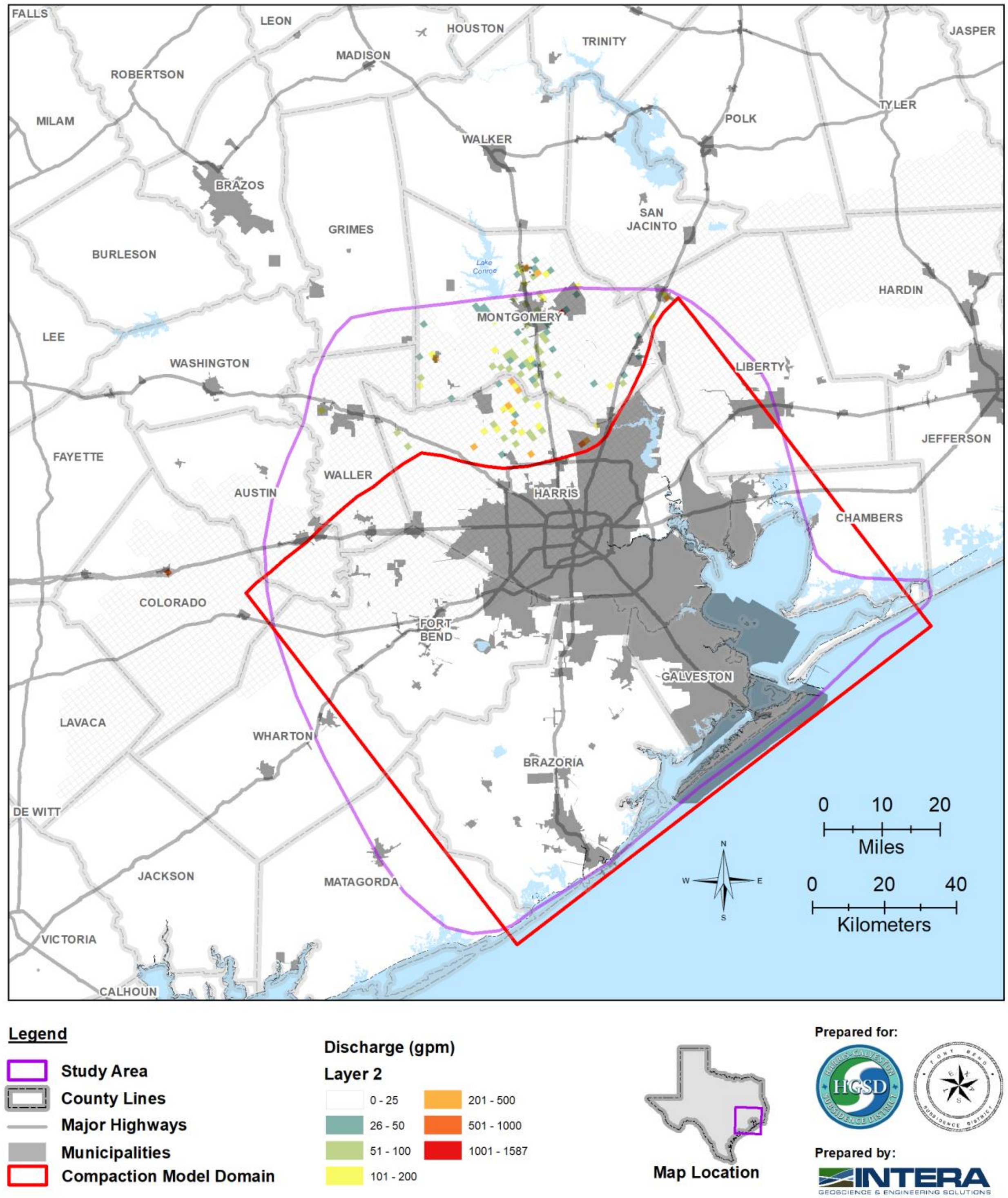


Figure 3-9 Extent of the Jasper compaction modeling domain

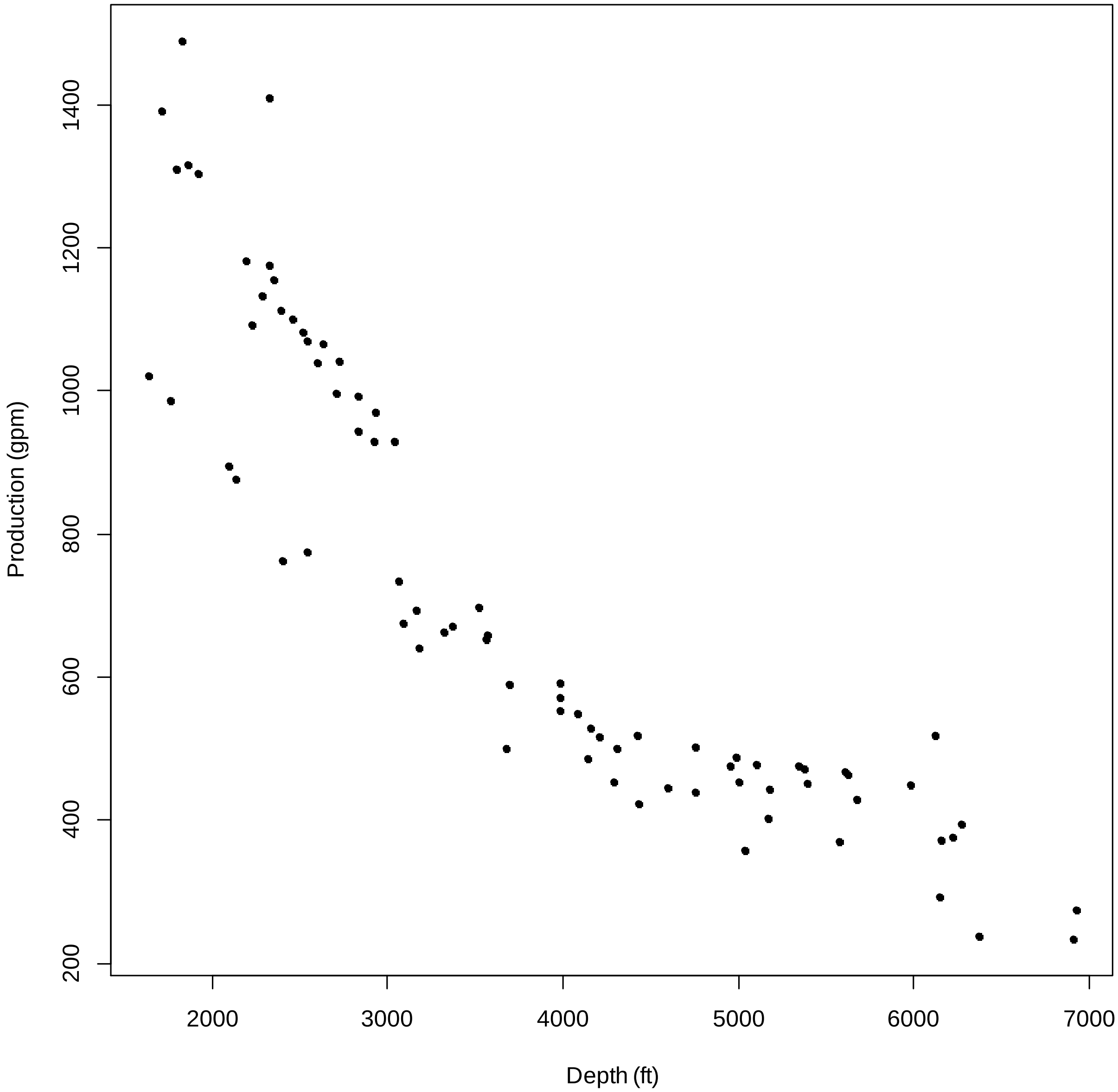


Figure 3-10 Simulated groundwater production rate with depth

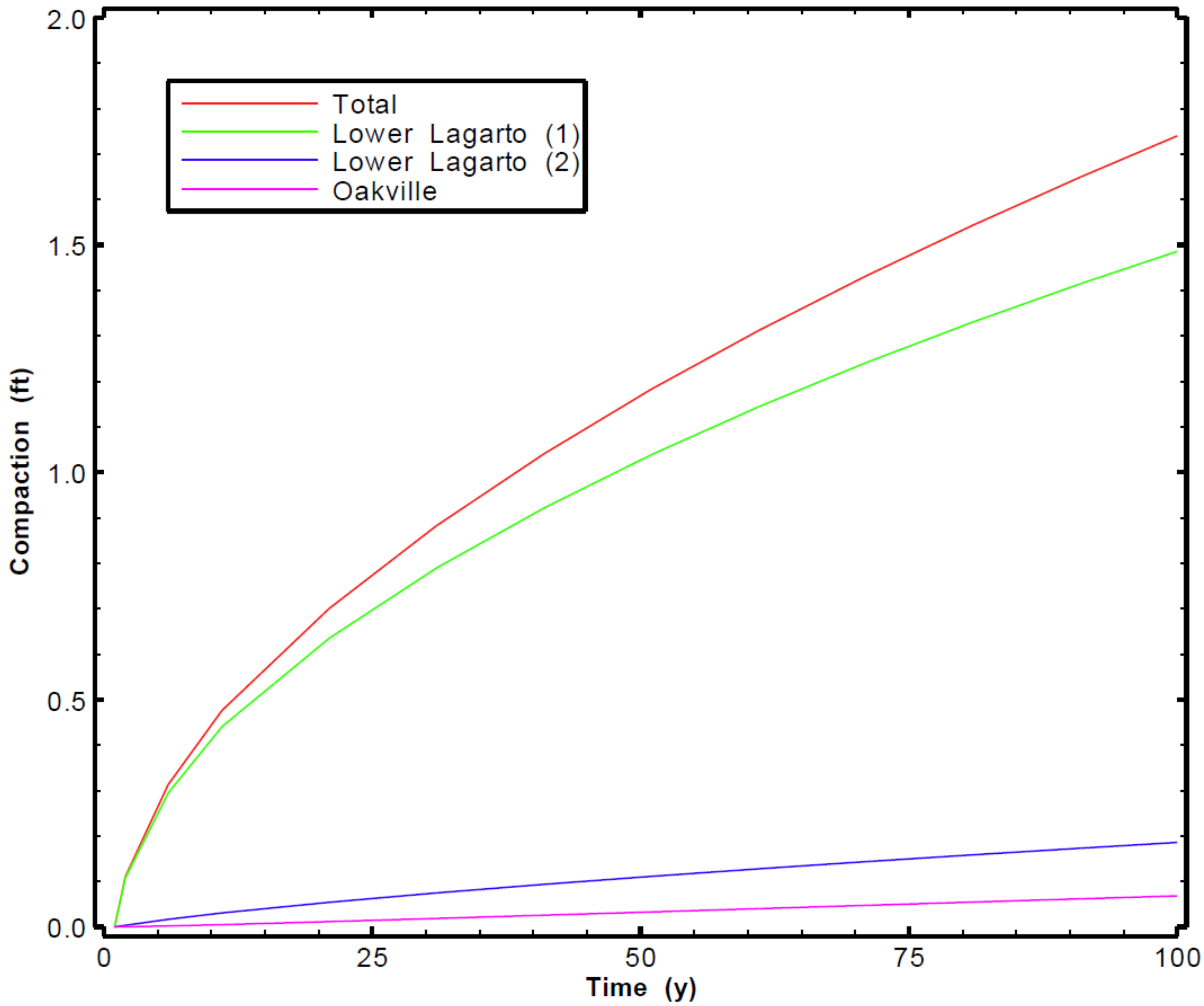


Figure 3-11 Simulated increase in compaction with time, by model layer at project grid number 59 (see Figure 3-8 for location).

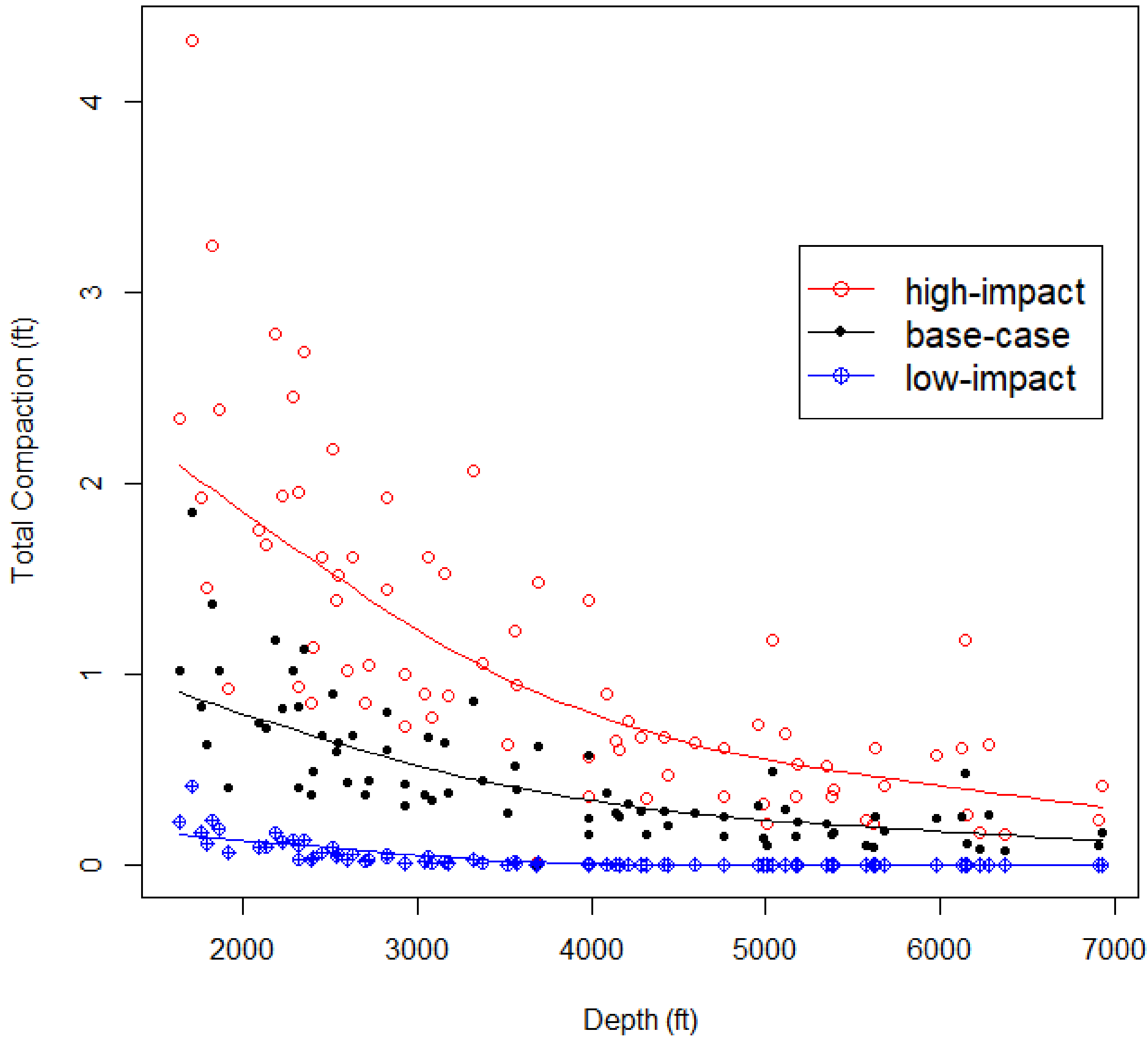


Figure 3-12 Simulated variation of 10-year compaction with depth for the three sensitivity cases

4.0 JASPER AQUIFER SUBSIDENCE RISK ASSESSMENT APPROACH AND RESULTS

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 in the Jasper Aquifer are uncertain. However, the available data from shallower aquifers, the calibrated models, 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.

This section describes the risk assessment approach used to develop a map of relative risk of subsidence that could result from groundwater development in the brackish portions of the Jasper Aquifer in the study area. After the approach is described, the results of the risk assessment methodology are presented.

4.1 Risk Assessment Approach

The approach used to develop a relative risk map for subsidence from development of the brackish Jasper Aquifer is based upon Multi-Attribute Utility Theory. Utility theory is a tool widely used by decision analysts for converting their preferences, expressed in monetary terms or other relevant performance measures, into a normalized scale to facilitate comparison of options (Clemen, 1986). In this case, an option is the relative risk of subsidence from pumping the brackish Jasper Aquifer at a given location in the study area. Performance measures are selected that inform risk of subsidence. One obvious performance measure is the amount of compaction in the Jasper Aquifer predicted by the JCM (Section 3). Other performance measures can be defined.

The process used in this analysis defines risk categories, risk performance metrics, and a relative risk score methodology. Each of those will be discussed below.

4.1.1 Risk Categories and Performance Metrics

A risk category is a class of performance metrics. A performance metric is a quantifiable condition that may pose a risk of, or a consequence from, subsidence. In this case, we limit the analysis to subsidence from the compaction of the Jasper Aquifer.

Table 4-1 provides a summary of the three risk categories that are considered: Jasper Aquifer compaction, land subsidence, and consequence from subsidence. In cooperation with the Districts, we reviewed multiple performance measures for each risk category. Based on the findings of that review, our final analysis only considers one performance measure for each risk category. Rationale for these selections is discussed below.

Jasper Compaction Risk Category – For the Jasper Compaction Risk Category, we used the JCM assessment of compaction within the Jasper Aquifer after 50 years of pumping. We chose Jasper Aquifer compaction at 50 years because it provided adequate time for compaction to occur in thicker clays, which are prevalent in the Jasper Aquifer approaching the coast and as the Jasper Aquifer gets deeper.

Land Subsidence Risk Category - Jasper Aquifer compaction occurs at depth within the Jasper Aquifer from withdrawal of groundwater and irreversible compaction of clays. The land subsidence risk category is a category meant to relate compaction in the brackish Jasper Aquifer at depth to land subsidence at ground surface. Investigators have studied how much deep reservoir compaction results in subsidence for oil and gas reservoirs (Geertsma, 1973; Du and Olson, 2001). Their analyses show that, for a given radius of compaction, the percent of compaction that equals subsidence at land surface decreases as the depth of the compacting radius increases. This implies that, as one moves deeper into the Jasper Aquifer, the amount of compaction that manifests itself as subsidence decreases. Because a rigorous calculation of land subsidence from Jasper Aquifer compaction is very uncertain and dependent upon scale of brackish water resources development, it was agreed to use a proxy performance measure. To account for the fact that the ratio of maximum subsidence to compaction at depth is, in part, a function of the ratio of the depth of burial over the radius of the area compacting (Geertsma, 1973), we used the depth to the top of the Jasper Aquifer as a proxy performance measure for the land subsidence risk category. This performance measure assumes there is a correlation between the risk of subsidence occurring at land surface and the depth at which groundwater production occurs. Consistent with the literature, the deeper the depth of burial, the lower the risk of subsidence at land surface for a given radius of compaction at depth.

Consequence from Subsidence - The consequence risk category would include performance measures that relate to the consequence of subsidence occurring at the ground surface. This category implies that there may be locations on the land surface for which the consequence of subsidence would be more deleterious or of concern than other locations. The most obvious performance measure for this risk category is the Federal Emergency Management Agency (FEMA) flood plain map. If one is in, or near a flood plain, the potential consequence from subsidence could be much greater than an area not in a flood plain. To account for this, we used the FEMA 100-year flood plain coverage for the study area as the consequence risk category performance measure.

4.1.2 Normalized Risk Score Methodology

Following utility theory, each chosen performance measure of interest (described above) is mapped into a utility curve such that the highest risk has a utility score equal to one and the lowest risk has a utility score equal to zero. This process requires normalizing each performance measure to a range from zero to one. The benefit of this process of normalization is the ability to combine quantitatively very different, and even qualitative and quantitative performance measures into a decision process. Once a performance measure is normalized, it will be referred to as a performance measure Normalized Risk Score (NRS). A performance measure can be positively or negatively correlated to the performance measure Relative Risk Score. **Figure 4-1** shows a utility function for a performance metric that is positively correlated to risk. An example of a positively correlated performance metric would be the predicted Jasper Aquifer compaction from the JCM. The example provided in Figure 4-1 assumes a linear relationship between the performance measure and the risk. If one has evidence to suggest the risk varies non-linearly with the performance measure, one can invoke non-linear relationships. We have used linear relationships for all three performance measures considered.

The calculation of the performance measure (NRS) for a positively correlated performance measure can be calculated by the following equation.

$$Normalized\ Risk\ Score\ (i) = \frac{PM(i) - PM_{min}}{PM_{max} - PM_{min}} \quad \text{(Equation 4-1)}$$

where:

PM(i) is the i_{th} value of the performance measure
PM_{max} is the maximum value of the performance measure for all values *i*
PM_{min} is the minimum value of the performance measure for all values *i*

Figure 4-2 shows the utility function for a negatively correlated performance measure to risk. An example of a performance measure negatively correlated to risk would be the depth of burial of the midpoint of the Jasper Aquifer. The assumption is that the deeper the Jasper Aquifer is, the lower the risk of subsidence. The calculation of the performance measure NRS for a negatively correlated performance measure can be calculated by the following equation.

$$Normalized\ Risk\ Score\ (i) = 1 - \frac{PM(i) - PM_{min}}{PM_{max} - PM_{min}} \quad \text{(Equation 4-2)}$$

The next step in the analysis is to combine the performance measure NRSs into one measure of risk termed the Total Subsidence Risk Score (TSRS). The process used is a simple summation that allows the decision maker to weight each NRS according to the decision maker's intuition about the decision problem. The equation for the TSRS is:

$$Total\ Subsidence\ Risk\ Score\ (TSRS) = \sum_{i=1}^{n} Weight(i) * Normalized\ Risk\ Score\ (i) \quad \text{(Equation 4-3)}$$

The final step in our analysis is a renormalization of the TSRS to a scale from zero to one. The final risk metric is termed the Total Subsidence Normalized Risk Score (TSNRS) and is calculated as follows.

$$Total\ Subsidence\ Normalized\ Risk\ Score = \frac{TSRS(i) - TSRS_{min}}{TSRS_{max} - TSRS_{min}} \quad \text{(Equation 4-4)}$$

The benefit or renormalizing the TSRS as the final step is that it makes the TSNRS comparable across the entire study area. For example, if one TSNRS is equal to 40% and one is 80%, the difference in risk is 40%. It simplifies the math such that spatial comparisons of risk are intuitive.

4.2 Jasper Aquifer Subsidence Risk Assessment Results

The development of the Jasper Aquifer Subsidence Risk Assessment requires two steps that will be described below: the calculation of the performance measure relative risk scores for the three performance measures being considered and the calculation of the TSRS and TSNRS.

4.2.1 Performance Measure Normalized Risk Scores

For the risk analysis of subsidence, there are three performance metrics which require calculation and then normalization using either Equation 4-1 or 4-2. Each performance measure NRS is calculated on the one-square mile risk grid introduced in Section 3 and is described and presented below.

Jasper Aquifer Compaction Normalized Risk Score – For the Jasper Aquifer Compaction Risk Category, we used the JCM prediction of compaction in the Jasper Aquifer and, using Equation 4-1, calculated the Jasper Aquifer Compaction Performance Measure NRS for each cell in the risk grid. **Figure 4-3** plots a map of the Jasper Aquifer Compaction NRS. The range in risk score is normalized to range from zero to one. Figure 4-3 shows that the NRS is highly correlated to the depth of the Jasper Aquifer. This is primarily due to the reduction in inelastic specific storage as a function of depth described in Section

3.2.3, as well as the decrease in vertical hydraulic conductivity with depth, which decreases the rate of compaction due to drawdown.

Depth to Top Jasper Aquifer Normalized Risk Score – The depth from ground surface to the top of the Jasper Aquifer is used as a proxy performance measure to account for the relationship between compaction occurring within the Jasper Aquifer and land subsidence at land surface. This performance measure is considered negatively correlated to risk, so Equation 4-2 is used to calculate the NRS, based on the depth to top of Jasper Aquifer Performance Metric. **Figure 4-4** plots a map of the Depth to Top of Jasper NRS. The risk score is normalized to range from zero to one. As would be expected, the relative risk score is negatively correlated to Jasper Aquifer depth of burial.

Flood Plain Normalized Risk Score – To calculate the Flood Plain NRS, the FEMA 100-year flood plain map (FEMA, 2010) was intersected with the JCM model risk grid. A calculation was made by dividing the area of flood plain in a grid cell by the area of the grid cell. The Flood Plain NRS varies from zero to one. A grid cell with an NRS of one is entirely within the flood plain. A grid cell with an NRS of zero is totally outside of the flood plain. **Figure 4-5** plots a map of the Flood Plain NRS. Comparing Figure 4-5 to Figures 4-3 and 4-4, one can see that the Flood Plain NRS is much more heterogeneous and tends to be dominated by very high NRSs (in flood plain) and very low normalized scores (outside of or minimally inside of flood plain).

4.2.2 Total Subsidence Normalized Risk Score

Once each performance measure NRS is calculated, the TSRS can be calculated using Equation 4-3. The calculation is simply a weighted sum. The weights one applies to a given performance measure NRS is determined through a combination of professional judgement and trial and error. The technical consulting team worked closely with the District's staff in the assignment of the weights used to develop the TSRS. Several weighting schemes were considered. The final weighting scheme used weights for the three-performance metric NRS. In the final equation, the TSRS is calculated as:

$$TSRS = \mathbf{0.5} * Jasper\ Compaction\ Normalized\ Risk\ Score + \mathbf{0.4} * \ Depth\ Jasper\ Normalized\ Score + \mathbf{0.1} * Flood\ Plain\ Normalized\ Score \qquad \text{(Equation 4-5)}$$

Because of the uncertainty associated with the parameterization of the compaction properties of the JCM, it was weighted 50% of the TSRS. Because of the body of literature suggesting that, at least for individual brackish projects, the risk of compaction becomes an equal amount of subsidence at land surface decreases with depth, we weighted the Depth to Top of the Jasper Aquifer NRS at 40%. Because consequence of subsidence is an important consideration, the Flood Plain NRS was weighted with a relatively low weight of 10%. The weight of 10% is warranted because the Flood Plain NRS is somewhat binary in magnitude and can add significant noise to the TSRS.

The TSRS does not vary from zero to one. The last step is to use Equation 4-4 to calculate the TSNRS, which varies from zero to one. **Figure 4-6** provides a map of the TSNRS for the Jasper Aquifer. A review of Figure 4-6 shows that the highest risk areas are in the shallowest portions of the brackish Jasper Aquifer. However, even with a Flood Plain NRS weight of only 10%, it has an influence on the TSNRS map. A good example is in Fort Bend County, where the influence of the Brazos River flood plain pushes the higher NRSs further towards the coast.

The TSNRS Score map has purposefully been developed to provide a means of documenting the relative risk of subsidence from a Jasper Aquifer brackish groundwater development project being developed in one location versus another within the boundaries of the Districts. For example, the range of relative risk associated with a project in southern Fort Bend County versus northern Fort Bend County could be as great as 40%.

This study and the results herein 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 the Jasper Aquifer. Figure 4-6 provides 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. Considerations for the regulation of brackish development in Jasper Aquifer will be discussed in Section 5.

Table 4-1 Summary of the three Risk Categories considered in the risk assessment methodology

Risk Category	Performance Measure	Performance Measure Source
Compaction in the Jasper Aquifer	Predicted compaction in the Jasper Aquifer	Jasper Compaction Model (JCM)
Land Surface Subsidence	Depth to the top of the Jasper Aquifer	TWDB – Young and others (2014)
Consequence from Land Subsidence	100-Year Flood Plain	Federal Emergency Management Agency

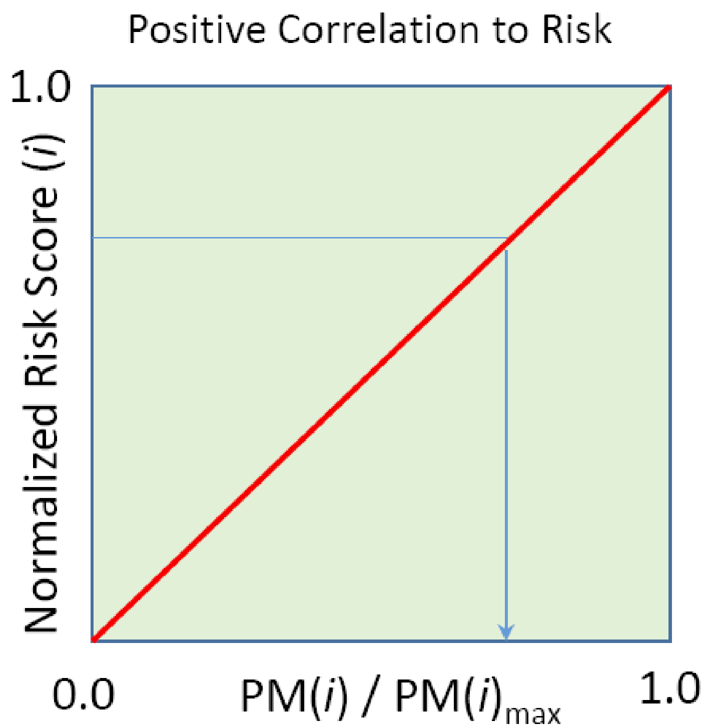


Figure 4-1 Utility function for a positively correlated performance measure

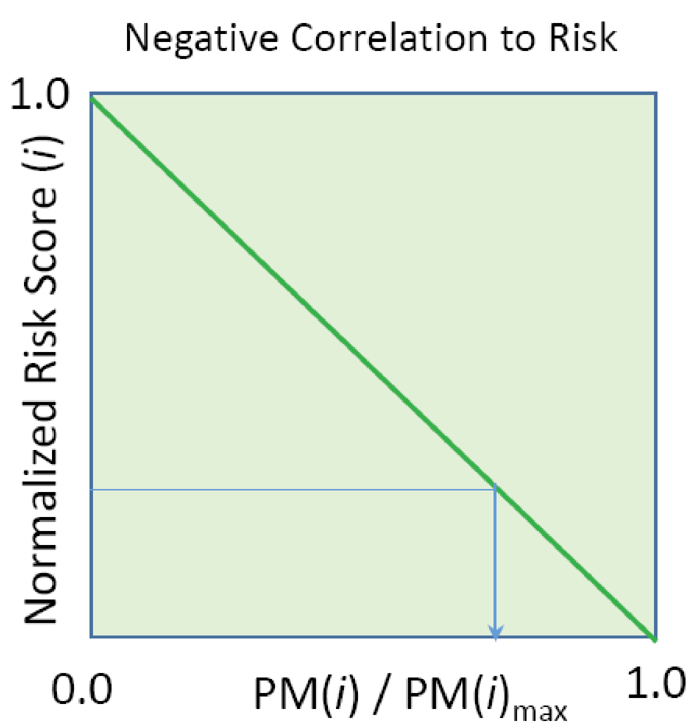


Figure 4-2 Utility function for a negatively correlated performance measure

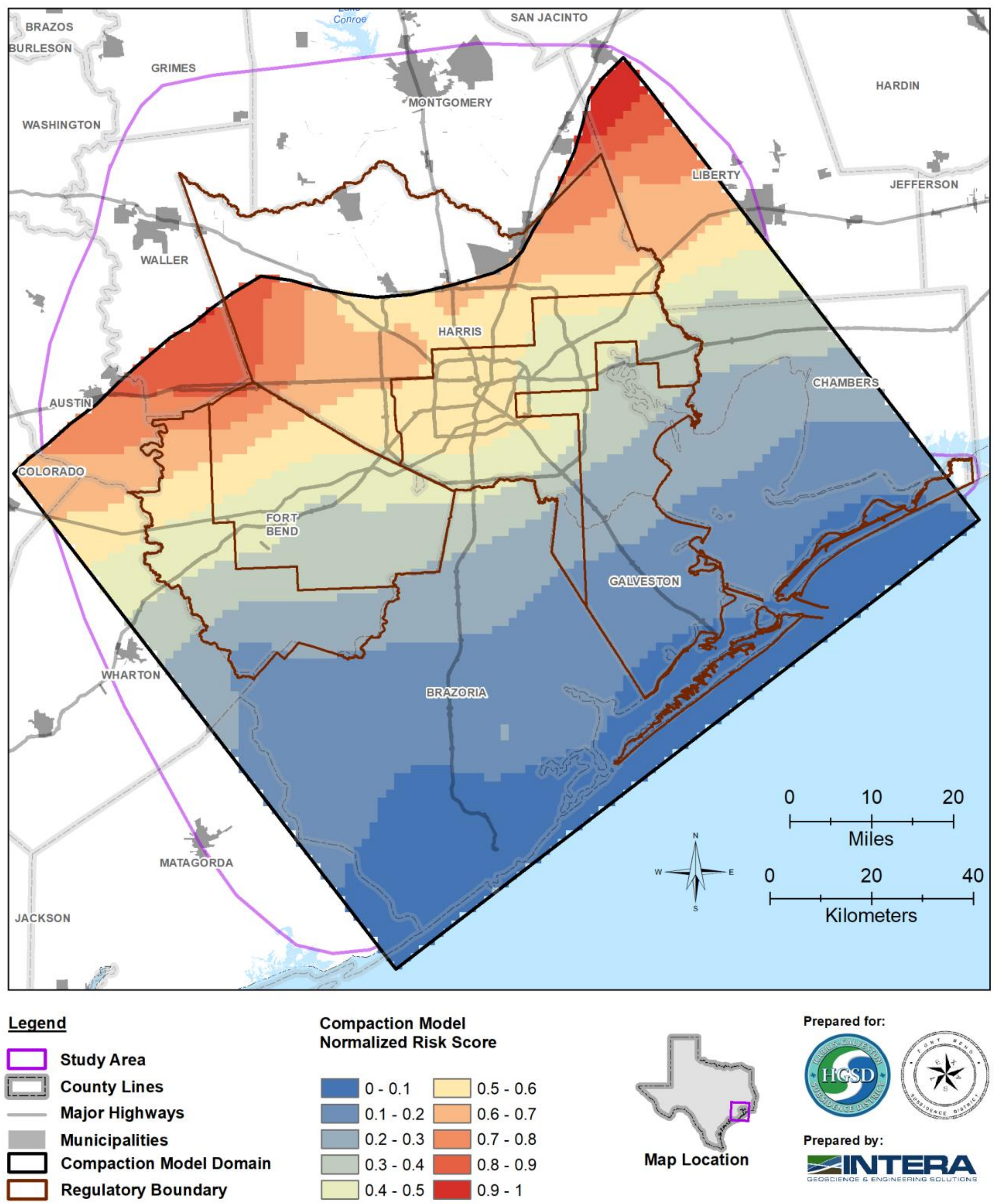


Figure 4-3 Jasper compaction model normalized risk score (NRS) map

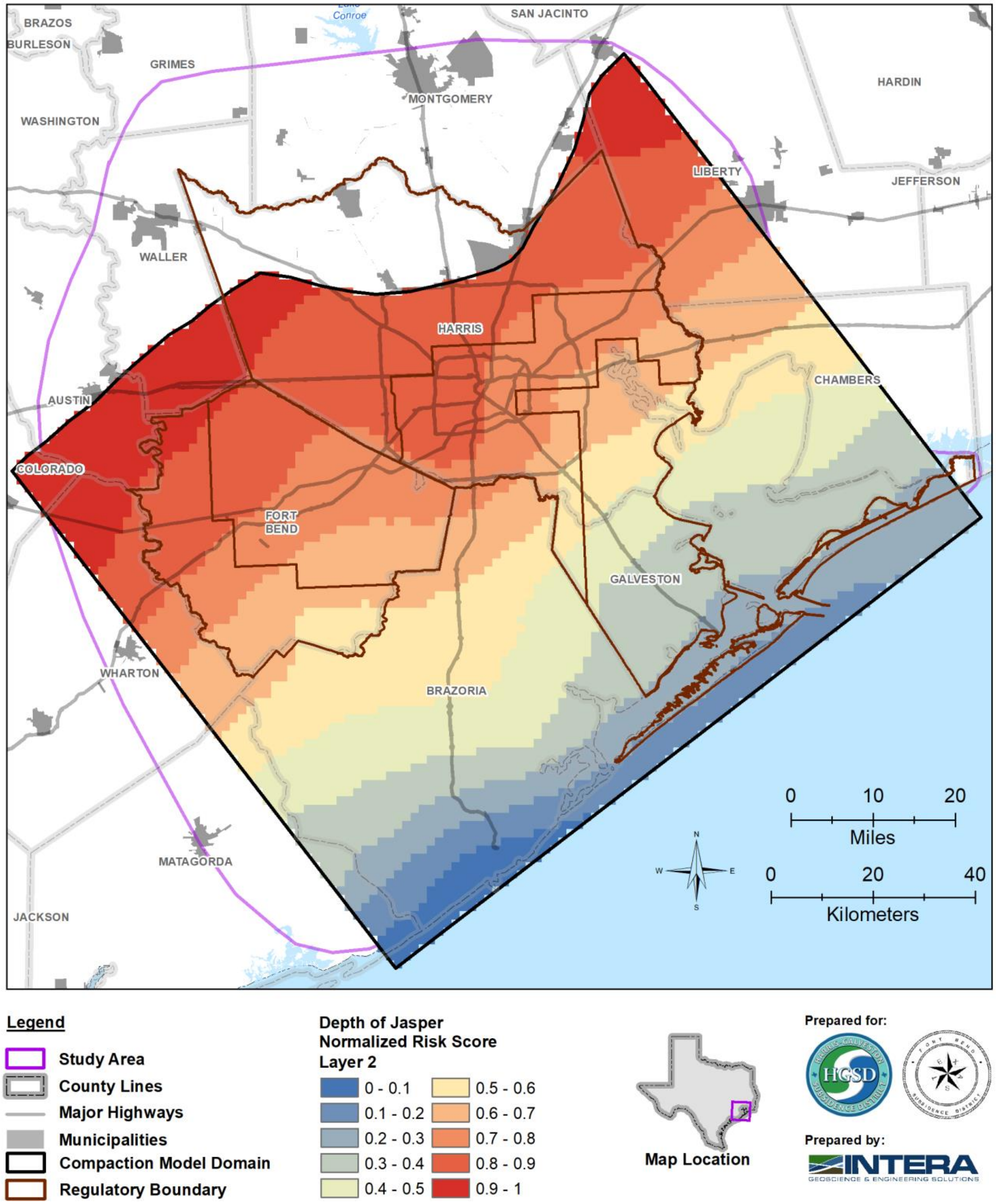


Figure 4-4 Depth to top of the Jasper Aquifer normalized risk score (NRS) map

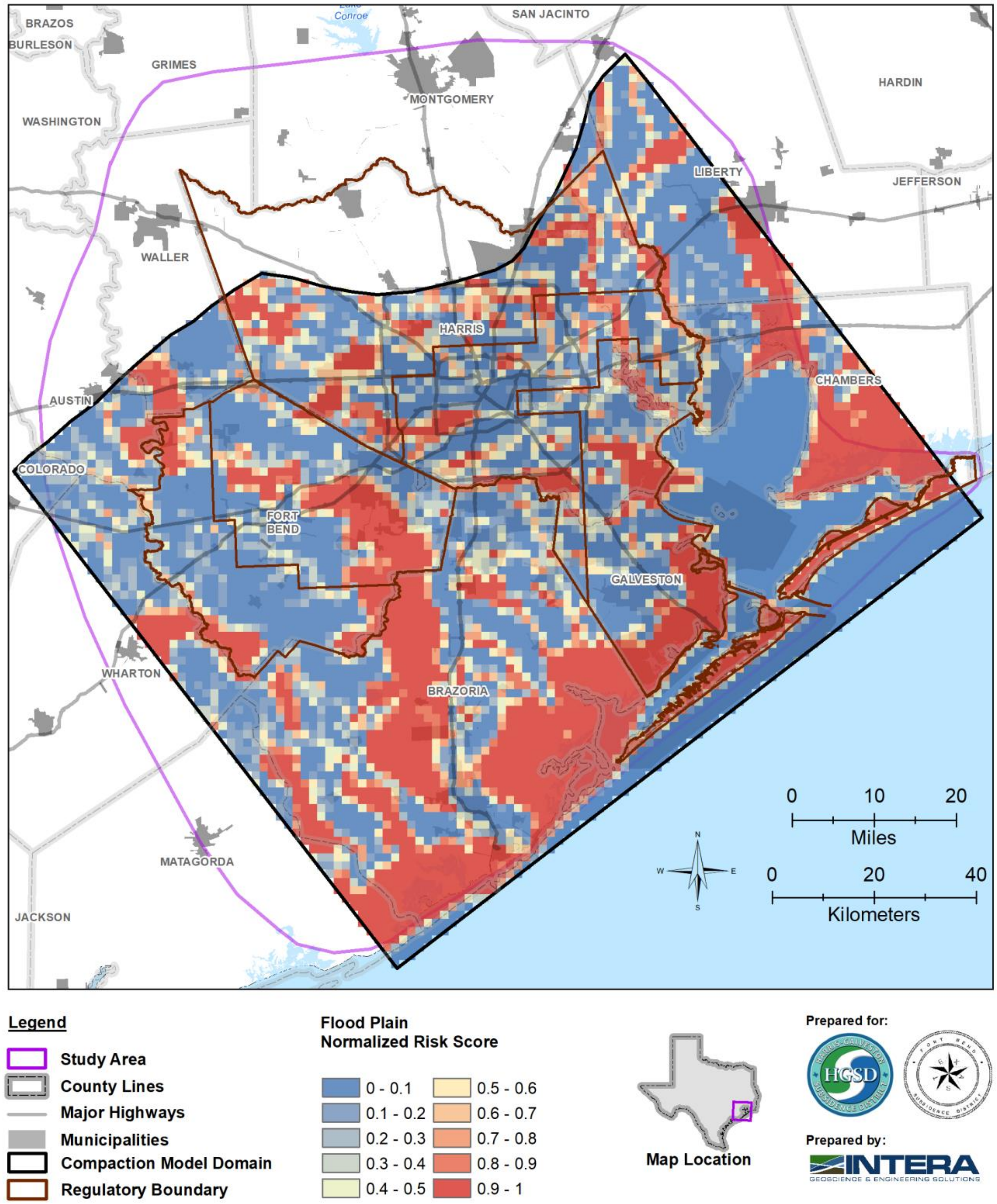


Figure 4-5 Flood plain normalized risk score (NRS) map

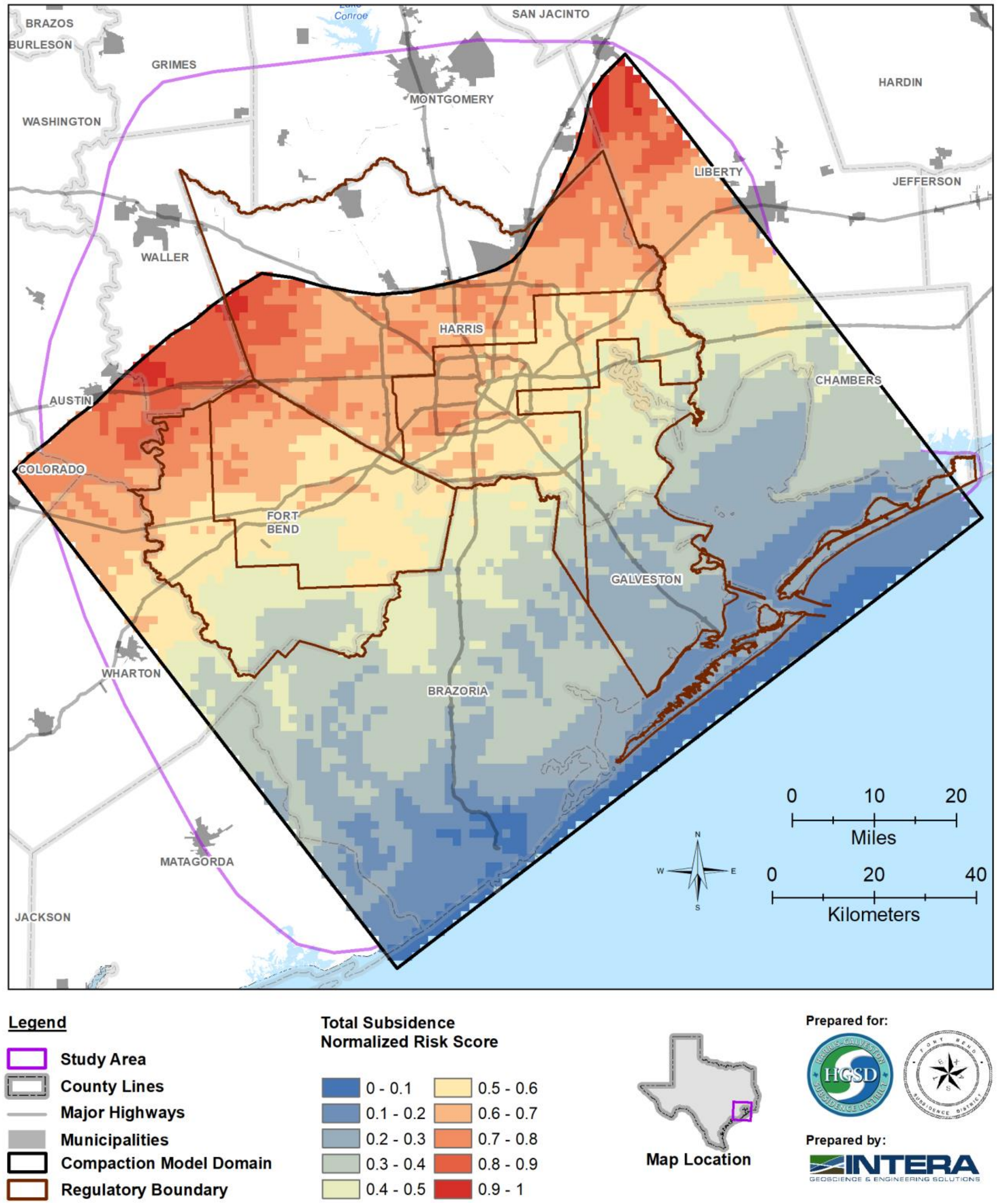


Figure 4-6 Jasper Aquifer total subsidence normalized risk score (TSNRS) map

5.0 CONSIDERATIONS FOR BRACKISH GROUNDWATER DEVELOPMENT REGULATION IN THE JASPER AQUIFER

The Jasper Aquifer is a freshwater supply for wells in Northern Harris County in HGSD Regulatory Area 3. These wells operate and are permitted under the HGSD Regulatory Plan. A limited number of wells have been completed in the brackish or saline portions of the Jasper Aquifer in the Districts. These wells also operate and are permitted under the HGSD and FBSD Regulatory Plans.

This Section provides a list of potential activities and data collection that a permittee of a brackish Jasper Aquifer well could be required to submit to the Districts. These activities have been divided into Tier 1 activities and Tier 2 activities. The Tier 1 activities and submittals are consistent with the mission of the Districts and are considered reasonable given the need for basic data in the brackish Jasper Aquifer. For these activities we have provided the objective of that activity. Tier 2 activities or data collection could be considered by the Districts when a project is considered of higher risk or the permittee is willing to collaborate with the Districts to get additional data to further the science. For Tier 2 activities, both the objective and the conditions for consideration of that activity have been summarized.

5.1 Recommendations for Regulation and Monitoring

Brackish groundwater development could be regulated within the current regulatory methodology or specifically identified with its own regulatory scheme. The recommendations in this section and the Risk Assessment results presented in Section 4 provide information for any policy options that may be adopted by the District's Boards. This report does not promote policy recommendations but rather has been written to inform policy set by the Districts.

If entities continue to be interested in the pursuit of brackish groundwater as an alternative water supply, then permitting requirements can be designed to maximize, to the extent practicable, the types and amount of data collected to better understand the risks of future production in the brackish Jasper Aquifer. Because of a general lack of data in the brackish Jasper Aquifer, current predictions are uncertain. The collection of data will reduce the uncertainty in regulation of the brackish portion of the Jasper Aquifer. The Districts could consider authorizing development of the brackish Jasper Aquifer in a gradual timeline, allowing time to collect data and improve understanding and predictions. It is recommended that brackish Jasper Aquifer wells should permitted be on a case-by-case basis.

This section provides activities and data collection that the Districts could require to be submitted to the Districts as part of the process of permit authorization. Because the collection of data has a cost, the activities, submittals and data proposed to be required of a permittee are divided into two categories; Tier 1 and Tier 2. Both tiers of activities and submittals are consistent with the mission of the Districts. Tier 1 activities are considered reasonable given the need for basic data in the brackish Jasper Aquifer. Tier 2 activities or data collection should be considered when a proposed project is considered of relatively higher risk or the permittee is willing to collaborate with the Districts to get additional data to further the science.

Assuming brackish Jasper Aquifer wells will be permitted in the future; we have proposed another step in the registration and permit process to allow the permittee time to submit some of the recommended data and analyses described below. One possible approach would be to have a three-step process to permitting a brackish Jasper Aquifer production well. The permittee would register the well and identify it as a brackish Jasper Aquifer well as defined by the Districts. Well registrations are currently checked within five days of registration to see if the well meets exclusions or exemptions provided in District Rules 5.8. It is expected that brackish Jasper Aquifer wells would not meet these exclusions and would require a permit.

Once the registration is reviewed by the Districts (five days), the permittee would submit a permit application to support a brackish Jasper Aquifer Drilling Permit. This would include well location (not currently required at registration), engineering design drawings, and a test plan consistent with District's rules. Once that permit is approved, the permittee can drill the well. The permittee would then provide the recommended post well drilling data and analyses to the District as part of a Brackish Jasper Aquifer Production Permit Application. The District could review the application and information provided and approve a well(s)'s annual production volume and impose any special condition provisions as required to the permit. This proposed process would modify the current permitting approach with the addition of a Drilling Permit that is separate from the Production Permit.

Table 5-1 summarizes the Tier 1 permittee activities. In this case, activities could be documentation or collection and interpretation of data. Table 5-1 includes a short description of the objective of the activity. **Table 5-2** summarizes the Tier 2 Jasper Aquifer activities, including short descriptions of the activity, the objective of the activity, and the conditions under which the Districts could consider this activity.

The proposed activities and their relevance to the science of predicting subsidence will be discussed below by category of activity. Each activity's objective and, if Tier 2, the conditions where that activity might be considered are discussed.

Table 5-1 Tier 1 Jasper Aquifer brackish groundwater well activities

Category	Activity	Objective of Activity
Well Design and Completion Documentation	Well Design Engineering Drawings	Project location, scale and engineering design
	Well Testing Plan	Provides documentation of the well test program for District review for compliance
	TDLR Well Completion Report (consultant report)	Provide well completion data, screens depths, water level, specific capacity
Geophysical Logs	Caliper	Diameter of borehole for log analysis
	Density Log (Gamma Gamma)	Estimate formation bulk density for log interpretation, porosity, lithology
	Temperature, Resistivity, Induction, Spontaneous Potential	Estimate formation lithology, water quality (TDS)
	Porosity (Sonic or Compensated Neutron Porosity)	Estimate porosity of the formation
	Cement-Bond Log	Estimate the quality of the cement job
Hydraulic Data	Aquifer Test (36-hour pumping and recovery)	Aquifer transmissivity and leakance
	Static Water Level (Well-Head Pressure)	Provides a means to accurately estimate change in effective stress
Geochemical Data	Water Quality Samples (charge balance less 10%)	Physical measurement of water quality and TDS
	Water Quality Estimated at Specific Depth Intervals using Logs	Provides an estimate of base of freshwater and isolation of brackish aquifer
	Vertical Profile of Water Quality	To insure freshwater is protected and brackish aquifer is isolated
Modeling	Modeled Drawdowns and Radius of Influence	Estimate project drawdown to assess impacts relative to risk assessment analysis
Monitoring	Monthly Water Level Measurements	Estimate change in effective stress at the production wells(s)
	PAM Installation	Determine site specific subsidence for all aquifers
Subsidence Management Plan	Estimate potential subsidence over expected project timeline	Establish a District defined subsidence value triggers corrective action
	Establish protocol for monitoring and reporting subsidence	To make sure Districts are informed of subsidence if it occurs
	Develop a plan to address measured subsidence	To implement an agreed upon corrective action plan including potential curtailment

Table 5-2 Tier 2 Jasper Aquifer brackish groundwater well activities

Category	Documentation / Data	Objective of Activity	Conditions for Consideration
Geophysical Logs	Acoustic Dipole	Provides estimate of clay non-elastic storativity	Optional if high risk or permittee is willing to collaborate
	Magnetic Resonance, Natural Gamma Spectroscopy, Elemental Capture Spectroscopy	Measures effective porosity of clays, clay heterogeneity, clay mineralogy	Optional if high risk or permittee is willing to collaborate
Hydraulic Data	Monitor Well(s)	Provides better estimate of aquifer properties and drawdown extent and degree	Optional if high risk or permittee is willing to collaborate (use a test well)
Geochemical Data	Interval Specific Water Sampling	Provides actual water quality data between the production horizon and freshwater	Optional if the isolation of freshwater is <200 ft and 100 feet clay
Geotechnical Core Data	Clay Compressibility	Physical measurement of clay void ratio and inelastic storativity	Optional if the project has large potential impact or is in high risk area
	Clay Vertical Hydraulic Conductivity	Physical measurement of property controlling timing of clay compaction	Optional if the project has large potential impact or is in high risk area
	Clay Mineralogy	Physical measurement of clay minerals; impacts potential for compaction	Optional if the project has large potential impact or is in high risk area
Modeling	Compaction model using District parameters and tools	Provides a project specific estimate of compaction and potential subsidence	Optional if the project has large potential impact or is in high risk area
Monitoring	Continuous Water Level Monitoring	Provides measurement of maximum drawdown and temporal variability	Optional if the project has large potential impact or is in high risk area
	Maximum allowable drawdown	Limits the degree of drawdown and resulting depressurization of clays	Optional if project predicts drawdowns in excess of 400 feet
	Extensometer Installation	Provides a physical measure of subsidence in Jasper Aquifer	Optional if high risk or permittee is willing to collaborate (retrofit a test well)

5.1.1 Well Design and Completion Documentation

Well design and completion data including the engineering drawings associated with the brackish Jasper Aquifer well needs to be provided to the Districts. This is standard information defining the well(s) and the project. All activities described below are recommended to be required.

Well Design Engineering Report and Drawings – It is important that the Districts have a complete record of the project design and specifications and an accurate location. The Districts reserve the right to inspect any well and associated meters consistent with District Rule 9.1.

Well Testing Plan – The Tier 1 suite of activities includes aquifer testing and the running of geophysical logs and their interpretation. It is recommended that the Well Test Plan be submitted prior to drilling of the well so that the Districts can review the plan for compliance.

Well Completion Report(s) – Well completion reports are required by the Texas Department of Licensing and Regulation (TDLR). The TDLR well completion report is formally called a State of Texas Well Report and has a tracking number. The submitted drillers reports provide the well completion information, the lithology encountered, the depths of the lithology changes, the total well depth, the well completion data, and sometimes a static water level and a specific capacity. This data should be provided to the Districts. In addition, many times, consultants responsible for drilling oversight provide more informative well completion reports that include detailed geologists' notes. Where available, these reports would be of benefit to the Districts.

5.1.2 Geophysical Logs

Borehole geophysics is the science of recording and analyzing physical and electrical property measurements made in wells or boreholes. Probes are lowered into the borehole to collect continuous or point data that are graphically displayed as a geophysical log. Multiple logs typically are collected to take advantage of their synergistic nature. Much more can be learned by the analysis of a suite of logs as a group than by the analysis of the same logs individually.

The different logging probes are not named according to a consistent system: some are named based on the parameter measured, others according to the principle by which the measurement is made, and still others based on the geometry of the probe or the trade name. The logs considered potentially applicable for brackish Jasper Aquifer wells will be described below. For any logs requested by the Districts, it is important that the permittee provide logs in digital format in addition to hard copies. Digital logs aid interpretation of the individual logs.

Caliper – A caliper log measures the radius of an open borehole or the radius of a casing of screen. The radius of the borehole is required for analysis of most geophysical logs and can also be an indicator of lithologic changes and unstable borehole conditions.

Density Log (Gamma gamma) – A density log uses a radioactive source and detector to measure gamma rays used to calculate the formation bulk density. Bulk density is a function of the density of the minerals comprising the aquifer and the fluid within the pore space. The density log also provides a method for estimating porosity of the formation. A gamma log can also be very helpful in lithology determination.

Temperature, Resistivity, Induction and Spontaneous Potential - This log suite uses electrical or electromagnetic signal tools to estimate the lithology of the aquifer and the groundwater quality estimated as TDS. Because these logs are dependent upon temperature corrections, a temperature log must be collected and is collected as part of resistivity, induction and spontaneous potential logging. Many logging companies have tools that include these individual logging tools. The use of this log suite is primarily for determination of aquifer lithology and water quality expressed as TDS. It is recommended that the permittee use tools that allow for identification of properties of the portion of the aquifer that is uninvaded by borehole drilling fluid. This requires dual induction logs and at a minimum shallow and deep resistivity measurements.

<u>Porosity (Sonic or Compensated Neutron Porosity) Log</u> – Porosity is typically estimated from a sonic log or a neutron density log. It is advantageous to use two types of logs to estimate porosity because of the uncertainty in the methods. A sonic log transmits and receives a seismic signal, which can be used to estimate porosity assuming the seismic velocity of the matrix and the pore fluid. A neutron density log is a nuclear log with an americium-beryllium source that can estimate porosity by interpretation of neutron scattering from the aquifer matrix and hydrogen atoms.

<u>Cement-Bond Log</u> – Cement-bond logs are acoustic logs used to evaluate indirectly the integrity and quality of the cement bond to the casing material. The basic principle underlying the log application is that the amplitude of the acoustic signal will be attenuated in a section of the well where there is a good cement bond and will not be in areas where the bond is poor or not present. Because cement is used to isolate the brackish groundwater production zone from the fresh groundwater in shallower intervals, the demonstration of a quality cement bond is very important to protect fresh groundwater quality.

<u>Acoustic Dipole Log</u> – Acoustic dipole logs have been used by the oil and gas industry for many reasons, one of which is to estimate geomechanical properties important to reservoir inelastic storativity. Poisson's Ratio and the formation shear modulus can be calculated from shear and compressional wave slowness if one knows the formation bulk density (determined from a density log). With the shear modulus and the Poisson's Ratio, Young's Modulus, bulk modulus (inverse of is compressibility), and Biot's elastic constant can be estimated. These geomechanical properties directly relate to the formation inelastic storativity and therefore compaction potential. Because the geomechanical properties measured from compressional waves from sonic logs are correlated to the frequency of the sonic frequency of the tool, analysts in the oil and gas industry make corrections to geomechanical properties determined from sonic logs based upon the sonic frequency employed by the logging tool (Olsen, 2015).

There is a general lack of in-situ geomechanical properties of clays in the Gulf Coast Aquifer System in the study area. The last cores that were analyzed for geomechanical properties were those collected by the USGS in the 1970s (Gabrysch and Bonnet, 1974, 1975, 1976a, 1976b). The use of sonic logs to estimate geomechanical properties has not been common practice in the hydrogeologic community. However, using state-of-the-art well logs and interpretation methods could be very beneficial to developing a better understanding of the potential for future compaction at depths greater than 2,000 ft bgs, where we have no physical core data or historical extensometer data. The conceptual model for compaction properties developed from available data and summarized in Section 2 of this report shows that properties that control compaction vary as a function of depth of burial. This is the case for all PRESS models and the HAGM. The geophysical logs may provide a method to see if the clays do have lower compressibility with depth. This data could provide evidence for the current compaction parameterization used in the Gulf Coast Aquifer System by the Districts. Because of the somewhat exploratory nature of the log, this is considered a Tier 2 activity.

<u>Magnetic Resonance, Natural Gamma Spectroscopy and Elemental Capture Spectroscopy</u> – Some of the more recent log and petrophysical techniques developed in the oil industry have proven to be valuable from an aquifer characterization perspective in the Tertiary Coastal Plain Aquifers of Texas (Marfice and others, 2001). These include magnetic resonance logs, natural gamma spectroscopy and Elemental Capture Spectroscopy. These logs are Tier 2 activities, but they may be worth consideration because they provide valuable characterization information. Each of these logs will be discussed below in terms of the relevance of the information that can be interpreted from them.

Magnetic resonance logs use a magnetic source to measure the porosity independent of the aquifer matrix composition creating an image of the aquifer porosity. Magnetic resonance works similarly to medical magnetic resonance images (MRIs). The strength of the MRI log is that it can determine the porosity of movable water versus the water in smaller unconnected pores that is effectively bound and immobile. The raw signal from an MRI log also provides information on pore size distribution, and thus information about heterogeneity of clays. This could be valuable when considering compaction and effective sizes of clay beds.

Natural gamma spectroscopy is a tool that breaks the standard gamma ray into its three main components: thorium, potassium and uranium. Thorium and potassium can be used to interpret the types and percentages of clays in the formation being logged (Marfice and others, 2001). For compaction studies, the percent clay is a very useful parameter to have detailed data on. In addition, studies have shown that clays rich in montmorillonite are more porous and more compressible under a given load than clays that consist of the other clay minerals such as illite and kaolinite (Lofgren and Klausing, 1969; Meade, 1964). For aquifer storage and recovery, the types of clay composing the clay interbeds is very important because of the potential for ion exchange and swelling. Elemental capture spectroscopy measures elemental concentrations of the formation being logged which can be correlated to mineralogy and lithology. With these tools, the logs can provide a clear understanding of the aquifer porosity, lithology and mineralogy.

5.1.3 Hydraulic Data

Hydraulic data is data collected to characterize the aquifer properties in the vicinity of a brackish well or well field. These properties provide the basis for hydraulic analysis of the drawdown and the distance drawdown extends radially away from the well(s). Finally, a good hydraulic aquifer test can provide information related to leakance from fine-grained sediments which is the source of compaction.

Aquifer Test – It is recommended that the permittee perform at least a 36-hour pumping test at each brackish well. Water level must be measured at the pumping well, and any available monitoring well (see below), on a schedule consistent with the design specifications of the test, making sure to capture adequate early-time data when water level change is the greatest. Best practices would require that the permittee also monitor water level recovery after pumping for a minimum period equal to the length of the pump test. The permittee must develop an aquifer test plan for review by the Districts. The aquifer test provides an estimate of aquifer transmissivity and storativity. From the transmissivity, an aquifer hydraulic conductivity can be estimated. The aquifer test can also provide information regarding leakance from clays and an estimate of a leakance coefficient. The permittee would document the test in an Aquifer Test Report to be submitted to the Districts as part of the production permit process.

Monitor Well – Monitor wells can be significant from a hydraulic testing perspective because they provide a means to estimate uniquely storativity of an aquifer. Storativity estimates from an aquifer test where water level is only monitored in the pumping well cannot provide a unique estimate of storativity. A monitor well(s) also provides an observed drawdown at distance. Storativity is an important parameter, in part, controlling the time evolution of drawdown from brackish development and the radius of influence of the development.

A monitor well is a large expense to require of a permittee. However, as in the case of the Cinco MUD #1 Jasper Aquifer brackish groundwater development, a test well will be drilled prior to drilling the larger diameter production well. This provides a great opportunity to use the test well as a monitor well or for extensometer installation as was done at the Cinco MUD #1 site. A monitor well would also be important to monitor during the brackish well production to see how model predictions of drawdown as one moves radially away from the production well(s) compares to model predictions.

Static-Water Levels (Well-Head Pressure) – Compaction and subsidence are the result of an increase in effective stress imposed on clays and fine-grained deposits within the aquifers. The increase in effective stress is due to water level decline in the affected area near a production well. As discussed in Section 2, both the initiation of compaction and the ultimate amount of compaction are functions of the drawdown that occurs within the aquifer. To calculate drawdown requires an estimate of the initial static water level or well head pressure measured at the well after drilling and prior to testing and development. This measurement should be made and reported to the Districts with the Aquifer Test Report. It is possible that the static water level may change (usually decrease) between the time of drilling and testing. The initial static water level or well-head pressure should be measured immediately after equilibration from drilling.

5.1.4 Geochemical Data

Brackish groundwater is defined by the TWDB as water that contains between 1,000 and 10,000 mg/L of TDS concentration. Significant areas of the Jasper Aquifer are brackish by this definition (Young and others, 2017). Water quality sampling at a new well would be important to augment the Districts' water quality data at depths and locations in the Jasper Aquifer.

Water Quality Analysis – It is likely that a future permittee will need to desalinate the groundwater for municipal or industrial use. The predominant technology used for desalination of brackish groundwater in Texas is reverse osmosis. Reverse osmosis is a pressure-driven process that relies on semi-permeable membranes to separate dissolved salts from water. These membranes are subject to fouling and scaling depending on the feed water quality and design and operation of the reverse osmosis system. Therefore, understanding the fouling and scaling potential of a water source are key considerations when developing a brackish groundwater supply. In addition, if the permittee is going to use the groundwater for public water supply, they will have to comply with potable water standards (TCEQ's primary and secondary drinking water standards). In this case, the brackish groundwater will need to be desalinated. Young and others (2016) outline both the common water quality parameters that need to be defined by the reverse osmosis technology as well as the potable water standards.

Of interest to the Districts is understanding the gross water quality to determine the salinity of the groundwater to assure that it is brackish or saline. We would recommend that the permittee analyze the groundwater for water quality constituents adequate to measure TDS through the ionic summation approach with a charge balance error less than 10% (Young and others, 2017). An analysis that can be used to independently calculate TDS provides valuable information on the brackish groundwater chemistry. This information can be used for other studies by the Districts and provides necessary concentrations of constituents in solution, such as bicarbonate, that can be used to estimate more accurately TDS from geophysical logs. In addition, we would propose that the permittee measure redox potential (Eh/Ph). This measurement can be valuable for future studies and builds on the work performed by the USGS and the City of Houston in the shallower aquifers analyzing chemical facies of the Gulf Coast Aquifer System (Oden, Brown and Oden, 2011; Oden, Oden and Szabo, 2011; Oden and

Szabo, 2015). We also recommend that the permittee be required to submit all water quality data collected by the permittee to the Districts.

Interval Water Quality Estimated by Geophysical Log Analysis – Isolation of a brackish well from freshwater aquifers is very important to the Districts. The permittee should analyze the TDS of groundwater at the production well, or nearby test well, from the base of the well to the base of freshwater (1,000 mg/L). The permittee should use standard geophysical log interpretation techniques documented by the TWDB and in Young and others (2016, 2017). The purpose of this analysis is to provide the Districts with an estimate of base of freshwater at the brackish well and to also provide data on the separation of the production interval from the freshwater/brackish water interface. The data and calculations used to make the water quality determination should be provided to the Districts.

Protection of Water Quality – The District's vision statement establishes the vision for the Districts to play an integral role in regional water management strategies to insure long-term viability of all water resources while protecting lives and property within the Districts from the impacts of subsidence and flooding. Insuring that freshwater quality is not impaired by the production of brackish groundwater is consistent with that vision statement. To meet this goal, the Districts could require: (1) a review of all injection wells within a one-mile radius of the brackish well; (2) a review of the proximity of salt domes within a two-mile radius of the production well; and (3) a calculation of the total thickness of clay between the production interval and the base of freshwater.

If the total vertical distance between the base of fresh water and the brackish production interval is less than 200 ft and has less than 100 ft of clay, the Districts have the option of requiring that the permittee perform interval water quality analysis through physical collection of water quality samples.

5.1.5 Geotechnical Core Data

Geotechnical data can be interpreted from modern geophysical log interpretation described above but this data type is not based upon direct measurement. To measure geotechnical properties directly requires core data of the clays within and bounding the production interval. Cores were collected and analyzed for geotechnical properties and clay mineralogy by the HGSD and the USGS at three sites in the District in the 1970s (Gabrysch and Bonnet, 1974, 1975a, 1975b). Since that time, cores have not been analyzed to our knowledge. Instead of doing traditional large diameter wireline coring, the costs can be decreased by performing side-wall coring. Side wall core generally have diameters of 1 to 1.5 inches. The two primary technologies used to collect side-wall core are percussion methods and mechanical coring methods. The former is known to compress and potentially fracture the core sample. Mechanical methods collect more intact samples and can have larger diameters than percussion methods.

This data collection activity is a Tier 2 activity and may only be considered when the Districts' concern regarding the risk of the project or the willingness of the permittee to collaborate with the District. The following describes the data that can be collected from core data.

Clay Compressibility – The collected sidewall core data can be sent to a geotechnical laboratory to determine sample void ratio versus load (stress). From this data, both the clay inelastic compressibility and the preconsolidation stress can be estimated. These properties directly affect compaction. The clay inelastic compressibility is conceptualized to decrease in magnitude as a function of depth. This depth dependence is seen in the limited field measurements and has been used in District PRESS modeling for over 20 years (see Section 2). Data of this type collected at various depths could be used to validate model assumptions used in the Regulatory Program.

Clay Vertical Hydraulic Conductivity – The collected sidewall core data can be sent to a geotechnical laboratory to determine the vertical hydraulic conductivity of the clay interbeds. The vertical hydraulic conductivity, as described in Section 2, dictates the time it takes for a clay to de-pressure, which is the phenomenon that leads to increased stress on the clay matrix causing compaction. The clay vertical hydraulic conductivity is conceptualized to decrease in magnitude as a function of depth. As with inelastic compressibility, this depth dependence is seen in the limited field measurements and has been implemented in District PRESS modeling. Data of this type collected at various depths could be used to validate model assumptions used in the Regulatory Program.

Clay Mineralogy – There is limited data on the clay mineralogy of the clays in the Gulf Coast Aquifer System. Studies performed by the USGS in California have shown that the compaction properties of clays are different depending upon the dominant clay mineral. Montmorillonite has the highest compressibility, and is therefore more prone to compaction, than other clay minerals. The permittee could also perform grain-size distribution analysis on the cores collected so that they can be used to correlate to geophysical log signatures.

5.1.6 Modeling

Permittees applying for a brackish well permit in the Jasper Aquifer should be required to perform some fundamental modeling to support the application. The risk assessment provided in this report is based upon assumptions regarding drawdown and does not account for the regional influence of one project on another. The risk assessment is also based upon assumptions regarding clay bed frequency and clay bed thickness from the nearest log interpreted in the HGSD and FBSD brackish groundwater characterization report (Young and others, 2017). A baseline of data and modeling should be submitted to the Districts for review as part of the permit process. It is proposed that hydraulic modeling be performed by the permittee as a Tier 1 activity. Compaction modeling is proposed to be a Tier 2 activity if the District finds that the hydraulic modeling is predicting drawdowns that are inconsistent with the assumptions in the risk assessment or field conditions that show significant deviation in clay bed thickness and frequency.

Model Drawdown and Radius of Influence – A proposed Tier 1 activity is to model the hydraulic response in terms of areal extent and magnitude of drawdown associated with the project. The modeling should predict a radius of influence of the production well. In the TWDB designation for a brackish production zone, one requirement in House Bill 30 was that a brackish production zone be separated by hydrogeologic barriers sufficient to prevent significant impacts to water availability or water quality in other aquifers, subdivisions of aquifers, or geologic strata that have an average total dissolved solids level of 1,000 mg/L or less. While the Districts were explicitly exempted from HB-30, this general guidance is appropriate. The modeling should be able to handle the heterogeneity in aquifer properties available through well testing and log analysis. Because freshwater sources are generally going to be above the Jasper Aquifer, separated by the Burkeville, impacts to overlying formations are considered unlikely. However, if a permittee proposes a well closer to the freshwater portions of the Japer Aquifer, they should extend the modeling radially such that the Districts can assess potential impacts to freshwater. The permittee can use applicable analytic models or numerical models to make the predictions of drawdown at the production well(s) as well as drawdown at distances where impacts are de minimis. The modeling should perform a sensitivity analysis over a reasonable range of flow rates and hydraulic properties.

Compaction Modeling – It is proposed that compaction modeling be a Tier 2 activity based upon the conditions described above. If the Districts request compaction modeling, it is proposed that they use District-defined compaction parameters unless they have site-specific data. It is proposed that the permittee use the lithologic column of sands and clays determined by interpretation of the geophysical logs run at the well. The modeling should perform a sensitivity analysis over a reasonable range of flow rates, hydraulic and compaction properties. The permittee should identify any mapped faults within 10 miles of the well(s) because subsidence has been correlated to proximity to faults (Qu and others, 2015).

5.1.7 Monitoring

Monitoring is currently required on the brackish Jasper Aquifer wells completed in the Districts. Permittees are required to install and operate a flow meter and keep accurate records on a monthly basis of groundwater withdrawn (Rules 5.3, d,e). The Districts have also imposed a special provision condition that the permittee must report water levels (if below land surface) or artesian pressure of all permitted wells monthly and provide that information to the District at least annually. This section builds off the approach the Districts have already been taking regarding monitoring and add a few additional proposed requirements. Because well flow meters are a standard permit condition we will not consider them in this section.

Monthly Water Level Measurements – Compaction and subsidence are the result an increase in effective stress caused by lowering the water level in an aquifer and subsequent depressurization of clay interbeds. Therefore, water levels are critical to characterizing the drawdown that occurs at a production well and for the science of compaction and subsidence. It is recommended that monthly water level measurements be made at all production wells and monitor wells under the control of the permittee and drilled as part of the permit.

Continuous Water Level Measurements – In some cases, the drawdown being predicted by the permittee could be of concern. In this case, the Districts may request that water levels are continuously measured over some practical time interval determined by the District. The subsidence risk assessment presented in this report has been developed assuming a practical estimate of drawdown surrounding a well field not exceeding 500 ft. This amount of drawdown is large relative to drawdowns generally seen near pumping wells in the Chicot and Evangeline aquifers. However, these aquifers are generally more transmissive than the deeper portions of the Jasper Aquifer that would be the target of brackish development. The assumptions regarding drawdown used in this risk assessment are reasonable given expected aquifer properties and typical water production equipment. However, larger drawdowns are possible because specific capacities are expected to be lower than in the overlying freshwater aquifers and available drawdown could be thousands of feet.

It is possible that applicants could turn to oil-field well technology to produce greater volumes through imposing larger drawdowns. The Districts must be aware of this potential and be prepared to impose a maximum allowable drawdown on brackish production wells. Because ultimate compaction is directly proportional to drawdown, compaction and potentially subsidence could be of greater risk in the deeper (greater than 3,000 ft) portions of the Jasper Aquifer than is predicted by the risk assessment presented in this report. District staff will have to monitor the design of deeper wells and the predicted design drawdown in the well and immediate vicinity to make sure drawdown does not significantly deviate from the assumptions of this analysis. If they do, we would recommend the Districts consider a special provision condition related to maximum allowable drawdown. If this condition is considered applicable by the Districts, we would recommend continuous water level measurement using a pressure transducer and a data logger in the production well and any monitoring wells completed as part of the development.

Port-A-Measure Installation – In 1993, the HGSD and the National Geodetic Survey signed a cooperative agreement jointly to pursue improved, less expensive methods of monitoring land-surface subsidence in the Houston area. This agreement supported an experimental study using a global positioning system (GPS) to measure subsidence. The study involves a network of fixed location and mobile GPS measuring setups. The fixed location setups are called Continuously Operating Reference Stations (CORS). The first CORS were established at existing extensometer sites. Currently, there are more than 40 CORS in the Houston area (Wang and Soler, 2014).

The mobile GPS units are referred to as Port-A-Measure (PAM) units. The GPS measurements at the extensometer locations are used as reference benchmarks for the measurements at the mobile GPS locations. The first PAM units began collecting data in January 1994. The PAM network has been continuously expanded, and the number of total stations was 80 as of 2014 (Wang and others, 2015).

HGSD has 50 PAM Sites reporting and FBSD has 16 PAM Sites reporting (https://hgsubsidence.org/subsidence-data/). There are 86 active PAM Sites including Montgomery and Brazoria counties. The University of Houston also operates 50 PAM Sites (Wang and others, 2015). The vertical accuracy of the PAM measured ground surface elevation is "plus or minus" 6 to 8 millimeters (Wang and others, 2015). Installation and operation of a PAM Site is very affordable as compared to survey re-levelling or extensometers. The PAM trailers cost approximately $10,000.

Because of the potential risk of compaction and potentially subsidence in development of the brackish resources of the Jasper Aquifer, it is recommended that a PAM be installed at any new brackish Jasper Aquifer project site if there currently is not one very close to the well(s).

Extensometer Installation – An extensometer is a stable benchmark installed at depth which can measure the subsidence that occurs from the benchmark installed at some depth and ground surface. They are essentially boreholes that are lined with a steel casing with slip-joints to prevent it from crumpling as subsidence occurs. An inner pipe rests on a concrete plug at the bottom of the borehole and extends to the top. This inner pipe then transfers the change in elevation of ground surface relative to the concrete plug at depth. A chart recorder provides a continuous record of subsidence over time. The USGS began installing extensometers in the Harris-Galveston region in the first half of the 1970s. There are currently 13 historical extensometers in the HGSD at 11 different sites. As part of the Cinco MUD #1 Jasper Aquifer brackish well project, the permittee completed a new extensometer in far eastern Fort Bend County, which set the concrete plug on the top of the Burkeville Confining Unit. In combination with a PAM Site, this extensometer provides means to discriminate subsidence occurring in the Evangeline and Jasper aquifers from subsidence occurring in the Jasper Aquifer at the Cinco MUD #1 well.

Borehole extensometers provide excellent subsidence data, but their high cost prohibits their use in sufficient numbers to provide adequate information for an entire study area. Zilkoski and others (2003) estimate the average cost of an extensometer at approximately $800,000 in 2001 dollars. For extensometers to be of value for development within the Jasper Aquifer, they must be very deep, which increases their cost significantly. The importance of extensometers is they provide direct evidence of compaction occurring in the Jasper Aquifer because of their design. It is proposed that the Districts maintain the option to have the permittee install or participate in the installation of a deep extensometer if the project is deemed to pose significant risk. Installation of a deep extensometer would be very valuable in a location where a shallow extensometer currently exists. This could help inform the question of how effectively compaction predicted to occur in the Jasper Aquifer translates to subsidence at land surface.

5.1.8 Subsidence Management Plan

A recommended Tier 1 activity to be performed by the Permittee is the development of a Subsidence Management Plan. It is recommended that each brackish Jasper Aquifer project have a PAM installed at the project well site (Tier 1). The purpose of the Subsidence Management Plan is to provide an agreed upon plan of corrective action if subsidence is determined to be resulting from the project by the District. The three key elements of Subsidence Management Plan are described below.

Estimate Potential Subsidence – The plan should provide an estimate of the potential subsidence that could occur at the project site over the timeline of the project. This estimate could be used by the Districts in addition to considerations regarding subsidence measurement error and the Regulatory Plan to review the Brackish Jasper Aquifer Production Permit Application and the Districts could establish a subsidence threshold value measured at the project PAM site which would trigger corrective action.

Protocol for Subsidence Monitoring and Subsidence Reporting – This element of the plan is to identify for the Districts how the PAM data will be maintained and analyzed, and the reporting methodology to the Districts. If the threshold subsidence agreed upon above is measured at the project site, the permittee could be required to notify the District in writing. This notification would trigger the corrective action plan described below. If the permittee has evidence that indicates that their project is not causing the observed subsidence, they may submit that to the Districts for review and consideration.

Plan to Address Subsidence – The Subsidence Management Plan could include a plan to address subsidence measured above the threshold agreed upon between the permittee and the Districts. The Districts could meet with the permittee and provide a timeline for corrective action to be implemented which would entail curtailment of production.

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6.0 CONCLUSIONS AND LIMITATIONS

This report presents a risk assessment of the potential for subsidence that may result from development of brackish groundwater resources in the Jasper Aquifer within the Harris-Galveston and Fort Bend Subsidence Districts. A limited number of brackish Jasper Aquifer groundwater wells are currently permitted. There is a general lack of data regarding subsidence potential for the Jasper Aquifer. The literature, available data and calibrated models confirm that the Jasper Aquifer will compact. Oil- and-gas fields much deeper in the Gulf Coast Region have initiated surface subsidence (Qu and others, 2015; Khorzad, 1999) as a result of deep reservoir compaction.

The objective of this study was to provide guidance to the Districts regarding the consideration and potential regulation of brackish groundwater development in the Jasper Aquifer. This report is a first step in improving the District understanding of the potential for subsidence which could occur from groundwater development in the brackish Jasper Aquifer. The risk assessment provides a framework for the Districts to evaluate projects in terms of potential subsidence risk based upon their location. The study also provides an approach to collecting additional data to support the Districts in further characterizing the brackish Jasper Aquifer and the potential for subsidence from its development. This section will briefly summarize the key study findings and recommendations and will then summarize some of the key limitations of the study.

6.1 Study Summary of Findings and Recommendations

This study accomplished three primary tasks to meet the objectives described above: (1) review of available data and models to develop a conceptual model for compaction in the Jasper Aquifer; (2) development and implementation of a risk assessment methodology to calculate the risk of brackish groundwater development in the Districts; and (3) provide recommendations regarding what activities and data could be collected to support understanding, regulation, and future investigations in the brackish Jasper Aquifer. Each of these main tasks are summarized in the following subsections.

6.1.1 Conceptual Model and Parameterization of Compaction Properties in the Jasper Aquifer

The first task in this study was the development of a conceptual model for compaction in the Jasper Aquifer. The available data, both laboratory geotechnical tests and subsidence measurements from extensometers and PAM sites were collected and reviewed. There are no available laboratory geotechnical measurements from core taken from clays in the Jasper Aquifer. There are also no historical extensometers in locations where Jasper Aquifer pumping is occurring. However, there are three historical extensometers that are completed in the Lower Lagarto (Burkeville). Recently, the Cinco MUD # 1 installed an extensometer to the top of Burkeville that combined with a PAM Site can provide subsidence data specific to the brackish Jasper Aquifer.

The available laboratory geotechnical analysis performed through the testing of cores of clay interbeds was collected by the USGS in the 1970s (Gabrysch and Bonnet, 1974, 1976a, 1976b). None of the core samples were at depths consistent with the depth of the brackish Jasper Aquifer, but this data, though limited, is significant. Geotechnical tests were performed to measure void ratio and clay storativity under a range of loading stress. This data can also be used to estimate preconsolidation stress.

The available models reviewed include the HAGM (Kasmarek, 2013), which is the regional groundwater model for the region and the 26 PRESS models calibrated to subsidence measurements at 26 PRESS sites across the Districts (Fugro, Inc., 2013). The models were reviewed to: (1) characterize each numerical approach to modeling subsidence and (2) review the parameters and the trends in the parameters that control compaction and subsidence.

From a review of the available laboratory and model data relating to parameters controlling compaction, a conceptual model for parametrization of compaction properties of clays was developed. Both field data and calibrated models provide evidence that inelastic storativity and the vertical hydraulic conductivity of clays in the Gulf Coast Aquifer System decrease in magnitude with depth. This implies that the total amount of compaction of clays from an equal change in effective stress (drawdown) would decrease as a function of depth of burial of the clay. It also implies that the time taken for a clay bed to completely compact in response to an effective stress change increases with depth, so the process of depressurization and resulting compaction takes more time to occur. Drawdown at preconsolidation stress is conceptualized as being greatest at shallower depths and decreasing with depth which means inelastic compaction will occur as effective stress increases at depths consistent with the brackish Jasper Aquifer. While there are theoretical reasons for this relationship between drawdown at preconsolidation stress and depth, it is also conservative from a regulatory perspective making the uncertainty in drawdown at preconsolidation stress unimportant to the risk assessment.

The focus of this study is on the brackish Jasper Aquifer at depths generally greater than 2,000 ft. The conceptual model for parametrization of compaction properties of clays indicates that the risk of compaction in the shallower freshwater section is high relative to the deeper brackish portions of the Jasper Aquifer.

6.1.2 Jasper Compaction Model and Subsidence Risk Assessment

With the conceptual parameterization of compaction properties determined, a numerical model was developed to simulate compaction in the brackish portions of the Jasper Aquifer, termed the Jasper Compaction Model (JCM). MODFLOW-SUB, the code used for the HAGM, was selected because of the regional nature of the risk assessment and because MODFLOW-SUB allows for simulation of flow and compaction in a coupled manner. The JCM was constructed to simulate only the Jasper Aquifer and the overlying Burkeville with a horizontal grid coincident with the HAGM grid and one-mile square in dimension. The JCM simulates compaction resulting from a brackish project located at the center of every 9- by 9-mile block of grid cells across the Districts. Each brackish project is simulated in an independent model simulation, with no other brackish projects included. The hydraulic effects of interfering drawdown cones in the Jasper Aquifer was not considered. Each simulation is run for a 50-year simulation period assuming 500 ft of drawdown. For the risk assessment compaction at 50 years was used.

The approach used to calculate subsidence risk associated with groundwater production in the brackish Jasper Aquifer uses an approach that calculates the relative risk of subsidence based upon three performance measures from three risk categories. The three risk categories considered are; (1) Jasper Aquifer compaction, (2) land subsidence and (3) consequence from subsidence. The performance measures for each risk category are, respectively: (1) JCM predicted compaction at 50 years, (2) depth of burial of the top of the Jasper Aquifer, and (3) the presence of FEMA flood plain. Each of the performance measures were calculated for the risk grid. Each was assigned a utility score from zero to one, with zero being no contribution to risk and one being maximum contribution to risk for that category. With a utility score from one to zero for each performance measure, the total subsidence risk score (TSRS) can be calculated for each risk grid by summing the three scores. Working with the Districts, we chose a weighted sum approach using weights for the JCM score of 50%, the depth to the top of the Jasper Aquifer score of 40%, and the flood plain score of 10%. The final step was to calculate the Total Subsidence Normalized Risk Score (TSNRS). This resulted in a geographic map of TSNRS that varies from zero to one.

The importance of performing the risk assessment in a normalized method is based upon the relatively large uncertainty in predicting an absolute compaction in the brackish Jasper Aquifer and resulting subsidence. By making TSNRS normalized from zero to one, the Districts can directly compare the subsidence risk from one location to the next. Another outcome of normalization of results is it makes the analysis much less dependent upon the drawdown value assumed for the analysis.

The brackish Jasper Aquifer subsidence relative risk map provides 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.

6.1.3 Considerations for Brackish Groundwater Regulation in the Jasper Aquifer

There are currently a limited number of Jasper Aquifer brackish groundwater production wells permitted in the Districts. The associated permits for these wells extend special provision conditions that must be met by each permittee to waive disincentive fees over the duration of the permit.

With the risk assessment presented in this report and the upcoming update of the Regulatory Plan, the District Boards have the option of treating brackish Jasper Aquifer production wells as they have in the past, with a separate regulatory process defined in the updated Regulatory Plan and revised rules, or to exclude them totally from the Regulatory Plan and evaluate them on a one by one basis through the registration and permitting process. Regardless of the policy and regulatory approach adopted, all reasonable opportunities to collect additional data should be explored.

Recommendations for consideration by the District have been proposed regarding activities and data collection to which could be performed and submitted to the Districts as part of the process of permit authorization. Our recommendations are based upon the need for data collection to better understand aquifer performance and to better to manage subsidence. Because the collection of data has a cost, the activities, submittals and data requested of a permittee is divided into two categories based upon data needs and cost of collection: Tier 1 and Tier 2. Both 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. For these activities we have provided the objective of that activity. Tier 2 activities or data collection could be considered by the Districts when a project is considered of higher risk or the permittee is willing to collaborate with the Districts to get additional data to further the science. For second tier activities, both the objective and the conditions for consideration of that activity have been summarized.

Assuming brackish Jasper Aquifer wells will be permitted in the future; it is recommended that another step be included in the registration and permit process to allow the permittee time to submit some of the recommended data and analyses. One way to handle the process is to have a three-step process to permit a brackish Jasper Aquifer production well. The permittee would first register the well and identify it as a brackish Jasper Aquifer well as defined by the District Rules. After the registration is approved, the permittee submits information to support a brackish Jasper Aquifer Drilling Permit. This would include well location (not currently required at registration), engineering design drawings, and a test plan consistent with District rules. Once that permit is approved, the permittee can drill the well. The permittee would then provide the post-well drilling data and analyses to the Districts as part of a Brackish Jasper Aquifer Production Permit Application. The Districts would review the application and information provided, approve a well(s)'s annual production volume, and impose any special condition provisions as required to the permit.

All results and recommendations provided in this report are made to inform the District as they review policy and regulation of development of the brackish Jasper Aquifer. This report is for the consideration of the District Board and does not set policy.

6.2 Limitations of the Risk Assessment

As is the case for any predictive modeling application, there are limitations to the risk assessment of brackish Jasper Aquifer groundwater development presented in this report. These limitations do not undermine the conclusions and recommendations presented in this report but should be identified better to inform the Districts of the application of the analysis. The data collection approach recommended is a tiered approach that recognizes these limitations and provides for optional data collection, modeling and special provision conditions to permits. The key limitations will be discussed below.

- This JCM is based upon a conceptual model of how clay properties controlling compaction vary with depth of burial. The conceptual model is based upon available data and numerical models (HAGM and PRESS) used by the Districts for the regulatory plan. Because there is a lack of geotechnical data on clays at the depths of the deeper portions of the brackish Jasper Aquifer, and there are no measurements of compaction that can be attributed directly to the brackish Jasper Aquifer, the conceptual model is uncertain. The conceptual model for compaction and associated properties for clay compaction are consistent with available data. It is our opinion that the general relative risk to subsidence from pumping in the brackish 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.
- To perform a risk assessment for production in the brackish Jasper Aquifer, assumptions were required to be made regarding how to model the brackish production well(s). The key question was whether to impose a constant flow rate or to impose a constant drawdown at the production well. Our initial analyses assumed a constant flow rate pf 500 gpm. By imposing a constant flow rate, drawdown in the very deep portions of the Jasper Aquifer was unrealistically large (greater than 1,000 ft) and varied at every pumping center. To overcome this issue, we assumed a constant drawdown boundary condition at each production well of 500 ft. This

produces a different flow rate at each pumping center ranging from approximately 1,400 gpm at shallow depths to 400 gpm at 5,000 ft. Because compaction is caused by drawdown and it is constant, the normalized risk assessment provides a method to compare subsidence risk from brackish Japer Aquifer development across the study area. The one caveat to this approach is, if drawdown in the deeper parts of the brackish Jasper Aquifer exceeds 1,000 ft, the relative risk of compaction in the deeper portions of the Jasper Aquifer could rise relative to shallower areas. Oil-field equipment can produce with drawdowns of this magnitude and greater. The Districts have the option to require compaction modeling if a project deviates significantly from the assumptions in this analysis and the Districts can impose a drawdown limit as a special provision condition to a permit.

- The JCM models each well field independently, with only one well field pumping at any given time. This approach is appropriate for the risk assessment and the ability to quantify the risk of production at one location versus another. What this analysis does not account for is the superposition of multiple brackish wellfield drawdown cones. This issue is a question of how much production in the Jasper Aquifer is too much. The potential for drawdown cones from the freshwater Jasper Aquifer wells and shallow brackish Jasper Aquifer wells will have to be considered in regulation. To address this issue, we have recommended that all permittees perform an aquifer pump test to get site-specific hydraulic properties and perform hydraulic modeling to define project-related drawdown and he radius of influence of the production well(s).
- In this risk assessment, the issue of incorporating a performance measure describing how compaction at depth in the brackish Jasper Aquifer will relate to measured land subsidence was handled through a proxy performance measure of the depth of burial of the top of the Jasper Aquifer. Literature confirms that the amount of subsidence resulting from subsurface compaction depends mainly on the ratio between depth of burial (i.e., the depth to top of the Jasper Aquifer) and the lateral extent of the aquifer being de-pressured and compacted (Geertsma, 1973). This risk assessment has addressed one part of this relationship, that being the effect of depth of burial. The risk assessment assumes that the area being compacted for each well field is essentially the same. A pertinent question for future analysis is the quantification of the relationship between subsidence and compaction based upon depth of burial and area of depressurization.
- The JCM model and the risk assessment methodology documented in this report do not explicitly include the overlying aquifers and formations overlying the Burkeville that have historically been developed and have compacted. As a result, the compounding effects of compaction of overlying aquifers are not considered in this analysis and could result in an inaccurate assessment of total subsidence risk. This issue warrants future study and future updates to the HAGM provide a good opportunity to account for these processes.

This report provides a basis for moving forward in regulation of the brackish Jasper Aquifer in an informed way and in a way that promotes the collection of data needed for the advancement of knowledge regarding the hydraulic and compaction properties of the brackish Jasper Aquifer.

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