HARRIS-GALVESTON SUBSIDENCE DISTRICT

Final Report —
Assessment of Subsidence and Regulatory Considerations for Aquifer Storage and Recovery in the Evangeline and Chicot Aquifers

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APRIL 2019

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Harris-Galveston Subsidence District

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ASSESSMENT OF SUBSIDENCE AND REGULATORY CONSIDERATIONS FOR AQUIFER STORAGE AND RECOVERY IN THE EVANGELINE AND CHICOT AQUIFERS

Harris-Galveston Subsidence District

Prepared By

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HDR ARCADIS ASR SYSTEMS

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GEOSCIENTIST AND/OR PROFESSIONAL ENGINEER SEAL(S)

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.

Signature

Date 12/19/2018

Neil Deeds was (P.E. 92741) was the technical lead the compaction modeling of the ASR projects and he is a co-author and investigator on the project.

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Date 12/19/2018

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EXECUTIVE SUMMARY

Aquifer Storage and Recovery (ASR) is an alternative water supply strategy that uses an aquifer for storage to increase water supply more cost effectively than traditional storage expansion strategies (Pyne, 2005). Because of the potential benefits of increasing the available water supply in the region, the Harris-Galveston Subsidence District (hereafter referred to as the District) sponsored a study to research the potential occurrence of subsidence from using ASR as a water supply strategy in the Gulf Coast Aquifer System.

Subsidence is the lowering of land surface elevation. Subsidence has occurred and had significant consequences in the Houston region including contribution to flooding. The District was created by the Texas Legislature in 1975 to regulate groundwater withdrawal from the Gulf Coast Aquifer to stop on-going and prevent future subsidence. In the Districts' region, subsidence is caused by the lowering of groundwater levels in the aquifers (depressurization) and compaction of the many clay lenses in the subsurface. Subsidence caused by the compaction of the generally shallow fresh-water portions of the aquifer is well understood and documented.

ASR is the recharge of water into an aquifer through a groundwater well for future recovery from the same recharge well or another well. Because ASR includes a period of pumping during recovery of the stored water, it can potentially cause compaction and potential subsidence. Two types of ASR projects were considered to estimate the potential for subsidence associated with the application of ASR in the District: a project to provide industrial water supply during a drought of record (DOR) and a project to provide for an annual municipal summer peaking water supply. The operational details of these two hypothetical projects were conceptually developed and potential induced subsidence was simulated for each project. To demonstrate the relative benefits of ASR, the predicted subsidence from each simulated hypothetical ASR project was compared to the predicted subsidence that would occur through the utilization of only groundwater pumping for the same water demand.

Subsidence was calculated using groundwater flow models developed using the United States Geological Survey (USGS) groundwater code MODFLOW-NWT. Groundwater models are developed using published computer programs (such as MODFLOW) to numerically represent the natural groundwater system, simulate water levels in the aquifer, and estimate any subsidence that may result from water-level decline. The MODLFOW code used for this study is the standard used in the hydrogeologic community to predict compaction and subsidence and is the code that was used in the development of the District 2013 Regulatory Plan and the Houston Area Groundwater Model.

Model results from each hypothetical ASR project simulated confirmed that there is potential for subsidence associated with the application of ASR in the Gulf Coast Aquifer System in the District. The predicted subsidence associated with the ASR projects is generally greatest within 1,000 feet of the ASR well(s).

This study provides insight into how an ASR project can be designed and operated to minimize compaction and potential subsidence. Results show that ASR, when utilized for seasonal peaking, can result in less subsidence while producing the same volume of groundwater. This study provides a basis for future research on subsidence associated with ASR in the District and provides a framework for consideration by the District for the potential regulation of ASR wells.

Definition of ASR and Statement of Research Needs

ASR is a proven water supply strategy to increase the availability of either groundwater or surface water through the storage of water in an aquifer using a well or wells. Just as surface water reservoirs are routinely used to increase surface water availability for the future, ASR uses an aquifer to increase availability of either stored surface water, groundwater or reuse water. Like a surface reservoir, a properly designed ASR project will define a yield (storage volume) that the ASR project will supply over some time horizon. **Figure 1** is a schematic of a hypothetical ASR well showing the stored water, often referred to as "the bubble," the buffer zone which represents a volume of mixed recharge and native aquifer groundwater and the target storage volume which encompasses both the bubble and the buffer zone.

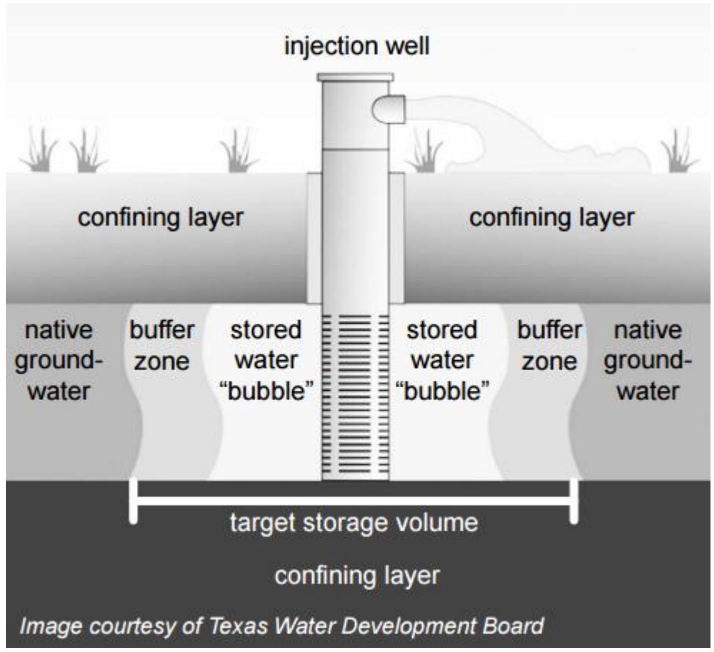

Figure 1 Schematic of an ASR well at the end of recharge and prior to recovery showing the stored water and the buffer zone.

An ASR project includes periods of recharge and periods of recovery (pumping). During recharge periods the water level at and near the well will rise greater than it was prior to recharge. During recovery periods the water level will fall below prior levels just as occurs in standard well pumping. The duration of recharge and recovery periods can vary significantly depending upon the volume of water stored and the needs of the project.

Historically, the Gulf Coast Aquifer System in the District had been the primary water source for the region's municipal, industrial, and agricultural water supply. The Chicot, Evangeline, and Jasper aquifers are the three primary water bearing units of the aquifer system, with the Chicot being the shallowest and the Jasper being the deepest. Extensive development of the Chicot and Evangeline aquifers in the District has resulted in a historical lowering of aquifer water levels and resulting subsidence. Land subsidence can contribute to infrastructure damage, coastal inundation, and inland flooding.

The District identified the need to study the potential for ASR as a viable water management strategy because ASR has been considered by both industrial and municipal water supply users within the District boundaries. The District Science and Research Plan (Turco, 2015) called for an assessment of the potential subsidence neutral yield of an ASR project in the Gulf Coast Aquifer System within the District. This desktop study evaluates the potential subsidence neutral yield of selected ASR project types and provides insight that can support future management and potential regulation of ASR wells in the District.

Mechanisms of Subsidence and Relevance to ASR

The Gulf Coast Aquifer System is composed of a complex sequence of sands and clays. Compaction and resulting subsidence in the Gulf Coast aquifer in the study area is caused by the reduction of the pore pressure in the clay beds as a result of groundwater pumping. This decline in pressure in the aquifer leads to a decrease in pore pressure within the numerous clay lenses, which then begin to compact. This permanent compaction of the sediments, caused by groundwater withdrawal, is the largest contributor to land subsidence throughout the region (Figure 2).

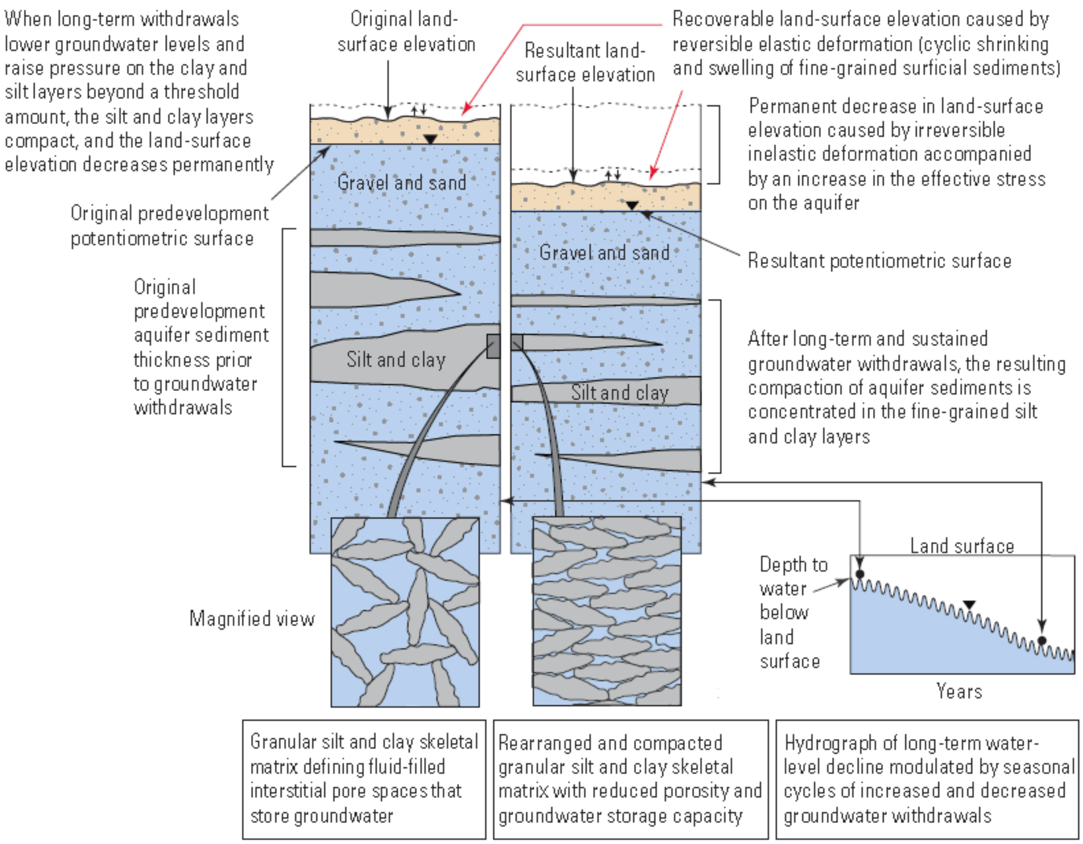

Figure 2 Mechanism of subsidence caused by water level declines induced by groundwater pumping (Source: Kasmarek and others, 2016).

Subsidence is measured as a lowering of ground surface elevation and is the surface manifestation of compaction occurring at depth. Compaction can be a slow process and the time it takes for compaction to occur within a clay bed depends on several clay characteristics. Generally, the thickness of the clay beds, the percentage of clay deposits relative to the total thickness of the aquifer, and the depth of burial of the deposits determine the potential for compaction under groundwater withdrawal and risk for subsidence.

There is potential for an ASR project to induce compaction and potentially contribute to subsidence in the Gulf Coast Aquifer. A literature review was performed on ASR in subsidence prone aquifers and five ASR case studies were reviewed for this study. The literature review showed that well-documented case studies for Managed Aquifer Recharge (MAR) in subsidence prone aquifers outnumbered ASR case studies. There are limited publicly documented case studies of the impacts of ASR in subsidence-prone aquifers. ASR case studies reviewed were the Las Vegas ASR and MAR project and the Antelope Valley, California ASR cycle test performed by the USGS. In both cases subsidence occurred in the vicinity of the ASR projects during their operation or testing.

The most significant finding from the case study review is that, in aquifers that have undergone significant regional subsidence, such as the Gulf Coast Aquifer System in the District, subsidence rates can increase again in response to additional pumping even when water levels remain above historical minimums. This has been documented in several areas of California and has been observed in the District in response to increased pumping during a regional drought in 2011. Therefore, maintaining water levels above historical lows does not guarantee the cessation of subsidence. These facts complicate the analysis of ASR projects impacts in aquifers that have experienced significant regional subsidence such as the Gulf Coast Aquifer System in the District.

Hypothetical ASR Cases and Simulation of Resulting Compaction

The base case hypothetical ASR project considered in this study is a water supply strategy for industrial water users to address the drought of record near Texas City. To develop the operational details for an ASR project, an analysis of industrial water demand and availability during drought was performed for industrial clients of the Gulf Coast Water Authority in Texas City. To investigate hydrogeologic variability in Regulatory Area 1, two additional project locations were considered: one on Galveston Island (downdip site) and one just southeast of Loop 610 in the area that comprises the Galena Park PRESS Site (updip site) in the far northwest edge of Regulatory Area 1. As the study progressed, a municipal ASR alternative water supply strategy to meet annual summer peak demands was added to the study. The summer peaking case was also simulated at the three hypothetical locations used for the DOR case.

A numerical groundwater flow model was developed to estimate compaction associated with the hypothetical ASR projects. The numerical model was developed using the United States Geological Survey (USGS) code MODFLOW-NWT which supports the USGS subsidence (SUB) package. The SUB package is the standard code used in the hydrogeologic community to predict compaction and subsidence and is the code that was used in the development of other groundwater models in the area.

The water source for the hypothetical ASR projects simulated was assumed to be treated surface water from Gulf Coast Water Authority's Thomas S. Mackey Water Treatment Plant. An analysis of geochemical compatibility of the source water with groundwater was performed based upon measured groundwater quality data and inferred formation mineralogy. Results of the geochemical analysis suggest that there could be potential for calcite precipitation which could reduce the ability of the aquifer to store and transmit water. Additionally, there could be potential for other chemical reactions as result of mixing the source water with groundwater which could mobilize arsenic and other metals, increasing the total dissolved solids of the recovered water. Pre-recharge treatment of the injected water and proper design of an ASR buffer zone can mitigate any potential water quality issues identified in this study.

Potential of Subsidence Induced by Compaction from ASR in the Chicot and Evangeline Aquifers

Using the numerical groundwater flow model, compaction was simulated for the DOR case and the summer peaking case at each of the three hypothetical sites. In addition, a simplified hypothetical ASR model was developed simulating a single ASR well completed in one hydrogeologic unit to isolate how various aquifer characteristics and ASR operational parameters can affect compaction.

Figure 3 plots predicted compaction versus time in the immediate vicinity of the well for the hypothetical DOR case and the summer peaking case at the Texas City location. Figure 3 also plots predicted compaction versus time for both sites from only production of an equal volume of groundwater. The difference in predicted compaction between the two curves provides a measure of the relative benefit of ASR over just groundwater pumping for an equal volume of groundwater. Model simulations predict that up to 0.3 feet of aquifer compaction will occur as a result of the hypothetical ASR projects analyzed as shown in Figure 3. At a radial distance of 1,000 feet from the ASR well(s), predicted compaction ranged from 25 to 30% of predicted compaction in the immediate vicinity of the ASR well(s). For both the DOR and summer peaking cases, ASR results in less compaction than production with no recharge. For the hypothetical DOR case, the benefit of ASR versus only groundwater production is 50% reduction in compaction after the first year of recovery, and approximately 3% reduction in compaction at the end of a 5-year recovery period (Figure 3). In the summer peaking case, the benefit of ASR versus only groundwater pumping is greater than 30% reduction in compaction after 20 years of annual operation (Figure 3).

Future ASR projects would require a site-specific analysis of their potential benefits as compared to traditional groundwater pumping based upon that project’s operational details and the detailed hydrogeology at the site. However, generally, model simulation results suggest that ASR projects can reduce the “effective drawdown” on the aquifer for a given groundwater yield and thus result in less compaction and potential subsidence.

The simulations also provide evidence that an ASR project can be designed and operated to minimize potential compaction. Simulations found that the key components of an ASR project to limit the potential compaction are: (1) maximizing the well spacing; (2) decreasing the recovery rate(s); (3) decreasing recovery duration prior to the next recharge cycle; and (4) targeting high transmissivity, low clay content intervals as the storage formation(s).

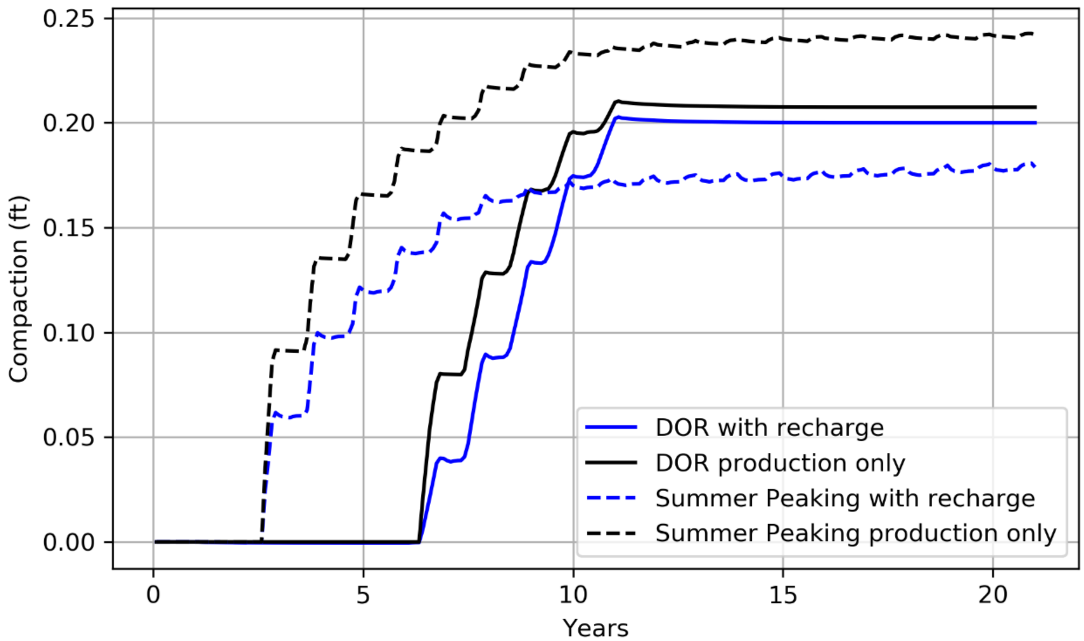

Figure 3 Compaction versus time for the DOR and summer peaking projects, comparing ASR simulations (recharge and production) to simulations with only production.

Relevance and Potential Impact on Future Regulations

This study is the first District study of the potential for subsidence from the implementation of ASR. This study provides new insight for how compaction may occur with the development of ASR in the Chicot and Evangeline aquifers.

TCEQ has the sole regulatory authority to permit Class V ASR injection wells. However, the TCEQ does not have primacy over the regulation of production from Class V ASR wells within the District. The results of this study have led to the development of recommendations for future data and research requirements for ASR projects in the District. Recommendations are based upon the need for data collection and research to better understand aquifer performance and to better manage subsidence risk. This study resulted in several recommendations that may be used in the development of future District policies or form the basis for future District rules specific to ASR development within Harris and Galveston Counties.

Project Overview

Project Start Date: December 1, 2016

Project End Date: January 30, 2019

Total Cost: $340,444

Funding Source: Harris-Galveston Subsidence District

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Kelley, V. and N. Deeds, 2019. Assessment of Subsidence and Regulatory Considerations for Aquifer Storage and Recovery in the Evangeline and Chicot Aquifers, – Report and Model Files for Harris-Galveston Subsidence District Consulting Report, 2019-002, 4/12/2019, 10.5 GB.

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ACROYNMS AND ABBREVIATIONS

%	percent
°F	degrees Fahrenheit
AF	acre-feet
AFY	acre-feet per year
amsl	above mean sea level
ASR	Aquifer Storage and Recovery
bgs	below ground surface
BRA	Brazos River Authority
COA	Certificate of Adjudication
CORS	Continuously Operating Reference Stations
CY	Calendar Year
District	Harris-Galveston Subsidence District
DOR	drought of record
ft	feet
ft/yr	feet per year
ft^2/d	square feet per day
GCD	Groundwater Conservation District
GCWA	Gulf Coast Water Authority
GHBs	general head boundaries
gpm	gallons per minute
GPS	global positioning system
GRP	groundwater reduction plan
HAGM	Houston Area Groundwater Model
HB-655	House Bill-655
InSAR	Interferometric Synthetic-Aperture Radar
IPS	Industrial Pump Station
Kv	hydraulic conductivity
m	meters
MAR	Managed Aquifer Recharge
MG	million gallons
mg/L	milligrams per liter
MGD	million gallons per day

PAM	Port-A-Measure
Plan	2013 Regulatory Plan
SNWS	Southern Nevada Water System
SUB	subsidence
TCEQ	Texas Commission on Environmental Quality
TDS	total dissolved solids
TMWTP	Thomas S. Mackey Water Treatment Plant
TSV	target storage volume
UIC	Underground Injection Control
USGS	United States Geological Survey
WAM	Water Availability Model

1.0 INTRODUCTION

Aquifer Storage and Recovery (ASR) is a popular alternative water supply strategy that provides a means to store water and increase water supply more cost effectively than traditional storage expansion strategies (Pyne, 2005) such as surface reservoirs. New surface reservoirs have become problematic to permit. ASR is particularly well-suited for cases where surface water availability is variable. In that case, conjunctive use of surface water and groundwater provides a proven means to increase supply and/or secure a water right.

ASR has been associated with subsidence mitigation resulting from the regional increase in aquifer water levels. Because of the combined potential benefits of increasing water supply and of mitigating subsidence, the Harris-Galveston Subsidence District (District) has sponsored this study to research the potential implications regarding subsidence from using ASR as a groundwater supply strategy in the freshwater portions of the Gulf Coast Aquifer System. This report documents the study and provides considerations to the District for development of their regulatory approach for ASR. This study provides a foundation of research on ASR for the District and serves to inform future research.

1.1 Study Background and Objectives

This section introduces the concepts of ASR and defines the need and objectives of the study of risk of subsidence as it relates to ASR implementation in the District.

1.1.1 Definition of ASR and the Concept of Subsidence Neutral Yield

ASR is a proven technology and is used as a water supply strategy to increase the availability of either groundwater or surface water. Most water resource engineers are familiar with the concept of using water supply reservoirs to store surface water in times of high availability for use in times of limited availability. Similarly, ASR increases storage by using the subsurface as a reservoir. ASR uses the aquifer to store excess water during times of plenty and recovers that water from the aquifer when it is needed.

Water that is stored will later be recovered through the pumping of the well through which the water was or another close by well. Like a surface reservoir, a properly designed ASR project will define a yield (storage volume) that the ASR project will supply over some time horizon. Because recharge water and the native groundwater mix within an aquifer, geochemical reactions can occur. These reactions can cause water quality changes and, under improper design and operation, reduce the aquifer's deliverability. Experience dictates that the initial ASR project recharge volume, termed the target storage volume (TSV) by Pyne (2005), should be approximately two times the project storage volume. This creates a buffer zone between the recharge water and the native groundwater and provides stability in terms of produced water quality and aquifer performance. **Figure 1-1** is a schematic of a hypothetical ASR well showing the stored water, many times referred to as "the bubble," the buffer zone which represents a volume of mixed recharge and native aquifer groundwater and the TSV which encompasses both the bubble and the buffer zone.

An ASR project includes periods of recharge and periods of recovery (pumping). Depending on the application, the period between recharge and recovery can vary significantly. For example, if one were using ASR to supply groundwater in a drought, the storage volume and the recharge and recovery periods could be large. In addition, the period between recharge and recovery could also be significant. In contrast, if one were using ASR as a seasonal supply, the storage volume and the recharge and recovery cycles could be relatively small and have an annual frequency or less.

In some projects, water is purposefully recharged to an aquifer specifically for environmental benefit, with no intention of recovering that water. Managed Aquifer Recharge (MAR) is a system of intentional recharge of aquifers for later recovery or for environmental protection and replaces the term “artificial recharge” when groundwater quality protection is being considered (Dillon, 2005; Sheng and Zhao, 2015). Historically, MAR has been used world-wide for storm water control and potential reuse, water quality control from saltwater intrusion, and subsidence mitigation. MAR and ASR have been used for decades to mitigate subsidence in groundwater aquifers. Recharge systems have evolved from mitigating geologic hazards related to groundwater pumping to a more proactive and powerful tool for conjunctive management of water resources (American Society of Civil Engineers [ASCE], 2001; Pyne, 2005; Sheng 2005).

In Texas, ASR has a specific regulatory denotation. Specifically, ASR involves the injection of water into an aquifer through a Class V injection well and then the retrieval of that water for beneficial use, as needed. The Texas rules provide that ASR stored water could be produced from the Class V well through which it was recharged or from another well.

In 2015, Legislation clarifying the statutes governing ASR in Texas was enacted through the passage of House Bill-655 (HB-655). This legislation was significant in that it established the Texas Commission on Environmental Quality (TCEQ) as the sole regulatory authority for ASR in Texas. However, it is important to note that Section 36.457 of the Texas Water Code states, “This subchapter does not affect the ability to regulate groundwater as authorized under…(2) Chapter 8801, Special District Local Laws Code for the Harris-Galveston Subsidence District.” The TCEQ has the sole authority to regulate Underground Injection Wells within the District, which could include ASR wells. However, applicable statutes do allow the District to regulate ASR in the District through the issuance of production permits.

In this study the term subsidence neutral yield, as it refers to an ASR project, is defined as the percentage of the recharged storage volume recoverable from an ASR well without causing additional subsidence. The application of subsidence neutral yield on an ASR project is a constraint that could impact the project’s recoverability. In standard ASR design and research, the recoverability of stored volume depends on factors such as operational details, aquifer stratification, native groundwater quality, regional groundwater flow patterns, and regulatory requirements. These factors constrain the project recovery percent. Similarly, the requirement that ASR be subsidence neutral constrains an ASR project’s recoverability.

1.1.2 Statement of Research Needs and Objectives

Historically, the Gulf Coast Aquifer System in the District has been the primary water source for the region’s municipal, industrial, and agricultural water supply. The Chicot, Evangeline, and Jasper aquifers are the three primary water bearing units of the aquifer system, with the Chicot being the shallowest and the Jasper being the deepest (**Figure 1-2**). Extensive development of the Chicot and Evangeline aquifers in the District has resulted in a historical lowering of aquifer water levels and resulting subsidence. Land subsidence can contribute to infrastructure damage, coastal inundation, and inland flooding.

In response to historical subsidence, the District has and continues to curtail groundwater use to mitigate subsidence. In response, water levels have rebounded across much of the District. Even though water levels have rebounded, they are still far below predevelopment levels in the Chicot and Evangeline aquifers. With the need for alternative water supplies within the District, and with the available storage capacity of the Chicot and Evangeline aquifers, water suppliers and users in the District are considering potential ASR projects in the Chicot and Evangeline aquifers. Most recently, the Harris County Flood Control District sponsored a study looking at the potential for (1) recharging flood water to mitigate flooding, (2) increasing potable water supply, and (3) mitigating subsidence. The report, called the Drainage Reuse Initiative Feasibility Study (Binkley and Barfield and others, 2018) looked primarily at MAR but also looked at the application of ASR. The report provided recommendations that included shallow recharge of stored flood water into the shallow Gulf Coast Aquifer System as well as in the deeper portions of these formations that are well below fresh portions of the aquifer system (3,700 to 7,000 feet [ft] below ground surface [bgs]).

Because ASR is an attractive alternative water supply strategy and has been, and likely will be, considered by both industrial and municipal water supply providers in the District boundaries, the District has identified the need for study of ASR and its potential impacts on subsidence in the District. The District Science and Research Plan (Turco, 2015) called for an assessment of the potential subsidence neutral yield of an ASR project in the Gulf Coast Aquifer System within the District. The objectives of this study are to:

- Estimate the time-dependent subsidence-neutral yield of a typical ASR project;
- Estimate the potential impact of water quality of an ASR project on native groundwater quality in the immediate vicinity of the ASR project; and to
- Develop a foundational knowledge base from which the District can evaluate ASR projects and that will inform regulation if the District Board so chooses.

In the project Kickoff Meeting, the project area of interest was narrowed to Regulatory Area 1 (**Figure 1-3**). In Regulatory Area 1, the 2011 drought caused surface water scarcity and a resulting increased need for groundwater production typical of droughts. However, the 2011 drought also raised concerns regarding the vulnerability and long-term viability of the surface water resources of the Brazos River in Regulatory Area 1. This is of importance for the District and for those in Regulatory Area 1 who rely on Brazos River surface water for 90 percent (%) of their total water demand (Turco, 2015). Industrial water users in Regulatory Area 1 have shown interest in ASR as a conjunctive water supply strategy, and Texas City studied the efficacy of ASR. As a result, the ASR base case project has been defined to be a drought of record (DOR) supply for industrial water users in Regulatory Area 1. During the project implementation, it was suggested that the study also consider a municipal water supply ASR strategy based upon meeting an annual summer peaking demand. This case was also considered in this report.

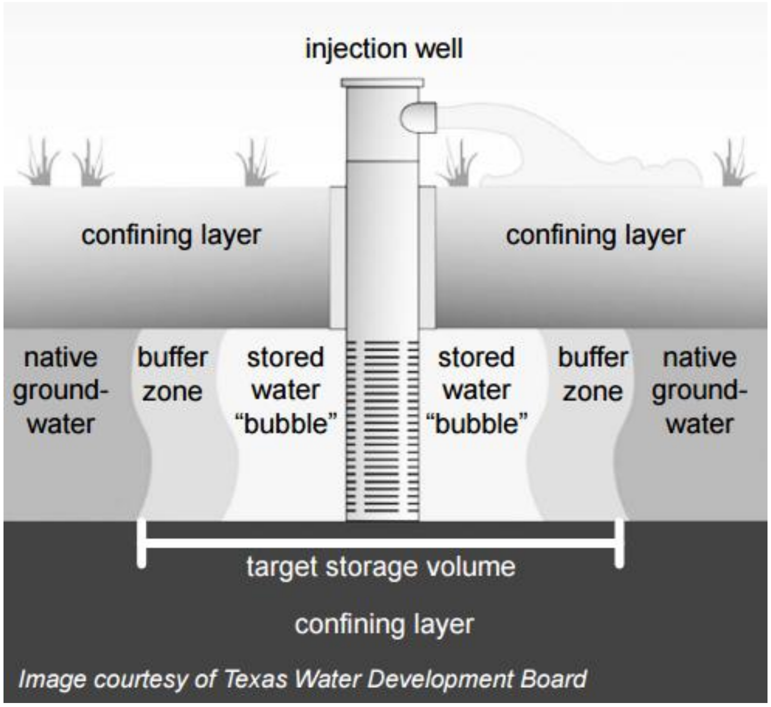

Figure 1-1 Elevation schematic of an ASR well at the end of recharge and prior to recovery showing the stored water and the buffer zone in relation to native groundwater (after the Texas Water Development Board; Pyne, 2005)

ERA	Epoch		Est. Age (M.Y)	Geologic Unit	Hydrogeologic Unit
Cenozoic	Pleistocene		0.7	Beaumont	CHICOT AQUIFER
			1.6	Lissie	
	Pliocene		3.8	Willis	
	Miocene	Late	11.2	Upper Goliad	EVANGELINE AQUIFER
			14.5	Lower Goliad	
		Middle	17.8	Upper Lagarto	
				Middle Lagarto	BURKEVILLE
		Early		Lower Lagarto	JASPER AQUIFER
			24.2	Oakville	
	Oligocene		32	Frio	CATAHOULA
			34	Vicksburg	

Figure 1-2 Geologic and hydrogeologic units of the Gulf Coast Aquifer System (modified from Baker, 1979)

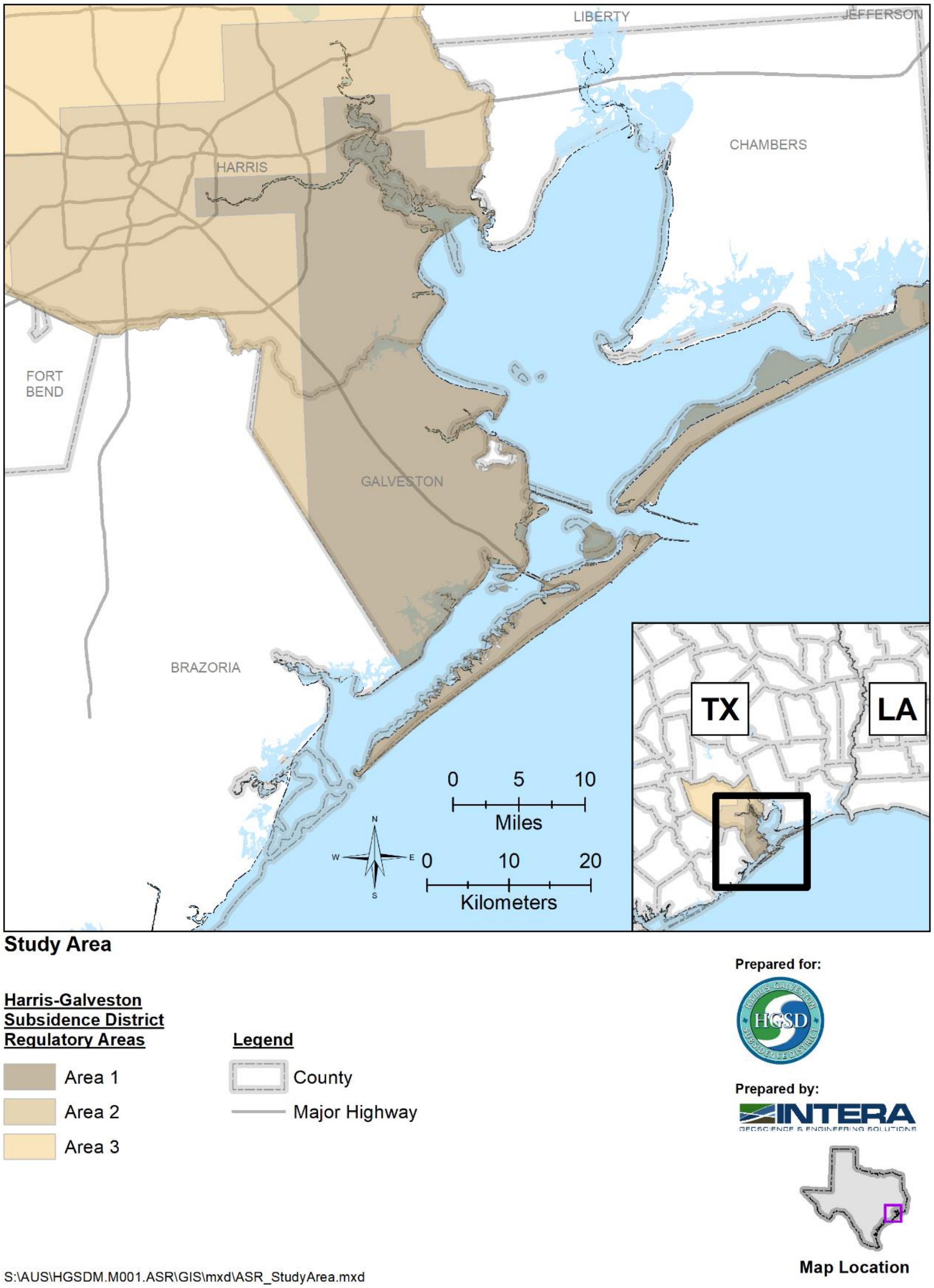

Figure 1-3 Base map of the study area delineated by the District Regulatory Area 1 boundaries

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2.0 AQUIFER COMPACTION AND SUBSIDENCE

This section introduces the concepts of compaction and subsidence and discusses the underlying properties and relationships used to characterize and predict subsurface compaction in the Gulf Coast Aquifer System. The section also provides a summary of the base-case compaction parameters used in this study, which are taken from Kelley and others (2018).

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 or aquitards. If pumping is significant, and the aquifer interbeds or aquitards are under-consolidated, 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 that that pore-fluid pressure decreases. 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 measured at the ground surface may be attenuated compared to compaction occurring at depth, depending on the depth at which compaction occurs, the area over which compaction occurs, and the geomechanical characteristics of the overlying sediments (Geertsma, 1973).

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:

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

where:

- Δb = change in thickness of sediment layer (compaction)
- b = overall thickness of sediment layer
- S_s = 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, this study focuses 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 with the sands and compaction ceases.

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% 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 2-5) 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 effective stress states since initial deposition because of changes in the depth of burial and in water levels within the aquifer. 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 have previously compacted under a higher effective 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 effective stress exceeds the preconsolidation stress, the clays in the aquifer will begin to experience *inelastic* (irreversible) compression. For both elastic and inelastic compression, 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.

As discussed previously, a change in water level (drawdown) is equal to a change in effective stress. The drawdown that creates an effective stress condition that is equal to the preconsolidation stress is called the "drawdown at preconsolidation stress." When current drawdown in an aquifer 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 irreversible compaction will begin to occur (Hoffman and others, 2003).

Large complex aquifer systems like the Gulf Coast Aquifer System will reach a new state of consolidation in a very complex manner. As stated in Section 2.2.2, the time it takes for compaction to occur is a function of several clay bed properties that can be very heterogeneous in an aquifer. As a result, it could take years or decades for the aquifer/aquitard clay beds to reach a consolidation state consistent with the drawdown caused by groundwater development. As a result, the drawdown at preconsolidation stress does not reset quickly or homogeneously in a complex sand and clay aquifer. Investigators have traditionally used the drawdown at which subsidence begins to occur as the initial drawdown at preconsolidation stress for an aquifer system (Holzer, 1981). Once subsidence in a large basin has been initiated, the drawdown at preconsolidation stress at any time after development is uncertain.

2.3 Compaction Properties of Gulf Coast Aquifer System Clay Beds

In the previous subsection, we detailed the properties that were important for developing a conceptual model of compaction in the Gulf Coast 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 provide the base-case parameters and their ranges used in the modeling in this report. The compaction properties are derived from a more detailed review of the available literature and laboratory studies documented in Kelley and others (2018).

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. In Kelley and others (2018) laboratory core data collected in the Houston area were analyzed to estimate clay porosity and the compressibility coefficient as a function of effective depth of burial. These estimates were used to calculate inelastic specific storage as a function of depth below ground surface, which was used to define a base case estimate. In addition, parameter ranges were also established as one half an order of magnitude each direction (factors of 0.3 and 3.0, respectively). The base case value and the high and low range values of inelastic specific storage are summarized for a range of depths of burial from 100 to 3,000 ft in **Table 2-1**. The calculated inelastic specific storage values were used to define the elastic specific storage of the clays. The elastic specific storage estimates were calculated by dividing the inelastic specific storage 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 specific storage is worthy of future study in the study area.

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 has been estimated at each log location. **Figure 2-3** 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 5% of Jasper Aquifer clay beds being greater than 160 ft thick as compared to <1% of the beds in the Chicot Aquifer. The 294 geophysical logs with lithology data are used to characterize local clay bed counts and thicknesses at across the study area.

This ASR study focuses on Regulatory Area 1. To better define the general trends in clay bed statistics in Regulatory Area 1, we analyzed the geophysical logs reported in Young and others (2017) in just the footprint of Regulatory Area 1 for clay bed characteristics including clay bed thickness, number of clay beds identified, clay percent and total clay thickness. **Table 2-2** provides both the arithmetic average and the median of these four metrics for the six formations that comprise the Chicot and Evangeline aquifers (see Figure 1-2). Because some geophysical logs do not cover all the formation, bias in the statistics can occur. This type of bias is likely the most prevalent in the Beaumont and the Upper Lagarto formations because logs are generally limited either in their shallow of deeper extents. A review of Table 2-2 shows that the formations comprising the Chicot Aquifer (Beaumont, Lissie and Willis formations) have less clay content with less frequent, thinner clay beds as compared to the formations comprising the Evangeline Aquifer (Upper Goliad, Lower Goliad and the Upper Lagarto formations). There is a general trend of increasing total clay thickness as one moves from the Chicot to the Evangeline aquifer formations. The total clay thickness for the Upper Lagarto (Lower Evangeline) is potentially underestimated because of log coverage. The clay bed characteristics are important inputs for the prediction of compaction.

2.3.3 Vertical Hydraulic Conductivity of Clays

In Kelley and others (2018), the vertical hydraulic conductivity for Gulf Coast Aquifer System clay beds were reviewed for both core measurements collected by the United States Geological Survey (USGS) and based upon calibrated estimates from PRESS models for 26 sites in Fort Bend, Harris, and Galveston counties. PRESS Sites are locations where detailed calibration of subsidence has occurred using the PRESS one-dimensional compaction model (Fugro Inc., 2013). Like the inelastic specific storage of clay beds, the vertical hydraulic conductivity value for clay beds has been measured and modeled as a parameter that is strongly dependent upon the depth of burial of the clay bed. A lower bound for vertical hydraulic conductivity of clays was determined based upon the calibrated PRESS model values (Fugro Inc., 2013). An upper bound was based upon analyses of core data performed by the USGS on clays (Gabrysch and Bonnet, 1974). An average of the two is considered the best estimate.

Table 2-3 provides clay vertical hydraulic conductivity values for depths between 100 and 3,000 ft based upon the data described above. The difference between the upper and lower bounds is about a factor of 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. The vertical hydraulic conductivity of a clay bed does not impact the potential total compaction that could occur but does impact the timing it takes for compaction to occur.

2.3.4 Drawdown at Preconsolidation Stress

Kelley and others (2018) developed a model for estimating drawdown at preconsolidation stress based upon available consolidation testing on clay core performed by the USGS (Gabrysch and Bonnet, 1974; 1976a; 1976b). For each core consolidation test, the Casagrande method (Casagrande, 1936) was used to estimate the preconsolidation stress (reported as equivalent freshwater head). In our conceptual model, the drawdown amount that causes a transition from elastic compaction to inelastic compaction (drawdown at preconsolidation stress) decreases as a function of depth. This means that, at shallow depths, some amount of drawdown can occur under elastic conditions. At deeper depths, inelastic compaction will occur immediately. The best estimate of drawdown at preconsolidation stress at ground surface was assumed to be 75 ft, consistent with the average value used in the Houston Area Groundwater Model (HAGM; Kasmarek, 2013). Drawdown at preconsolidation stress was conceptualized to decrease linearly with depth until it reaches zero at 870 ft bgs. At depths greater than 870 ft, any drawdown would initiate inelastic consolidation. This is considered a conservative assumption consistent with a regulatory perspective.

The relationship describing drawdown at preconsolidation stress described in Kelley and others (2018) was defined to perform a risk assessment of subsidence potential from development of the brackish Jasper Aquifer. The brackish Jasper Aquifer is largely undeveloped, meaning that the preconsolidation state could be near equilibrium (static). In contrast, this study focuses on the shallower Chicot and Evangeline aquifers where development and resulting drawdown have been significant and the current preconsolidation state of the aquifers is likely currently not at steady-state. The drawdown and rebound history that has occurred in Regulatory Area 1 and other areas of the District complicates estimation of the preconsolidation stress at any potential ASR Project location. Subsection 2.3.4.1 will expand on this concept based upon USGS water-level monitoring data.

2.3.4.1 Aquifer Head Trends in Regulatory Area 1 and Residual Compaction

The District was created in 1975 to provide for the regulation of groundwater withdrawal in the District in order to end subsidence. The District has adopted four regulatory plans beginning in 1976. The initial 1976 Plan regulated pumping in all of Galveston County and much of southeastern Harris County in an area referred to as the "Area of Concentrated Emphasis" where subsidence rates were high. This area generally coincides with the Current Regulatory Area 1.

Prior to the late 1970s, water levels were falling very quickly in Regulatory Area 1 and subsidence rates were very high. With the curtailment of groundwater pumping, water levels rebounded over 100 ft, and subsidence rates were significantly mitigated. **Figure 2-4** contours the maximum drawdown in the Chicot Aquifer based upon the USGS monitoring data for the region. For most control points in Regulatory Area 1, the maximum drawdown occurred in the 1970s, and water level rebound has subsequently regionally occurred. **Figure 2-5** contours the drawdown at the maximum rebounded water level, which equals the historical minimum drawdown which has occurred in the aquifer. In all cases, this minimum drawdown occurred after the maximum drawdown consistent with pumping curtailment associated with the District's regulatory program. Drawdowns in Regulatory Area 1 are anywhere from 50 to 125 ft, relative to predevelopment water levels. In Regulatory Area 1, the maximum rebound water levels are very recent, with water levels still rebounding over most of the area from their maximum drawdowns in the late 1970s. Moving northwest in the District into Regulatory Area 3, the maximum drawdowns have occurred in the last decade, with very little historical head rebound having occurred. In other words, in

Regulatory Area 3, drawdown is the dominant trend in water levels. Not coincidentally, Regulatory Area 3 is seeing the largest subsidence rates being measured in the District.

Similar maps were developed for the Evangeline Aquifer. **Figure 2-6** contours the maximum drawdown in the Evangeline Aquifer based upon the USGS monitoring data. Maximum drawdowns exceed 400 ft in the northern part of Regulatory Area 1 to 250 ft or less in Galveston County. Again, maximum drawdowns were observed in the 1970s in Regulatory Area 1, with rebounding water levels since that time. **Figure 2-7** contours the drawdown at the maximum rebounded water level, which equals the historical minimum drawdown which has occurred in the aquifer. At maximum rebound, there is still from 100 to 150 ft of drawdown in the Evangeline Aquifer in Regulatory Area 1.

These contour maps depict a similar trend in Regulatory Area 1 of water levels decreasing through the 1970s and rebounding after the 1970s, when the District Regulatory Plan implementation initiated the process of curtailed pumping. While water levels started rebounding as far back as the late 1970s, subsidence rates did not start to stabilize until the 1980s or, in some cases, the 1990s or later, decades after water level rebound was significant (Kasmarek and others, 2016).

Pavelko (2000, 2004) and Ireland and others (1984) termed this condition "residual compaction," which is the continued compressive deformation of a formation even after heads have rebounded. When assessing residual compaction at Edwards Air Force Base in Antelope Valley, California, Sneed and Galloway (2000) concluded that it is likely caused both by the lingering effects of seasonal drawdown on the aquifer system and the ongoing long-term effects of delayed yield from thick, slowly drained aquitards still responding to large water-level declines between 1950 and 1975.

Residual compaction observed in the District is the result of continuing depressurization of fine-grained sediments. One of the factors contributing to continued subsidence in Regulatory Area 1 after pumping was curtailed is the fact that drawdown relative to predevelopment conditions still exists as can be seen in Figures 2-4 and 2-6. Also, as discussed in Section 2.2.2, compaction is a slow process governed by the propagation of pressure through clay interbeds (see Equation 2-5). It also takes time for compaction at depth to manifest as subsidence measured at ground surface.

2.3.4.2 Theoretical Discussion of Drawdown at Preconsolidation Head

The fact that the compaction process duration varies has implications for defining the drawdown at preconsolidation stress in an aquifer that has been developed with heads that have declined hundreds of feet. The long-term, asymptotic reduction in subsidence that has been observed in Regulatory Area 1 reflects the slow re-equilibration of stress within aquifers as a result of changes in effective stress caused by the observed water level drawdowns and subsequent rebounds. In modeling of subsidence, one defines the initial preconsolidation stress. In the case of the USGS MODFLOW code, one defines the drawdown at preconsolidation stress. Defining a current drawdown at preconsolidation stress in Regulatory Area 1 or in any aquifer after significant compaction, is an uncertain task.

Recall that preconsolidation stress is defined as the maximum effective stress to which an aquifer has historically been subjected. In a confined aquifer, under the assumptions of one-dimensional compaction, the change in effective stress can be equated to a change in water level (Equation 2-3). In the previous subsection, we have seen that heads in the Evangeline Aquifer in Regulatory Area 1 have historically declined from 450 to 150 feet and have rebounded significantly, though not completely. If the preconsolidation stress is the highest effective stress the aquifer has historically experienced, then how does the trend in historical water levels impact the preconsolidation stress? The following discussion considers this question.

Compaction within a clay interbed occurs as the pressure in a clay decreases in response to decreased water levels in the sand portions of the aquifer. If compaction was instantaneous, the drawdown at preconsolidation stress would be approximately equal to the maximum observed drawdown. However, Equation 2-5 shows that the pressure decline and the resulting compaction of a clay interbed takes time. The amount of time is dependent upon the clay interbed vertical hydraulic conductivity, thickness and specific storage.

These facts have implications for the conceptualization and parametrization of the drawdown at preconsolidation head in predictive simulations in areas with a complex history of water level decline. **Figure 2-8** is a conceptual time series plot of drawdown at a well (left y-axis) and drawdown at preconsolidation head for clay bed(s) (right y-axis) near a hypothetical Evangeline Aquifer well pumping at an assumed depth of approximately 1,000 ft. Figure 2-8 assumes for sake of clarity that the initial drawdown at preconsolidation head is equal to zero feet of drawdown. The x-axis is time in years. This example assumes 400 ft of historical water level decline (drawdown) has occurred over a period of 30 years, followed by 200 ft of rebound over a period of 30 years. In Figure 2-8, the blue curve is drawdown at the hypothetical well. The red curves are hypothetical traces of how clay interbed drawdown at preconsolidation stress could vary over time based upon the properties of the clay interbed.

There are 5 theoretical clay interbeds (denoted 1 through 5) considered in Figure 2-8. For Interbed 1, we assume that the clay has an infinite hydraulic diffusivity so that the pressure in the clay will immediately equal the pressure in the sand aquifer at any time. Under this assumption, the drawdown at preconsolidation stress at any time will be exactly equal to the maximum drawdown (maximum effective stress) that was observed at that location at any time. While the assumption of an infinite hydraulic diffusivity is unrealistic, it provides a good end member analysis to consider. Assuming an infinite clay interbed hydraulic diffusivity, a pumping or ASR project developed at this well would not experience further subsidence if no more than 200 ft of drawdown were created. In this case, clays would always respond elastically resulting in no irreversible compaction. In contrast, Interbed 5 (Figure 2-8) would represent a very thick clay bed with low vertical hydraulic conductivity and a low specific storage. At time equal to 60 years for the Interbed 5 case, the drawdown at preconsolidation stress would be 100 ft below the initial pre-project head. In this case, any additional drawdown would result in inelastic compression of the clays and increased rates of compaction. Interbed 3 offers an interesting example. For this case, the drawdown at preconsolidation stress is equal to 220 ft at the end of 60 years. Theoretically, for Interbed 3 (Figure 2-8), one would have 20 feet of additional drawdown to work with before the clays begin inelastic compression and clay compaction rates start increasing again.

This discussion demonstrates the uncertainty in predicting drawdown at preconsolidation stress of interbeds after an aquifer has had significant subsidence. A real aquifer has clay interbeds of varying thicknesses and properties that all equilibrate differently to a different effective stress, and therefore drawdown at preconsolidation stress at any given time after development. This complex behavior has been observed at extensometers in the District and has also been observed in several basins in California undergoing subsidence.

Because of the significant uncertainty in defining a bulk aquifer clay interbed drawdown at preconsolidation stress after significant development, we have assumed that any additional drawdown created by an ASR project will initiate inelastic compression. This assumption is regulatorily conservative and consistent with the inherent uncertainty in the physical process being modeled. As this report will discuss in later sections, this assumption does not mean that ASR is not a potentially important water supply strategy for the region. This assumption does correctly define a primary uncertainty associated with the ASR as well as any increase in pumping within the District.

Table 2-1 Estimated inelastic specific storage of clay beds as a function of depth of burial

Depth (ft)	Clay Inelastic Specific Storage (1/feet)		
	Best Estimate	Low Estimate	High Estimate
100	3.50E-04	1.05E-04	1.05E-03
250	1.90E-04	5.70E-05	5.70E-04
500	1.10E-04	3.30E-05	3.30E-04
750	8.60E-05	2.58E-05	2.58E-04
1,000	7.00E-05	2.10E-05	2.10E-04
1,500	5.30E-05	1.59E-05	1.59E-04
2,000	4.30E-05	1.29E-05	1.29E-04
2,500	3.70E-05	1.11E-05	1.11E-04
3,000	3.30E-05	9.90E-06	9.90E-05

Table 2-2 Selected clay bed statistics from geophysical logs located in Regulatory Area 1

Formation	Clay Thickness (ft)		Number of Clay Beds		Clay Percent		Clay Bed Thickness (ft)	
	Average	Median	Average	Median	Average	Median	Average	Median
Beaumont	161	178	8	8	0.29	0.29	22	21
Lissie	232	247	9	9	0.43	0.48	30	23
Willis	279	259	14	13	0.47	0.48	33	20
Upper Goliad	441	505	14	12	0.56	0.55	33	29
Lower Goliad	650	665	18	16	0.36	0.36	39	35
Upper Lagarto(1)	441	402	12	12	0.24	0.24	42	34

1) Statistics can be biased by percent of the formation sampled by the geophysical log

Table 2-3 Estimated vertical hydraulic conductivity of clay beds as a function of depth of burial

Depth (ft)	Vertical Hydraulic Conductivity (feet/day)		
	Best Estimate	Low Estimate	High Estimate
100	4.29E-05	7.90E-06	7.80E-05
250	1.43E-05	5.39E-06	2.32E-05
500	6.08E-06	2.85E-06	9.30E-06
750	3.48E-06	1.51E-06	5.45E-06
1,000	2.26E-06	7.96E-07	3.72E-06
1,500	1.20E-06	2.23E-07	2.18E-06
2,000	7.76E-07	6.22E-08	1.49E-06
2,500	5.64E-07	1.74E-08	1.11E-06
3,000	4.39E-07	4.86E-09	8.72E-07

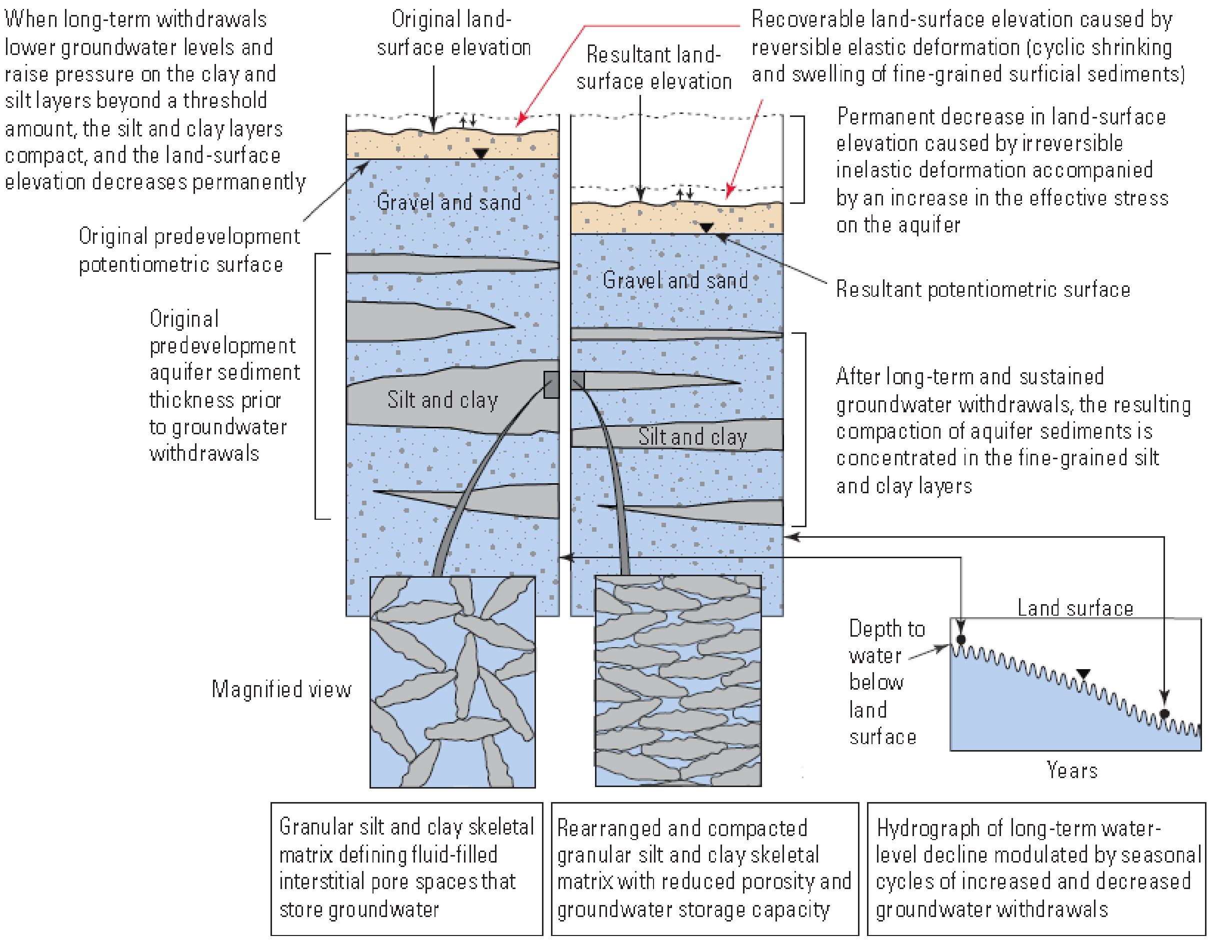

Figure 2-1 Mechanism of subsidence caused by potentiometric surface (pore-fluid pressure) declines induced from groundwater withdrawals in an aquifer composed of gravel, sand, silt and clay (Galloway and others, 1999; Kasmarek and others, 2016)

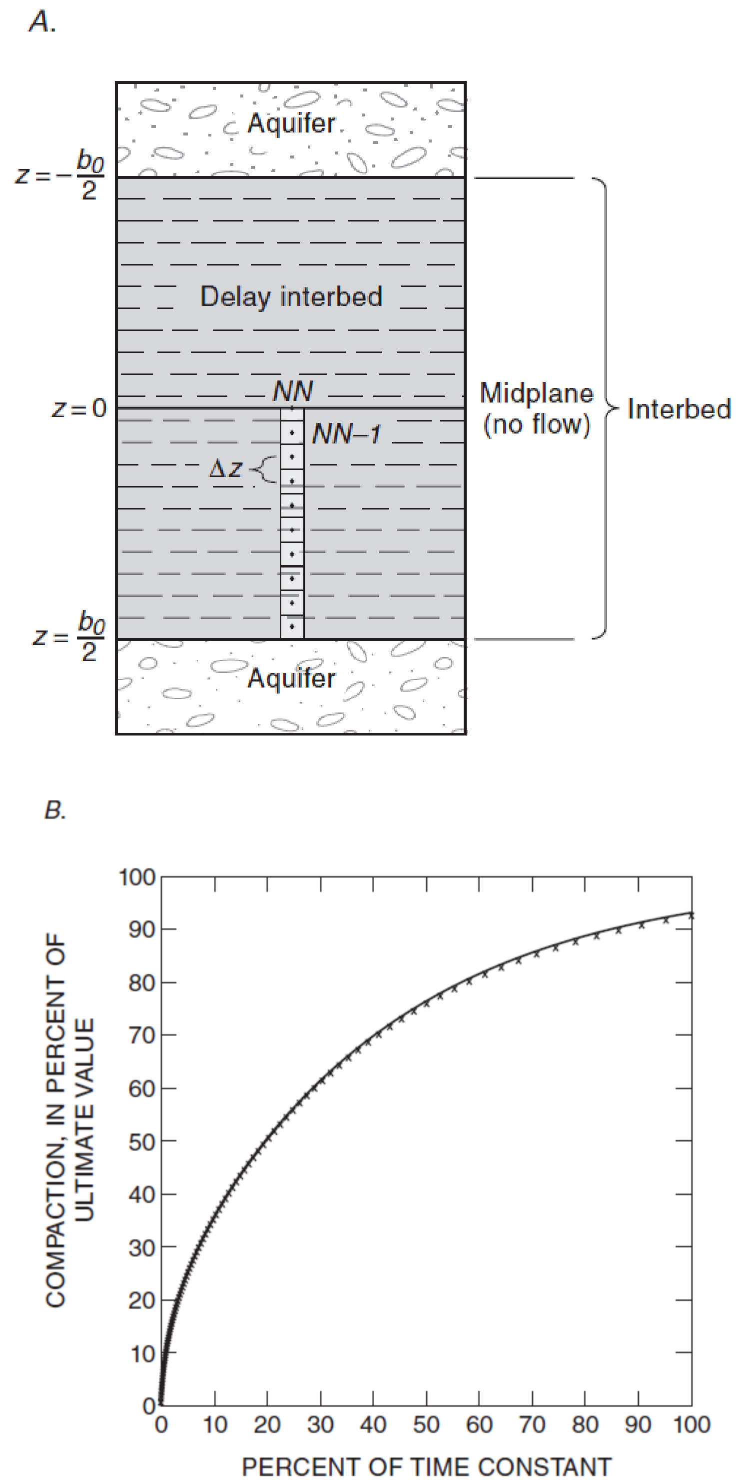

Figure 2-2 Illustration of the relationship between the aquifer layers and the clay-rich interbed layers (A) and the resulting delay in ultimate compaction that occurs (B) due to the time required for water to drain from the interbed and pressure to equilibrate between the aquifer and the interbed layers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

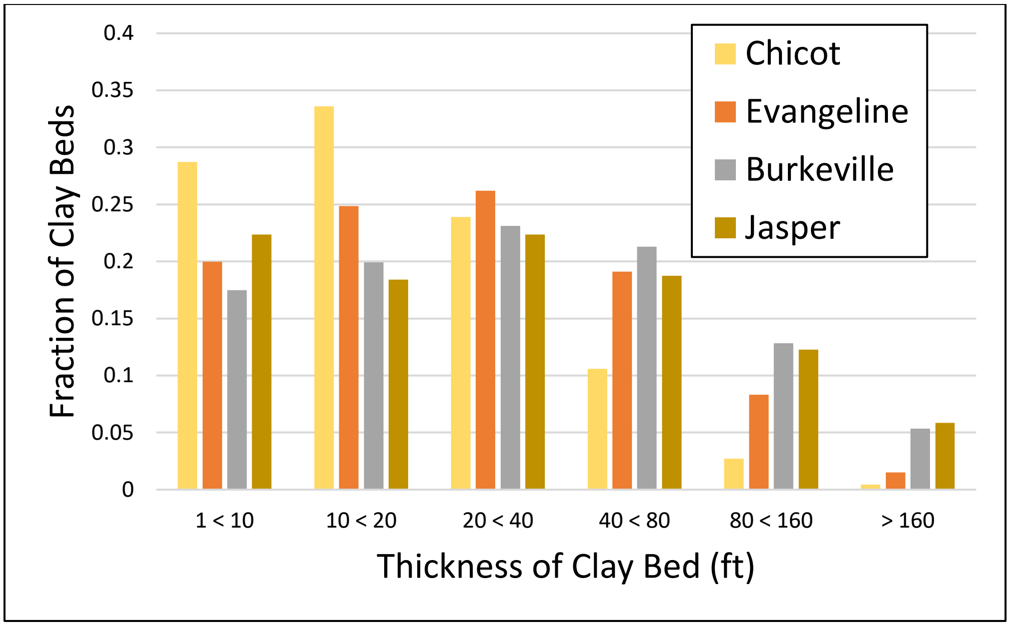

Figure 2-3 Distribution of clay bed thicknesses in the Gulf Coast Aquifer System based on geophysical log analyses in the study area (after Kelley and others, 2018)

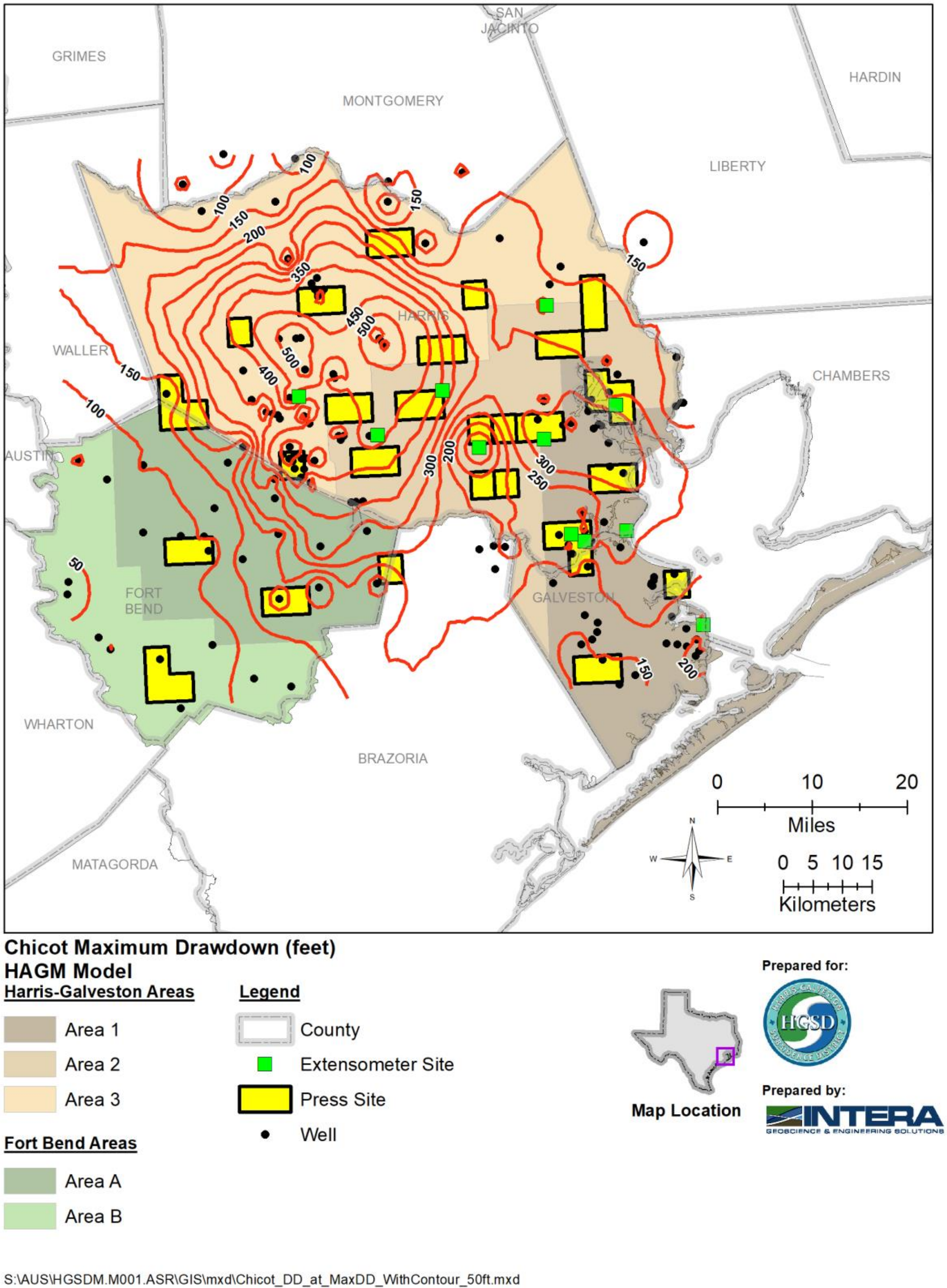

Figure 2-4 Chicot Aquifer maximum historical drawdown (ft)

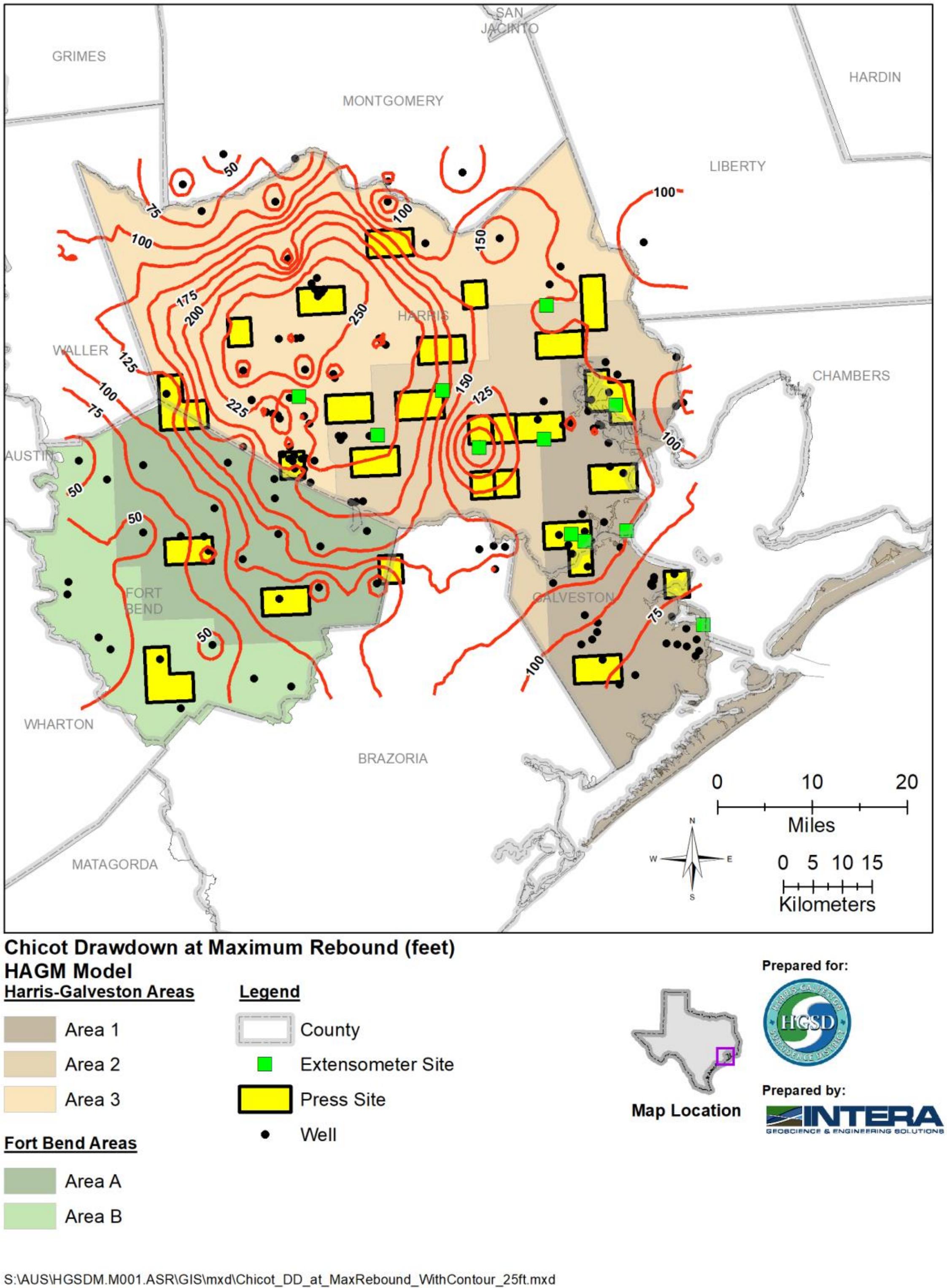

Figure 2-5 Chicot Aquifer minimum historical drawdown (ft) recorded at historical maximum water level rebound

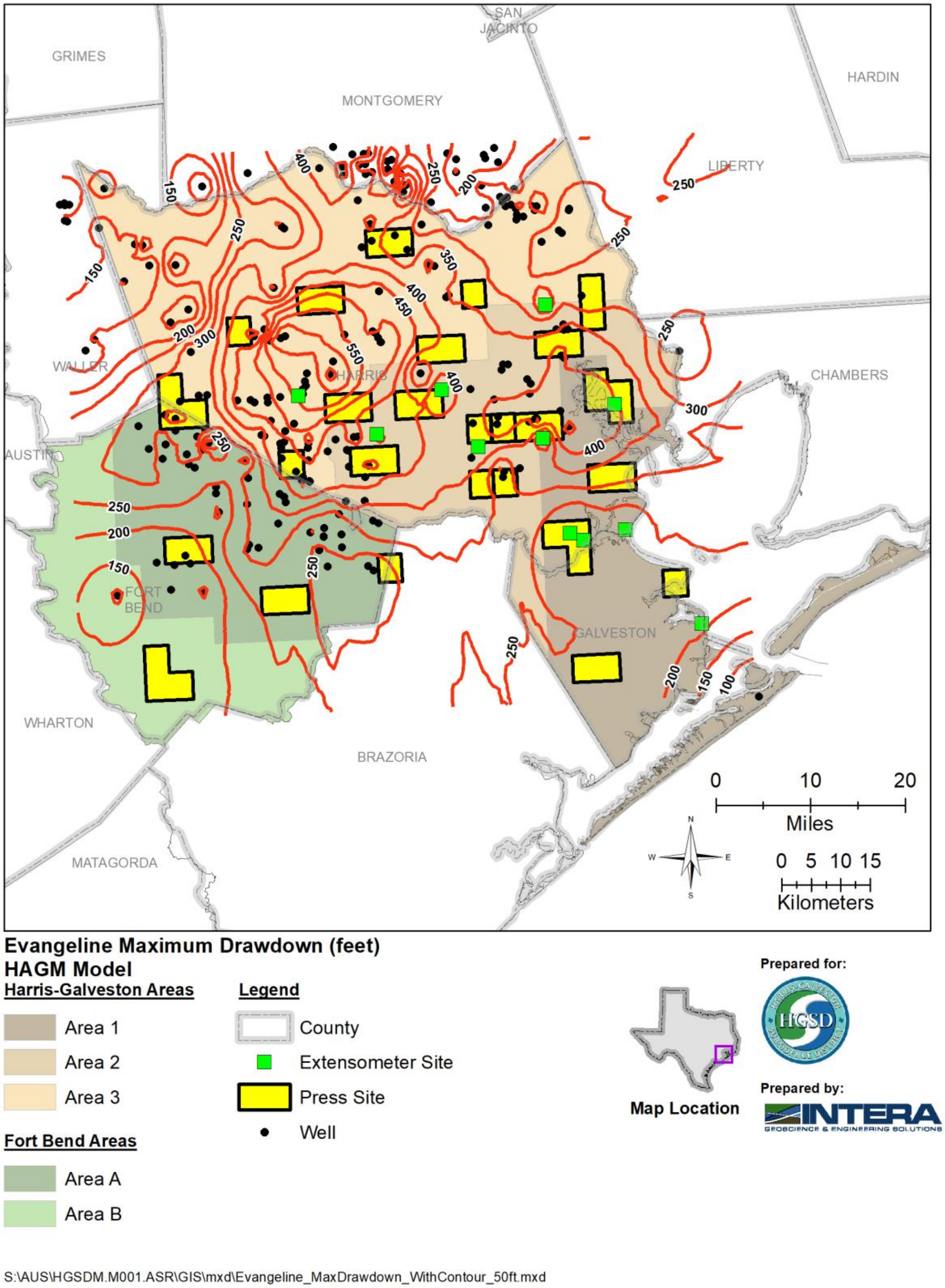

Figure 2-6 Evangeline Aquifer maximum historical drawdown (ft)

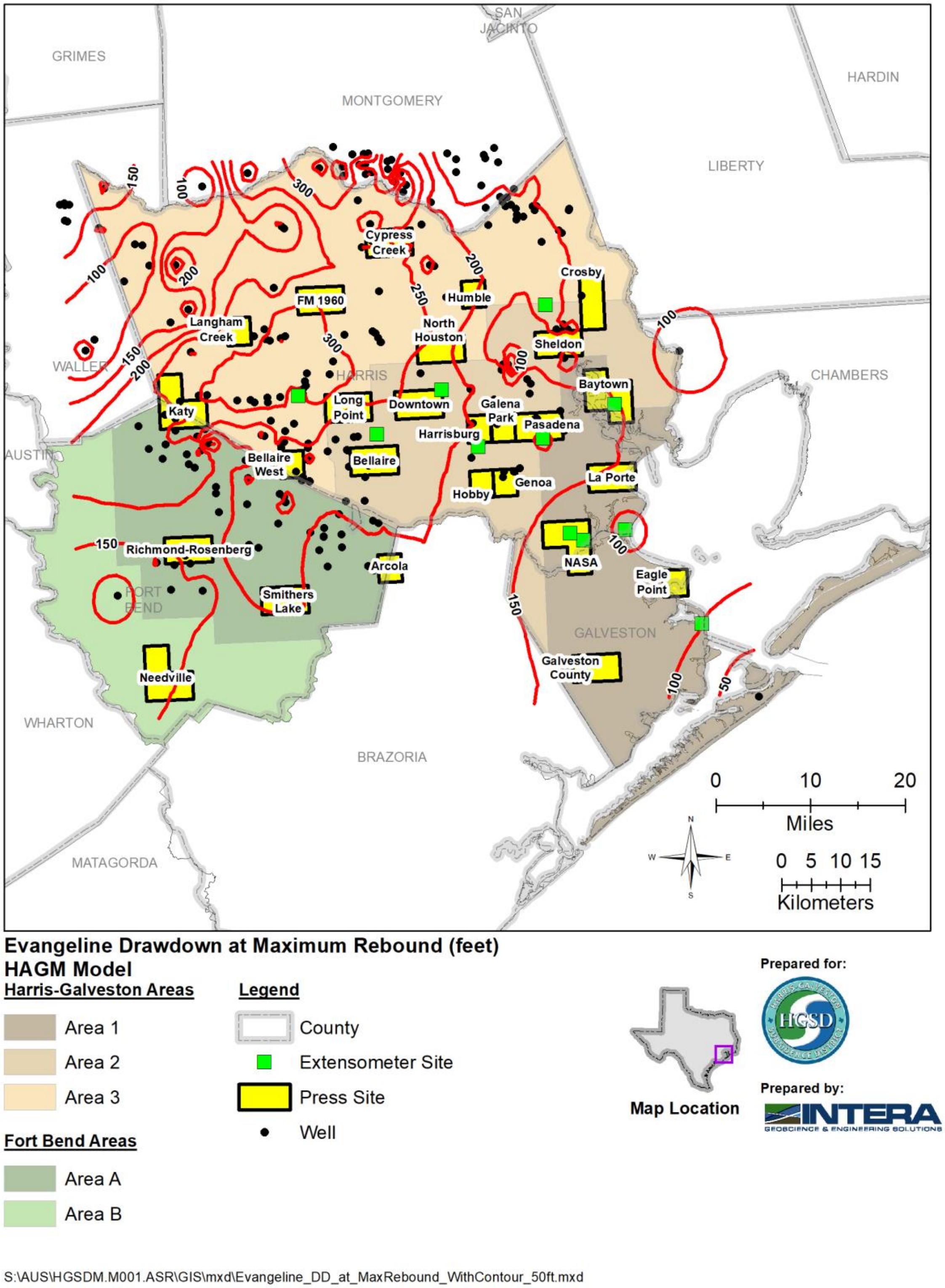

Figure 2-7 Evangeline Aquifer minimum drawdown (ft) recorded at historical maximum water level rebound

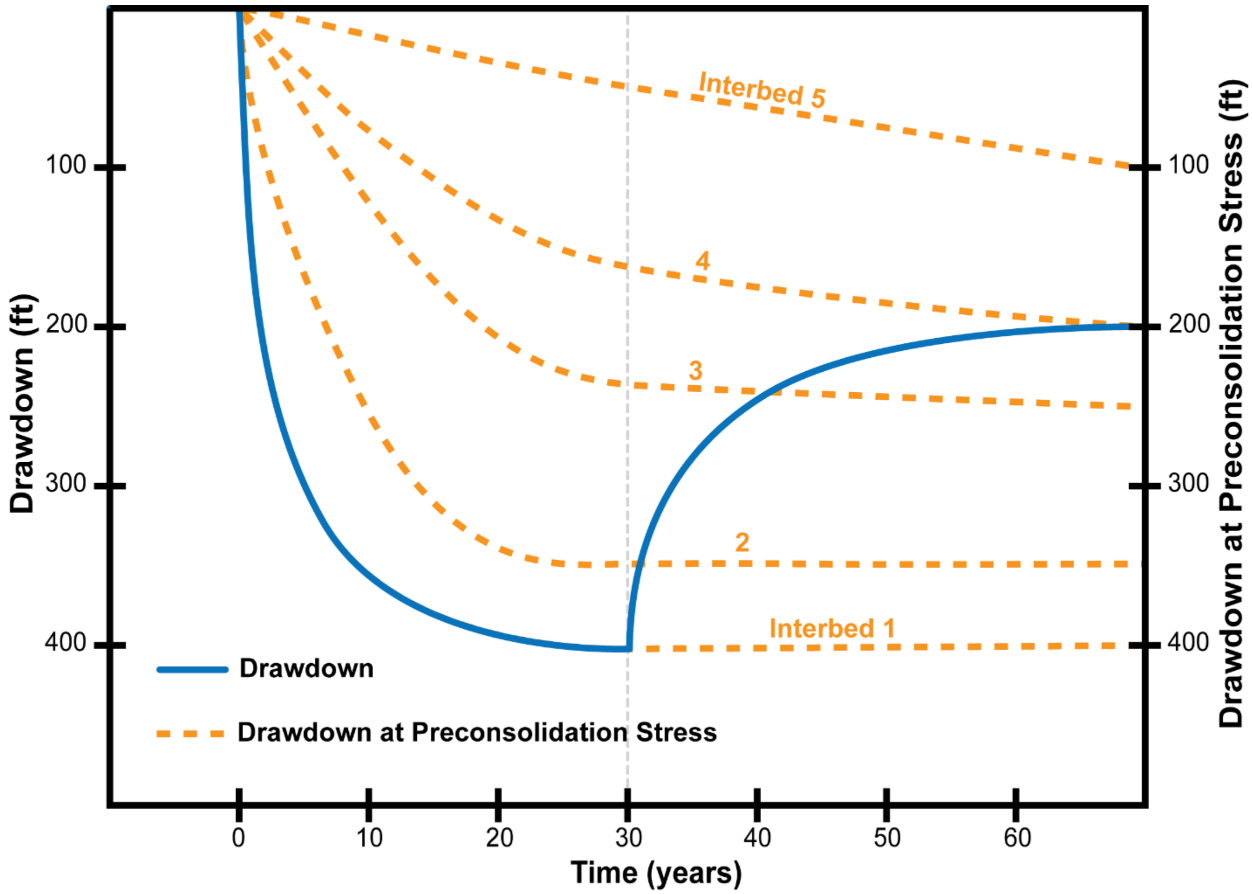

Figure 2-8 Conceptual diagram showing drawdown (ft) and drawdown at preconsolidation stress (ft) for an aquifer that has experienced a period of extended drawdown by a period of extended rebound

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3.0 CASE STUDIES OF ASR AND MAR IN SUBSIDENCE PRONE AQUIFERS

Land subsidence has occurred around the world from compaction of unconsolidated aquifer materials, especially more compressible clay interbeds, in response to increased effective stress from groundwater pumping. To control such subsidence, measures have been taken, including reduction of groundwater pumping with alternative sources of water supplies such as surface water, reclaimed wastewater or MAR to control groundwater level drawdowns and increase groundwater storage. To better understand hydrological conditions of subsidence and effects of MAR and ASR in areas prone to land subsidence, we have reviewed several case studies summarized in **Table 3-1**.

This section summarizes the review of documented ASR or MAR case studies in five subsidence prone aquifers across the U.S. and in China. This review is not comprehensive, and there are many ASR projects that have been tested or operated in subsidence prone aquifers that are not publicly documented. Unlike ASR, MAR has well-documented case studies which are relevant to the District and ASR and therefore are included in the case study review. MAR has been recognized as a strategy for the mitigation of subsidence since the 1960s (Poland, 1984). Prior to the year 2000, MAR was generally referred to as artificial recharge. We will use the term MAR in this report. MAR was specifically studied by the USGS (Garza, 1977) in the 1970s as a strategy for the abatement of subsidence occurring in the Johnson Space Flight Center area. The Harris County Flood Control District has performed a study which considered MAR and ASR as possible technologies for recharging flood water to mitigate flooding and potentially increase potable water supply and mitigate subsidence (Binkley and Barfield, 2018). The section will conclude with observations that are relevant to the consideration of ASR in the District.

3.1 California, USA

California has several basins that have experienced compaction and resulting subsidence from historical groundwater development. Areas to be discussed in this subsection include the San Juaquin portion of the Central Valley, Santa Clara Valley and the Lancaster area of Antelope Valley. In many California alluvial basins, subsidence from increasing use of groundwater has necessitated increased use of surface water, curtailment of groundwater pumping and MAR. MAR has been used to mitigate subsidence and increase storage.

Table 3-1 Case studies of land subsidence and mitigation measures

Country	Location Name	Aquifer Type	Maximum Subsidence, m	Area of Subsidence, km^2	Time of Principal Occurrence	Identified Mitigation Measure*	Selected Principal References
USA	San Joaquin Valley, CA	Basin and Range basin-fill aquifers	9	13,800	mid-1920	1,2,3	Faunt and others, 2015; Poland and others, 1975; Galloway and others, 1999; Ireland 1984
USA	Santa Clara Valley, CA	Basin and Range basin-fill aquifers	1.5	980	1912 to 1995	1,2,3	Galloway and others, 1999; Ingebritsen and Jones, 1999, Poland and Ireland, 1988.
USA	Antelope Valley, CA	Basin and Range basin-fill aquifers	2	2,435	1930-1992	1,2,3	McMillan 1973; Ikehara and Phillips 1994; Galloway and others, 1999; Nishikawa and others, 2001; Hoffmann and others, 2003; Leighton and Phillips 2003
USA	Las Vegas Valley, NV	Basin and Range basin-fill aquifers	2	4,144	1935-2002	1,2,3	Maxey and Jameson 1948; Malmberg 1964; Mindling 1971; Harrill 1976; Holzer 1984; Bell and Price 1991; Pavelko and others, 1999; Pavelko 2000; Pavelko and others, 2006; Bell and others, 2008
China	Yangtze River Delta, Shanghai	Quaternary deposits of fluvial, lake, lagoon and marine origins	3.02	1,256	1921-2017	1,2,3	Shanghai Hydrogeological Team, 1973; Shi and Bao, 1984; Yang and others, 2005; Zhang and others, 2015; Shi and others, 2016

*Mitigation Measure: 1-Ground-water withdrawal has been reduced as a result of substituting imported or locally treated surface water; 2- Ground-water withdrawal has been reduced by regulation; 3- Artificial recharge of ground water has been implemented.

3.1.1 San Juaquin Valley

The San Juaquin Valley makes up the western portion of the southern two thirds of the Central Valley in California. The Central Valley Aquifer System is composed of fine-grained deposits over half of its thickness in the valley (Faunt, 2009). Land subsidence resulting from aquifer pumping began in the 1920s and, by the 1970s, approximately one half of the valley had subsided more than a foot. In localized areas, subsidence magnitudes of 29 ft had occurred by the 1980s (Ireland, 1986). In response to subsidence, an extensive surface water delivery system was developed in the valley starting in the 1950s with the Delta-Mendota Canal followed by the California Aqueduct in the 1970s (Faunt and Sneed, 2015). With the importation of surface water, groundwater pumping decreased significantly in the valley with rebound of groundwater levels. Subsidence rates decreased and, in some areas of the valley, active subsidence was stopped (Ireland, 1986).

It is important to note that ASR has not been applied in San Juaquin Valley to our knowledge. The curtailment of pumping and the subsequent raising of water levels has been successful in mitigating subsidence rates. Currently, there is significant interest in surface spreading of excess water in non-irrigation months. San Juaquin Valley is included as a case study because of valley's documented record of subsidence with fluctuating water levels which is relevant to ASR.

Historically, droughts in the San Juaquin Valley have generally resulted in decreased availability of surface water and increased groundwater pumping. During the droughts of 1976 to 1977 and 1987 to 1992, groundwater pumping increased, groundwater levels reversed their upward trends, and subsidence began again. Swanson (1998) documented this re-occurrence of subsidence in his 1998 publication on land subsidence in the San Joaquin Valley. **Figure 3-1** plots depth to water and compaction measured near Cantua Creek in the San Juaquin Valley (Swanson, 1998). Figure 3-1 shows that water levels in the area recover from lows approximately 600 ft bgs in the 1960s to a high of nearly 250 ft bgs by 1987. Figure 3-1 also plots compaction. As the water levels rise (Figure 3-1), compaction rates decrease until the 1970s drought when water levels drop to just below 500 ft bgs. During the 1970s drought, compaction restarts at a high rate. After the 1970s drought when water levels rebound to approximately 400 ft bgs (Figure 3-1), compaction ceased. In the longer drought of the 1990s, water levels again dropped from their historical high of approximately 250 ft bgs to approximately 475 ft bgs after having rebounded to near 250 ft bgs from the late 1970s. With the falling water levels, compaction again restarts in the drought only to cease when water levels rebound.

This is an interesting case study because it demonstrates the complexity of defining the drawdown at preconsolidation stress (see Section 2.3.4.2) in a developed basin where subsidence has occurred. In both the 1970s and 1990s, droughts the water level during the drought did not reach the historical low but subsidence restarted. This indicates that the historical low water level did not redefine the drawdown at preconsolidation stress in the fine-grained portions of the aquifer. During the 1990s drought water levels did not reach the lows in the 1970s drought but compaction restarted. Subsidence began again even though water levels in the 1990s drought were approximately 175 ft above the historical low (50% of historical drawdown).

Subsidence is continuing today in the San Juaquin Valley because of large scale droughts occurring from 2007 through 2010 and from 2012 through 2015 (Faunt and Sneed, 2015). With the combined impacts of land use change and surface water scarcity, groundwater pumping, and subsidence rates, have increased. The continued subsidence and its spatial variability has resulted in infrastructure problems as the land slope has changed impacting water delivery and flood control infrastructure (Faunt and Sneed, 2015).

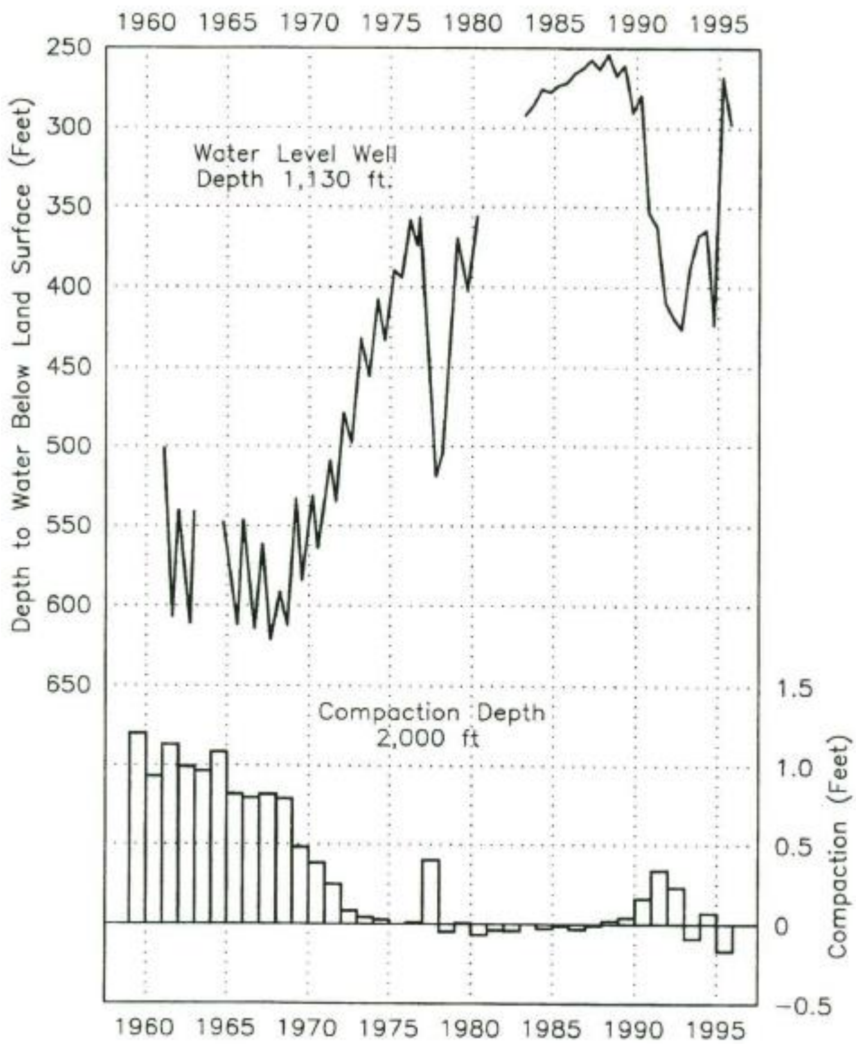

Figure 3-1 Groundwater levels recorded in well 16/15-34N4 and measured compaction at 16/15-34N1 near Cantua Creek (from Swanson, 1998)

3.1.2 Santa Clara Valley

The summary provided regarding Santa Clara Valley is based upon the work of Galloway and others (1999). Santa Clara Valley, more commonly referred to today as Silicon Valley, started subsiding in the early 1900s with groundwater development (Galloway and others, 1999; Poland and Ireland, 1988). In fact, the Santa Clara Valley was the first basin in the United States where land subsidence as a result of groundwater development was recognized (Tolman and Poland, 1940). From the early 1900s through to the mid-1940s, land use in the valley was predominated by irrigated agriculture. Post war growth in the valley led to a transition from an agricultural landscape to an urban landscape of rapid growth.

The subsidence in Santa Clara Valley was first documented in 1933 with the re-surveying of benchmarks in San Jose originally established in 1912. These benchmarks subsided 4 ft between 1912 and 1933. In response, the Santa Clara Valley Water Conservation District (now the Santa Clara Valley Water District) built five storage dams to capture local stream flows. The objective was to increase focused recharge through downstream releases. These measures did not mitigate falling water levels and further subsidence in the 1950s and 1960s. In 1965, groundwater MAR was greatly enhanced through the importation of surface water to the valley. Recharge ponds were implemented across the valley to enhance recharge and increase water levels. By 1969, subsidence was all but halted with minor residual compaction continuing. There are currently recharge basins at over 18 locations in the valley. To our knowledge, there are no ASR wells.

Importation of water supplies, reductions in groundwater pumping, and MAR in the Santa Clara Valley has been extremely successful at allowing continued growth in the region while arresting subsidence. It is important to note that the Santa Clara Valley Water District maintains water levels well above their historic lows to avoid the recurrence of subsidence. This is true in non-drought as well as drought periods. The Santa Clara Valley case is another case study demonstrating that drawdown at preconsolidation stress in a basin post development and post subsidence is poorly known. To address this uncertainty, Santa Clara Valley Water District maintains water levels at all times well above historic low water levels as a management principle (Borchers and Carpenter, 2014).

3.1.3 Antelope Valley

Antelope Valley is a triangular topographically closed basin about 50 miles north of Los Angeles in the Mojave Desert. Historical groundwater development of the basin at annual rates in excess of recharge has resulted in water levels falling as much as 200 ft and land subsidence measured as much as 6 ft (Metzger and others, 2002). To mitigate these conditions, water was imported into the basin from northern California as part of the State Water Project and the California Aqueduct. Even with surface water importation, by the 1990s growth and demand had increased groundwater withdrawals renewing concerns regarding subsidence.

Antelope Valley is of interest because it is the only publicly available data where an ASR cycle test has been performed monitoring water levels as well as ground elevation. The USGS performed recharge and recovery tests near Lancaster to evaluate the feasibility of artificially recharging the aquifers in that area. Monitoring networks were developed to measure vertical deformation of the aquifer, groundwater levels, changes in microgravity, land surface deformation and recharge and discharge chemistry and rates (Metzger and others, 2002). Two production wells were used for the recovery tests. The aquifer is subdivided by an upper, middle and lower aquifer. The ASR test wells were completed across the upper and middle zones.

Three ASR cycles (injection, storage and recovery) were completed between September 1995 and September 1998. Injection cycles were a minimum of five months and surrounding production wells within two miles of the ASR wells were shut down during injection and recovery periods. There were two production wells used for recharge and recovery. Recharge rates were relatively constant at 750 to 800 gallons per minute (gpm). Recharge periods were followed by a 2- to 4-week storage phase allowing hydraulic conditions to equilibrate.

Water levels were monitored in two nested piezometers located in the vicinity of the ASR wells. Each piezometer nest had four monitored intervals at depths from 350 to 900 ft bgs. **Figure 3-2**, reproduced from Metzger and others (2002), shows the measured depth to water in two deeper monitoring wells (725 and 925 ft bgs). The gray shading shows the recharge periods and the resulting water level increases, and the arrows point to the extraction cycles corresponding to water level drops. The piezometer data generally show the same water level response with the magnitude of water level change being a little less in the shallowest interval. The minimum (lowest) water level measured between ASR cycles is slightly rising indicating an ambient rising water-level trend.

Two extensometers were installed within a mile of the ASR wells. One measured vertical deformation to a depth of 700 ft bgs, and a deeper extensometer measured vertical deformation to a depth of 1,180 ft bgs. Figure 3-2 and **Figure 3-3** plot the data for these two extensometers during the three ASR cycles. Figure 3-3 shows that the deformation history is complex in that, during the recharge cycle, elastic deformation occurs as the aquifer expands. However, there appears to be inelastic deformation occurring during extraction as the aquifer irreversibly compacts during each production cycle following each recovery cycle. This behavior could be the result of several dynamics. First, there could be residual compaction occurring in the basin unrelated to the ASR tests. Figure 3-2 shows that the average water level across the testing period is not dropping on average and may be slightly increasing. Another consideration is that the production wells in the vicinity of the test wells may have produced during the test recovery cycle. The concept of pumping interference is counter to the fact that the water levels show a slight increasing average water level trend. Theoretical calculations of multiple recharge and recovery cycles (presented later in this report) reproduce the observed compaction behavior. That is, with each ASR cycle, the clays compact a little more even though drawdown is consistent in each recovery cycle. The test also shows that the magnitude of compaction diminishes with each cycle. This also reproduces our theoretical calculations.

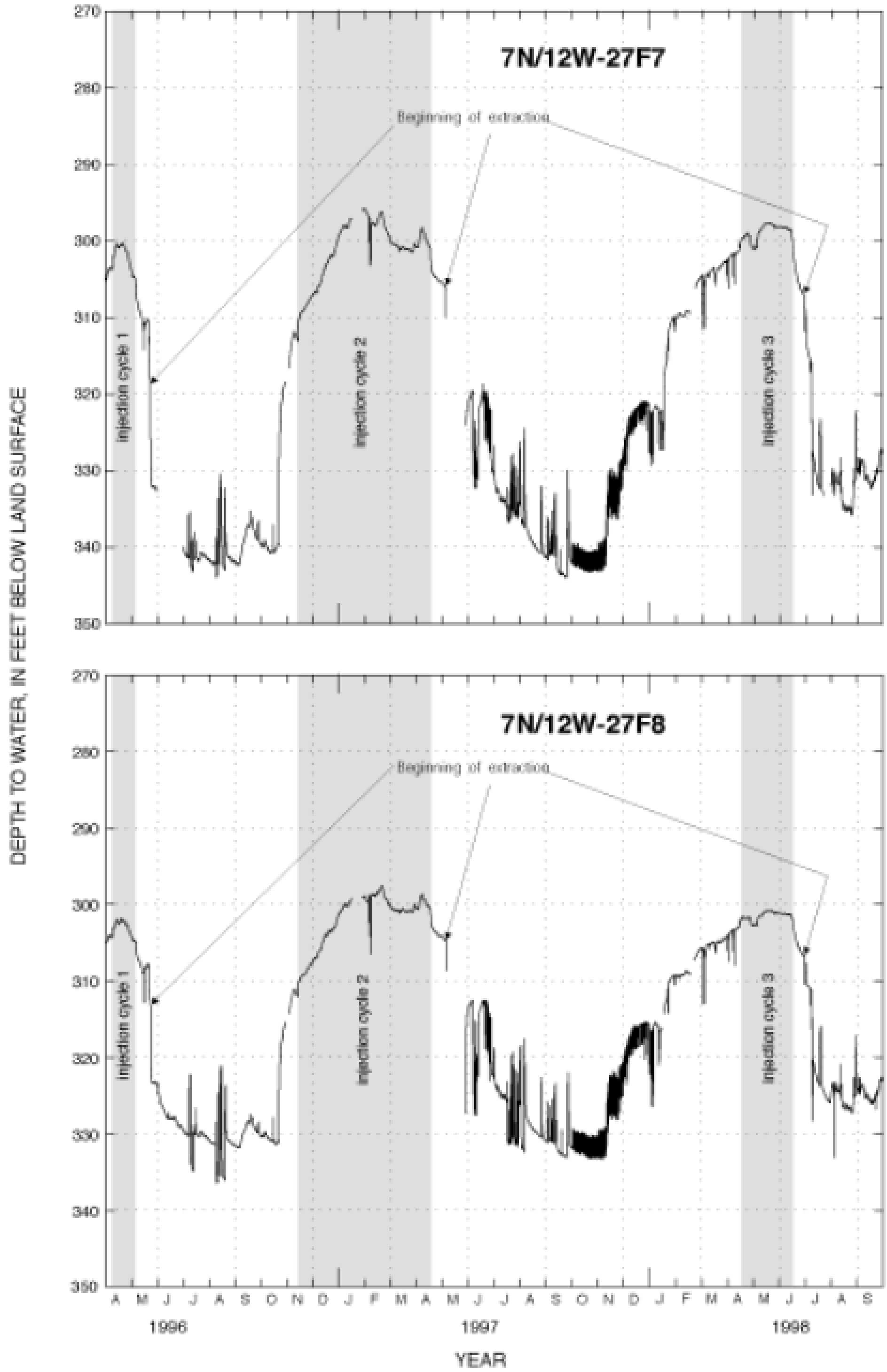

Figure 3-2 Groundwater levels recorded in piezometers 7N/12W-27F5 and F8 (from Metzger and others, 2002)

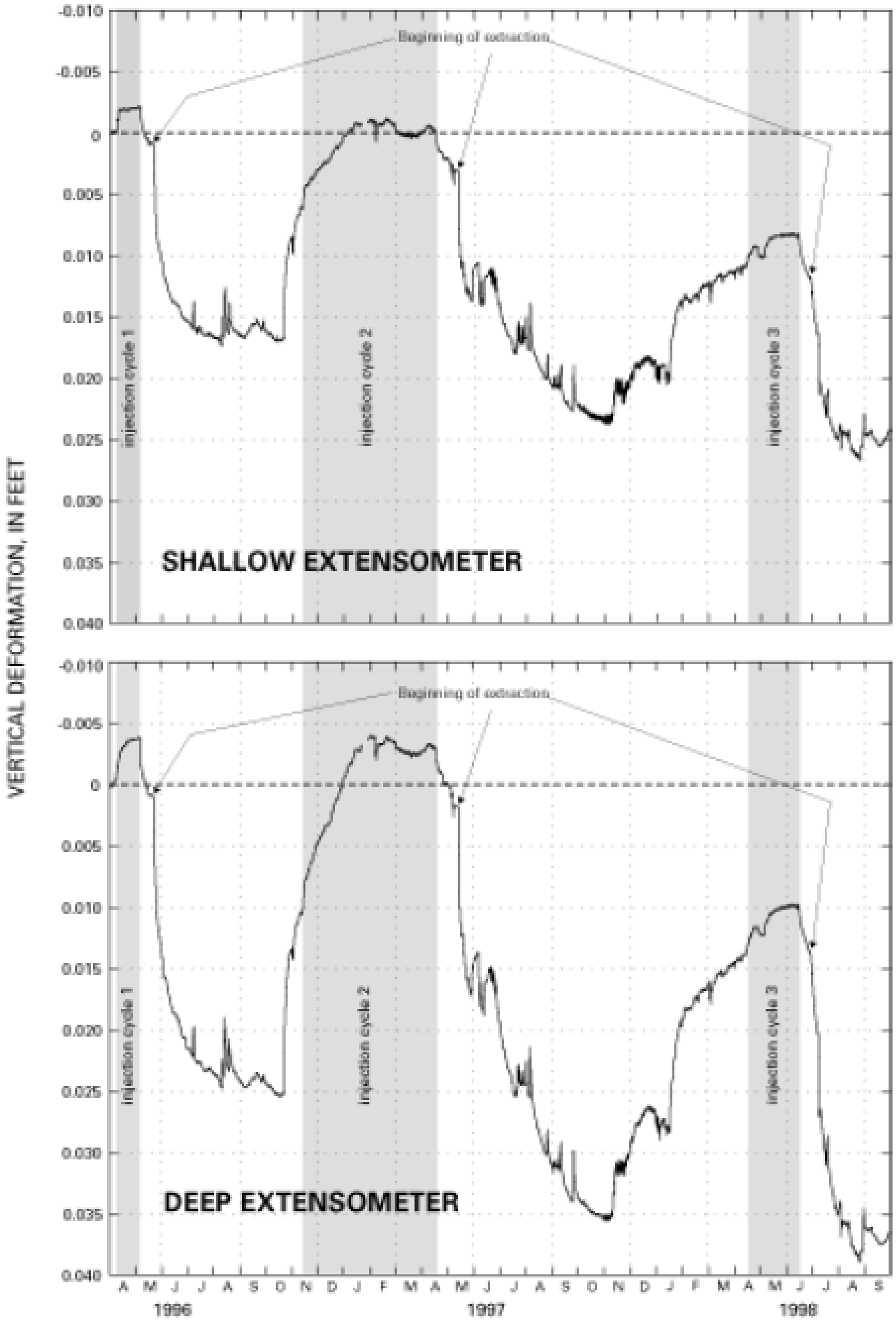

Figure 3-3 Vertical deformation measured at extensometers 7N/12W-27F9 and F10 (from Metzger and others, 2002)

3.2 Las Vegas, Nevada

3.2.1 History of Land Subsidence in the Las Vegas Valley

Las Vegas Valley is a large structural depression in southern Nevada, bounded on the west by the Spring Mountains, on the north by the Sheep and Las Vegas Ranges, and on the south and east by River Range and Frenchman Mountain. It drains a 1,564-square-mile watershed southeastward through Las Vegas Wash into Lake Mead. The valley floor is underlain by unconsolidated and partially consolidated deposits of continental and lacustrine origin. Groundwater development quickly exceeded natural recharge and caused groundwater level declines of up to 300 ft by 1990, resulting in land subsidence and earth fissures (Bell and others, 2002; Pavelko and others, 1999; Sheng and others, 2003). In the 1980s, MAR (artificial recharge wells and ASR wells) was implemented to control land subsidence and earth fissures (Sheng and others, 2003). As result of reduced pumping and artificial recharge, elastic rebound (uplift) has been observed in some areas while small rates of subsidence continue in other areas.

Land subsidence in Las Vegas Valley was first detected in 1935, when the U.S. Coast and Geodetic Survey established a first-order vertical-control network across the valley as a regional monitoring program to document the effects of loading of water impounded in Lake Mead behind Hoover Dam. Land subsidence was monitored as the entire network was releveled in 1940-41 and again in 1949-50, extended and releveled in 1963, 1972, 1980, and 1986-87. The 1935-1950 releveling data indicated a broad, shallow regional sinking of the Boulder Canyon area centered about 11.8 miles upstream of the dam was found (Longwell, 1960) in response to Lake Mead impoundment. In the area of Las Vegas, northwest of Hoover Dam, this depression was expressed as a southeastward tilt of about 4 to 5 inches.

Land subsidence due to groundwater withdrawal is superimposed on this broad regional depression caused by Lake Mead. Maxey and Jameson (1948) first noted the relationship between subsidence and groundwater withdrawals in the valley. The center of the valley had subsided as much as 3.2 ft by 1963 and by about 4.9 ft by 1980 (Bell, 1981a,b). A later assessment by Bell and Ramelli (1991) using 1986-87 data showed that subsidence has continued, and the location and rates of subsidence have remained relatively constant at least since 1963. A broad regional subsidence bowl occupies the central portion of Las Vegas Valley. Three localized subsidence bowls are superimposed on the broad pattern and are located in the central (downtown), southern (Las Vegas Strip), and northwestern parts of the valley (**Figure 3-4**). Based on the leveling history across the faults, Bell and others (1992) reported that fault zones were preferred sites for localized, subsidence-induced, vertical differential movement. Fissures have been observed in Las Vegas Valley since 1925 and documented in many reports (*e.g.*, Mindling, 1971; Patt and Maxey, 1978; Mifflin and others, 1991). Recent Interferometric Synthetic-Aperture Radar (InSAR) images provide better monitoring of the spatial distribution and evolution of the subsidence (up to 6.6 ft) in the central Las Vegas Valley and uplifts in some areas resulting from a large-scale MAR program (Bell and others, 2002; Hoffman and others, 2003; Zhang and Burbey, 2016). InSAR is a remote sensing technique that can map ground deformation to the precision of an inch or less.

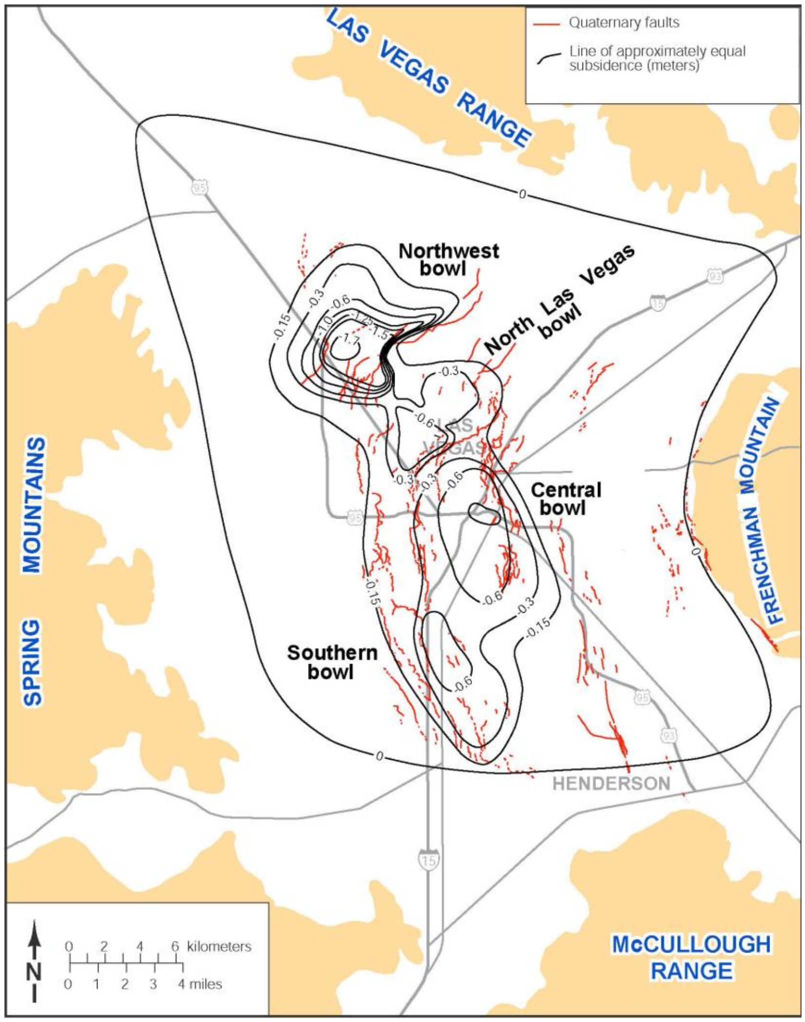

Figure 3-4 Land subsidence in Las Vegas Valley (Bell and others, 2002)

3.2.2 Managed Aquifer Recharge and Aquifer Storage and Recovery

In 1988, Las Vegas Valley Water District employed MAR as one of their conjunctive water resources management strategies aimed at storing water for future use (long-term and short-term peak water demands), reversing declining groundwater levels and in turn controlling land subsidence (Johnson and others, 1997). The source water is treated Colorado River water from the Southern Nevada Water System (SNWS). A pilot project was conducted using an existing unused production well in 1987 to assess the feasibility of MAR. A demonstration project with two wells in 1989 proved the geochemical and mechanical viability of recharging through wells, setting the baseline for development of the nation’s largest ASR program. Additional ASR wells were added thereafter. A total of 78 recharge wells have been constructed in the valley. In addition, 46 of these wells are equipped for both recharge and recovery and are therefore ASR wells as defined by Pyne (2005). In 2003, a recharge rate of 102.8 million gallons per day (MGD) was achieved. By 2008, a gross total volume of 351,017 acre-feet (AF) was recharged into the aquifer (Groundwater Geek, 2017).

Water is recharged primarily during cooler months from October to May, when water demand is lowest, thereby raising groundwater levels above typical winter conditions. Recently, continued MAR has succeeded in raising groundwater levels in some local areas to the extent that they are generally higher both at the beginning and end of the peak water demand (summer) season (Johnson and others, 1997; Pavelko and others, 1999; Zhang and Burbey 2016). Groundwater level recovery after 1990s is shown in **Figure 3-5** in comparison with groundwater level declines prior to 1990s.

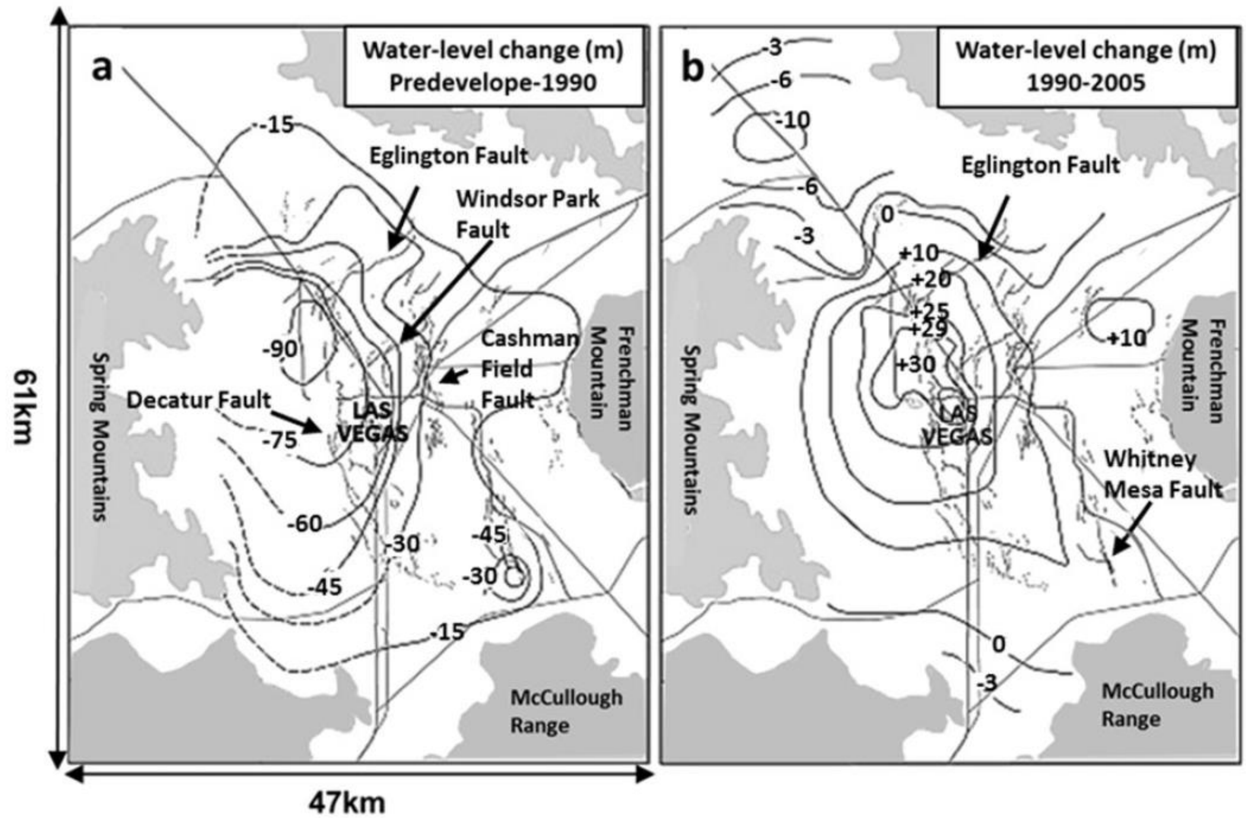

Figure 3-5 Water-level change in the principle aquifer (a) from predevelopment to 1990 based on water-level measurements (from Burbey, 1995) and (b) from 1990 to 2005 based on water-level measurements (from Zhang and Burbey 2016)

While water levels have rebounded from historical lows in the valley, a significant amount of land subsidence from continued pumping and residual compaction will continue to occur at lower rates than historical maximums. This occurs for at least two reasons. Despite ambitious efforts to artificially recharge the aquifer system, net groundwater pumpage within the Las Vegas Valley still exceeds natural recharge resulting in a net storage decrease over the long term (average regional water levels will continue to decline). Also, residual compaction is occurring in the basin as water levels within the clays equilibrate to the water levels in the aquifers. Riley (1969) predicted that the residual compaction in Las Vegas may require years, decades, or even centuries to be realized. Present day conditions indicate that minor rates of compaction still occur in areas of the Las Vegas Valley. Recent InSAR analysis has also detected uplift attributed to the MAR and ASR program (Bell and others, 2002; Hoffman and others, 2003; Zhang and Burbey, 2016).

Both uplift (elastic rebound) and slow subsidence have been documented in detailed head and subsidence data collected near operating ASR wells at the Lorenzi Site in Las Vegas (Pavelko, 2000). The data was collected from November 1994 through December 1999. The subsidence data was collected from an extensometer (USGS-EXT1), which measured the compaction between 12 and 800 ft bgs. The extensometer data exhibited thermal effects in the summer months when a temperature variation 55 degrees Fahrenheit (°F) occurred in the extensometer shed. There were also step-like changes in the extensometer data, referred to as “stick-slips,” from release of frictional pressure (Pavelko, 2000). Water levels were measured in three nested piezometers. The three piezometers were completed corresponding to the shallow, middle and deep aquifers (USGS-PZS, -PZM and -PZD, respectively). Pumping wells near the piezometers were generally pumped during the summer (May to September) and recharged in the other months (Pavelko, 2000).

Figure 3-6 plots the nested piezometer data along with the extensometer data from the Lorenzi Site. The water level data clearly show the recharge and discharge cycles from the nearby ASR wells. From late 1994 through 1996, minimum water levels are decreasing while maximum annual water levels are constant. In late 1997, recharge volumes were increased, and from 1997 through 1999, both annual maximum and minimum water levels increased year to year.

A review of the extensometer data reflects a clear downward trend in the vertical deformation across the entire period of record. In the deformation record, we see evidence of aquifer expansion during recharge events followed by a measurable increase in subsidence during pumping. The rates of subsidence are observed to be highest during the pumping cycles and smallest during the recharge cycles. These observations are consistent with the data reviewed from Antelope Valley and is consistent with ASR simulations discussed later in this report.

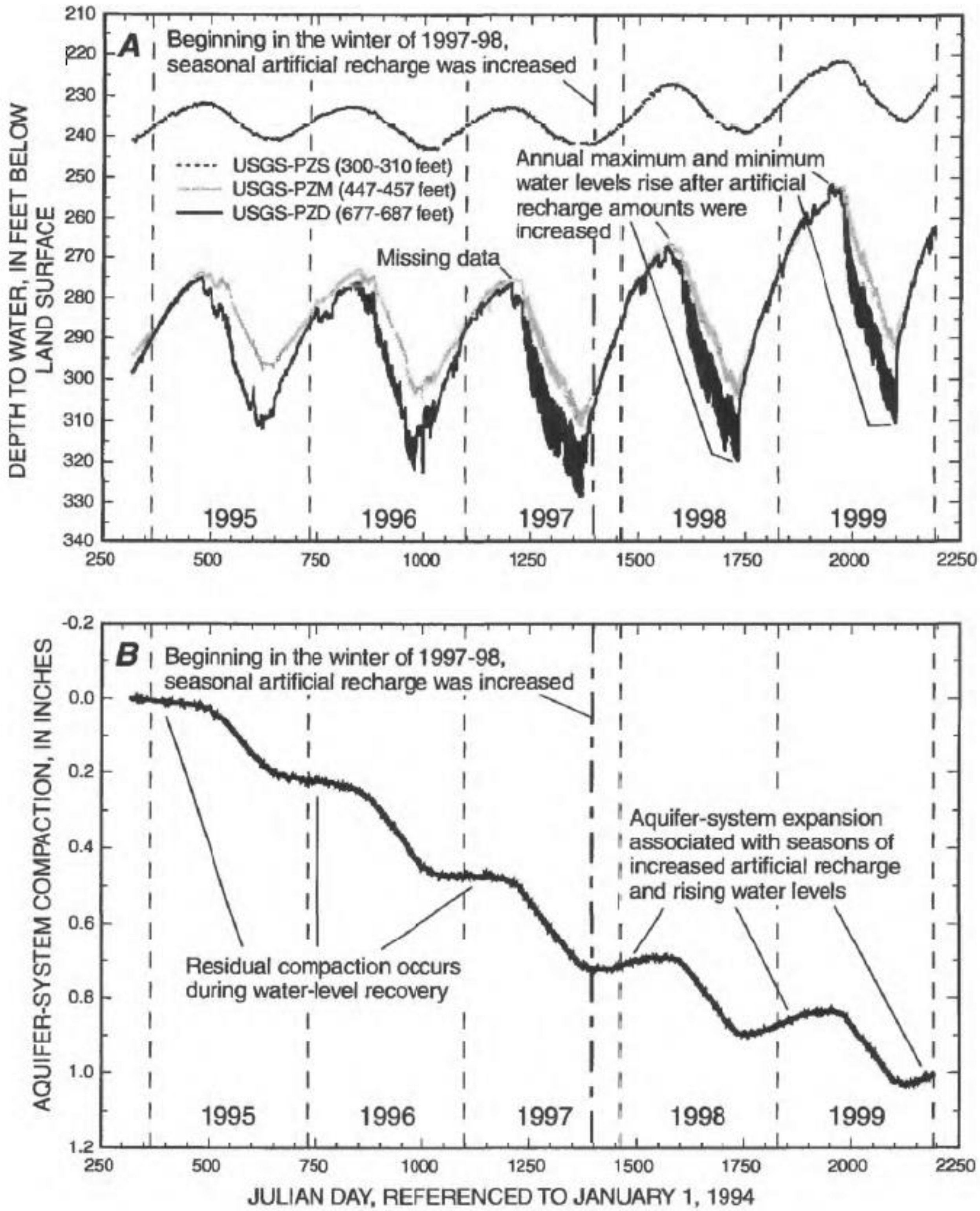

Figure 3-6 Groundwater piezometer depth to water measurements and extensometer data from the Lorenzi Site, Las Vegas, Nevada from November 1994 through December 1999 (from Pavelko, 2000)

3.3 Shanghai, China

Shanghai is located on the Yangtze delta in the east of China on a topographically flat coastal plain with an average elevation of approximately 13 ft above mean sea level (amsl). The aquifers are comprised of Quaternary deposits of fluvial, lake, lagoon and marine origins (Zhang and others, 2015; Shi and others, 2016). The aquifer system consists mainly of medium-to-dense sands and sands with gravels. The uppermost aquifer is an unconfined aquifer and the other five are confined aquifers (A1-A5 as shown in **Figure 3-7**). Between those aquifers are confining aquitards which consist mainly of clay and silty clay. The hydraulic conductivity of the confining clay units is much lower than the aquifers. Several of the clay units are highly compressible and subject to compaction causing land subsidence (SGEAEB 2002, Zhang and others, 2007 and, Zhang and others, 2015).

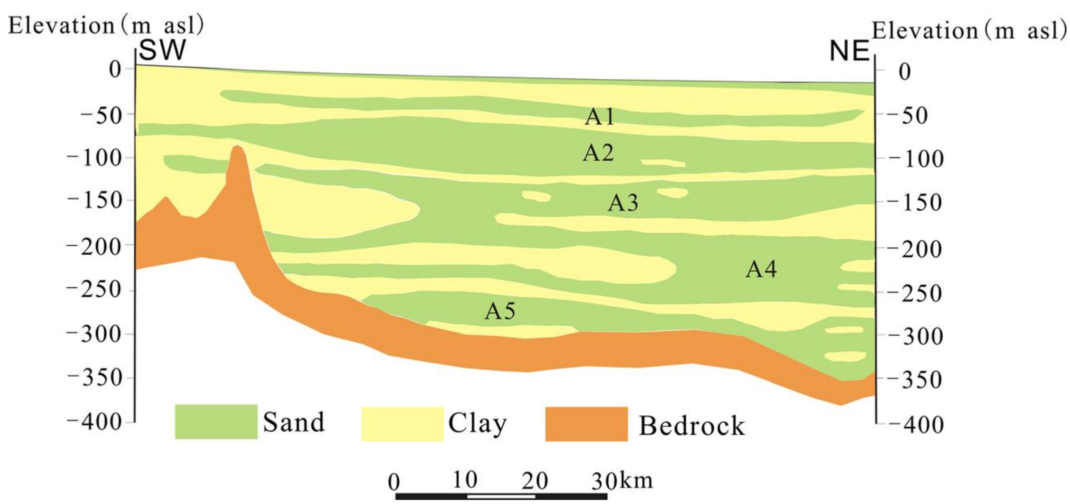

Figure 3-7 Shanghai conceptual hydrological profile (SGEAEB 2002; Zhang and others, 2015)

Groundwater use in Shanghai dates back to 1860 (Gong and others, 2009). Large-scale groundwater development started in the 1950s, with the majority (80.5%) of the total pumping from the A2 and A3 confined aquifers (Figure 3-7), resulting in significant compaction of the shallow aquifers and forming a subsidence bowl centered on downtown Shanghai (Gong and others, 2009). After 1966, pumping from the A2 and A3 confined aquifers was restricted to control land subsidence, and pumping was focused on the deeper (A4 and A5) confined aquifers (Wei, 2002). Land subsidence was first observed in Shanghai in 1921 (Xue and others, 2008; Gong and others, 2009; Zhang and others, 2007). Since 1921, in Shanghai, the maximum observed subsidence has been 9.9 ft. There is a subsidence bowl in downtown Shanghai with an impacted area of 485 square miles (mi^2), with subsidence over 4.9 ft. The downtown subsidence was largely caused by pumping from the A4 aquifer.

Several strategies were employed in the mid-1960s to control subsidence. These included reducing total pumping volumes, moving pumping to deeper aquifers (primarily from the A2 aquifer to the deeper A4 aquifer) and starting a large-scale MAR program. **Figure 3-8** plots the total pumped groundwater volume and the total groundwater recharge volume in the basin by aquifer from 1958 through 2002 (Shi and others, 2016). Both the pumping and recharge volumes are reported in (10^4) m^3 consistent with the literature source. To put that in perspective, the pumping peaked at approximately 162,000 AF from 1960 to 1963. The maximum recharge volume was approximately 24,000 AF in 1986. Between 1967 and

2002 recharge volumes were always smaller than pumping volumes. However, after 2010, MAR volumes exceed groundwater pumping (Zhang and others, 2015). The response to pumping and MAR in Shanghai has been complex because pumping and MAR have occurred in several aquifers of vary magnitude over time. Figure 3-8 also shows that the MAR is mostly recharged into the aquifers which are not being pumped at the highest levels.

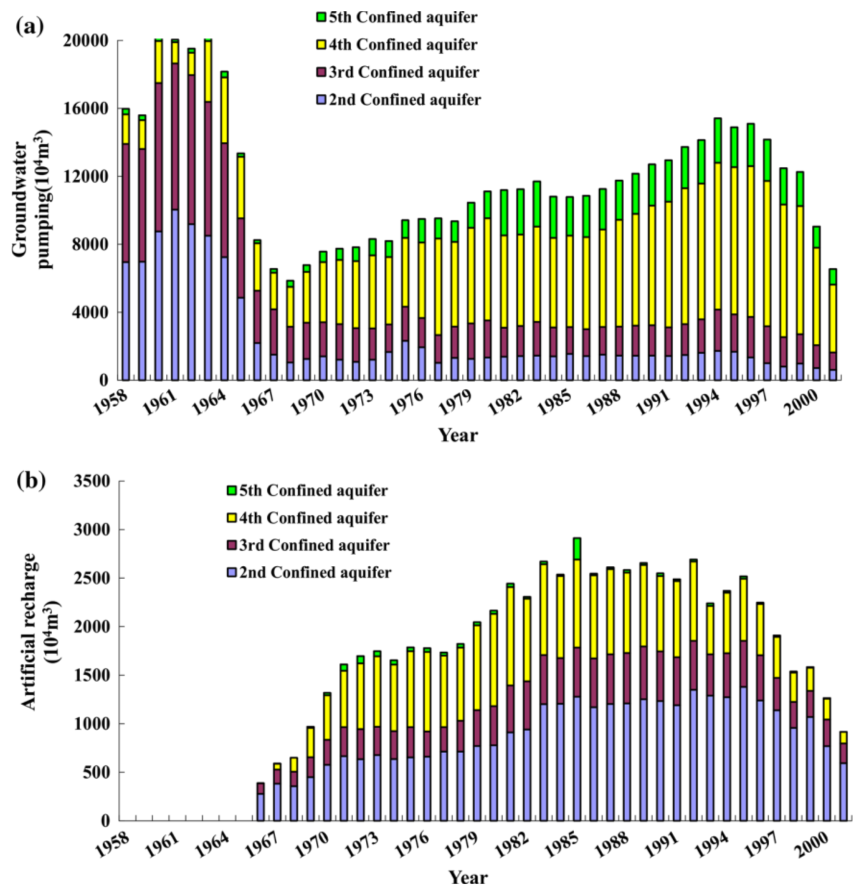

Figure 3-8 The history of groundwater pumping (a) and artificial recharge (b) from the confined aquifers in Shanghai from 1958 to 2002 (Shi and others, 2016)

To examine the relationship between pumping, subsidence and MAR, we will focus on the area within the major subsidence bowl in downtown.

Figure 3-9 plots net annual groundwater pumping and land subsidence rate (millimeters/year) from 1956 through 2002 (after Shi and others, 2016). There are 25.4 mm in an inch. Net annual pumping is calculated by subtracting total pumping in the downtown area by the total volume of recharge from MAR. A positive net pumping means that pumping exceeded MAR; a negative net pumping means that MAR exceeds pumping. Based on observation of subsidence rates in the downtown area of Shanghai, its history can be divided into five stages, as shown in Figure 3-9:

- Stage I – (1958-1961) rapid subsidence of 0.36 feet per year (ft/yr) without any control measure;
- Stage II - (1962-65) reduced subsidence of 0.22 ft/yr from pumping reduction;
- Stage III - (1966-71) slight rebound (-0.01 ft/yr) with beginning artificial recharge;
- Stage IV – (1972-89) slight increase in subsidence at 0.11 ft/yr with more recharge than pumping;
- Stage V – (1990-2001) slow increase in subsidence at 0.05 ft/yr due to adjustment of pumping and recharge rates within the vertical aquifers (Shi and others, 2016).

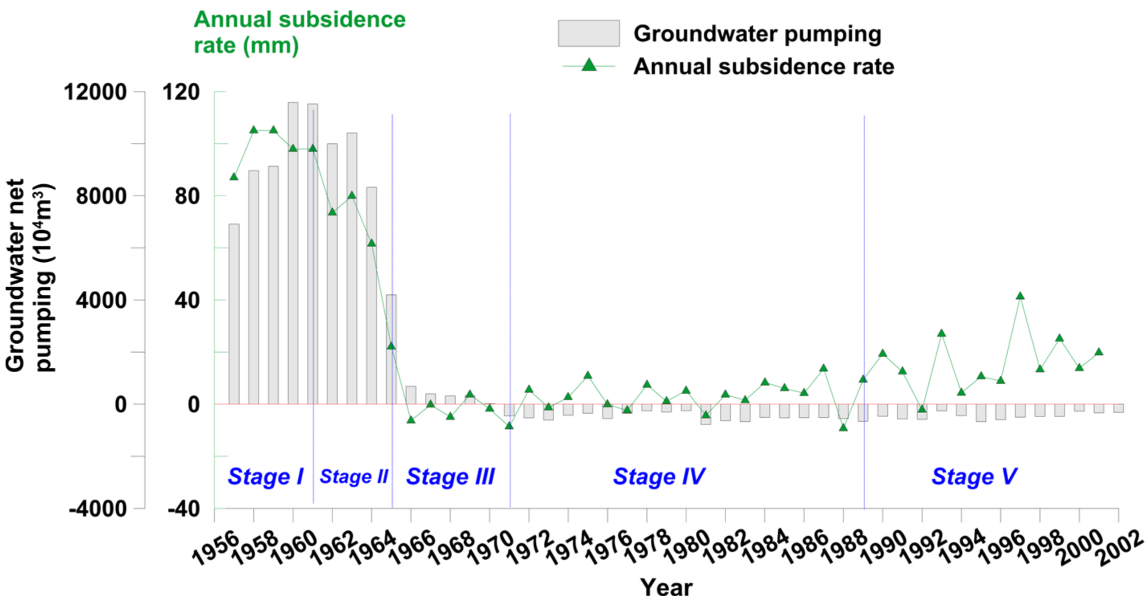

Figure 3-9 The relationship between land subsidence (positive value for compression and negative for rebound) and net groundwater pumping (after Shi and others, 2016)

As summarized by Shi and others, (2016), the contribution of MAR to the land subsidence control was significant during the time period MAR was ramping up to maximum rates (1966 – 83; Stages III and Stage IV in Figure 3-10). However, it is interesting to note that, even after the late 1960s when net pumping was negative (MAR greater than pumping), subsidence still occurs. This is likely because the MAR was not occurring in the same aquifers where most of the pumping was occurring and also because of residual compaction.

The recharge water used in the MAR program is treated surface water (tap water) containing chemical constituents different from in the natural groundwater. As a result, the groundwater quality has been affected by artificial recharge. In response to aquifer recharge, the concentrations of sodium, calcium, magnesium, bicarbonate, chloride and TDS have decreased as groundwater salinity fell. However, concentrations of sulfate, iron and manganese have increased. Concentrations of carbon and nitrogen compounds have also increased. Water quality changes from recharge have been observed radially away from the recharge wells at distances of up to 328 ft for single recharge well and 3,280 ft from the centroid of a group of recharge wells. The influence of MAR on regional groundwater quality is relatively localized to within a small area in Shanghai. To avoid clogging, pre-treatment of recharged water and regular redevelopment has been required.

3.4 Observations from the Case Study Review

There are several key observations from the case studies considered that are important to the study subsidence in the District and the Gulf Coast Aquifer System. They will be summarized in bullets below:

- There are few case studies in the public domain that have documented and analyzed the impacts of ASR on subsidence;
- Unlike ASR, MAR has many well documented case studies where it has been performed around the world to mitigate subsidence. Because these case studies provide relevant information to this study, MAR has been included in the case study review;
- MAR has been recognized as a strategy for the mitigation of subsidence since the 1960s (Poland, 1984). MAR was specifically studied by the USGS (Garza, 1977) in the 1970s as a strategy for the abatement of subsidence occurring in the Johnson Space Flight Center by the USGS (Garza, 1977). MAR has been implemented successfully across the globe reducing rates of subsidence and in some cases ending subsidence;
- The aquifers of interest within the District are not conducive to MAR from surface infiltration because of shallow water tables, fine-grained sediments and low topographic gradient;
- MAR has typically been implemented in groundwater basins which are also undergoing pumping reduction. As a result, water levels are increasing both in response to MAR and to decreased pumping. Therefore, their interrelated effects on subsidence in a basin should be evaluated carefully;
- The evidence shows that basins will continue to subside many years, if not decades, after water levels have rebounded. Such continued subsidence is most likely the result of residual compaction caused by lingering effects of seasonal drawdown on the aquifer system and the ongoing long-term effects of delayed yield from thick drained aquitards. Pavelko (2000, 2004) and Ireland and others (1984) define residual compaction as the continued subsidence of a basin even after heads have rebounded;
- In basins that have undergone significant regional subsidence because of water level declines, the water levels rarely rebound to predevelopment levels after pumping reductions and MAR. As a result, there is still a potential pressure gradient capable of slowly de-pressuring and compacting clays long after water levels have rebounded. This is likely one of the contributors to residual compaction;
- In basins that have undergone significant regional subsidence, subsidence rates can increase again even when water levels are far above historical minimums;
- The most relevant case study found in the literature was an ASR cycle test performed in Antelope Valley, California. The test was instrumented to monitor water levels, water chemistry and ground elevation. The test observed a small amount of irreversible subsidence during the ASR cycle test. What is uncertain is how much of that subsidence is the result of residual compaction resulting from decades of water level decline versus the ASR cycle test;
- ASR wells are the viable method for recharging the aquifers. Based upon experience including those in Las Vegas and Shanghai, ASR wells need to be equipped with pumps capable of providing high production rates for short time periods to backflush the screens and filter packs to effectively manage clogging.

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4.0 BASELINE PROJECTS CONSIDERED FOR ANALYSIS

This section delineates the two types of hypothetical ASR projects considered in the analysis: a drought-of-record (DOR) ASR project developed for an industrial user in Regulatory Area 1; and a summer peaking ASR project that was developed based upon a municipal user's needs for extra water in the summer. The details of these two projects are in no way representative of all the possible permutations that could exist in an ASR project within the District. A strength of ASR is that it can be used in a multitude of ways to increase or secure a water supply. However, the two projects have been developed to be representative of possible projects in the District. The applicability of the results of this study to the broader class of ASR projects will be discussed in Sections 7 and 8. Both baseline ASR projects considered in this study will be described in the following subsections.

4.1 Drought of Record Project – Industrial Use

The first project considered was the type of project originally envisioned by the District when the scope of work for this study was developed where ASR is used to address deficits in an industrial water supply resulting from a prolonged drought. In the project Kickoff Meeting, the project area of interest for this ASR project was narrowed to Regulatory Area 1, which has uncertainty regarding current firm water supply during times of drought. Industrial water users in Regulatory Area 1 rely on surface water supplies, primarily supplied by the Gulf Coast Water Authority (GCWA). Those that rely on the Brazos River Basin and the San Jacinto River Basin to supply their surface water experienced water scarcity in the 2011 drought. The concerns regarding Brazos River water vulnerability and availability in droughts have some water users in Regulatory Area 1 showing interest in ASR as a conjunctive water supply strategy to increase reliability of water supplies in times of drought. The base case DOR ASR project was developed to be relevant to Regulatory Area 1 industrial users in the Texas City area. **Appendix A** presents a detailed analysis of the demand and availability of water for the DOR project. The following subsections will define the DOR project and summarize the key information from Appendix A.

4.1.1 Drought of Record Industrial User Project

Regulatory Area 1 is a highly-urbanized area on the west side of Galveston Bay, including all or portions of the cities of Galveston, Texas City, League City, Pasadena, La Porte and Baytown. The industries within the area that are a likely to implement ASR as a water management strategy are in the Texas City Industrial Complex and along the Houston and Texas City Ship Channels.

In the Project Kickoff Meeting, it was determined that an ASR wellfield would be located in the general area of the GCWA's Thomas S. Mackey Water Treatment Plant (TMWTP) and the Texas City Industrial Complex (see **Figure 4-1**). The most likely wellfield sites in this area are: at the TMWTP; at the GCWA's administration property; or near the industrial users (marked as the Texas City Industrial Complex on Figure 4-1).

Treated water from the 49.7-MGD TMWTP would be the most likely source of water for ASR storage in or near the Texas City Industrial Complex. The proximity of the TMWTP to the industrial complex reduces the required infrastructure such as pump stations, and collection and distribution pipelines.

The industrial ASR project approach would be to: (i) operate the TMWTP at its maximum sustainable capacity to provide water available for storage; and (ii) store any treated water not required by GCWA's municipal customers in the Gulf Coast Aquifer at the ASR wellfield.

For purposes of this Project, the availability of water for ASR storage is a function of:

1. the raw water available under GCWA's water rights; and
2. excess treated water available from the TMWTP after the demands of GCWA's municipal customers have been met.

Figure 4-1 General location of the base case DOR ASR Project for an industrial user – Texas City Industrial Complex (from Appendix A)

4.1.2 Raw Water Available Under Gulf Coast Water Authority Water Rights

The 2016 Region H Water Plan documents that most of the municipal and manufacturing (industrial) water supplied to Regulatory Area 1 is surface water supplied by the GCWA from the San Jacinto-Brazos Intercoastal Basin (SJ-B) and the Brazos River Basin. The GCWA's raw water supply is governed by run-of-river Certificates of Adjudication (COAs) from the State of Texas through the TCEQ and stored water contracts with the Brazos River Authority (BRA). For purposes of this study, the BRA contracts were not considered because they provide a firm supply from storage in upstream reservoirs and are typically not subject to curtailment, even during a severe drought. **Table 4-1** summarizes the COAs that can currently be used to supply water to GCWA's industrial customers in the study area and the authorized maximum annual volume of water in acre-feet per year (AFY) for each certificate.

Table 4-1 Evaluated GCWA certificates of adjudication and authorized annual volume

Certificate No.	Diversion Point	Authorized Annual Volume (AFY)
11-5169	Oyster Creek	12,000
11-5357	Chocolate Bayou	57,500
12-5171 SR	Brazos River	75,000
12-5171 JR	Brazos River	50,000
12-5168	Brazos River	99,932
Total		**294,432**

Run-of-river water rights like the GCWA COAs are subject to reduction during periods of drought. The results of the TCEQ Water Availability Model (WAM) were reviewed to determine how much water might be available to the GCWA's industrial customers during a drought and how much water might be required from ASR storage to make up the deficits. **Table 4-2** documents the volume of water available for the GCWA's COAs during periods of drought and during more "normal" hydrologic conditions. As shown in Table 4-2, in the worst year of the DOR, the COAs will be able to supply only 58% of the authorized annual volume (a reduction of 42%), and, in the five worst years of the DOR, the availability will be on average about 74% of the authorized annual amount (a reduction of 26%).

Table 4-2 Summary of water availability under GCWA COAs (in AF or AFY)

Certificate No.	Diversion Point	1940-1997			1947-1957 (5-Year Low)			1947-1957 (4-Year Low)
		Maximum Volume	Mean Volume	Minimum Volume	Percent of Maximum	Mean Volume	Percent of Maximum	Mean Volume
11-5169	Oyster Creek	12,000	10,533	0	0%	5,350	45%	6,687
11-5357	Chocolate Bayou	57,500	46,099	15,930	28%	32,173	56%	36,234
12-5171 SR	Brazos River	75,000	73,237	49,192	66%	58,193	78%	60,444
12-5171 JR	Brazos River	50,000	45,288	11,700	23%	22,746	45%	25,508
12-5168	Brazos River	99,932	99,775	94,943	95%	98,112	98%	98,904
Total		**294,432**	**274,932**	**171,765**		**216,575**		**227,777**
Percent of Max		**100%**	**93%**	**58%**		**74%**		**77%**
Percent Reduction				**42%**		**26%**		**23%**

In 2006, GCWA purchased the Chocolate Bayou Water Company (Juliff Canal System) and the associated water right (COA 12-5322). That water right is not included in Table 4-1 or 4-2 because water diverted under that water right is not currently available for treatment at the TMWTP or use in the Texas City Industrial Complex. GCWA is in the process of amending COA 5322 so that it can be used to supply water in the Texas City area, but the provisions of such an amendment are not known at this time.

For purposes of evaluating the treated water available for storage in an ASR wellfield, we calculated the difference between the TMWTP capacity (49.7 MGD) and the actual daily volume of water delivered from the TMWTP. Based on the data provided by GCWA for the 2014-2016 period, the:

- Maximum daily treated water production was 42.9 million gallons (MG) (131.7 AF);
- Minimum daily production was 10.8 MG (33.2 AF); and
- Average daily production was 30.7 MGD (94.2 AF/day).

Therefore, the volume of water available for ASR storage, on a daily basis, during the period of record:

- Ranges from 6.8 MG (20.8 AF) to 38.9 MG (119.3 AF); and
- Averages 19.0 MGD (58.3 AF/day).

4.1.3 Water Demand from Drought of Record ASR Project

The DOR ASR project is assumed to supply an industrial user in the Texas City area. We reviewed the water the GCWA water supply contracts with each of its industrial customers in the Texas City area. **Table 4-3** provides the contracted volume with each major industry in the Texas City area. The water is delivered through GCWA's Industrial Pump Station (IPS). A much smaller industrial user (ISP Technologies/Ashland Chemical) is supplied directly from a GCWA terminal storage reservoir and is not included in this analysis.

Table 4-3 GCWA major industrial customers and contract water volume for industries in the Texas City area

Industrial Customer	Contract Water Supply Volume (MGD)	Contract Water Supply Volume (AFY)	Percent of Total Contracted Volume
Dow/Union Carbide Corporation	12.391	13,878	21%
Marathon-Galveston Bay Refinery	28.600	32,032	48%
Valero Refining Texas, LLP	6.510	7,291	11%
Marathon Petroleum, LLC (Texas City Refinery)	4.000	4,480	7%
Eastman Chemical Company	8.542	9,567	14%
Total	**60.043**	**67,248**	**100%**

An estimate of the volume of water required from ASR storage to meet the total demand of the five industries in the Texas City complex (listed in Table 4-3) during a repeat of the DOR was developed, with the understanding that the hypothetical initial ASR wellfield might be conceptually "designed" with a lower capacity and expanded in later phases. Estimates of the daily water demand (required from ASR storage), were based on the actual industrial water supplied by the GCWA during Calendar Years (CYs) 2011 through 2016 compared to the reduction in raw water available from GCWA during periods of drought, as shown in Table 4-2. CY 2011 was an extremely dry year and could be considered the worst year of a five-year drought. To estimate the demand for ASR water during the worst year of a five-year drought, the water delivered to the five industries each day in 2011 was multiplied by 42%. Forty-two percent is the modeled reduction in water availability in the worst years of the DOR and can be considered the demand for stored water. For the remaining four years (CYs 2012 through 2016), the actual daily delivered water was multiplied by 26% (see Table 4-2), and that deficit became the volume of water required from ASR storage to meet the industries' daily demands. Therefore, the demand for ASR storage for industrial purposes equals the maximum cumulative deficit in supply from GCWA each day during a simulated five-year drought.

The 2016 Region H Water Plan was reviewed to evaluate the potential future demand for industrial customers supplied by the GCWA. The Regional Plan shows that GCWA's industrial water demand in Galveston County will only increase 3% over the 50 years between 2020 and 2070 (from 55,871 to 57,587 AFY). This may have been a reasonable assumption when the 2016 Region H Plan was developed given the built-out conditions in the area. However, contrary to the plan, there has been information in recent months signifying that industrial water demand may increase significantly due to new plants and expansions. For this study, estimating future industrial water demand based on actual demand during the 2011 through 2016 period is a reasonable approach.

4.1.4 Source Water Quality

The treated water quality data for the TMWTP was reviewed and summarized. Data were collected from the GCWA's Annual Water Quality Reports and through the TCEQ's Drinking Water Watch database for Public Water System Number TX0840153. All available data from 2002 through 2017 were reviewed. Data for the treated water, distribution system, and combined filter effluent are summarized in **Tables 4-4** through **4-6**, respectively. These data were used to look at geochemical compatibility at the hypothetical industrial user site to provide insight into water quality issues that may need to be considered in an ASR project in the Gulf Coast Aquifer System in Regulatory Area 1.

Additional parameters of interest to an ASR project, which were not included in the available data, include:

- Total Suspended Solids
- Color
- Temperature
- Dissolved Oxygen
- Reduction-Oxidation Potential (Eh)
- Total Silica
- Non-Carbonate Hardness
- Calcium Hardness
- Phosphate
- Ammonia
- Hydrogen Sulfide
- Carbon Dioxide
- Total Halogenating Hydrocarbon
- Specific Gravity or Fluid Density

A geochemical analysis has also been performed to investigate the compatibility of the industrial source water identified for recharge with the Gulf Coast Aquifer System groundwater. The analysis was limited to Chicot Aquifer groundwater samples from 152 wells located in the vicinity and within Regulatory

Area 1 within a selected target area bounded by ten miles to the north, south, east and west of the GCWA TMWTP. The discussion of this analysis can be found in **Appendix B**. The key conclusions from the geochemical compatibility analysis are discussed in Subsection 4.1.5.

Table 4-4 Treated water (entry point) water quality results from 2002 through 2017

Parameter	Minimum	Average	Maximum
Total Alkalinity, mg/L	97	126	156
Total Dissolved Solids, mg/L	210	358	733
Conductivity, UMHO/cm	432	682	1386
Specific Conductance, mS/cm	328	559	1145
pH	6.9	7.3	7.5
Chloride, mg/L	39	85	275
Fluoride, mg/L	0.18	0.5	0.95
Sulfate, mg/L	33	58	122
Carbonate Alkalinity (as CO_3^{2-}), mg/L	<1	<2	<2
Bicarbonate Alkalinity (as HCO_3^{1}), mg/L	118	154	190
Calcium, mg/L	37	48.2	67.6
Magnesium, mg/L	6.95	10.5	17.4
Sodium, mg/L	36.6	60.4	163
Potassium, mg/L	4.54	5.13	5.85
Iron, mg/L	<.01	<0.1	<0.46
Aluminium, mg/L	<0.02	<0.03	<0.05
Copper, mg/L	0.0026	0.0149	0.0335
Manganese, mg/L	<0.001	<0.0036	<0.0127
Zinc, mg/L	0.0978	0.1356	0.224
Cadmium, mg/L	<0.001	<0.001	<0.0012
Selenium, mg/L	<0.003	<0.0034	<0.0066
Total Hardness (as $CaCO_3$) mg/L	121	163	240
Nitrate, mg/L	0.09	0.63	1.48
Chloroform, µg/L	1	4.9	12
Bromodichloromethane, µg/L	1	9.9	16
Dibromochloromethane, µg/L	1	13.4	22
Bromoform, µg/L	.7	5.7	17
Total Trihalomethanes, µg/L	4	33.9	49.8

Table 4-5 Distribution system water quality results from 2004 through 2016

Parameter	Minimum	Average	Maximum
Chloroform, µg/L	2.9	9.2	17.6
Bromodichloromethane, µg/L	11.2	16.7	23.1
Dibromochloromethane, µg/L	13.4	22.0	32.2
Bromoform, µg/L	1.8	8.1	27.4
Total Trihalomethanes, µg/L	39.5	56.0	75.3

Table 4-6 Combined filter effluent turbidity statistics (nephelometric turbidity units) from 2015 through 2017

Parameter	Minimum	Average	Maximum
Highest Measured Turbidity	0.07	0.19	0.90

4.1.5 Geochemical Compatibility of Source Water

The ASR source water, assumed to come from the TMWTP, was evaluated for water quality compatibility with groundwater in the Chicot and Evangeline aquifers in Regulatory Area 1. A detailed memorandum documenting this geochemical analysis is provided in Appendix B. Most of the groundwater water quality data available was for the Chicot Aquifer. The groundwater water quality data was collected from 152 locations in the Chicot Aquifer and three water quality data were analyzed from the Jasper Aquifer up dip of Regulatory Area 1.

Thermodynamic equilibrium modeling was performed for a range of groundwater samples to examine the range in observed pH, Eh, temperature and silica. Essentially, all well locations where groundwater quality was collected and analyzed could be considered for ASR purposes. However, some are geochemically more readily acceptable than others. There are too few water quality analyses in the upper and lower Chicot Aquifer (Beaumont and Willis formations) to be considered representative. However, there were adequate middle Chicot Aquifer (Lissie Formation) water quality analyses to develop an understanding of the potential geochemical issues that could be encountered recharging into the Chicot Aquifer.

The potential for calcite precipitation using system water from the TMWTP as the recharge source and the potential for iron sulfide (pyrite) and iron carbonate (siderite) oxidation and dissolution are two of the potential mineralogic problem issues identified by geochemical modeling. Calcite precipitation may present a plugging problem while oxidation of pyrite may mobilize arsenic and metals and increase the total dissolved solids (TDS) of the recovered water. These issues can be addressed through pre-recharge treatment and through proper design of an ASR buffer zone.

Relatively few wells in Regulatory Area 1 have adequate data for the broad range of geochemical constituents necessary to guide an equilibrium geochemical model analysis. Adequate water quality data for wells in the Evangeline Aquifer is generally lacking in the study area because most wells in Regulatory Area 1 are completed in the Chicot Aquifer. The absence of geochemical and geotechnical data from continuous wireline cores is a significant constraint upon modeling and conceptual design of an ASR wellfield. If an ASR program moves forward, an initial recommended task would be to obtain cores and to construct test/monitor wells at a selected site. Analyses of the data collected from these facilities would guide subsequent wellfield design and operation.

Because the equilibrium geochemical modeling is limited by available water quality data and a lack of physical or mineralogic data from cores and core analysis, our conclusions regarding potential issues are strongly informed by experience at other ASR wellfields in unconsolidated aquifer systems. All potential geochemical issues, described briefly in this section and in more detail in Appendix B, could be addressed by proper characterization, analysis and engineering. These same water quality issues have been dealt with in similar aquifers in coastal fluvial geologic settings with alternating layers of sands and clays across the nation. Proper buffer zone delineation, formation and maintenance are key factors to preventing the recovery of stored water containing increased concentrations of metals including arsenic.

In the Texas City test well, data provided to the District indicate that a slightly elevated concentration of arsenic (14.8 micrograms per liter; µg/L) was present in the recovered water at the end of recovery during a third cycle; however, the recovery volume was 151% of the recharge volume. Experience in other states has demonstrated the viability of a simple approach to controlling arsenic concentrations in the recovered water, which is to initially form and maintain a buffer zone around the well, typically comprising about 30 to 50% of the TSV. This standard procedure was not implemented at Texas City. Over-recovery of the small volumes of stored water during each cycle most likely contributed to the slightly elevated arsenic concentration.

4.1.6 Baseline Project Conceptual Design

Recharge into the storage aquifer through the ASR wells would occur during winter months and other times when excess capacity exists at the 49.7 MGD TMWTP, operated by the GCWA at Texas City. Water produced at this treatment plant supplies municipalities in its service area, providing water meeting drinking water quality standards. The industries recovering water from ASR storage may not need treated water quality for process use. However, recharging with raw surface water can cause well clogging and other problems. Recharging with water from the TMWTP increases the operational efficiency of the ASR project.

Recovery of water stored in ASR wells would occur primarily during severe droughts, with durations up to five years. A secondary objective could be to provide supplemental peak water supply capacity during summer months each year. This would entail no additional capital investment but would entail storing more water. Recovered water from ASR wells would not be expected to require re-treatment for industrial process purposes. Recovery of stored water for municipal purposes would require restoration of a disinfectant residual.

Based on data presented in a Freese & Nichols (2014) report entitled “Long Range Water Supply Study - Detailed Evaluation of Selected Strategies,” peak potable water demand and projections for the TMWTP are estimated at 1.40 times average demands. Treated water demand plus losses (unaccounted-for water; conveyance losses, etc.) is expected to exceed the 49.7 MGD plant capacity, and the contracts for potable water supply, by about 2045. A real project would refine these 2014 estimates. However, for purposes of this study, it is reasonable to assume that excess supply and treatment capacity exists during the winter months and non-peak periods.

Supplementing the Freese & Nichols (2014) report, daily treated water data (“produced water”) and monthly summaries were reviewed for 2014-2016 for the TMWTP. **Table 4-7** shows a summary of the water use based upon treated water for each year.

Table 4-7 Historic treated water production, TMWTP

Metric (MGD)	2014	2015	2016
Minimum Daly Treated	10.83	15.76	25.61
Average Day Treated	30.00	30.62	31.38
Peak Day Treated	40.80	42.91	40.51

For its purposes, this report assumed that a continuous supply of 5.0 MGD of recharge water (treated drinking water) would be available for at least five years; initially to form the TSV, declining to at least 3 MGD during subsequent years to restore and maintain the TSV following summer peak demand periods and droughts. ASR offers a versatile water supply strategy which could also be used to access (or better take advantage of) the firm peak day capacity of the TMWTP.

The four industrial users being supplied by GCWA in the Texas City area currently combine for a total contractual demand of 60 MGD. The worst year of the DOR defines the required capacity of the ASR project. In the worst year of the DOR, there was a 42% reduction in supply which equates to 25 MGD deficit. Assuming one of the industrial users is developing an ASR project, we assumed a deficit of about 5 MGD in the worst year of the DOR.

A detailed analysis of Brazos River daily flows, and daily treated water production records for the TMWTP have not been conducted for this project. However, a similar analysis has previously been conducted by members of the team for two other ASR feasibility studies in Texas, one for New Braunfels Utilities and another for the City of Victoria. We used these detailed simulations as a proxy as to what could be expected in a daily analysis of the ASR operation. Based upon the Victoria and New Braunfels Utility (NBU) ASR simulation model analyses, a hypothetical five-year drought for Regulatory Area 1 might reasonably be characterized as having five, six, seven, eight and nine months of recovery from ASR storage during each successive year of the drought, and with recharge for two months during the first year, one month during the second year, and no recharge during the remaining three years. This hypothetical drought water availability pattern was utilized to prepare a preliminary estimate of the TSV for the hypothetical DOR ASR project.

From the above assumptions regarding project goals, the TSV for the ASR wells may be estimated. The TSV is the sum of the Stored Water Volume that will be recovered to meet the ASR goals (5MGD), plus a buffer zone volume that will stay in the aquifer to ensure acceptable water quality during a design recovery period. The buffer zone volume is the first water recharged, separating the stored drinking water that will be recovered (storage volume) water from the surrounding native groundwater.

Important considerations in determining the volume of the buffer zone are ambient groundwater quality relative to the recharged water quality, ambient hydraulic gradients, and heterogeneity in aquifer properties. An average buffer zone volume of 100% of the project storage volume is considered reasonable for a storage zone containing brackish groundwater or formation materials potentially containing arsenopyrite.

The volume of water in the buffer zone is a one-time addition of water to the ASR well. It is often referred to as the walls on your imaginary tank holding the ASR storage volume. The water recharged to develop the buffer zone is lost to the aquifer with the intention of not recovering that water at the ASR well. It may take several years to achieve the TSV. During that time, the level of water supply reliability will steadily improve as the stored water volume steadily increases. Once the TSV has been achieved, essentially all the subsequently stored water will be recoverable, but the Buffer Zone volume should not be recovered. As a result, cumulative recovered water volume at an ASR well should always be less than the stored water volume. That is, unless the buffer zone volume is recovered from the ASR well. If that occurs, the operator of the ASR well takes on a greater risk of recovering water that does not meet water quality requirements, whether elevated concentrations of TDS, arsenic or other metals. Blending and/or re-treatment may then be necessary.

Based on the goal of achieving a firm supplemental supply with a recovery capacity of 5 MGD during a five-year drought, the ASR recovery schedule is as follows:

- First year of drought: 5 months (152 days) at 5 MGD = 760 MG
- Second year of drought: 6 months (182 days) at 5 MGD = 912 MG
- Third year of drought: 7 months (213 days) at 5 MGD = 1,064 MG
- Fourth year of drought: 8 months (243 days) at 5 MGD = 1,216 MG
- Fifth year of drought: 9 months (274 days) at 5 MGD = 1,368 MG

We also assume that water availability during the first two years of drought would allow aquifer recharge through the ASR wells for 90 days a year at a rate of 3 MGD. We determined that the required TSV to meet the 5MGD recovery capacity was approximately 9,102 MG (28,000 AF).

Figure 4-2 plots the recharge and recovery cycle of the theoretical industrial DOR ASR project case. The plot provides cumulative water stored in millions of gallons (red curve) and the recharge and recovery rates in million gallons per day (blue curve). The TSV, roughly 1.8 times the ASR Storage Volume (5 MGD), is recharged over the first five years. After the TSV has been established, the recovery cycle begins. You can see from inspection of Figure 4-2 that recharge occurs in the first two years of the drought. One can also note that greater than 4,000 MG of the recharged water is left in the aquifer at the end of the drought. This is the Buffer Zone Volume.

The hypothetical ASR wellfield conceptual design is based upon conventional ASR vertical well design concepts, with multiple ASR wells in a cluster, each penetrating a different storage interval within the sand and clay layers of the Gulf Coast Aquifer System. The initial well array assumed in our analysis was a potential 10-well array with two parallel sets of 5 wells assuming 5 possible completion intervals. The discussion of the potential recharge intervals, their properties and how they are assigned are discussed in Section 5.

4.2 Summer Peaking Municipal User Project

Over the course of the project, interest was shown by the District in considering a summer peaking municipal water user ASR project in addition to a DOR industrial user project. It is expected that the summer peaking case would also be applicable to a municipality in Regulatory Area’s 2 or 3, which are actively trying to meet the Regulatory Plan curtailment schedule.

4.2.1 Summer Peaking Assumptions and Project Conceptual Design

The demand and supply assumptions were derived for a growing municipality In Regulatory Area 3. Through water resource planning, the municipality found that ASR could be a benefit to the city by allowing them to take their full contract of surface water in months when their demand was less than their allotment and have that water available in months when their contract allotment is inadequate to meet demand.

We have assumed that the water supply is available in excess of demand from November through February. The project storage volume is assumed to be 2,000 AF, which is approximately 650 MG. Unlike the industrial drought-of-record case above, we did not estimate a rigorous TSV for the summer peaking case. That is because this case was not originally contemplated in the scope of work. We used a conservative rule-of-thumb TSV factor-of-two times the Storage Volume which (see Pyne, 2005) would be 4,000 AF (1,300 MG). The Storage Volume (2,000 AF) would be recovered from July through September of each year. Because recharge intervals in Regulatory Area 3 would likely have fresh water, the actual design TSV for a real project could be less than a factor-of-two of the storage volume.

Figure 4-3 plots the recharge and recovery cycle of the theoretical summer peaking case. The plot provides cumulative water stored in millions of gallons (red curve) and the recharge and recovery rates in million gallons per day (blue curve). The TSV, roughly two time the desired annual recovery amount, is recharged in the first year. The time series for years 2 through 20 are identical. We ran the summer peaking case out for 20 years because that was an approximate time over which a municipality could pay for a similar ASR project.

Interestingly the summer peaking case ended up an equivalent size project (in terms of rates) as the long-term DOR case. While volumes requiring storage are quite different (2,000 versus 14,670 AF), the rates are very similar. Capital costs for the summer peaking case would be only slightly more than for the industrial DOR case, depending upon whether additional transmission capacity may be needed to meet slowly-increasing peak summer demands.

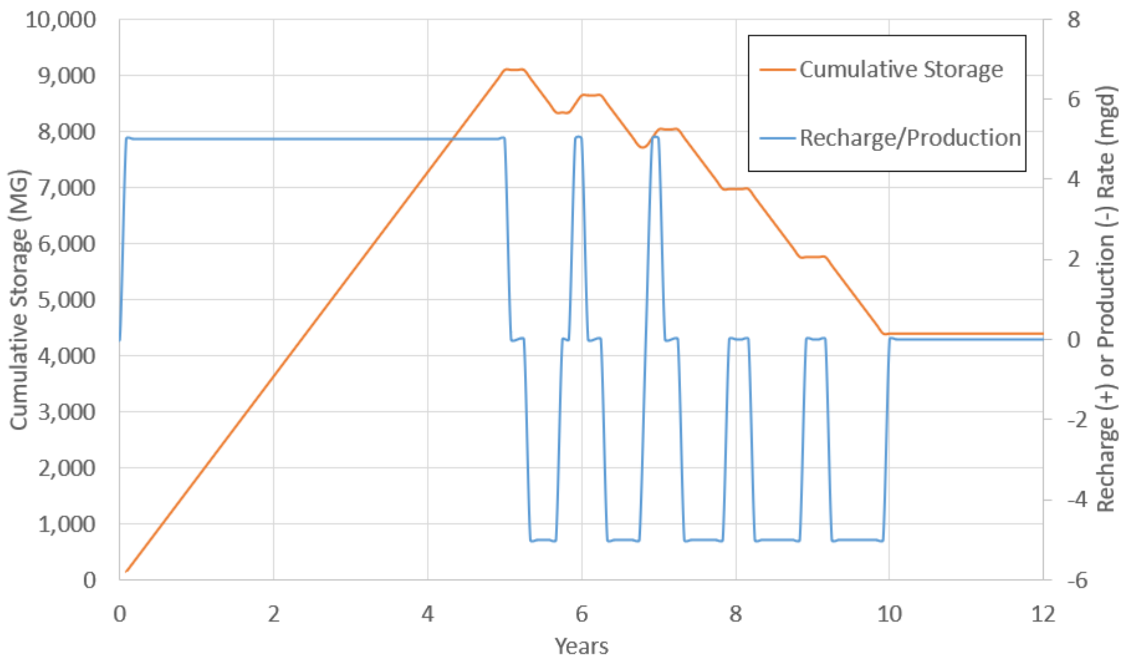

Figure 4-2 Time series of cumulative volume and recharge or production rate – DOR case

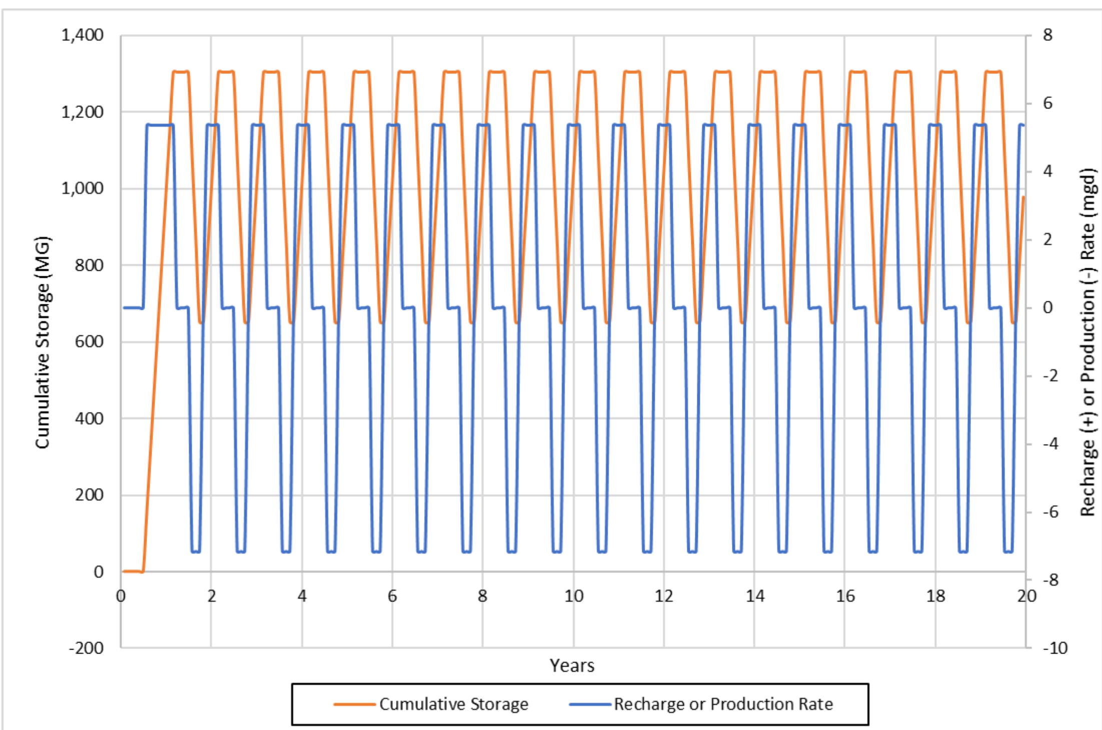

Figure 4-3 Time series of cumulative volume and recharge or production rate – summer peaking case

5.0 SUBSIDENCE MODEL

A groundwater model was developed to simulate subsidence under the cycle pumping conditions of an ASR project. This section describes the construction of that groundwater model.

5.1 Modeling Code

The code that was used for model development was MODFLOW-NWT (Niswonger and others, 2011), which is one of the family of MODFLOW codes developed by the USGS. MODFLOW-NWT supports the subsidence (SUB) package (Hoffman and others, 2003), which allows simulation of a compaction response to pressure change in the aquifer.

The SUB package can simulate either time-dependent compaction (termed “delay beds” in SUB), or instantaneous compaction (termed “no-delay beds”). Compaction is simulated as a one-dimensional process, and the key compaction parameters described in Section 2 are required as inputs. This includes both elastic and inelastic storativity, preconsolidation drawdown, and vertical conductivity of the clays.

MODFLOW-SUB simultaneously simulates hydraulic head and compaction at each grid cell, and the groundwater released from storage due to depressurization of the clays is 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.

5.2 Representative Model Locations

The study area was restricted to Regulatory Area 1. In the Kickoff Meeting, the base case model was determined to be located in the Texas City Industrial Complex. Because the results from the study should be representative of the whole of Regulatory Area 1, alternate locations for ASR projects are also required. It is important to note that this study does not go through the site selection process consistent with the feasibility-level approach used for an actual ASR project. The approach does not consider land ownership, infrastructure or proximity to a specific structure. Because this study is hypothetical in nature, the ASR project locations are defined by a general area.

To choose alternate locations, we reviewed the physical character of the formations comprising the Chicot and Evangeline aquifers at 25 geophysical logs in Regulatory Area 1. Our initial approach for selecting alternative sites was based on the physical attributes of clay in the aquifers. The attributes considered included total net clay thickness, number of clay beds, average and median clay bed thickness and clay percent. Based upon these attributes, we attempted to locate an “average” log (location), a minimum clay content location and a maximum clay location. The attributes were analyzed by the six formations comprising the Chicot and Evangeline aquifers (see Figure 1-2). The data were analyzed statistically and plotted spatially to discern any significant trends and to define the logs that would typify the average and extreme cases. Our conclusion was that an “average” log for all six formations at a single location does not exist. Many have described the Gulf Coast Aquifer System as an undifferentiated assemblage of sands and clays. The challenge in the original concept for site selection is that a log may exhibit average or extreme clay properties in one formation but not the others. The system is complex in terms of lithology both vertically and horizontally. Walther’s Law of facies succession supports why lateral correlation of individual clays is challenging in the Gulf Coast Aquifer System.

A second approach was adopted which was based upon the depth dependence of the physical properties of clays that govern compaction (see Subsections 2.2 and 2.3). A secondary factor considered was the desire to select one location near the coast, that would likely target the Chicot Aquifer, and one location updip where an ASR project could target both the Evangeline and Chicot aquifers. **Figure 5-1** plots Regulatory Area 1 with the geophysical logs used to perform the selection process and the three sites chosen for theoretical ASR subsidence modeling. Figure 5-1 also shows the approximate location where the base of groundwater below 10,000 milligrams per liter (mg/L) TDS intersects the base of the Chicot Aquifer. This indicates the thinning of the fresh groundwater section as you approach the coast in Galveston County. ASR storage has been successful in aquifers well in excess of 10,000 mg/L TDS. The remainder of this Subsection will describe the selected ASR project locations.

5.2.1 Base-Case Model Location

The base-case model location is in the Texas City Industrial Complex. This location was selected consistent with the consideration of a DOR industrial user scenario. The industrial users in the area have been identified as well as their source water, demands and deficits in DOR conditions (see Subsection 4.1).

Although an exact project location is not specified, the subsidence model requires definition of the aquifer and clay interbed depths as well as the physical properties and hydraulic properties of the aquifer sands and clays. Both the potential for compaction and the hydraulic properties of an aquifer system are dependent on the lithologic composition of the aquifer and specifically the juxtaposition of sands and clays. As a result, geophysical logs from oil and gas wells have been used to characterize the physical nature of the aquifers in the vicinity of each project location. For the base case Texas City location, the geophysical log from well API 4216700966 was used. **Figure 5-2** provides a map of the location of this log in Texas City and an interpreted stratigraphic and lithologic column from the log. **Table 5-1** provides general information from the geophysical log regarding aquifer formation depths and clay interbeds. Figure 5-2 presents the interpreted stratigraphic and lithologic column for the location (log). Intervals on Figure 5-2 are colored based upon both lithology (sand, clay) and interpreted TDS. All colors other than black are sand dominated intervals. The colored intervals are dominantly sand lithology and the color corresponds to the interpreted TDS measurement for that interval using the geophysical log. Figure 5-2 illustrates that the Lissie (mid-Chicot Aquifer) is very sand rich and very fresh.

Table 5-1 Physical description of formations at geophysical log API 4216700966, base case location

Aquifer (Formation)	Depth to Top (ft)	Depth to Bottom (ft)	Formation Thickness (ft)	Net Clay Thickness (ft)	Number of Clay Beds	Clay Percent
Chicot (Beaumont)	GS	450				
Chicot (Lissie)	450	995	545	335	16	61%
Chicot (Willis)	995	1833	838	89	4	11%
Evangeline (Upper Goliad)	1833	2643	811	649	9	80%
Lower Goliad	2643	3763	1119	856	13	76%
Upper Lagarto	3763		987	423	13	43%

5.2.2 Downdip Model Location

For the downdip location, the geophysical log from well API 4216701846 was used. **Figure 5-3** provides a map of the location of this log, which is on Galveston Island. This site was chosen because ASR could be a valuable water supply strategy on the island. Also, the location was chosen near the gulf because clays tend to increase in thickness towards the gulf. Figure 5-3 presents the interpreted stratigraphic and lithologic column for the location (log). The log is colored consistent with the one presented above. Figure 5-3 shows that all the sands at this location are interpreted to have TDS concentrations in excess of 1,000 mg/L, which means the groundwater is not fresh and could range from brackish to brine. Below the Lissie Formation (Mid-Chicot Aquifer), groundwater quality degrades quickly to saline conditions. The Lissie Formation has good sands at this location for recharge and recovery. **Table 5-2** provides general information from the geophysical log regarding formation depths and clay interbeds.

5.2.3 Updip Model Location

For the updip location, the geophysical log from well API 9965223010 was used. **Figure 5-4** provides a map of the location of this log which is just southeast of Loop 610 in the area that comprises the Galena Park PRESS Site. This is also the northwest edge of Regulatory Area 1. This location was chosen because very good sands and water quality were available in the Evangeline Aquifer. Figure 5-4 presents the interpreted stratigraphic and lithologic column for the log. The log is colored consistent with the one presented above. Figure 5-4 shows that there are many 100-foot-thick, isolated freshwater sands from ground surface through the base of the Evangeline Aquifer (2,400 ft bgs. This location appears ideal hydraulically for ASR storage. This log is within the area in the Gulf Coast Aquifer System where the freshwater extends the deepest in Harris County (Young and others, 2017). **Table 5-3** provides general information from the geophysical log regarding formation depths and clay interbeds.

Table 5-2 Physical description of formations at geophysical log API 4216701846, downdip model location

Formation	Depth to Top (ft)	Depth to Bottom (ft)	Formation Thickness (ft)	Net Clay Thickness (ft)	Number of Clay Beds	Clay Percent
Aquifer (Formation)	GS	780	780	227	14	29%
Chicot (Beaumont)	780	1275	495	169	13	34%
Chicot (Lissie)	1275	1866	591	384	20	65%
Chicot (Willis)	1866	3096	1230	600	27	49%
Evangeline (Upper Goliad)	3096	4403	1307	1034	14	79%
Lower Goliad	4403	5181	778	617	10	79%

Table 5-3 Physical description of formations at geophysical log API 9965223010, updip model location

Formation	Depth to Top (ft)	Depth to Bottom (ft)	Formation Thickness (ft)	Net Clay Thickness (ft)	Number of Clay Beds	Clay Percent
Aquifer (Formation)	GS	234	234			
Chicot (Beaumont)	234	930	695	389	13	56%
Chicot (Lissie)	930	1234	394	167	9	42%
Chicot (Willis)	1234	1450	126	108	4	86%
Evangeline (Upper Goliad)	1450	2041	591	265	12	45%
Lower Goliad	2041	2440	399	239	3	60%

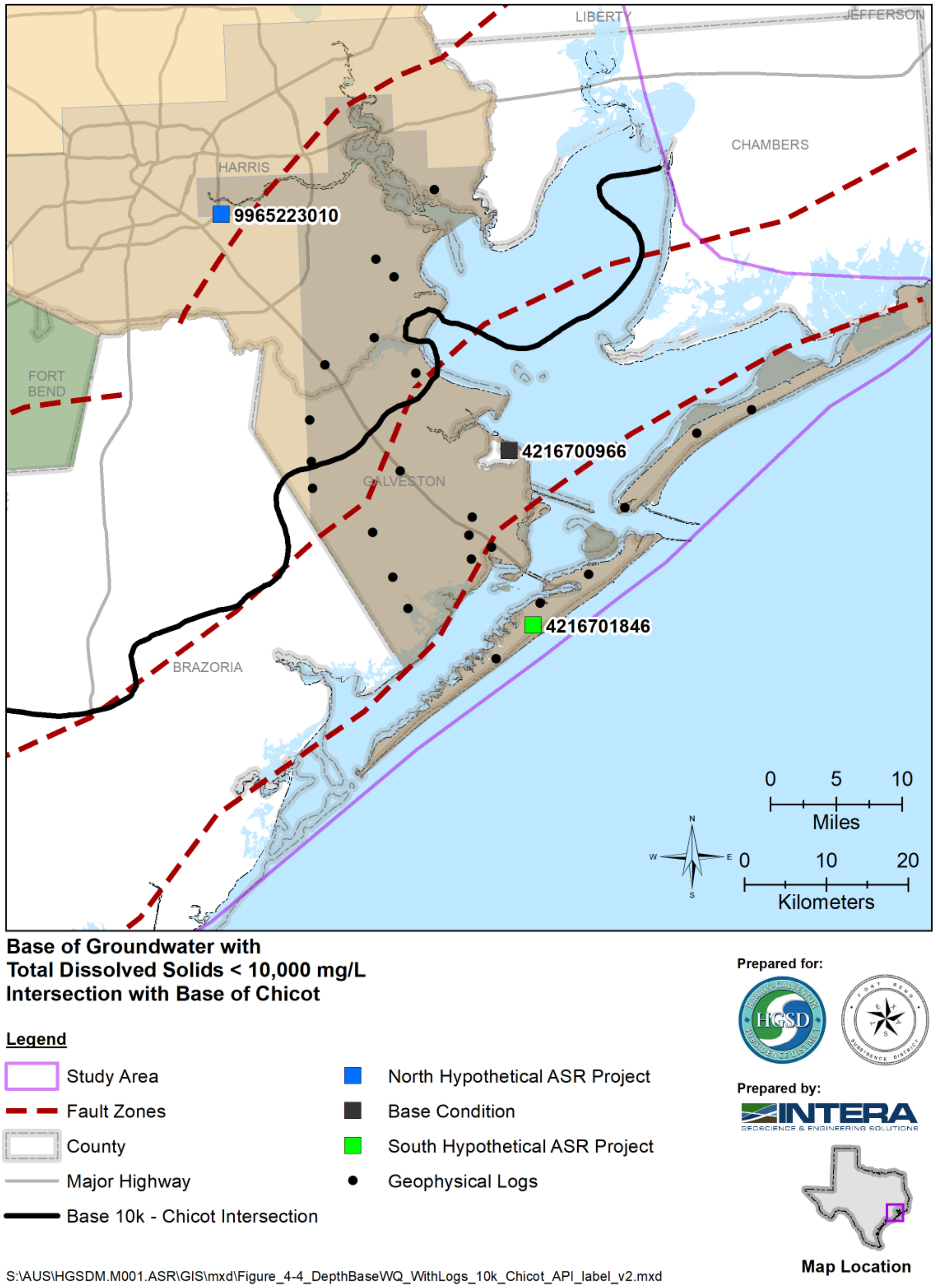

Figure 5-1 Base map of the study area showing the location of analyzed geophysical logs, the three selected ASR project locations and the approximate boundary where the base of groundwater at 10,000 mg/L intersects the base of the Chicot Aquifer

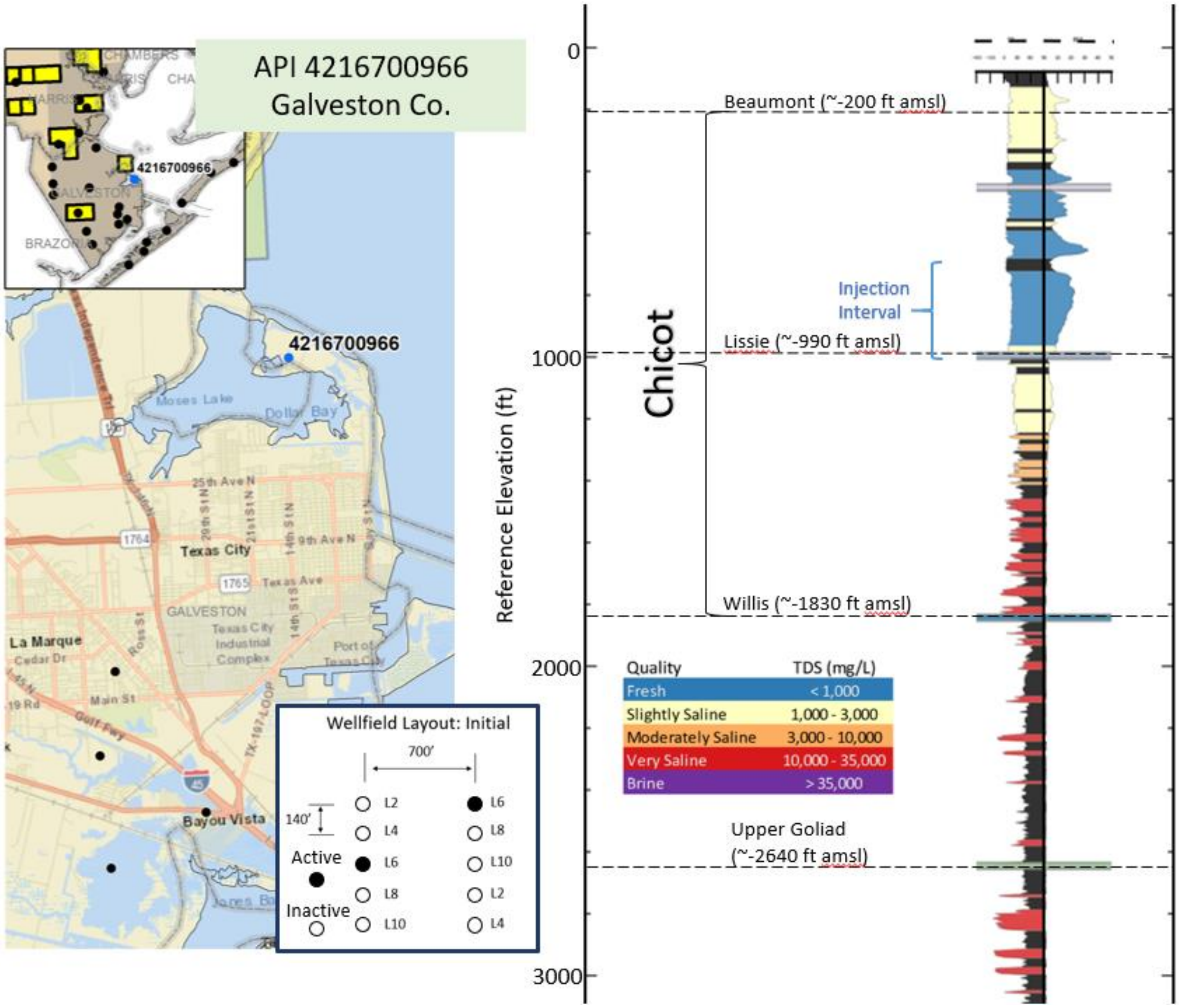

Figure 5-2 Base Case ASR Project base map with interpreted geophysical log

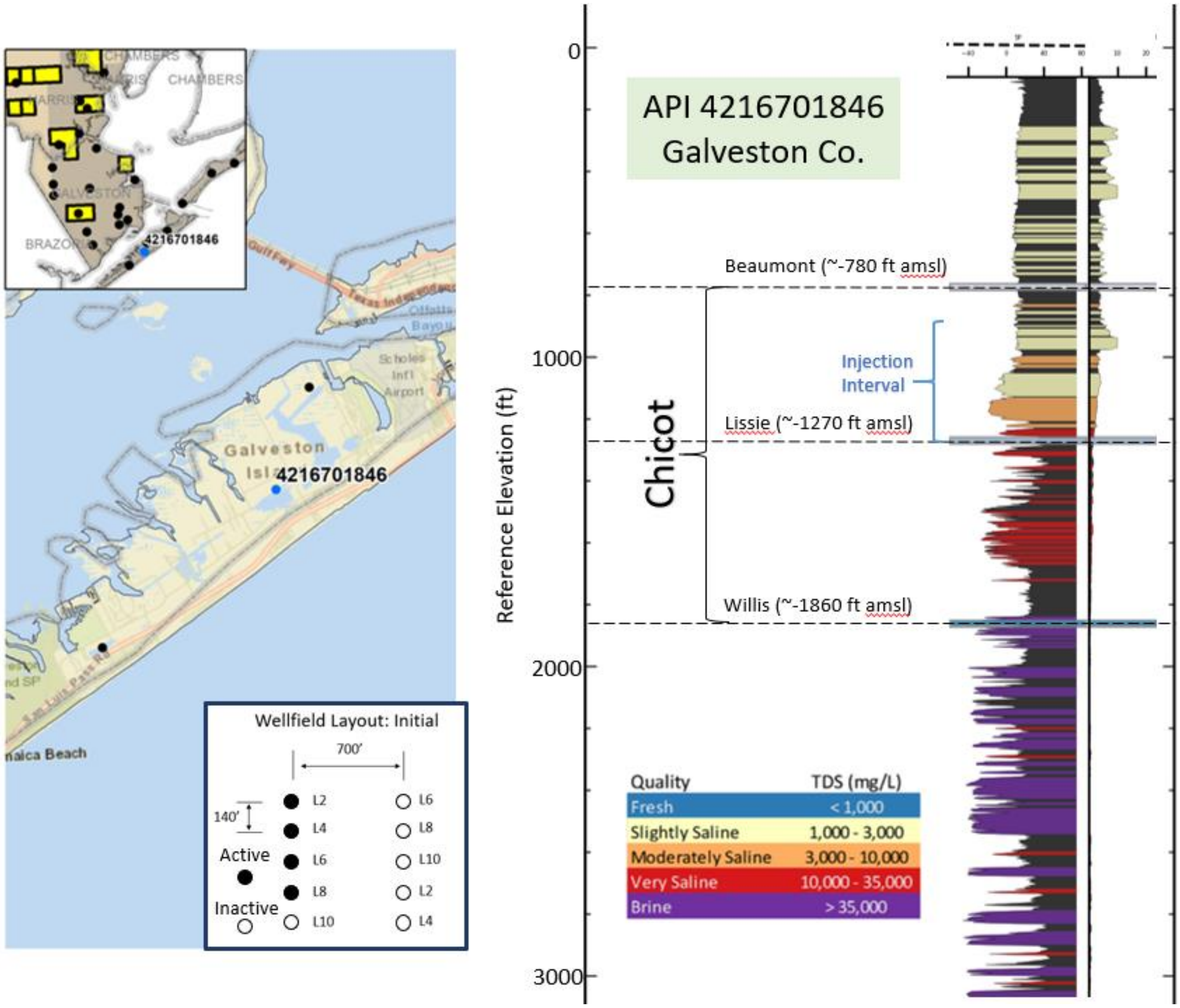

Figure 5-3 Downdip ASR Project base map with interpreted geophysical log

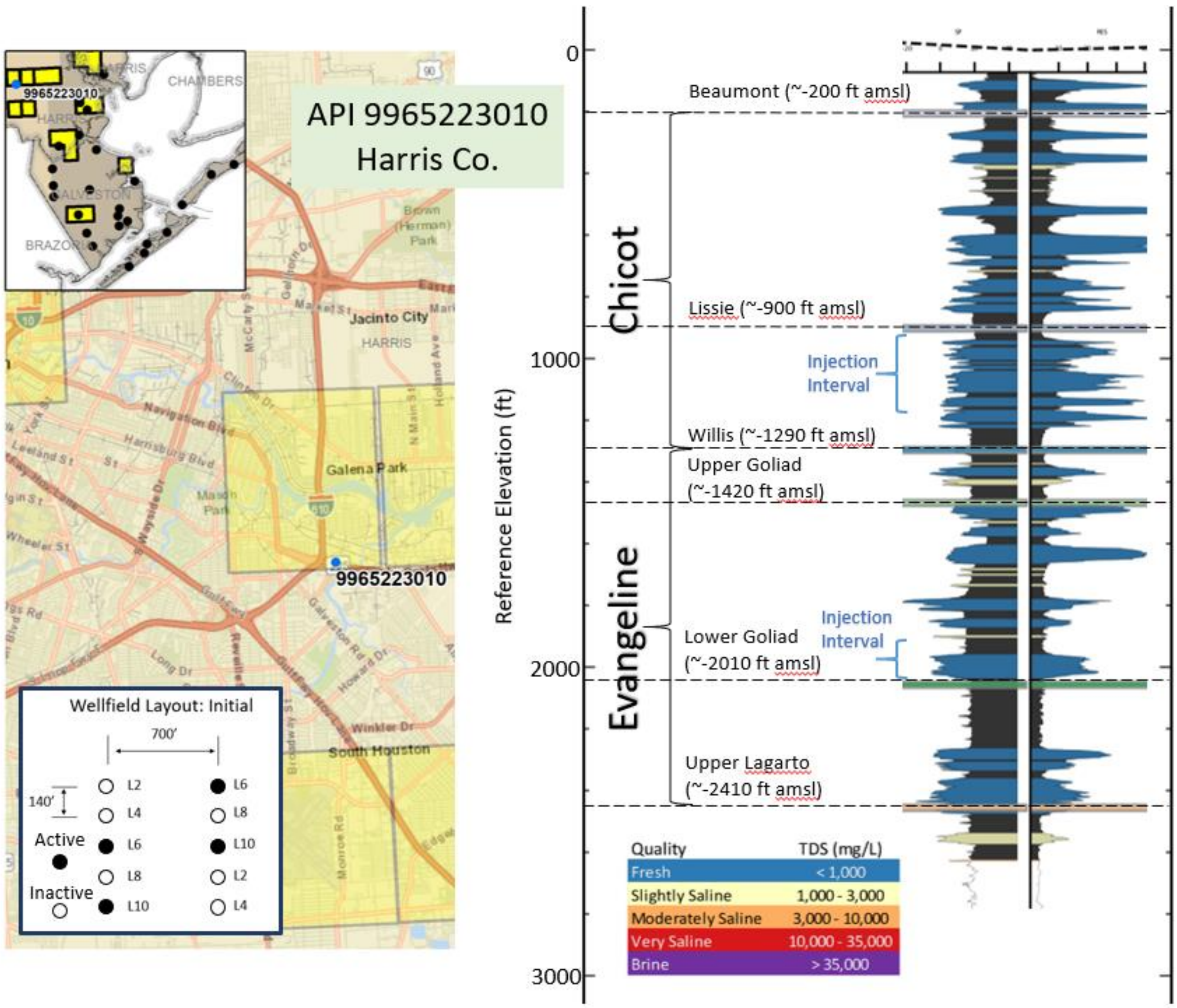

Figure 5-4 Updip ASR Project base map with interpreted geophysical log

5.3 Model Construction

This section describes the construction of three models in terms of model extent and discretization, boundary conditions, and basic parameterization.

5.3.1 Model Extent and Grid

Each of the three models were constructed with the same dimensions. The grid is 100 x 100 cells, with 35-foot square grid cells, for a total grid size of 3,500 by 3,500 feet. The 3,500 feet grid extent was chosen such that the model perimeter boundary conditions would have only a small effect on the aquifer hydraulics near the ASR wellfield at the center of the grid. For the base-case model, doubling the grid size was found to change the 20-year prediction of maximum compaction by 1.3%, and the mean compaction over 1,000 ft by 8.7%. This was considered acceptable, given the tradeoff on runtime, and the scoping level nature of the model predictions.

There were 11 layers in each model, each of which could represent different combinations of sands or clay layers, depending on the modeled location. The elevation of the top layer was set to land surface elevation, and the relative thicknesses of the next 11 layers were determined based on vertical mapping to the geophysical log that was representative of each model, as shown in Figures 5-2 through 5-4.

In general, when mapping vertical intervals to model layers, we selected intervals that contained sufficient thickness of sand to consider for recharge. If the potential recharge intervals were separated vertically, we used a model layer to represent the clays and sands that lie between potential recharge intervals. All 11 layers were required for the most complex representation of sands and clays that was considered during the exploratory portion of the modeling.

For a particular model, if all 11 layers were not needed to represent the potential injection intervals and the sediments in between, then the required number of layers, starting with the layer 1, were used to represent the “active” portion of the model. Any remaining layers at the bottom were set to a constant 100-foot thickness and given the associated properties of the sands/clays from the geophysical log at the elevation of those intervals. While these “extra” layers at the bottom were appropriately parameterized based on the geophysical log, they had a minimal effect on the result since the pressure change in the active layers did not propagate to any significant extent vertically into any “extra” layers below because of good pressure confinement below the recharge interval.

5.3.2 Boundary Conditions

Two types of boundary conditions were implemented in the models, general head boundaries (GHBs) and wells.

5.3.2.1 General head boundaries

GHBs were placed on the perimeter of the model in all layers to simulate the continuation of the aquifer layers beyond the model grid. A GHB is a head-dependent variable flux boundary that allows the model to approximate the interaction with the aquifer outside of the active model grid. The hydraulic head for all layers were set to 50 ft bgs, so no natural vertical gradients were simulated. Because of the large vertical stresses being applied during the recharge and production cycles, we would expect any natural vertical gradient to be swamped by the well-induced vertical gradient.

The conductivity of the GHB cells was set to 100 square feet per day (ft^2/d). This value was based upon sensitivity calculations to ensure that the hydraulic gradient remains smooth as one nears the boundary.

5.3.2.2 Well package

The well package was used to simulate recharge and production cycles in the wellfield. The wellfield layout was the same in each case, with ten possible locations. The horizontal configuration of the wellfield is shown in Figures 5-2 through 5-4. For each north-south line of 5 wells, multiple vertical intervals were considered for recharge and production. The recharge intervals that were chosen were based on an estimate of the amount of compaction that would occur in those intervals. This was dependent primarily on the transmissivity, the thickness of clay (above, below and within the interval), and the inelastic compressibility of the interval. Greater transmissivity correlates with less drawdown during production, and less compaction. That is, transmissivity is inversely correlated to compaction. Smaller total clay thickness and smaller inelastic compressibility both correspond with less ultimate compaction in the layer (directly correlated). Potential compaction of the potential recharge intervals can be compared using the following empirical equation:

$$compaction\ potential = \frac{b_{clay} S_{skv}}{T} \qquad \text{(Equation 5-1)}$$

Where T is the interval transmissivity, b_{clay} is the thickness of clay in the interval, and S_{skv} is the specific inelastic storativity in the interval.

The lower the compaction potential, the more suitable an interval is for recharge and production. The interval with the lowest compaction potential is activated first, and the rate that is recharged and produced from that interval is limited by the amount of head increase at the well during recharge. We set the limit at 100 feet of increase from static water level. The overall target recharge and production was thus distributed among one or more intervals based on their ranking of compaction potential and the limit to head increase for any particular recharge interval.

The actual recharge/production rates and head response for wells in each model are discussed in Section 6.

5.3.3 Approach to Parameterization

The models were parameterized based on estimated hydraulic properties from literature and the approach to compaction properties discussed in Section 2.

5.3.3.1 Hydraulic Properties

Because we do not have aquifer tests at the specific locations, the hydraulic conductivity of the sands in the aquifers have been estimated through a hydrostratigraphic model developed for the Gulf Coast Aquifer System, which will be referenced below. Numerous studies have related facies and hydraulic conductivity values to changes in lithology (Magara, 1978; Domenico and Schwartz, 1990). These studies include approaches and algorithms for estimating hydraulic properties based on the following physical characteristics: particle size, arrangement or sorting of the particles, degree of compaction of the particles, and depositional facies. As a result of these studies, groundwater modelers often examine lithologic information to help understand the aquifer flow system. One type of lithologic information that modelers commonly use to guide the development of transmissivity values are sand thickness maps. These maps provide a relative measure of transmissivity based on the assumption that transmissivity should increase with increased sand thickness and interconnectivity among the sand channels. A straightforward method for assigning hydraulic conductivity values to lithologic classes is to use information from a well that is associated with both a measured transmissivity and a lithology profile. At such a well, calculated values of transmissivity based on assumed hydraulic conductivity values of the lithologic classes can be readily compared to a measured transmissivity value. If this analysis is performed at several wells in an aquifer, and most of the analyses support similar hydraulic properties for each distinct lithology class, then there is a good basis for applying the relationships between lithology class and hydraulic conductivity as part of the calibration process.

Young and Kelley (2006) provide an example of a successful application of using aquifer tests to estimate properties using lithology. They used pumping tests performed in the Chicot and Evangeline aquifers to estimate an average hydraulic conductivity value for a sand and clay litho-facies. In this situation, the clay lithology class represented any deposit that was not clearly labeled as a sand in the driller logs. To estimate the transmissivity from the lithology profile, **Equation 5-2** was applied across the total interval of the well screen to develop a calibrated model relating lithology to sand hydraulic conductivity.

$$T = K_{sand} * Z_{sand} + K_{clay} * Z_{clay} \qquad \text{(Equation 5-2)}$$

where:

T = transmissivity (ft^2/day);
K_{sand} = hydraulic conductivity of sand (ft/day);
Z_{sand} = sand thickness (ft);
K_{clay} = hydraulic conductivity of clay (ft/day); and
Z_{clay} = clay thickness (ft).

The work of Young and Kelly (2006) was later refined by Young and others (2009) to estimate hydraulic conductivity relationships for the sand litho-group in the Chicot and Evangeline aquifers as a function of two depositional facies and six geological units. These relationships were used with minor modification to develop effective formation hydraulic conductivities at the geophysical logs selected for analysis. The hydraulic properties for each model layer are shown in **Tables 5-4** through **5-6**.

Specific storage was estimated to be 1×10^{-6} ft^{-1}, and vertical hydraulic conductivity between the flow layers (not the interbeds, see next section) was estimated to be 1×10^{-3} ft/day. These values are based on ranges used in regional groundwater models of the Gulf Coast Aquifer System (Young and others, 2009). Because these are approximate values not based on direct measurement, the importance of these parameters is explored in the sensitivity analysis described in Section 6.4.

5.3.3.2 Compaction Properties

The compaction properties for each of the layers were determined using the functions described in Section 2. The compaction properties vary primarily with depth, with the relative amount of compaction generally decreasing at greater depths. This trend is due to the conceptualization that inelastic storativity decreases with depth (less ultimate compaction for a given drawdown), and clay vertical conductivity decreases with depth (slower propagation of stress into the clays).

The clay inelastic specific storage was varied with depth based on “best estimate” values shown in Table 2-1. The clay vertical conductivity was varied with depth based on the “best estimate” values shown in Table 2-3. The drawdown at preconsolidation head was assumed to be zero for the simulations. The reasoning for this assumption is discussed in detail in Section 2.3.4.2. The compaction properties for each of the model layers are shown in Tables 5-4 through 5-6 for each location modeled.

Table 5-4 Layer properties for base-case model location, based on log #4216700966

Layer Number	Bottom Elevation (ft amsl)	Thickness (ft)	Horizontal Hydraulic Conductivity (ft/d)	Vertical Hydraulic Conductivity (ft/d)	Specific Storage (1/ft)	Total Clay Thickness (ft)	Clay Inelastic Specific Storage (1/ft)	Clay Vertical Hydraulic Conductivity (ft/d)
1	-200	207	12.0	0.001	1E-06	30.8	3.45E-04	4.13E-05
2	-453	253	11.5	0.001	1E-06	43.4	1.52E-04	1.01E-05
3	-695	243	17.7	0.001	1E-06	48.4	1.03E-04	4.98E-06
4	-1017	321	17.2	0.001	1E-06	41.1	7.78E-05	2.83E-06
5	-1193	176	11.3	0.001	1E-06	53.2	6.52E-05	1.92E-06
6	-1426	233	10.4	0.001	1E-06	72.7	5.79E-05	1.47E-06
7	-1526	100	2.0	0.001	1E-06	67.9	5.33E-05	1.22E-06
8	-1626	100	13.0	0.001	1E-06	20.3	5.09E-05	1.11E-06
9	-1726	100	3.0	0.001	1E-06	56.3	4.87E-05	1.01E-06
10	-1826	100	2.1	0.001	1E-06	64.4	4.68E-05	9.21E-07
11	-1926	100	2.5	0.001	1E-06	60.0	4.51E-05	8.49E-07

Table 5-5 Layer properties for downdip model location, based on log #4216701846

Layer Number	Bottom Elevation (ft amsl)	Thickness (ft)	Horizontal Hydraulic Conductivity (ft/d)	Vertical Hydraulic Conductivity (ft/d)	Specific Storage (1/ft)	Total Clay Thickness (ft)	Clay Inelastic Specific Storage (1/ft)	Clay Vertical Hydraulic Conductivity (ft/d)
1	-259	259	2.6	0.001	1E-06	190.0	2.95E-04	3.14E-05
2	-397	138	11.4	0.001	1E-06	41.0	1.53E-04	1.03E-05
3	-616	219	8.4	0.001	1E-06	101.4	1.13E-04	5.98E-06
4	-784	168	7.0	0.001	1E-06	84.6	9.01E-05	3.84E-06
5	-912	128	2.7	0.001	1E-06	96.1	7.88E-05	2.90E-06
6	-1026	115	15.4	0.001	1E-06	26.9	7.17E-05	2.37E-06
7	-1271	245	15.7	0.001	1E-06	46.1	6.37E-05	1.82E-06
8	-1412	141	2.0	0.001	1E-06	99.2	5.71E-05	1.43E-06
9	-1655	243	3.7	0.001	1E-06	120.0	5.20E-05	1.16E-06
10	-1839	184	1.5	0.001	1E-06	161.1	4.75E-05	9.51E-07
11	-1907	68	9.8	0.001	1E-06	18.3	4.52E-05	8.56E-07

Table 5-6 Layer properties for updip model location, based on log #9965223010

Layer Number	Bottom Elevation (ft amsl)	Thickness (ft)	Horizontal Hydraulic Conductivity (ft/d)	Vertical Hydraulic Conductivity (ft/d)	Specific Storage (1/ft)	Total Clay Thickness (ft)	Clay Inelastic Specific Storage (1/ft)	Clay Vertical Hydraulic Conductivity (ft/d)
1	-262	269	10.7	0.001	1E-06	107.1	2.87E-04	3.00E-05
2	-412	150	8.9	0.001	1E-06	70.5	1.48E-04	9.75E-06
3	-505	93	2.0	0.001	1E-06	83.7	1.20E-04	6.68E-06
4	-596	92	3.7	0.001	1E-06	60.9	1.06E-04	5.26E-06
5	-940	343	5.9	0.001	1E-06	156.2	8.39E-05	3.32E-06
6	-1211	271	17.0	0.001	1E-06	58.7	6.64E-05	2.00E-06
7	-1524	313	3.1	0.001	1E-06	186.0	5.62E-05	1.38E-06
8	-1677	152	8.8	0.001	1E-06	52.5	5.03E-05	1.08E-06
9	-1956	279	2.1	0.001	1E-06	183.4	4.61E-05	8.91E-07
10	-2054	98	13.3	0.001	1E-06	19.8	4.30E-05	7.70E-07
11	-2260	206	1.5	0.001	1E-06	206.1	4.09E-05	6.92E-07

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6.0 SIMULATION OF ASR AND COMPACTION

After the models for the three sites were constructed, ASR and any resulting compaction was simulated for both the DOR case and the summer peaking case at each site location. This section describes our approach to modeling ASR and compaction, our approach to assessing the outcomes of the modeling, and how predictions differed for two operational cases. This section also discusses a sensitivity analysis that was performed to assess how variations in the assumptions about hydraulic and compaction parameters could change the results of the simulations.

6.1 Modeling Approach

In simulating an ASR operation, we simulated the recharge of water into the aquifer and the resulting increase in water levels in and around the wellfield, and subsequent recovery of some portion of the recharged water with resulting decrease in heads. In the modeling section, we have presented model simulated water levels in terms of hydraulic head. A water level is a depth to water from a datum such as ground surface. That water level depth can be converted to an elevation by knowing the elevation of the datum. The water level expressed as elevation is called a hydraulic head which is usually just referred to as a head.

Each simulation was initialized with a steady-state stress period followed by monthly transient stress periods. The initial steady-state period ensures that any changes observed in the system during the transient periods are due to the simulated operation of the ASR, and not re-equilibration of simulated heads.

Because compaction occurs under drawdown conditions, we would expect simulated compaction to be greatest where drawdown is greatest, at the immediate location of the ASR wells. Because drawdown decreases radially away from the well in all directions, compaction may also occur over a similar footprint decreasing with radial distance from a well. To capture this effect, we use both the maximum and spatially-averaged (mean) compaction to assess the impacts of the ASR project. If the ASR project has multiple wells, the maximum compaction is measured at the well with the maximum compaction. We assessed several distances from the ASR wells over which to average aquifer compaction. A 1,000 ft distance was selected as the averaging distance because it captured the majority of the impact around the wellfield. The maximum compaction was predicted at the grid cell that had the greatest compaction. An individual rectilinear grid cell represents an effective wellbore radius of 6.6 feet. In addition to compaction, we also track the percent recovery of the ASR project which is defined as the percentage of the Storage Volume that is recovered as a function of predicted compaction. This metric is plotted as a function of time.

6.2 Operational Case 1: Drought of Record Industrial

The first operational case considers a hypothetical ASR operation that is being used to provide water to industrial users during a drought. The basis for the demands is described in Section 4.1.3.

6.2.1 Recharge and Recovery Cycle

The recharge and recovery cycle simulated for Case 1 is shown in **Figure 6-1**. Five years of recharge is followed by five years of recovery. In the first two years of recovery, several months of recharge occurs during months of lower demand, when excess water is still available from the TMWTP. In years three through five, the drought has worsened to the point where only recovery occurs.

About 9.1×10^9 gallons (about 28,000 AF) of water is stored during the operation, and 4.5×10^9 million gallons (about 14,000 AF) of water is recovered, leaving the Buffer Zone Volume intact.

6.2.2 Case 1 Results for Base-Case Site

Because operational case 1 consists of a long recharge cycle followed by recovery, heads in the recharge interval are elevated significantly over the recharge period. Similarly, once recovery occurs, heads decrease very quickly in response to pumping. **Figure 6-2** plots the simulated head at the ASR well for the DOR operational case at the base case location. Also plotted in Figure 6-2 are the maximum compaction (measured at the well) and the average compaction. Maximum compaction is about 0.2 feet over the course of the operational period at the base-case site. Head increases about 85 feet in the recharge interval at the well location. Note that this head is averaged over the size of the grid cell (effective radius of 6.6 feet) so the head in a well would be expected to vary more (higher during recharge, lower during recovery). During recovery, head decreases about 80 feet from the initial level. Each time a recovery cycle occurs, some compaction occurs in the clays in that interval. When recovery ends and additional recharge occurs (for example, in year 7), the rate of compaction quickly slows to zero until the next recovery cycle occurs. Each successive recovery cycle results in less compaction, as it takes longer for the pressure change to propagate deeper into the uncompacted portions of the clays. In addition, the thinnest clay bed has already reached ultimate compaction in one of the earlier years of production. This is illustrated in **Figure 6-3**, which shows the head response in the individual delay beds (the compacting clay beds in layer 4). MODFLOW-SUB terms a distinct clay bed as a delay bed. Delay bed #6 is 41 ft thick and does not reach ultimate compaction during production. Delay bed #7 is only 2.1 ft thick and reaches ultimate compaction (head in the delay bed has drawn down as much as the overall head in the interval) after the second year of production.

Figure 6-4 shows the simulated maximum and mean compaction compared to the percent of total recovery, i.e. the cumulative volume recovered divided by the total design volume to be recovered during the operation (approximately one-half of the TSV). The figure shows that simulated compaction starts to occur immediately upon recovery, and the maximum compaction increases throughout recovery, reaching a peak when recovery is 100%. **Figure 6-5** shows recovery percent plotted against maximum and mean compaction. While there is a slight leveling of the compaction curves compared to percent recovery, for the most part compaction occurs proportionally to the percent recovered.

6.2.3 Sensitivity Cases for Base-Case Location

Three sensitivity cases were explored at the base-case location for operational case 1. In the first, we consider an operational history where no recharge in the wellfield occurs, i.e., only production occurs. The objective is to estimate the reduction in compaction that can occur due to the effect of aquifer storage (recharge). **Figure 6-6** shows a time series of maximum compaction for the recharge versus no-recharge cases. The results show how recharge has the potential to decrease compaction early on, with a 50% decrease in maximum compaction after the first recovery cycle. However, by the end of the full recovery period, there is only 3% difference in maximum compaction. Long-term recovery, and the accompanying drawdown, will eventually cause compaction regardless of the recharge history (Section 6.3 explores an operational case with short-term recovery cycles).

The second sensitivity case considers a lower vertical hydraulic conductivity (Kv) in the clay beds. Section 2.2 discusses the approach to estimating the vertical hydraulic conductivity of the clay beds based on laboratory test data and calibrated PRESS models. The current conceptualization uses the average between those two sources. However, because the PRESS models are calibrated to field data, and there are always some questions about the scalability of laboratory tests to field conditions, we considered a case where the vertical conductivity was based on the PRESS estimates only.

Figure 6-7 shows the difference in maximum compaction between the base-case and PRESS vertical conductivity estimates. Because the lower vertical conductivity decreases the rate at which pressure change can propagate into the delay beds, less compaction occurs during each annual production cycle, and the final compaction for the PRESS Kv case is over 25% less than the base Kv case.

In the third sensitivity case, we consider a wellfield with smaller and larger well spacing. A smaller well spacing will increase interference between the wells during recharge and recovery, while a larger well spacing will decrease this interference between the wells. **Figure 6-8** shows the results of the well spacing sensitivity, where the base case is represented by the 140-foot spacing. Decreasing and increasing spacing has the expected impact on compaction, with decreasing well spacing increasing compaction and increasing well spacing decreasing compaction.

6.2.4 Case 1 Results for Downdip and Updip Locations

Operational Case 1 was simulated at the downdip and updip locations to determine how much location effects predicted compaction. Section 5.2 discusses the characteristics of the base-case, downdip and updip locations. Two key differences between the base-case location and the other two locations is the thickness of the sand unit that is present for recharge at the location and the number of clay beds that are present within and within proximity of the recharge interval. The recharge interval at the base-case location is comprised of a large 250-foot sand, one 41-foot thick clay near the top, and a small clay near the bottom of the interval. The large, high transmissivity sand reduces drawdown during production relative to smaller sands. The small number and total thickness of clay beds reduces the ultimate compaction potential.

The downdip location has two recharge intervals containing eight clay beds ranging in thickness from 4 to 20 ft, with a total clay thickness of 79 ft. The updip location has two recharge intervals containing eight clay beds ranging in thickness from 3 to 48 ft, with a total clay thickness of 73 ft.

Figure 6-9 compares the simulated compaction through time for the three locations under Operational Case 1, while **Figure 6-10** compares simulated compaction versus recovery percent for the three locations. Because of the larger number of thin clay beds at the updip and downdip locations, more simulated compaction occurs at those locations, and it occurs at a greater rate in early time. This result emphasizes the importance of designing ASR wells such that the recharge and production intervals are in the cleanest possible sands, and not unnecessarily spanning clay beds within an interval.

6.3 Operational Case 2: Summer Peaking Municipal

The second case considers an ASR operation that is designed to meet summer peaking requirements for a municipality. This is one of the most common uses for ASR, where adding peaking capacity can delay the construction or expansion of water treatment capacity.

6.3.1 Recharge and Recovery Cycle

The recharge and recovery cycle for the summer peaking case is shown in **Figure 6-11**. The time required to reach the TSV of 1,300 MG (about 4,000 AF) at the start of the operation is small compared to the DOR case. A smaller storage volume is required since recovery only occurs over a short period before another recharge cycle is started. After the operation begins, recharge occurs over four months at 5.4 MGD, while recovery occurs over three months at 7.2 MGD. The operation was modeled to have a 20-year operational period based on an estimate of a reasonable return on the investment based on consideration of the debt service over a 20-year bond period.

6.3.2 Case 2 Results for the Base-Case Location

The cyclic nature of the summer peaking operation case is reflected in the head response at the wellfield, as shown in **Figure 6-12**. Head increases about 90 ft during recharge, while heads drawdown about 115 ft during recovery. While this is a larger drawdown than for the DOR case (80 ft), the simulated maximum and mean compaction is less than for the DOR case, at 0.18 and 0.07 ft, respectively, compared to 0.21 and 0.08 ft for the DOR case. Less compaction occurs even though the drawdown is greater in magnitude, the duration of the drawdown is significantly less. Therefore, the negative pressure change does not have as much time to propagate into the clay beds before a positive pressure is applied during the next recharge cycle. The “effective” drawdown impacting the clay beds is dependent on the duration of drawdown relative to recharge cycles and the periodicity of each full cycle. In this example, even though the recovery drawdown is equal to 115 ft, the effective drawdown (or average long-term drawdown) is less than 80 ft we observed in the DOR case.

6.3.3 Sensitivity Cases

The difference in compaction response due to short duration recovery versus longer duration recovery was further explored in two sensitivity cases. Recall that the summer peaking case consists of a 3-month recovery period each summer at 7.2 MGD. Two other cases were considered, the first with a 1-month recovery cycle at three times the rate (21.6 MGD), and a 2-month recovery cycle at 1.5 times the rate (10.7 MGD). The same volume of water is recovered but at different durations.

Figure 6-13 compares the one, two, and three-month recovery cases. The results indicate that for this ASR operation, the greater drawdown associated with the higher recovery rate (and shorter recovery period) produces more simulated compaction than the longer recovery period. As a result, more compaction will occur for a quick recovery period unless the overall volume recovered is reduced along with the recovery period.

The second sensitivity case assumes that no recharge occurs. The purpose of this sensitivity case is to characterize the potential benefit that occurs from recharging prior to recovery, compared to groundwater production without recharge. **Figure 6-14** compares the compaction through time for the two sensitivity cases. As with the DOR operational case, the recharge provides a benefit with respect to reducing simulated compaction over the period of operation. However, the cyclical nature of the summer peaking case creates an opportunity for more benefit with respect to reduced compaction throughout the entire operational period, ending with about 0.06 ft less compaction, or about 33% less compaction than the no-recharge case. This sensitivity case demonstrates the importance of the operation schedule of an ASR system on the predicted compaction. In many ways, an operator has limited flexibility on their site geology but may have significant flexibility on the recharge and recovery cycles.

6.3.4 Case 2 Results for Updip and Downdip Locations

As discussed in 6.2.4, the updip and downdip locations contain more clay beds in the recharge/ production intervals than in the base case, so simulated compaction is expected to be higher at those locations. This is true for the summer peaking case, as shown in **Figure 6-15**. The updip and downdip locations show almost double the simulated compaction by the end of the operational period, as compared to that at the base case location. This finding reinforces the importance of avoiding clay beds, as much as possible, in the recharge and production intervals, regardless of whether the operation is characterized by cyclical or longer-term recovery strategies.

6.4 Single-ASR Well Sensitivity Analysis

The three models discussed previously that were developed for the base-case, updip, and downdip locations, were based on a representative geophysical log at those locations. The simulated compaction was affected by the actual hydrogeologic conditions at each site. While we can explain the differences in the compaction response among the three locations in terms of hydraulic conductivity, clay bed occurrence and thickness, and depth of interval, we cannot isolate these effects in the results.

We performed an additional sensitivity analysis with a model that was created explicitly to allow the isolation of how particular parameters can affect the amount of simulated compaction that occurs. This model has a single 200-foot thick recharge interval, with 100-foot confinement layers on the top and bottom, and a single ASR well completed in the active interval. The recharge interval contains two ten-foot clay beds for the base case. The model setup is illustrated in **Figure 6-16**.

The parameters that were explored included operational parameters (pumping rate and completion depth) and physical parameters (hydraulic conductivities, clay bed occurrence, and inelastic compressibility).

6.4.1 Recharge and Recovery Cycle

The recharge and recovery cycle that was used for the single-well sensitivity analysis was similar to the DOR case, except that recovery was limited to 10 months. The recovery duration was limited so that the timing of compaction could be seen in the results, *i.e.*, so that delay beds did not reach ultimate compaction for most cases.

Figure 6-17 shows the recharge and recovery cycle rate time series. For the base sensitivity case, the recharge and recovery rates for the well were set to 1,000 gpm.

6.4.2 Sensitivity Simulation Results

Table 6-1 lists the parameters that were varied for the sensitivity runs, as well as the parameter values for each run. In Table 6-1 below the column labeled V3 shows the base sensitivity parameter values. When one parameter was varied (represented by a row in the table), all other parameters were kept at their base value, unless they were constrained by correlation to the varied parameter. For example, if sand percent is varied, both horizontal hydraulic conductivity and clay thickness must be varied in order to enforce consistency.

For a given parameter, we picked a realistic range and varied the parameter over that range either using linear or logarithmic increments. Parameters such as hydraulic conductivity which are typically lognormally distributed were varied in logarithmic increments. **Table 6-2** lists the resulting maximum compaction that occurs for each of the sensitivity runs. In the following, we discuss these sensitivity results for each parameter.

Table 6-1 Parameter values used in one-layer model sensitivity analysis

Parameter	V1	V2	V3 (Base)	V4	V5
Depth (ft)	0	400	800	1200	1600
Production Rate (gpm)	-	500	1000	1500	-
Percent Sand	60	70	80	90	-
Number of Clays	10	5	2	1	-
Clay Bed Thickness (ft)	5	10	20	40	80
Clay Bed Conductivity (ft/d)	1.87E-07	1.87E-06	1.87E-05	1.87E-04	-
Specific Inelastic Storativity (1/ft)	-	2.17E-05	2.17E-04	2.17E-03	-

Table 6-2 Maximum compaction (ft) for each of the one-layer model sensitivity cases(1)

Parameter	V1	V2	V3 (Base)	V4	V5
Depth (ft)	0.33	0.36	0.39	0.43	0.48
Production Rate (gpm)	-	0.24	0.39	0.56	-
Percent Sand	0.86	0.57	0.39	0.25	
Number of Clays	0.58	0.55	0.39	0.24	
Clay Bed Thickness (ft)	0.14	0.26	0.39	0.41	0.40
Clay Bed Conductivity (ft/d)	0.06	0.19	0.39	0.57	-
Specific Inelastic Storativity (1/ft)	0.01	0.05	0.39	1.14	3.52

(1) See associated range in parameter values above in Table 6-1.

Depth to top of the upper confining unit was varied from 0 to 1,600 ft. Depth is a parameter that can be controlled by design, to the extent productive sand intervals are available for different depths at an ASR site location. Increase in depth decreased all depth-dependent parameters, including horizontal hydraulic conductivity, clay bed vertical hydraulic conductivity, and inelastic specific storage. The combination of parameter changes resulted in increased compaction. This is due to the increase in drawdown from decreasing horizontal hydraulic conductivity. **Figure 6-18** illustrates this trend, where drawdown increases from about 53 to over 85 ft. In this sensitivity case, the reduction in transmissivity and increase in drawdown for a constant production rate as one goes deeper had more impact than the decrease in compaction properties that has been observed. For a given fixed drawdown, the amount of compaction would decrease with depth.

Production rate was varied from 500 to 1,500 gpm. Production rate is also a parameter that can be controlled by design and is an important consideration for an ASR projects in compaction-prone areas. Increasing production rate increases drawdown, which results in increased compaction.

The percent sand was varied from 60 to 90%. While percent sand is a parameter that is intrinsic to geologic conditions at a site, estimates of percent sand for each potential recharge interval should be available during well design and it must be one of the factors considered. As shown in Table 6-2, increasing percent sand significantly decreases simulated compaction. As the percent sand increases, the horizontal hydraulic conductivity increases, decreasing drawdown. In addition, increasing percent sand corresponds to decreasing occurrence of clay beds, further reducing the potential for compaction.

The number of clay beds was varied from ten to one, while keeping the total clay bed thickness constant at 20 ft. For the case with ten clay beds, each bed was 2 ft thick, while for the case with one clay bed, there was a single 20-foot thick clay bed. Decreasing the number of clay beds increases compaction because even though the ultimate compaction (which from Equation 2-4 is based only on total clay bed thickness) is constant, thinner clay beds compact more quickly and thus approach ultimate compaction during the 10-month recovery period. This can be quantified by considering the characteristic time of thin versus thick clay beds, calculated using equation 2-5. **Figure 6-19** shows the change in the time constant and fraction of ultimate compaction reached when the number of clay beds decreases, with a corresponding increase in thickness. When the time constant is large (with a single 20-foot clay bed), only about 40% of ultimate compaction is reached. When the time constant is small (with ten 2-foot clay beds), nearly 100% of ultimate compaction is reached. Like percent sand, the number of clay beds in an interval is intrinsic to the geology at the site but should be considered when choosing a recharge interval.

Clay bed vertical hydraulic conductivity was varied over four orders of magnitude based on Table 2-3, which shows a large variation in clay bed conductivity can occur with changing depth. Increasing clay conductivity has the same effect as decreasing clay bed thickness, allowing clay beds to compact more quickly, and increasing compaction over the 10-month recovery period. Clay conductivity is a parameter that cannot be easily measured under field conditions, and thus is one of the largest sources of uncertainty in attempting to predict how much compaction will occur due to a particular ASR project. We do expect clay bed conductivity to generally decrease with depth due to overburden pressure.

Specific inelastic storativity varied over three orders of magnitude based on Table 2-1, which shows the variation in estimated specific inelastic storativity that can occur with depth. Specific inelastic storativity is directly related to ultimate compaction (Equation 2-4), so compaction increases with increasing values of the parameter. Like clay bed conductivity, specific inelastic storativity is difficult to measure under field conditions, so is a large source of uncertainty in compaction predictions. We expect it to also generally decrease with depth.

6.5 Design Factors to Mitigate Compaction

The ASR compaction modeling described in Section 6 can be combined with existing guidance to inform a discussion of design factors that can mitigate compaction. These factors can include hydrogeologic factors, well design/spacing factors and operational factors. Note that our discussion will be limited to those factors affecting compaction, not those that affect clogging or other considerations that can be important to a successful ASR project (see Pyne, 2005).

6.5.1 Hydrogeology

Both the contrast between the simulated compaction at the base-case site versus the other sites, and the sensitivity analysis in Section 6.4 indicate that one of the most critical hydrogeologic factors is the percent sand in the recharge/recovery interval (storage formation). Having a high percent sand will typically correlate with higher horizontal hydraulic conductivity, which reduces drawdown, and will also correlate with fewer compacting clay beds in the interval. Having a short well screen isolated to a clean sand interval is the ideal design approach. Long well screens that span multiple sand/clay packages is undesirable in terms of mitigating compaction.

While considerable uncertainty exists in estimating vertical hydraulic conductivity and inelastic storativity of clay beds, they should generally both decrease with depth. In general, deeper intervals should have less potential for compaction than shallow intervals. In areas where historical compaction has occurred in shallower intervals, better estimates of these properties may be available from simple estimates of compaction per foot of drawdown, or calibrated compaction (typically PRESS) models. Because cost increases with depth for any ASR operation, targeting deeper intervals in the absence of any other information may not be a feasible design approach. However, ASR wells have been completed to depths of 3,000 ft to date.

6.5.2 Well Design

The well design factors share overlap with the hydrogeology for where the screens are located, *i.e.*, with respect to the sand percent in the interval targeted for recharge/recovery, and the depth of the interval chosen (and its effect on the estimate of compaction parameters). One additional consideration for well design is whether to “stack” wells at the same location ASR location. That is targeting different high transmissivity vertical intervals, separated by confining units. In the simulations described in Section 6.2, we found that targeting different vertical intervals only made sense from a theoretical perspective if it is required to meet design recharge and recovery rates and associated design issues such as maximum recharge head increase. The model predicts that “maxing out” the interval with the least compaction potential (based on equation 5.1) is theoretically better than spreading recharge/recovery among several intervals vertically, even if the per-interval drawdowns are less than that with a single interval. A major caveat to this statement is that it is based upon the assumption of perfect knowledge regarding the factors in Equation 5.1. This is never the case, so stacking should be based upon the concept of decreasing recovery rates to decrease drawdown unless there is a compelling case for high transmissivity interval with a relative lack of clays compared to other potential recharge intervals. In either case, it needs to be based upon site specific lithology and hydraulic property data. Stacking water storage intervals vertically in a single wellfield is typically more cost-effective than distributing ASR wells more widely in a single storage aquifer and as a result is increasingly popular.

Wells spacing is another design consideration. As shown in Figure 6-8, greater well spacing results in less interference during recovery, less average drawdown, and less compaction. Spacing wells to minimize drawdown interference during recovery will help mitigate compaction. Once a site has been characterized, it may possible to design a wellfield where multiple storage intervals can be optimally operated to minimize drawdown and compaction while meeting long-term or seasonal needs.

6.5.3 Operational Factors

The two different operational cases (DOR and summer peaking) illustrated how operating strategy can significantly impact compaction potential for an ASR wellfield. Most of the benefit with respect to reduced compaction occurs when recovery is initiated soon after recharge, when heads are still above static. After time elapses, with or without recovery, those elevated heads will return to static and then recovery will have the same compaction effect as if recharge had not occurred.

While the DOR case showed significant benefit in reducing compaction in the first recovery period after recharge, the benefit was reduced in each successive recovery cycle. The summer peaking case, because recharge and recovery occurred in the same year for each cycle showed a more consistent benefit with respect to reduced compaction for the ASR wellfield versus a production wellfield.

The bottom line is that to optimize an ASR project, or a pumping well in general, to minimize compaction requires finding ways to minimize drawdown. This could simply be via reducing recovery rates (more wells). If an ASR project's objectives were varied ranging from emergency or peaking supply to drought supply, the design could be designed and operated to use intervals more susceptible to compaction for short-term supply and drought supplies coming from deeper intervals.

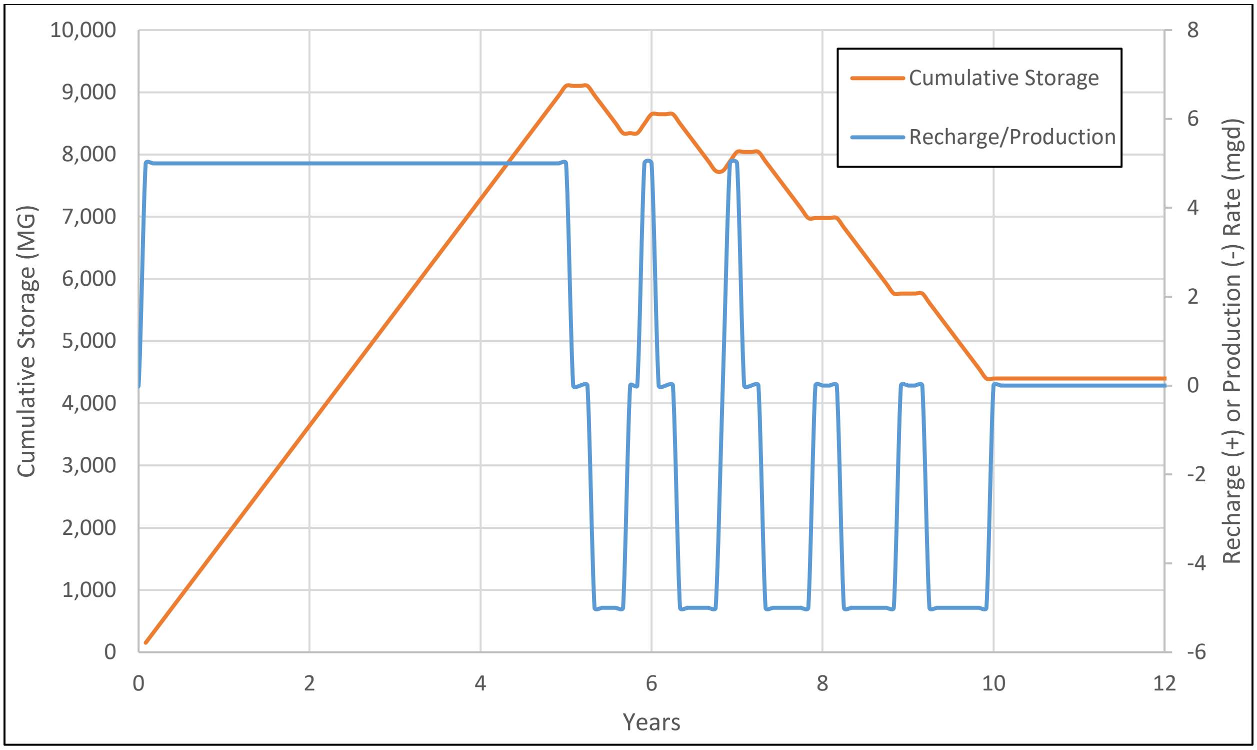

Figure 6-1 Recharge and recovery cycle for operational case 1 (DOR industrial user)

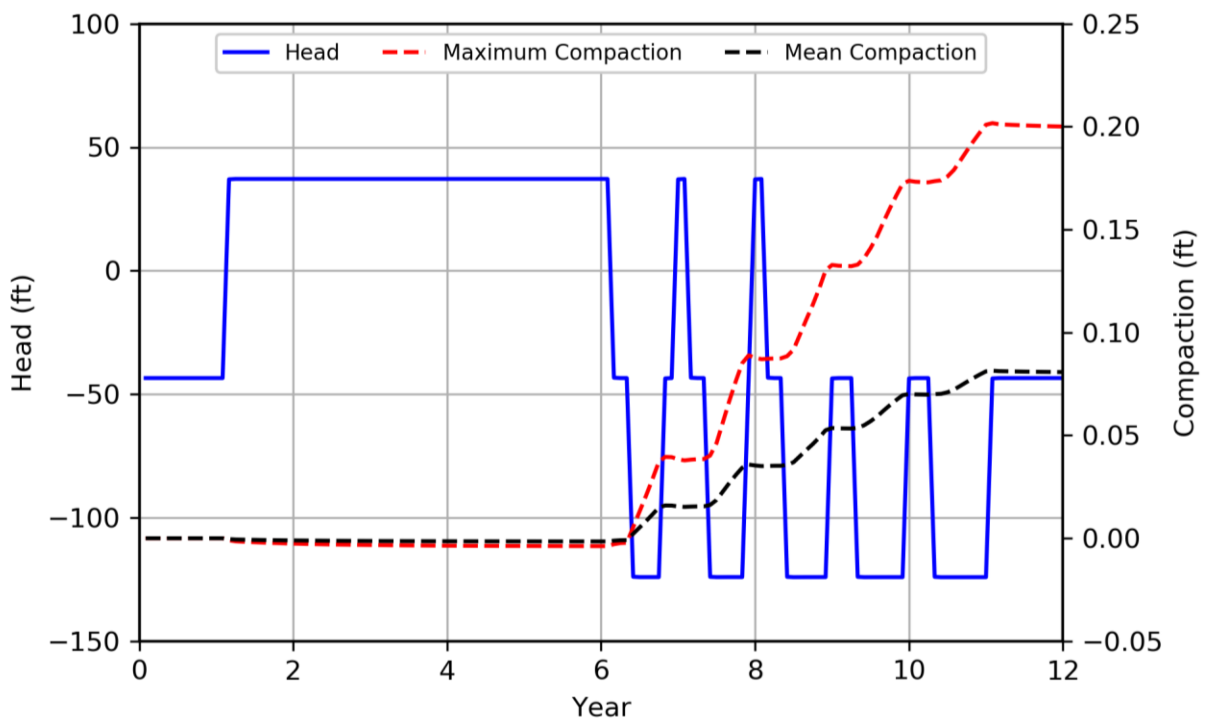

Figure 6-2 Head response at the well location in model layer 4 for DOR operational case 1 at the base case location, and the corresponding compaction response

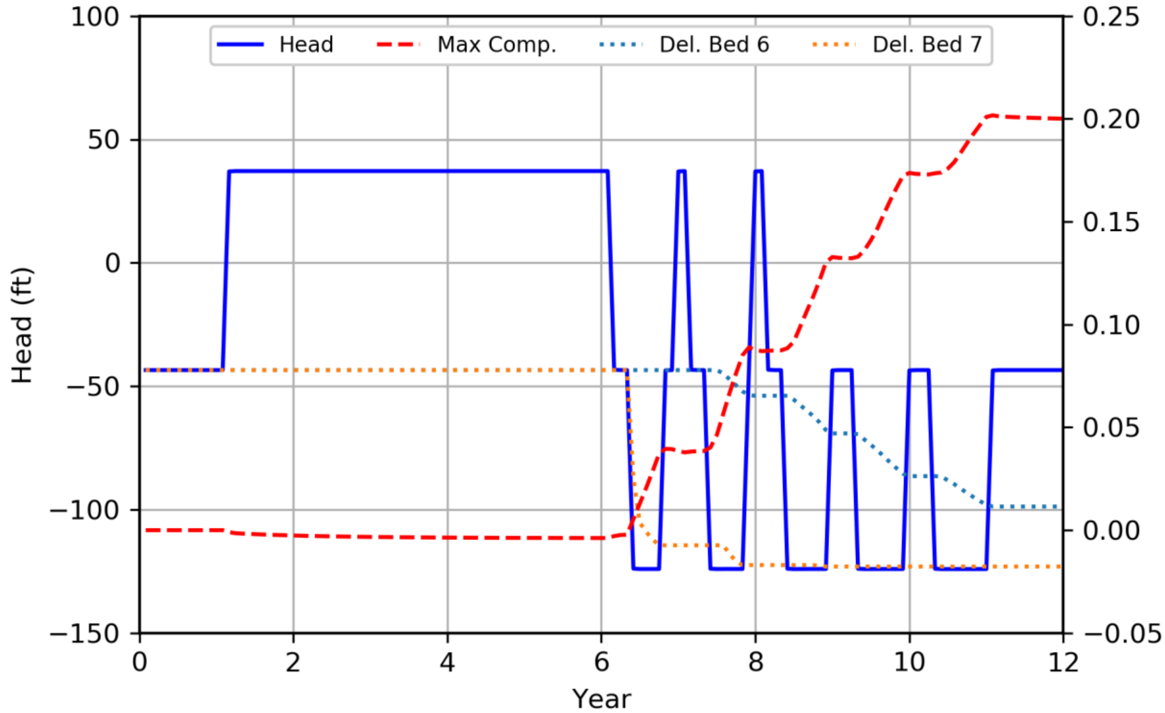

Figure 6-3 Overall head response at the well location in model layer 4 for DOR operational case 1 at the base case location, and the individual head responses in the two delay beds

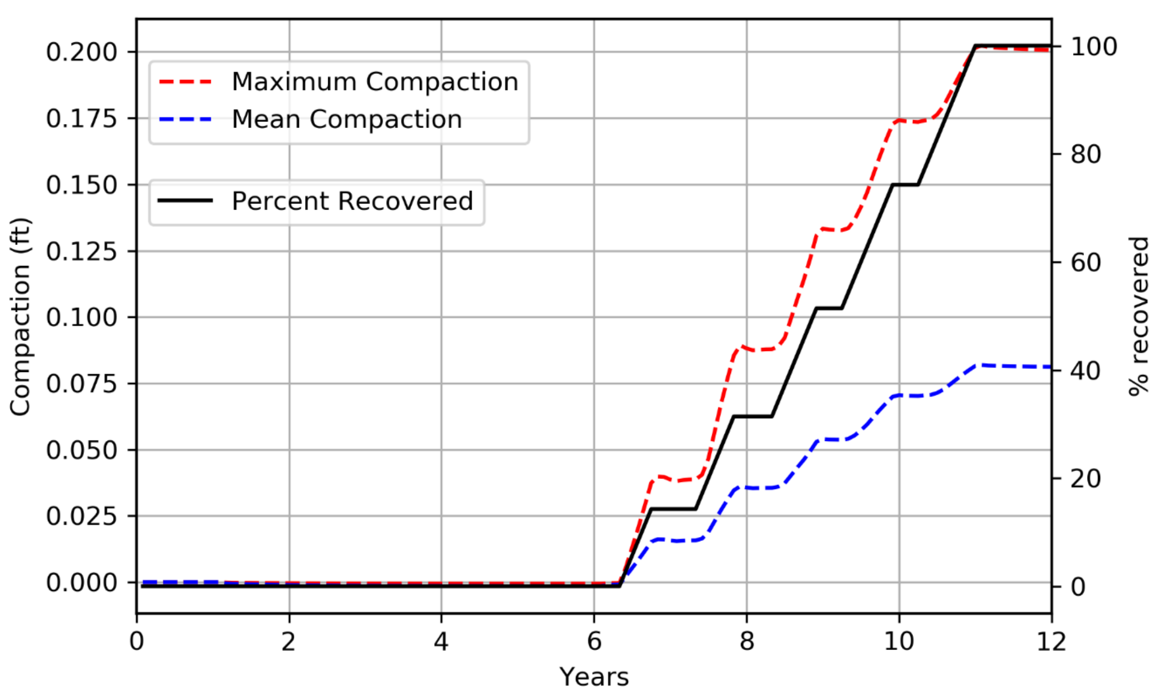

Figure 6-4 Compaction and percent recovery with time for DOR operational case 1 at the base-case site

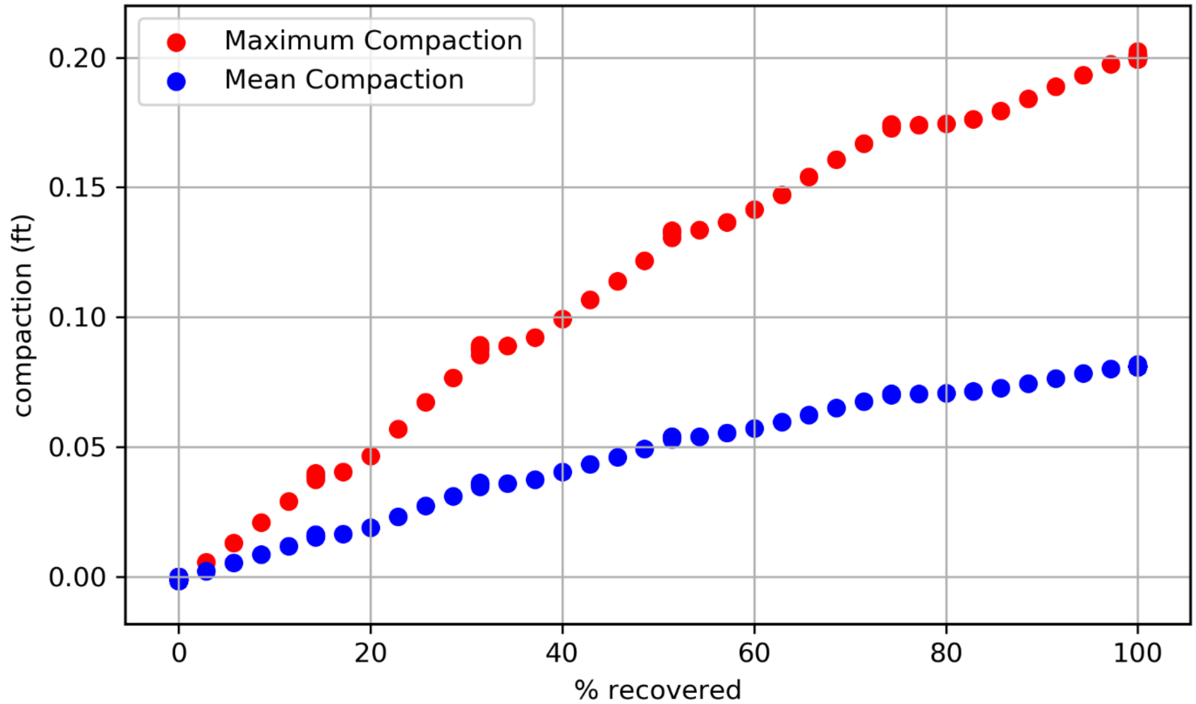

Figure 6-5 Compaction versus recovery percentage for DOR operational case 1 at the base-case site

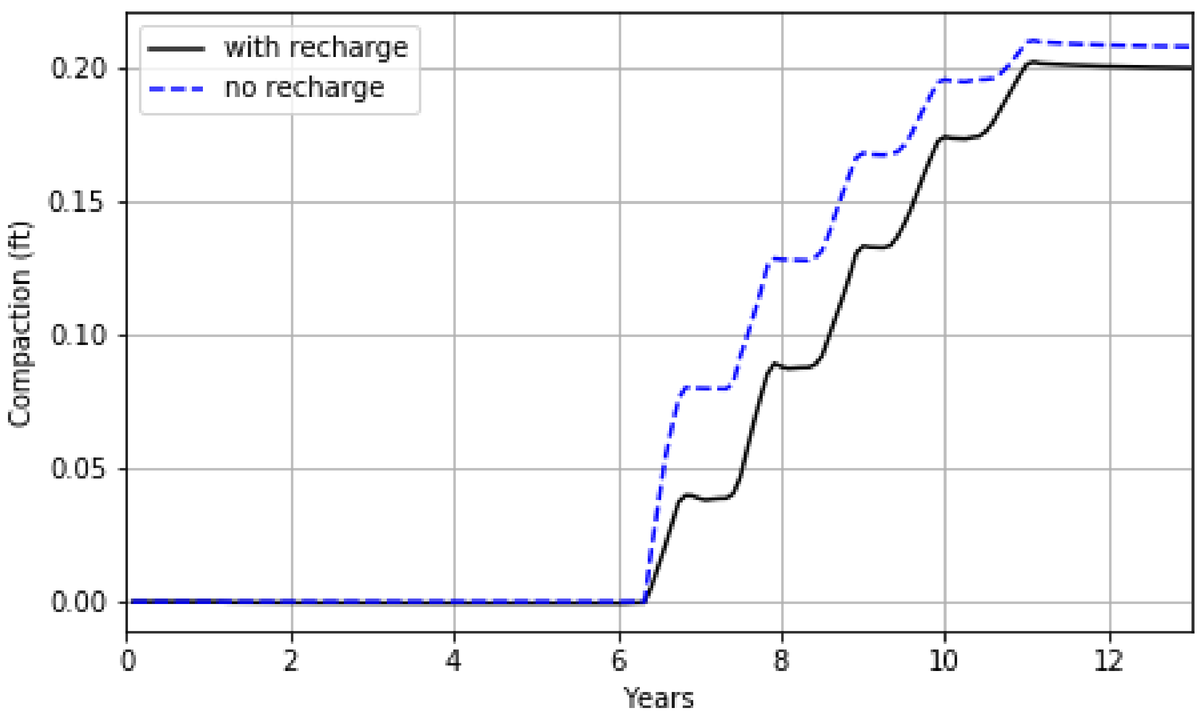

Figure 6-6 Effect of not recharging prior to recovery on simulated maximum compaction for DOR operational case 1 at the base-case site

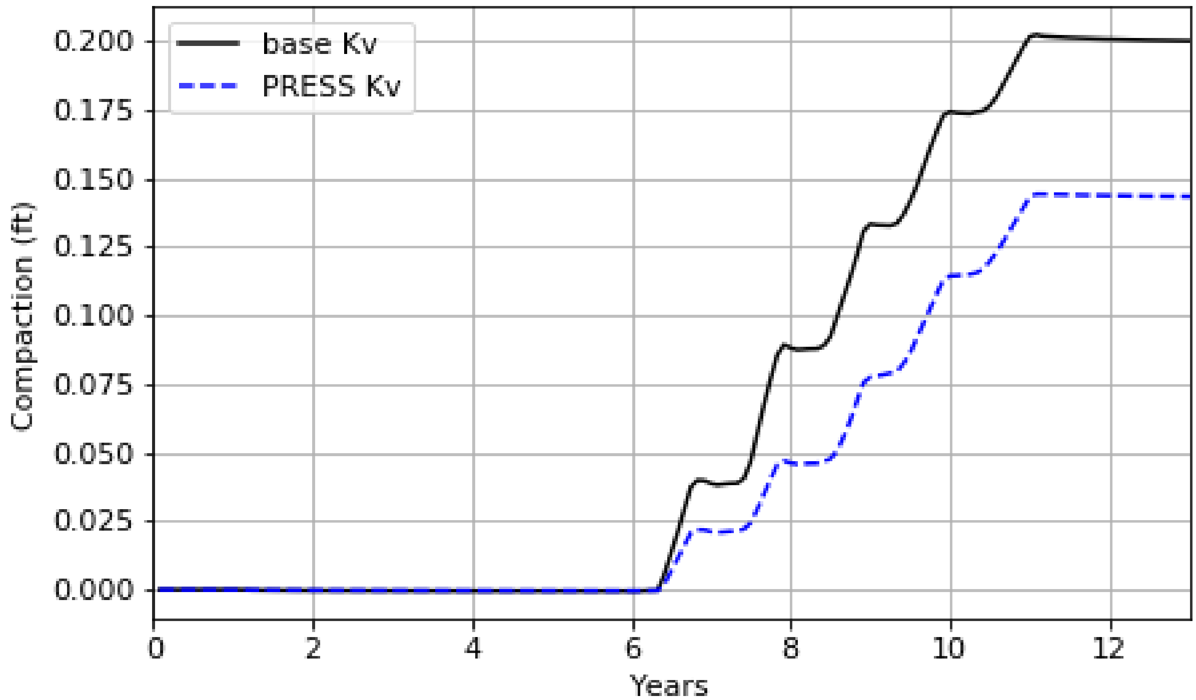

Figure 6-7 Effect of decreasing vertical conductivity on simulated maximum compaction for DOR operational case 1 at the base-case site

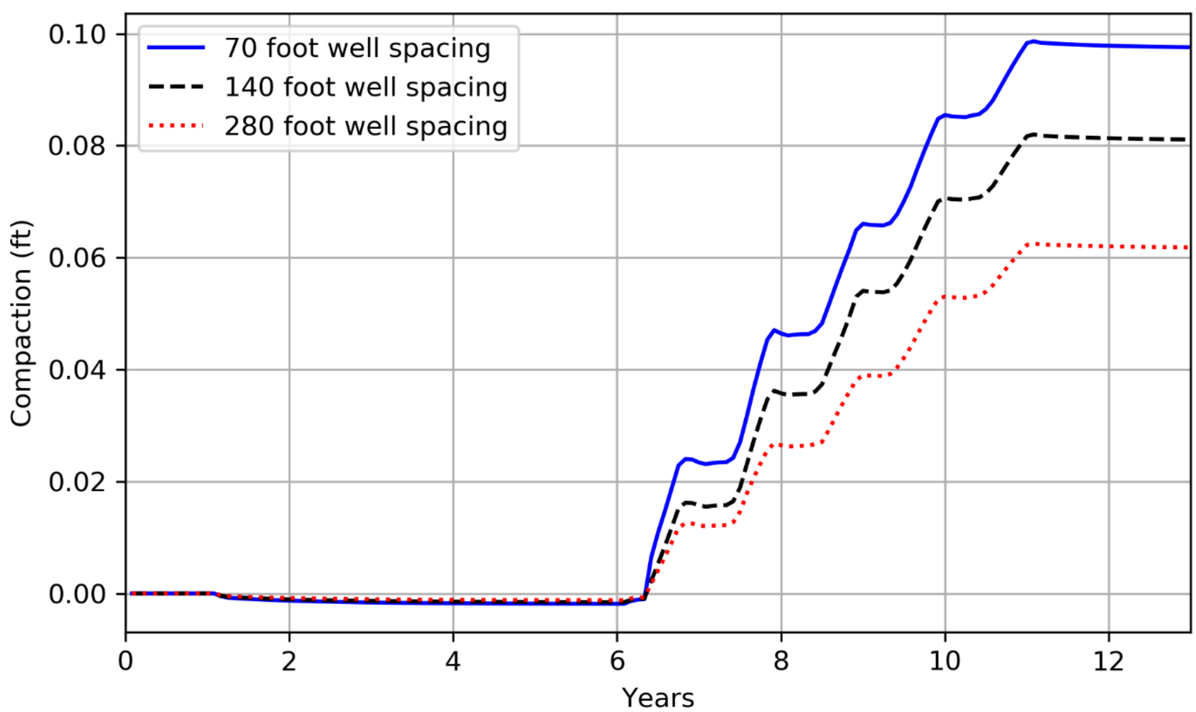

Figure 6-8 Effect of wells spacing on mean compaction for DOR operational case 1 at the base-case site

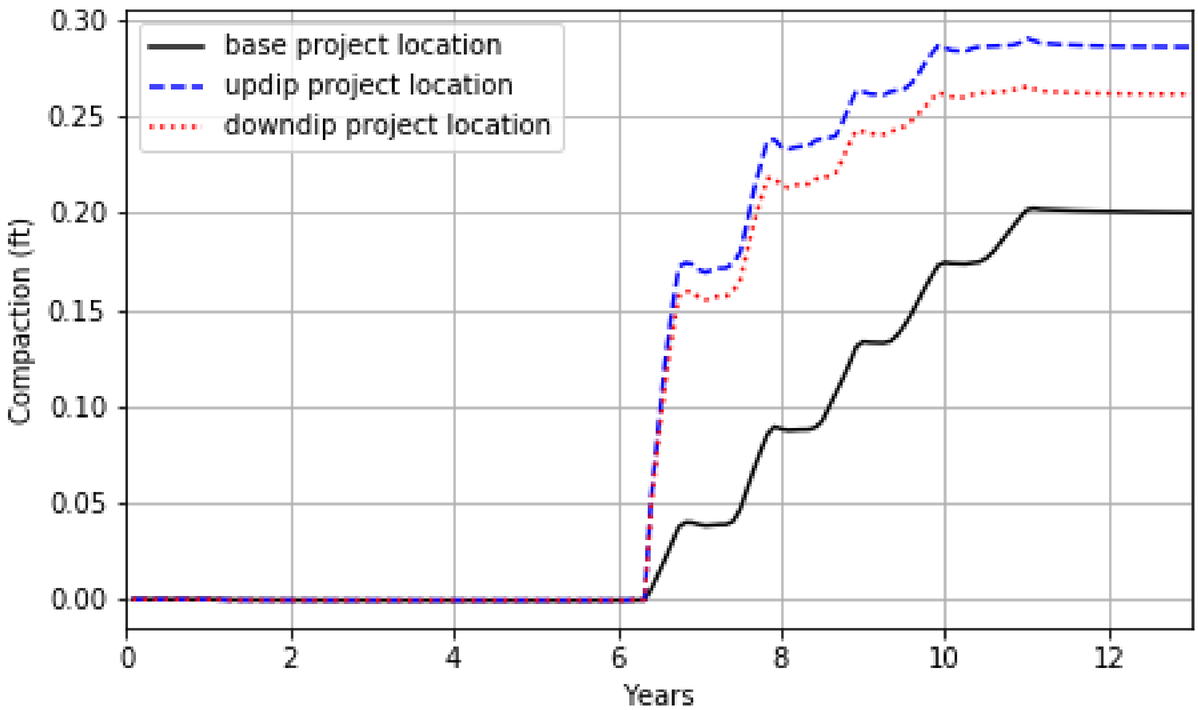

Figure 6-9 Comparison of compaction versus time for the three project locations, DOR operational case 1

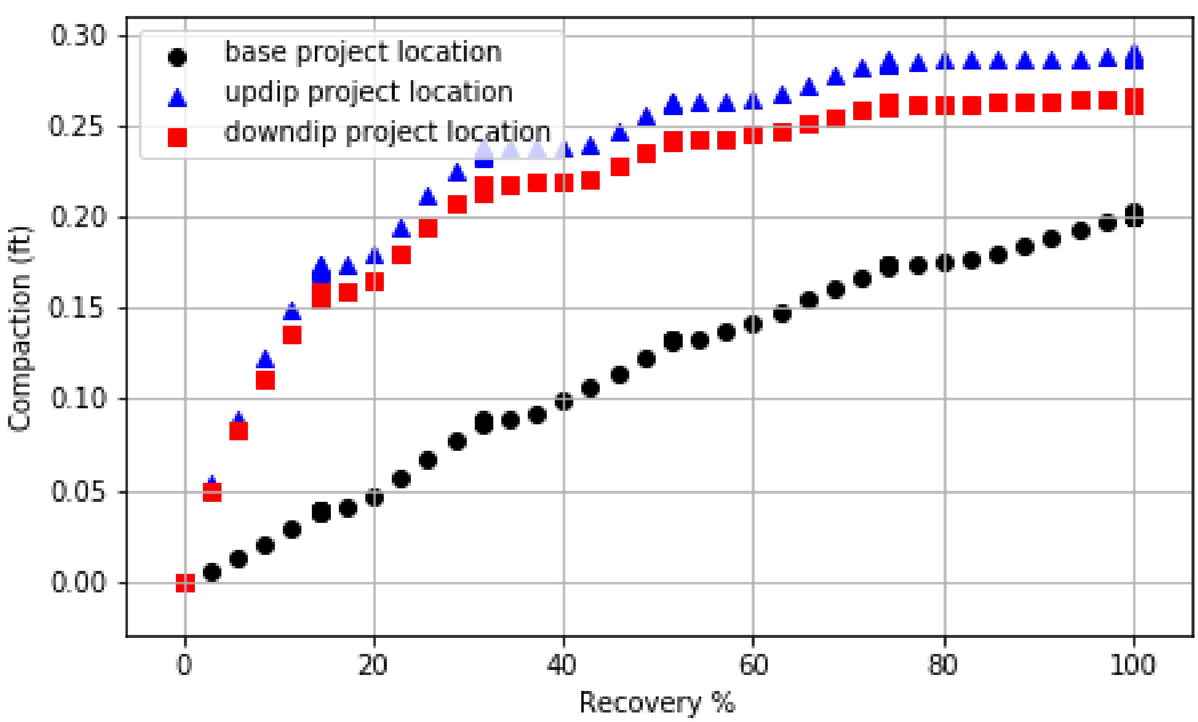

Figure 6-10 Comparison of recovery percentage versus compaction for three project locations, DOR operational case 1

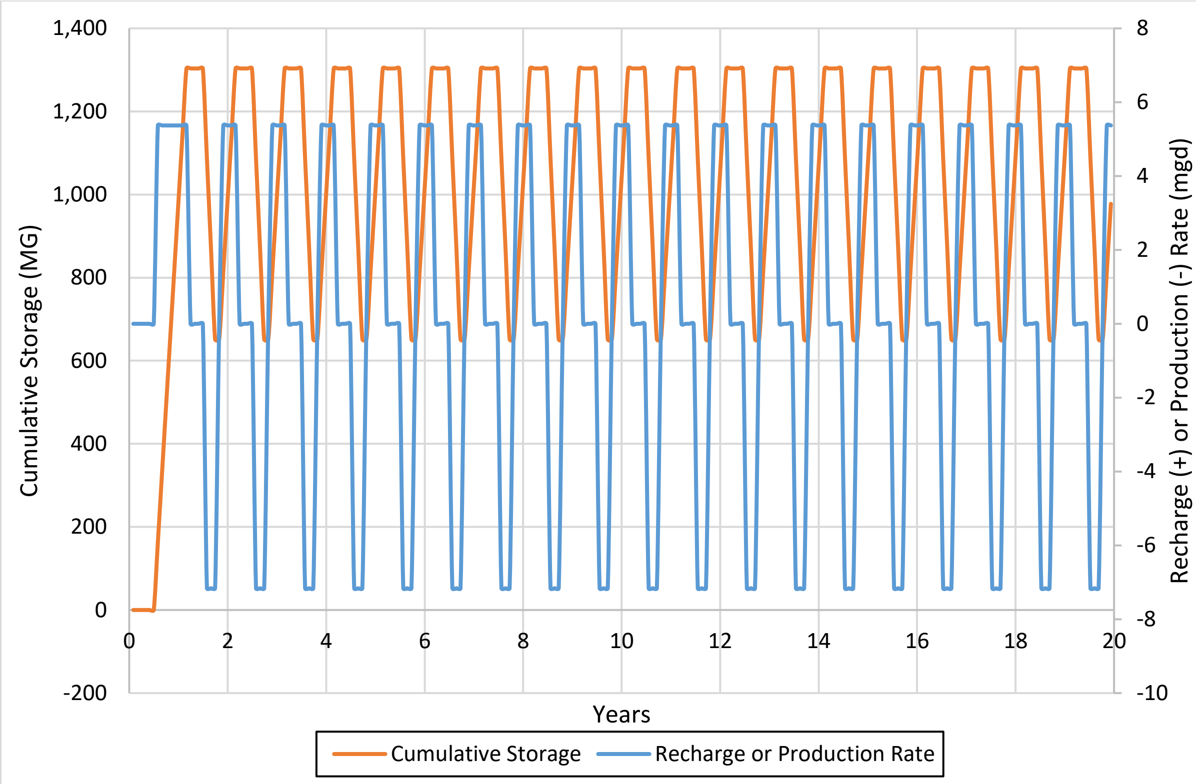

Figure 6-11 Recharge and recovery cycle for operational case 2 (summer peaking)

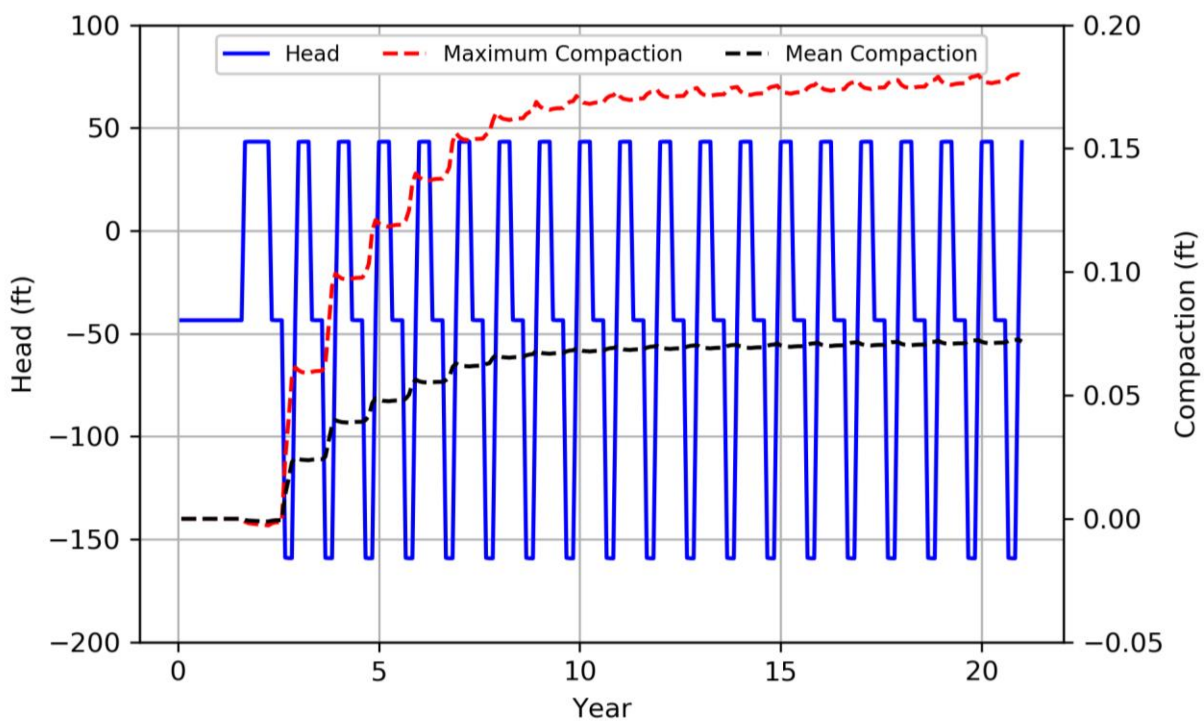

Figure 6-12 Head response at the well location in model layer 4 for the operational case 2 (summer peaking) operation at the base case location, and the corresponding compaction response

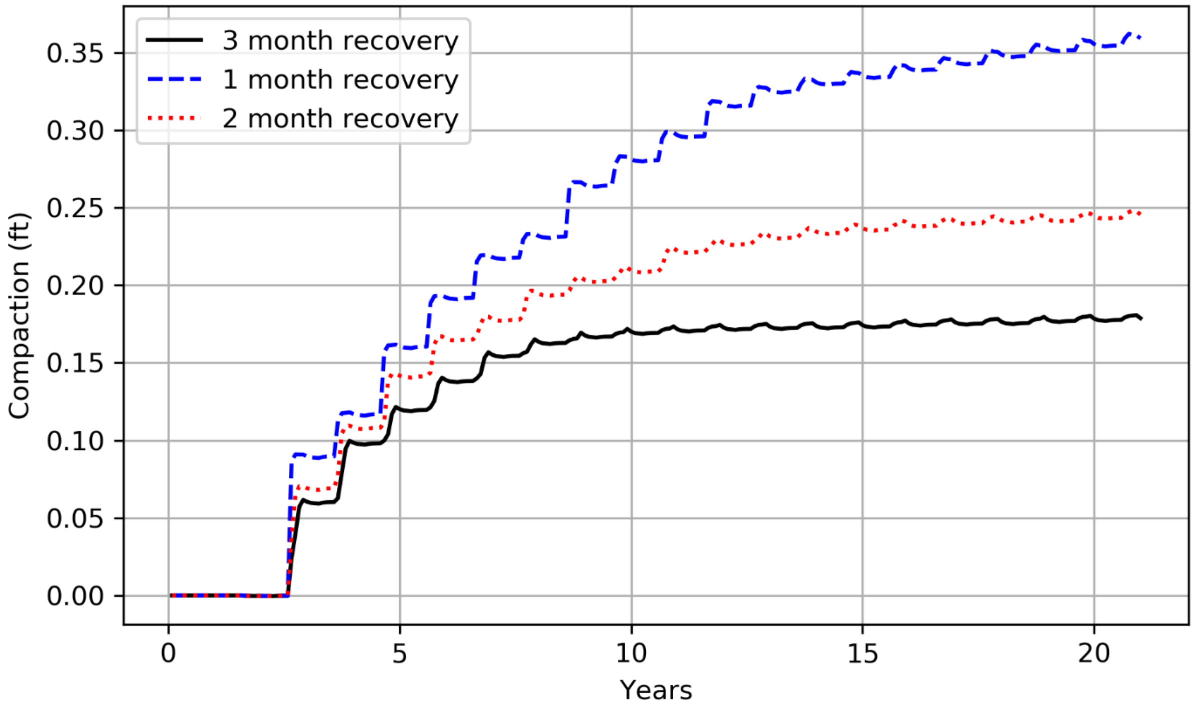

Figure 6-13 Maximum compaction simulated with three different recovery durations for the operational case 2 (summer peaking) operation at the base-case location

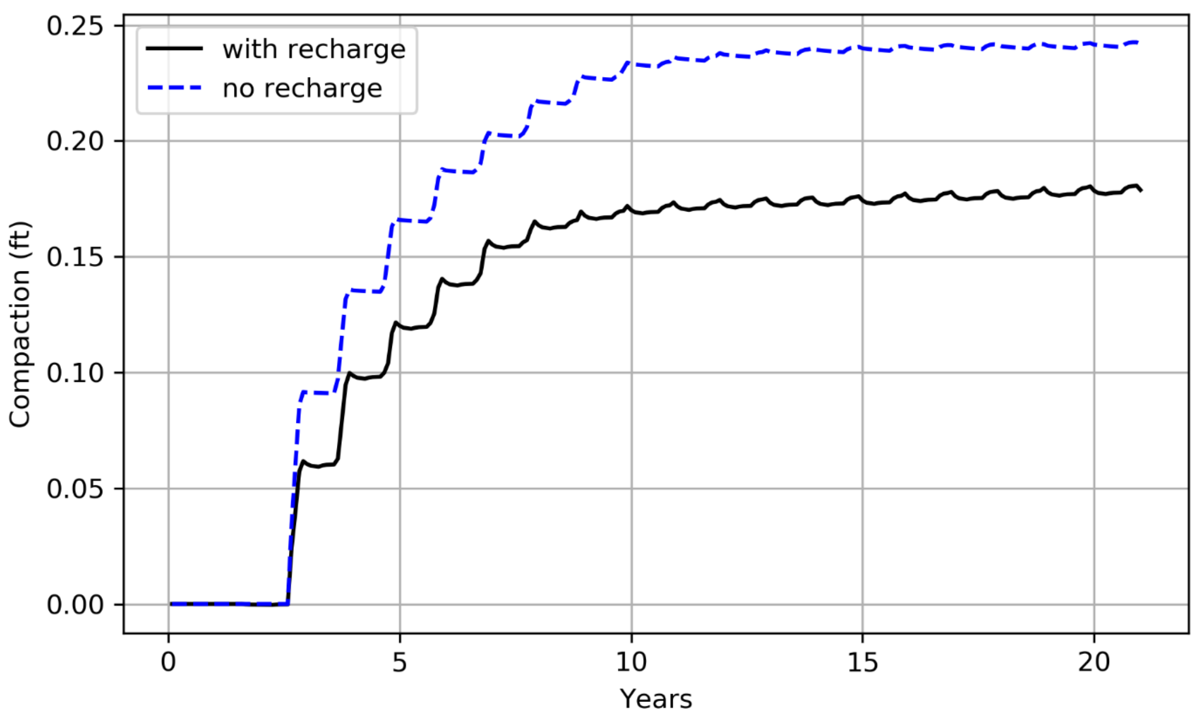

Figure 6-14 Effect of not recharging prior to recovery on simulated maximum compaction for operational case 2 (summer peaking) at the base-case site

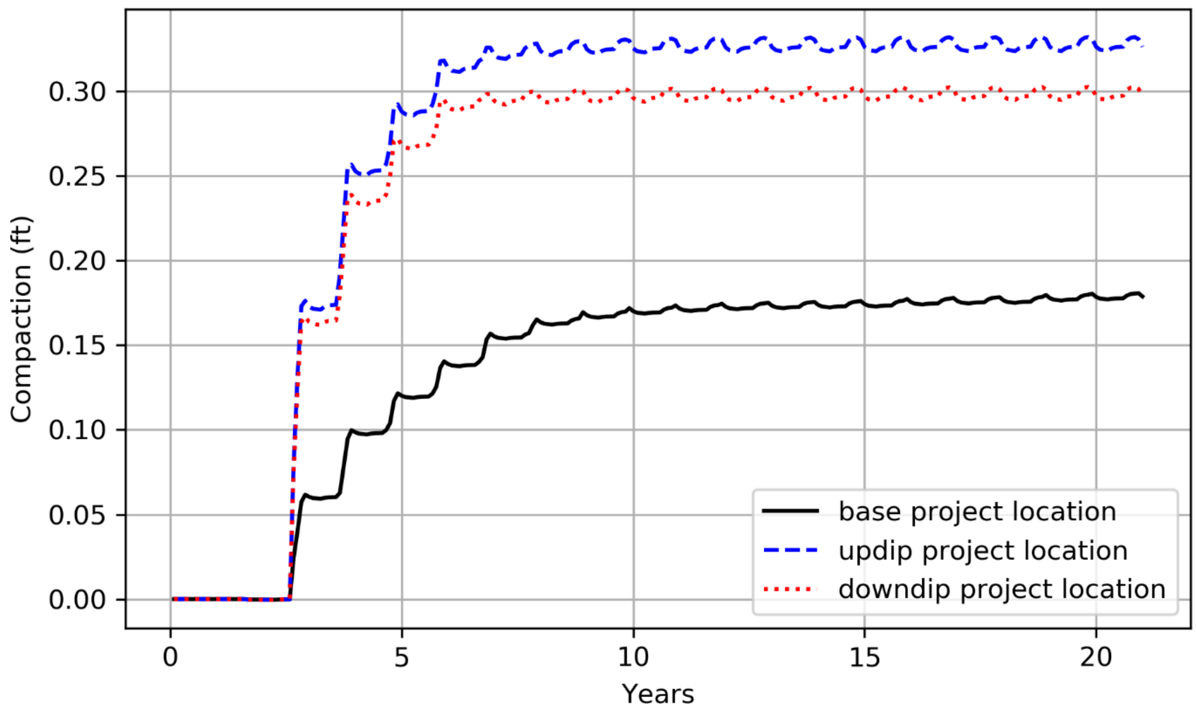

Figure 6-15 Comparison of compaction versus time for the three project locations, operational case 2 (summer peaking)

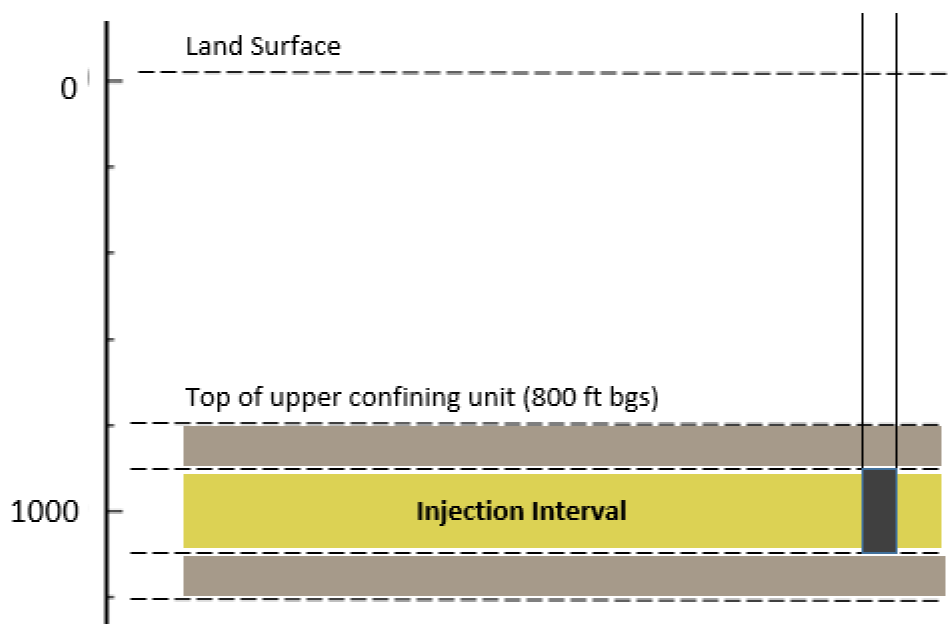

Figure 6-16 Schematic of single-well ASR model constructed for a sensitivity analysis

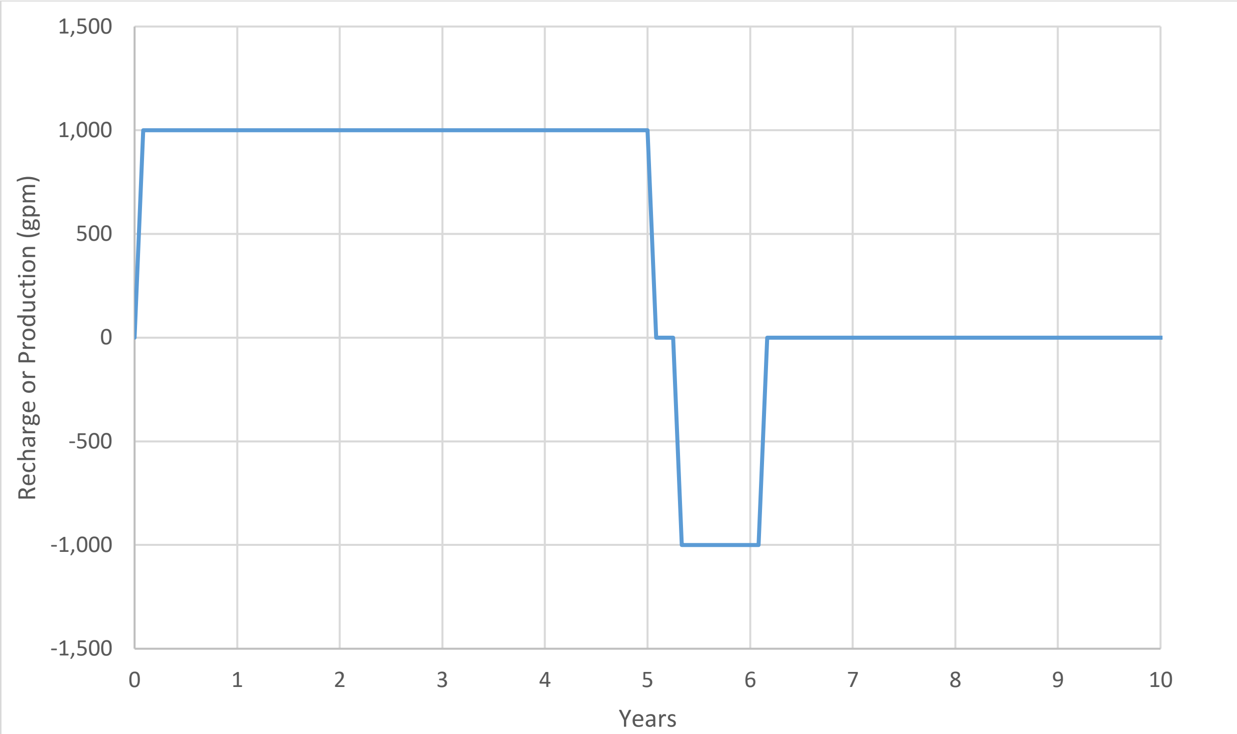

Figure 6-17 Recharge and recovery cycle for the single-well sensitivity analysis

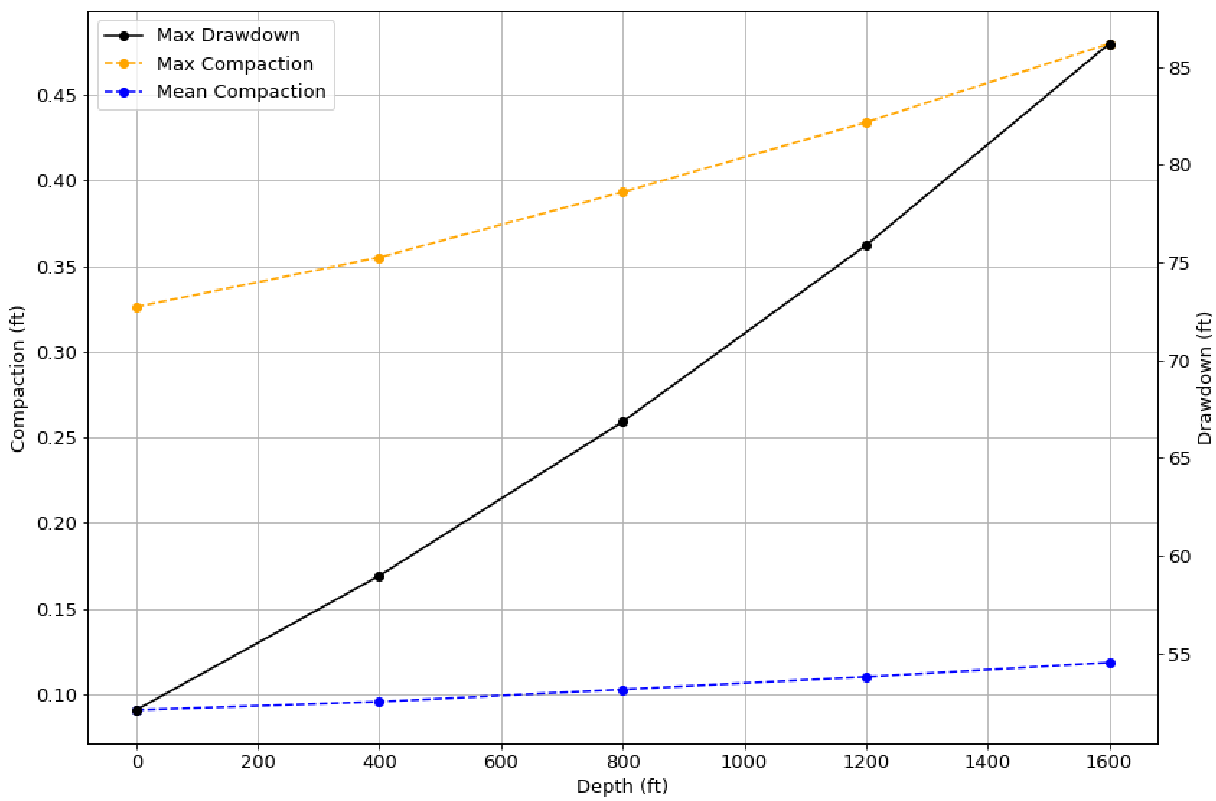

Figure 6-18 Sensitivity of maximum and mean compaction to depth to top of confining unit

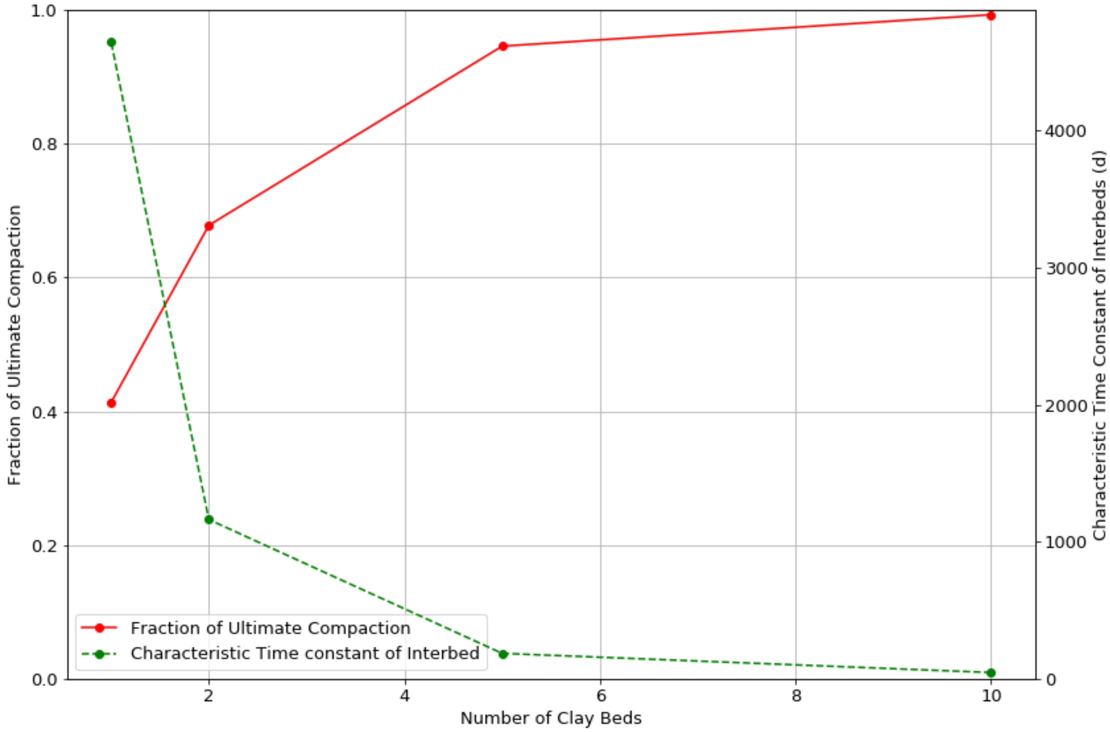

Figure 6-19 Change in interbed time constant and fraction of ultimate compaction with number of clay beds

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7.0 CONSIDERATIONS FOR ASR REGULATION

This section is divided into three subsections. The first subsection summarizes the regulatory framework for ASR in Texas and how that relates to the District. The second subsection discusses a conceptual framework for consideration by the District for regulating ASR wells within the District. The third subsection provides considerations for documentation and analysis of potential ASR well permit applications within the District.

7.1 Regulation of ASR in Texas

This subsection briefly describes the current regulatory framework for permitting ASR wells in Texas. TCEQ has the sole regulatory authority to permit Class V ASR injection wells. Although TCEQ has regulatory primacy over Groundwater Conservation Districts (GCDs), it does not have primacy over the regulation of water volumes recovered from storage in ASR wells within the District.

7.1.1 TCEQ Regulation of ASR Wells

House Bill 655, enacted by the Texas Legislature in 2015, established the current regulatory framework for ASR in Texas. HB-655 was passed in the 84th Legislative Session and made the TCEQ the sole regulatory authority for permitting ASR wells in Texas. The new legislation was passed to address several impediments to permitting ASR in Texas, including: (1) multiple permitting authorities; (2) water quality rules more restrictive than the Clean Water Act; and (3) uncertainty in storing appropriated surface water and the need for an amendment to the applicable water right.

In response to HB-655, the TCEQ amended Chapters 39, 295, 297, and 331, Title 30 of the Administrative Code. The new rules became effective May 19, 2016 and established TCEQ as the sole regulatory authority. HB-655 also allows TCEQ to permit ASR through general, individual and permit-by-rule. The latter permitting method simplifies the public comment process. The new rules also established the criteria to be considered during the permit review. The TCEQ requires information on, and in some cases demonstration of, issues such as the confinement of the injection interval, compliance with the Safe Drinking Water Act, groundwater quality standards and the ability to minimize the loss of recharged water – termed “recoverability.”

ASR projects are regulated under TCEQ’s Class V Underground Injection Control (UIC) Program. Statutory requirements for ASR projects are in the Texas Water Code, Chapters 11, 27 and 36. The TCEQ has exclusive jurisdiction over the regulation and permitting of a Class V injection well used for ASR. To receive authorization to operate an ASR project, the operator must submit to the satisfaction of the TCEQ;

- ASR Project Application (TCEQ-20772) with supporting material, and
- Core Data Form (Form 10400).

TCEQ is authorized to grant the operation of an ASR Project and use of a Class V Injection Well for storage in an ASR project through a general permit, individual permit and a permit-by-rule. A permit-by-rule (also called authorization-by-rule) forgoes the public comment process generally required for a Class V UIC General or Individual Permit.

In making its determination to issue an authorization for a permanent Class V Injection Well for ASR purposes, the TCEQ considers the following: (1) whether the project complies with the Safe Drinking Water Act; (2) the extent to which the cumulative volume of stored water can be successfully recovered from the formation, taking into account that the injected water may be comingled to some degree with native groundwater; (3) the effect of the ASR project on existing wells; and (4) whether injection of water will alter the physical, chemical or biological quality of the native groundwater to a degree that would: (i) render the groundwater harmful or detrimental; or (ii) require an unreasonably-higher level of treatment in order for the native groundwater to be suitable for beneficial use. These are shared objectives with the District. Much of the data collected in support of the TCEQ Class V ASR Injection Well authorization application would be data that would be relevant, and in some cases required, for the District to evaluate the potential subsidence impact of a project. Table 7-1 provides a listing of the data and analyses required of an applicant for a Class V ASR Injection Well authorization for a ASR project.

Until recently, the TCEQ recommended that those seeking a Class V ASR Injection Well authorization to first seek a temporary Class V Experimental Well (Class 5X25) authorization. The purpose of the Class V Experimental Well authorization was to provide a test well that could be used to assemble the data needed to later obtain a permanent Class V ASR Injection Well authorization. A temporary Class V Experimental Well falls under a different chapter of the Water Code than a Class V ASR Injection Well. Certain protections afforded to a project sponsor are not available under a Class V ASR Experimental Well authorization. For that reason, it is our understanding that the TCEQ will not recommend Class V Experimental Well authorizations and therefore they will not be discussed further in this section.

Table 7-1 Relevant information collected from TCEQ Class V ASR injection well application form (TCEQ-20772, June 18, 2018)

Section	Information Requirement
I. General Information	Type of application and authorization requested
	Operator Information
	Site Owner
	Facility Description and Location
	Authorized persons
	Confidential Material
	Injection Zone Water Quality (TDS)
	TCEQ Core Data Form (TCEQ-10400; 4/15)
	Legal Description of Land to be Used
	Indicate if in Chapter 8801 Special District (Subsidence Districts)
II. Information Required to Provide Notice	Groundwater Conservation District Jurisdiction, if any
	Person who will provide notice
III. ASR Project Area	Map with property boundaries and cultural features
IV. Area of Review	Map of the Area of Review (AOR) consistent with 30 TAC 331.183 (1/2-mile radius)
	Location and artificial penetrations within AOR
	Detailed information on artificial penetrations that intersect/transect injection interval
V. Well Construction and Closure Standards	Map of ASR wells and monitoring wells
	Detailed construction information for each ASR injection well
	Describe ASR injection well compliance with 30 TAC 290.41
	Describe ASR well compliance with closure standards (30 TAC 331.183)
	Number and construction details of all monitoring wells
VI. Injection Well Operation	Describe how drinking water sources are protected
	ASR Project operations
	Discussion of effects of injection water on native groundwater
VII. Project Geology, Hydrogeology and Geochemistry	Geology Report: regional and site-specific geology and hydrogeology
	Physical and geologic description of the ASR interval including geochemistry
	Physical characteristics of water being injected including source
	Discussion of injected water/aquifer water/well material compatibility
	Total injected volume
	Available aquifer test data
	Available geophysical logs
VIII. Demonstration of Recoverability	Analysis of the volume of injected water that will be recovered (TWC 27.154(b))

7.2 Considerations for District Regulation and Monitoring

While TCEQ has regulatory authority of Class V ASR Injection Well authorizations in Texas, local GCDs may regulate production from an ASR project only if the volume of water recovered is in excess of the volume of water determined to be recoverable in the TCEQ Class V ASR Injection Well authorization. However, HB-655 specifically provides that the amendments to Chapter 27 of the Texas Water Code do not affect the ability of the District (and four other special purpose districts) to regulate production (recovery) from an ASR project as authorized under Chapter 8801, Special District Local Laws Code for the Harris-Galveston Subsidence District. So, while the TCEQ has sole authority over injection, the District has sole authority over recovery from an ASR well. This makes the District an integral part of an ASR project authorization. An operator could get an ASR project authorized by TCEQ and not have the production permit from the District required to recover the stored water.

7.2.1 Regulatory Plan and District Rules

This subsection explores how ASR projects might fit within the District's Regulatory Plan and Rules. The District is currently operating under the 2013 Regulatory Plan (Plan) which was established to reduce groundwater withdrawal to no more than 20% (10% in Regulatory Area 1) of total water demand. The Plan uses disincentive fees to promote groundwater withdrawal reduction consistent with the schedule set forth in the Plan. Disincentive fees also promote participation within a certified groundwater reduction plan (GRP).

Water users are replacing groundwater use with alternative water supplies which are defined in Rule 1.1(b). To date, all alternative water supplies within the District are non-groundwater, *e.g.*, surface water, re-use, or treated effluent. However, groundwater can be utilized if it is provided as part of an approved GRP (District Rule 1.1(b)). Therefore, ASR used as an alternative water supply is consistent with the District's rules if it is within a GRP.

Many ASR wells nationwide are storing advanced treatment reclaimed wastewater, treated surface water, and groundwater from overlying or underlying aquifers or from other locations in the same aquifer. The water is stored in deep aquifers, often brackish, and is usually recovered from the same ASR well. Other than a small and steadily-diminishing amount of mixing between the stored water and the native groundwater, the recovered water usually has similar quality to the recharge water. The native groundwater is unaffected but is laterally displaced a short distance from the ASR injection well, typically a few hundred feet, and experiences changes in pressure during recharge and recovery. Since the stored water is recovered through a well, it is considered to be "groundwater" under current District rules, even though the recharged water source may be surface water.

The following are two ways in which ASR might be used within the District:

- Some municipalities and industries that currently use surface water to meet all their needs (e.g. many customers of GCWA) may want to use ASR to firm up interruptible run-of-river surface water supplies during periods of severe drought.
- Groundwater users may want to use ASR as an alternative to allow them to use a greater percentage of groundwater. The following discussion will focus on this second approach.

ASR has a myriad of potential uses within the District including providing for a supply during emergencies like hurricanes or infrastructure failures. However, from a regulatory perspective we have assumed that some groundwater users will seek to use ASR as an alternative water supply within a GRP only if it allows them to increase their percent of groundwater production relative to demand. This increase in the percentage of groundwater production allowable would be derived from the recovery of stored water determined to be recoverable by the District from an ASR project. A realistic case could be where a user within a GRP is going to fall short of its reduction requirement. In this case, ASR could potentially provide a means to increase the amount of groundwater pumping allowable in a GRP without theoretically causing more subsidence than is currently assumed in the Plan.

How does this work in the context of "subsidence neutral? The theoretical modeling of an ASR project in this study has demonstrated that any ASR project would predict some compaction assuming there were compressible clays in the storage aquifer. However, as we have seen in Section 6 above, pumping (recovery) from an ASR well or wellfield is predicted to result in less compaction and potential subsidence compared to pumping an equal volume of groundwater without a previous recharge cycle. In the DOR case, the benefit of ASR versus traditional groundwater production is approximately 3% at the end of a 5-year recovery period (Figure 6-6). For the summer peaking case the benefit of ASR versus traditional pumping is greater than 30% after 20 years of operation. Interestingly, the early time benefit of ASR for the DOR case (compared to pumping without recharge) is largest in the first year (50%) and least at the end of recovery after 5 years (3%). The converse is true for the summer peaking case. In that case, the maximum benefit of ASR (compared to pumping without recharge) is after many cycles of recharge and recovery (see Figure 6-14). The percentages referred to above should only be used to inform regulation. They are subject to change based upon the operations of a real project.

The limited ASR simulations herein show that short duration recharge and recovery cycles bring the most benefit compared to traditional pumping without recharge. The reason the recharge cycle provides the benefit is because the time average drawdown in the ASR aquifer is less than if recovery cycles are long or as compared to straight pumping with no recharge. This assumes a similar recovery flow rate. As the duration of recovery cycles increase, the average drawdown approaches the drawdown that would occur without recharge, and the benefit of ASR correspondingly decreases.

Therefore, from a regulatory point of view, the District could consider subsidence neutral ASR as allowing the production of more groundwater without creating additional subsidence relative to that assumed under authorized pumping. In Regulatory Area 3, current District rules allow for earning over-conversion credits for groundwater pumping reductions in excess of District requirements. The over-credit allows a user to increase authorized withdrawals that exceed the groundwater reduction requirements without having to pay a disincentive fee. A comparable concept could be used with the concept of ASR Credits. We specifically do not use "recharge credit" or similar terminology because it is anticipated that the District will authorize ASR Credit production permits at volumes less than the cumulative volume that has been recharged. That is, an ASR Credit would be a fraction of the water stored in an ASR project that would be subject to a credit to be applied against an authorized withdrawal permit approved in the Plan. The concept of an ASR Credit would be similar to an over-conversion credit in that it expands the amount of groundwater a permit holder could pump within a GRP. Unlike an over-conversion credit, an ASR Credit is associated with a specific project site condition and predictions of compaction. Therefore, it is unlikely an ASR Credit could be transferred, and if so, very far geographically.

The regulatory challenge of this proposed concept is in defining the ASR Credit fraction of the project total storage volume. The ASR Credit for each ASR project is dependent upon that project's unique operating requirements and the hydrogeology at the site. Given these contributing factors, defining a "rule-of-thumb" ASR Credit may not be possible. Under the framework proposed, the ASR Credit is equivalent to the subsidence neutral yield.

Permitting of ASR wells as an alternative water supply in the District will likely require case-by-case feasibility analysis, data collection and monitoring. The District's permitting process could also include provisions for adjusting the ASR Credit over time as the ASR project produces actual observed data regarding performance and subsidence to validate models and initial understanding. Because ASR projects must be optimized based upon demands and site conditions, the assessment of those projects also must be specific to the individual project design and operation.

7.2.2 Considerations for a District Review Process

Much of the data that would be of interest to the District in its consideration and permitting of ASR wells is required to be submitted to the TCEQ (see Table 7-1). Therefore, it is recommended that the District first meet with the TCEQ and develop a memorandum of understanding or some other type of agreement to allow for the timely, sequential flow of information from the TCEQ to the District, and vice versa. It is important for the TCEQ to make the applicant aware of the regulatory authority of the District and who to contact at the District to understand how to apply for an ASR-related authorization.

In development of this report, we reached out to the TCEQ to see how they would handle the dual regulatory authority between the TCEQ and the District. They stated that, if an applicant came forward within the District boundaries, they would immediately put them in touch with the District. The TCEQ Class V ASR Injection Well application requires notification if the project is within the District (See Table 7-1 under General Information). The TCEQ preference, based on past experience, is to have the applicant and the GCD, or District in this case, be present at the pre-application meeting with the TCEQ. The pre-application meeting is not mandatory.

The current regulations require that the TCEQ will notify a GCD of an ASR project proposed to be authorized *by rule* within the GCD jurisdictional boundary. This may mean that if an ASR project were to be authorized *by permit*, the TCEQ would use the public notice process as the means of district notification. It is uncertain what the TCEQ believes is required for the District because the District is specifically mentioned in HB-655. It is also contemplated by the TCEQ that an ASR applicant may submit confidential information that could be relevant to the District. While the TCEQ discourages the submittal of confidential information, an applicant can mark material as confidential if needed. However, it is possible that the District could file a Public Information Request and get that information.

The remainder of this subsection will propose a possible permitting process for Class V ASR well. A Class V ASR well could be used for recharge and recovery. The District permitting process only applies to the recovery aspects of the well. The approach assumes a protocol for the participation and notification activities between the District and the TCEQ. This protocol also attempts to avoid duplication of activities or data collection that is currently performed under TCEQ authority. The proposed approach is based upon findings in this report and should be considered a conceptual framework. This report does not promote policy recommendations but rather is written to inform policies that the District may adopt and use in the future.

It is recommended that the District develop a new District well classification for Class V UIC ASR well. The District should also develop a fact sheet that the TCEQ could provide to an ASR applicant explaining the dual regulatory authority within the District boundaries and the District's requirements for a production permit associated with a Class V ASR well.

The District currently has defined criteria it can consider in the decision and issuance of a permit defined in District Rule 5.2(d). Because there are issues unique to ASR that would be of interest to the District and the fact that there is a paucity of field data on subsidence resulting from ASR nationwide, there are some additional considerations proposed in these recommendations. Also, because ASR will likely be considered by a GRP as an alternative water supply strategy designed to increase the permit holder's groundwater allocation under the Plan, data and analyses must be able to support the evaluation of potential impacts, benefits and an ASR Credit. Again, in this section, we have conceptualized this increased production volume associated with an ASR project as an ASR Credit that is subsidence neutral. The determination of the ASR Credit is the core requirement of the recommended ASR permitting process.

Figure 7-1 provides a flow chart of a possible permitting process for Class V ASR wells within the District. Figure 7-1 does not address the TCEQ process. However, a TCEQ Class V ASR Injection Well authorization is essential for moving forward on an ASR project. A project sponsor could choose to go through the entire TCEQ Class V ASR Injection Well authorization process before starting the District permitting process. This tact is considered quite risky on the part of the sponsor. A far better approach would be for the sponsor to initiate the process with the TCEQ and the District near the same time. For example, the District will require aquifer testing and detailed modeling (see below) before defining the ASR Credit for an ASR well. Aquifer testing and detailed modeling results will be necessary elements of the TCEQ Class V ASR Injection Well authorization. Therefore, the results of collecting necessary information for the District will be applicable to requirements for TCEQ, and vice versa.

Prior to the pursuit of a Class V ASR Injection Well authorization, the sponsor should have an ASR Feasibility Study addressing several fundamental elements such as an assessment and ranking of ASR objectives; evaluation of variability and trends in water supply, water demand and water quality; storage volume requirements and associated recharge and recovery rates; hydrogeology; geochemistry; aquifer hydraulics and water quality; ASR well or wellfield location and selection of storage intervals; conceptual design of facilities; preliminary cost estimate; and an evaluation of legal, regulatory, institutional and other factors that may impact ASR viability. Because it is expected that ASR could be part of GRPs, it may be beneficial to require an ASR feasibility study with the GRP documentation provided to the District.

If the results from a feasibility analysis are favorable, the project sponsor would approach the District to register a Class V ASR Injection Well. It is possible that a project sponsor wants to use existing wells. In this case, the District should be able to identify that well as an ASR well. It would be ideal if the District and the applicant had met with the TCEQ prior to well registration. The TCEQ has stated that they would like to have the District at the TCEQ non-mandatory pre-application meeting. Once the registration is reviewed by the Districts (five days), the permittee can submit a Class V ASR Well Drilling Permit. This would include well location (not currently required at registration), engineering design drawings, and a Drilling Test Plan consistent with the District's rules. The agreement with the TCEQ should allow the District the ability to review and comment on test plans or cycle test plans submitted to the TCEQ.

Once the District has reviewed the Drilling Test Plan and any data made available by the TCEQ, the Class V ASR Well Drilling Permit may be authorized. The data collected during the drilling and testing of the well will be integrated by the applicant to develop a Modeling Report and a Subsidence Management Plan. These two documents could be the only significant additional information required of the applicant above the TCEQ requirements. The purpose and content of the Modeling Report and a Subsidence Management Plan will be discussed in Subsection 7.3. It is possible that an applicant desires to perform cycle testing as part of the well testing program. This District has the option of allowing a limited amount of pumping associated with cycle testing in the well testing phase. If pumping associated with an ASR test well is significant, the District may require the applicant include cycle testing in the production permit.

Based upon a review of the Modeling Report and a Subsidence Management Plan the District will consider the ASR project potential impacts, benefits and may potentially define an ASR Credit to the project. Consistent with current production permits, it is expected that an ASR Credit will be contingent upon an operational plan consistent with the assumptions used to define the credit. The District could review the application and information provided and approve a well(s)'s production volume and impose any special condition provisions such as maximum drawdown or average head at the well. This proposed process would modify the current permitting approach with the addition of a Drilling Permit that is separate from the permit for production.

7.3 Recommended Documentation and Analysis

The TCEQ's Class V ASR Injection Well authorization process requires submittal of a very complete document of well design and operations, geology, hydrogeology and geochemistry (see Table 7-1). The recommended approach for the District to take is to become a partner to the TCEQ in review of data and analyses submitted and only ask an applicant for needed additional information that is not required under TCEQ rules.

Under District Rule 5.2(d) the District can consider groundwater quality in the decision for the issuance of a production permit. As we have seen in Subsection 7.1.1 above, the TCEQ already considers potential impacts to water quality. As a result, no additional water quality considerations are proposed for consideration in this subsection that would require action by the District. This is not meant to say that data collected specifically to understand potential water quality is not important to ASR. Experience has shown that collection of cores and geochemical equilibrium modeling (as in Appendix B) is required to prevent well plugging or poor recovered water quality that could then require post-treatment or pre-treatment, or both. Because the TCEQ reviews these issues, the documentation is focused on understanding the potential for compaction.

7.3.1 Data Collection, Analysis and Documentation

Accomplishing the regulatory goals of the District requires additional documentation and data collection on top of the TCEQ requirements. These additional requirements will be discussed below.

7.3.1.1 Well Design and Completion Documentation

Well design and completion data, including the engineering drawings prepared by a Texas licensed engineer or geologist, needs to be provided to the District. This is standard information defining the well(s) and the project, much of which will be submitted to TCEQ and could also be provided to the District. In addition to TCEQ requirements, it is recommended that the District require submittal of a

Well Test Plan. The test plan will be reviewed to make sure that the appropriate aquifer data, water quality information and hydraulic data are collected and available for review and use by the District.

As part of well testing, the following data should be collected by the applicant. This data and its interpretation will be the foundation for two document submittals to the District; a Modeling Report, and a Subsidence Management Plan.

7.3.1.2 Geologic and Geotechnical Data

The District should require that the lithology from ground surface to below the ASR recharge interval to be estimated through either geophysical log analysis or core samples if collected. The distance below the base of the ASR storage interval should be sufficient to establish the adequacy of lower confinement. At a minimum the geophysical logs run and interpreted should include caliper, temperature, resistivity, induction, spontaneous potential, and porosity. The lithology analysis should catalog sands and clays over the entirety of the geophysical logged section. This data should be augmented by the Driller's Log and core data.

To accurately evaluate geochemical compatibility of recharge water with ambient groundwater requires determination of the mineralogy of the aquifers and confining units. This data is generally collected from core data. Cores should extend above and below the storage interval, defining the thickness and adequacy of the overlying and underlying confining layers, in addition to the full thickness of the storage interval(s). During preparation of the geochemical analysis included in Appendix B, it became apparent that no publicly-available cores exist in Regulatory Area 1 that are useful for ASR purposes. Storage aquifer and confining layer geotechnical and hydraulic properties, and water quality from deeper storage aquifers, could only be inferred from interpretation of geophysical logs. An important early task for any proposed ASR project would be to obtain and analyze cores, providing real data to support aquifer hydraulic modeling and subsidence-neutral modeling. It is recommended that core data be collected and following geotechnical data be analyzed using core data.

<u>Clay Compressibility</u> – 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. These laboratory tests also provide estimates of porosity as a function of stress and bulk density. This data can be used to support subsidence modeling.

<u>Clay Vertical Hydraulic Conductivity</u> – The collected core data can be sent to a geotechnical laboratory to determine the vertical hydraulic conductivity of the clay interbeds. The vertical hydraulic conductivity 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. This data can be used to support subsidence modeling.

<u>Clay Mineralogy</u> – 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.

7.3.1.3 Hydraulic Data

Aquifer Test – It is recommended that the applicant perform at least a 36-hour pumping test at each ASR well. The aquifer test plan will be included in the Well Test Plan. Water level must be measured at the pumping well, and any available monitoring wells 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 applicant also monitor water level recovery after pumping for a minimum period equal to the length of the pump test. The aquifer test provides an estimate of aquifer transmissivity and storativity. From the transmissivity, an aquifer hydraulic conductivity can be estimated. The aquifer test should also provide information regarding leakance (measure of vertical confinement) from clays and an estimate of a leakance coefficient. Ideally, the applicant will estimate leakance between the overlying and underlying confining layers and the ASR interval through monitor wells. The applicant would document the test in a Modeling Report to be submitted to the Districts as part of the production permit process.

Monitor Wells – Monitor wells can be important from a hydraulic testing perspective because they provide a means to uniquely estimate storativity of an aquifer and to define the source of leakance in an ASR interval. Having an accurate estimate of storativity is key for assessing an ASR project and the ASR Credit. Storativity estimates from an aquifer test where water level is only monitored in the pumping well cannot provide a unique estimate of storativity. Monitor well(s) also provides an observed drawdown and buildup (water level rise during recharge) at distance. Storativity is an important parameter, in part, controlling the time evolution of drawdown from the ASR project. It is common practice to have monitor wells in close vicinity of ASR wells to observe water quality changes radially away from the well and to get better aquifer properties like storativity. In some settings, existing wells could be used to defray costs. It is proposed that a storage aquifer monitor well be required for a single-well ASR project. The well will be used to monitor water levels away from the ASR wells and will be central to the estimate of an ASR Credit. For ASR projects with multiple ASR wells, some of the ASR wells can initially be utilized as monitor wells during initial hydraulic and cycle testing.

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 District with the Modeling 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.

7.3.1.4 Modeling

Operators applying to the District for an ASR Well Permit would be required to perform modeling to support the application. This is especially true given the need to determine the benefit of the ASR project (i.e., ASR Credit). The applicant would be required to model the hydraulic response in terms of areal extent and magnitude of drawdown associated with the ASR project. The modeling should predict a radius of influence of the well(s), in terms of radial extent of the stored water and also radial extent of pressure response. The modeling would predict the water level rise and decline at any project monitor wells over the course of the ASR project operation. This information data will be used to validate the science supporting the ASR Credit and will be a key aspect of the Subsidence Management Plan and the annual permitting process.

The modeling should be able to reasonably represent the heterogeneity in aquifer properties estimated through well testing and log analysis. It is also proposed that compaction modeling be performed to determine the potential benefit of the ASR project and to provide a basis for the District production permit and potential ASR Credit. It is proposed that applicants use District-defined compaction parameters unless they have site-specific data. It is proposed that the applicant use the lithologic column of sands and clays determined by interpretation of the geophysical logs run at the well or cores collected. The modeling should perform a sensitivity analysis over a reasonable range of operational conditions, hydraulic and compaction properties. The applicant should identify any mapped faults within 4 miles because subsidence has been shown to be accelerated close to growth faults (Qu and others, 2015). The results of both the hydraulic modeling and the compaction modeling will be documented in the Modeling Report.

7.3.1.5 Monitoring

During recharge periods and storage periods water levels in each storage interval will be raised substantially, potentially exceeding historic levels in the vicinity of each ASR well or wellfield, and exceeding land surface in deeper storage aquifers. Minor elastic rebound may occur. During ASR recovery periods water levels will decline. As a result, ASR has the potential to exacerbate residual compaction and ongoing subsidence in the District and monitoring of operations of an authorized ASR project should be required. Periodic review of the monitoring data, such as through annual permit review provides a reasonable basis for adjustments to the ASR Credit and the associated production permit.

Permittees should be required to install and operate a bi-directional flow meter and keep accurate records on a monthly basis of water recharged and recovered, under current District Rules 5.3, d,e. Flow meters are also a standard TCEQ permit condition and are applicable to Class V ASR wells. Additional monitoring considerations will be discussed below.

Continuous Water Level Measurements – Compaction and subsidence are the result of 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 understanding and predicting the potential for compaction and subsidence. It is recommended that continuous water level measurements be made at all ASR wells and monitor wells under the control of the permittee and pertinent to the permit. A reasonable measurement interval can be determined in discussions with the District.

Port-A-Measure Installation – In 1993, the District 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 involved 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).

The District has 50 PAM Sites reporting and the Fort Bend Subsidence District 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.

It is recommended that a PAM be installed at any ASR project site or wellfield if there is not one in proximity to the project wells.

7.3.1.6 Subsidence Management Plan

A recommended activity to be performed by the applicant is the development of a Subsidence Management Plan. The purpose of the Subsidence Management Plan is to provide the basis for operation of the ASR well(s) and an agreed upon plan of corrective action if excessive subsidence is determined by the District to be resulting from the project by the District. The key elements of Subsidence Management Plan are described below.

Estimate Drawdown and Water Rise at Project Monitor Well(s) – The plan should provide an estimate of water level decline and rise at project monitor well(s) during operation of the ASR Project. These predictions will be documented in the Modeling Report. These estimates will be reviewed to make sure that predicted drawdown and water level rise are consistent with the terms of the permit and the assumptions underlying any permitted ASR Credit.

Estimate Potential Subsidence – The plan should provide an estimate of the potential subsidence that could occur at the ASR well(s) over the timeline of the project, based on findings in the Modeling Report and the applicant's plan for operation of the well(s). This estimate could be used by the District in addition to considerations regarding subsidence measurement error and the Regulatory Plan to review the ASR project and any permitted ASR Credit. An alternative approach is that the District establish a subsidence rate threshold value measured at the project PAM site which would trigger review of the ASR well permits and any granted ASR Credits. This rate increase could be based upon local subsidence rate data currently being collected by the District in cooperation with the University of Houston.

Protocol for Subsidence Monitoring and Subsidence Reporting – This element of the plan is to identify for the District how the PAM data will be maintained and analyzed, and the reporting methodology to the District. If the actual local subsidence rate exceeds the subsidence anticipated at the project site (above), the permittee should be required to notify the District in writing. This notification would trigger permit review by the District. Such notification would also trigger implementation of the permittee's Subsidence Management Plan. If the permittee has evidence that indicates that its project is not causing the observed subsidence, the permittee may submit that to the District for review and consideration.

Mitigation Program to Address Subsidence – The Subsidence Management Plan should include a mitigation program to address actual subsidence measured above the threshold agreed upon between the permittee and the Districts. This program could include procedures to increase recharge into the

ASR wellfield and/or reduction of pumping from the ASR project. A policy question that could be considered by the District is how much local subsidence, if any, would be allowed in a defined radius (*i.e.*, property) of the ASR project.

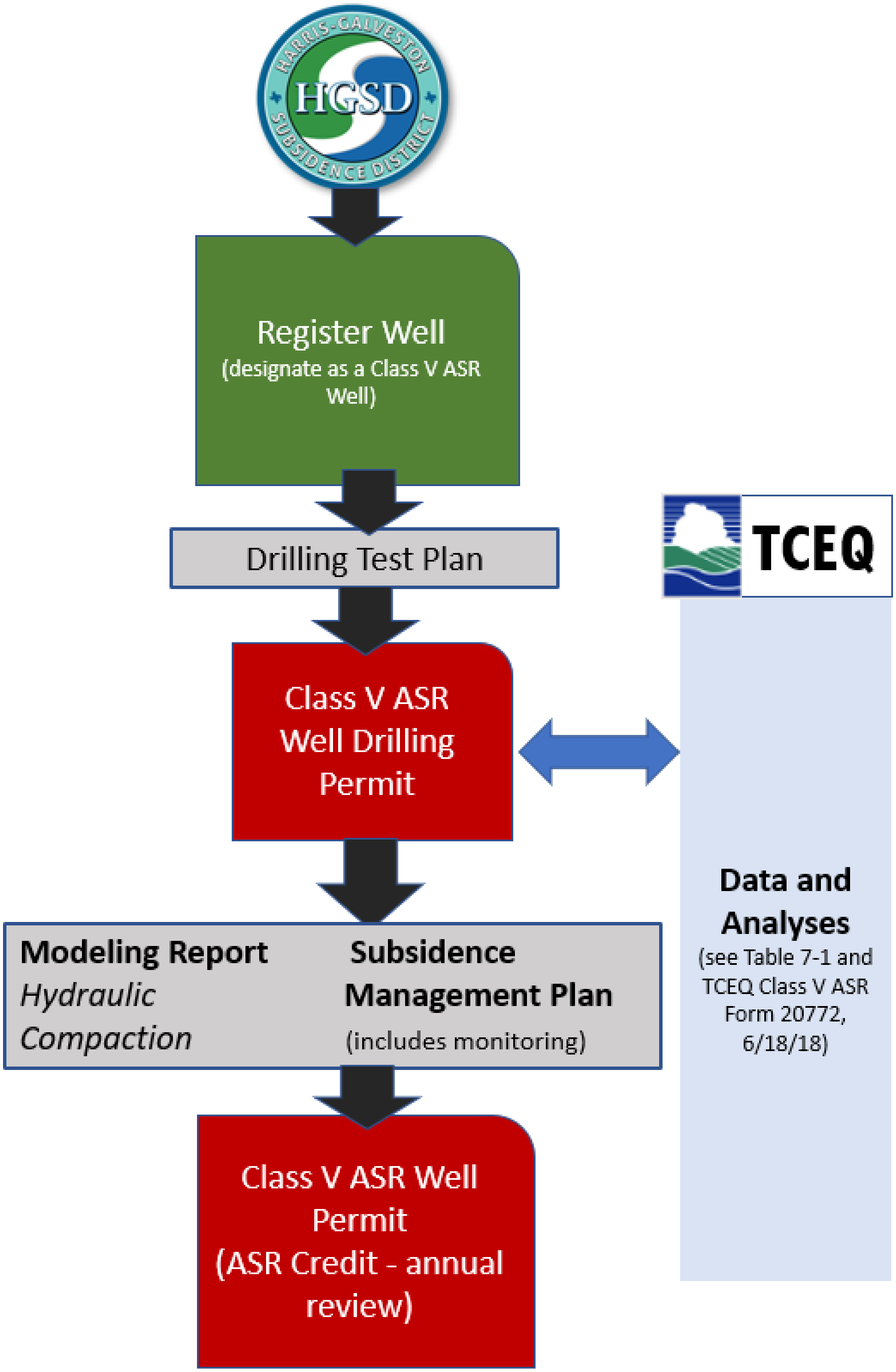

Figure 7-1 Permitting work flow for a Class V ASR Well

8.0 CONCLUSIONS AND RECOMMENDATIONS

This report presents an assessment of the potential for compaction and resulting subsidence associated with the application of ASR as an alternative water supply strategy in the Chicot and Evangeline aquifers within the Harris-Galveston Subsidence District. The study is focused on Regulatory Area 1. However, the conclusions and recommendations from this study are broadly applicable to the entire District.

The broad objective of this study was to provide guidance to the District regarding its consideration and potential future regulation of ASR wells and their use in the District. This report and its findings are a first step in improving District understanding of the potential for subsidence which could occur from the application of ASR within the District. This section will briefly summarize the key study findings and recommendations. This section will also summarize some of the key limitations of the study.

8.1 Summary of Findings and Recommendations

This study accomplished three primary tasks to meet the objective described above: (1) review of the relevant literature regarding ASR and MAR in subsidence-prone regions and/or regions that have experienced historical subsidence from groundwater extraction; (2) development and implementation of hydraulic and compaction modeling to investigate the potential for compaction associated with ASR; and (3) provide recommendations regarding what activities and data should be collected to support understanding, regulation, and future investigations in the application of ASR in the District. Each of these main tasks are summarized in the following subsections with associated key finding and recommendations.

8.1.1 Conclusions from Literature Review of ASR and MAR in Subsidence-Prone Aquifers

Land subsidence has occurred around the world from compaction of unconsolidated aquifer materials, especially more compressible clay interbeds, in response to lowered water levels in the aquifer from groundwater pumping and resulting increased effective stress. To limit subsidence, measures have been taken including reduction of groundwater pumping, MAR and ASR to control groundwater level drawdowns and to restore groundwater storage. MAR was specifically studied by the USGS (Garza, 1977) in the 1970s as a strategy for the abatement of subsidence occurring in the Johnson Space Flight Center south of Houston.

To better understand hydrological conditions of subsidence and effects of aquifer recharge in areas prone to land subsidence, five publicly documented case studies were selected and reviewed for their potential relevance to this study. Our review found that well-documented case studies for MAR in subsidence prone aquifers outnumbered ASR case studies. As a result, the review was broadened to include MAR. MAR has been recognized as a strategy for the mitigation of subsidence since the 1960s (Poland, 1984) and has been implemented successfully across the globe reducing rates of subsidence and in some cases stopping subsidence. MAR is generally used in conjunction with reductions in groundwater pumping. As a result, water levels are increasing both in response to MAR and to decreased pumping. Therefore, their interrelated effects on subsidence in an aquifer are hard to separate.

The evidence shows that basins will continue to subside for many years, if not decades, after water levels have rebounded. Such continued subsidence is most likely the result of residual compaction caused by lingering effects of large drawdown on the aquifer system and the ongoing long-term effects of delayed yield from thick drained aquitards. This has been termed "residual compaction" and is an ongoing process within the District in areas where groundwater production has been reduced.

Perhaps the most significant finding from these studies is that, in aquifers that have undergone significant regional subsidence, such as the Gulf Coast Aquifer System in the District, subsidence rates can increase again with additional pumping even when water levels are above historical minimums. This has been documented in several areas of California and has been observed in the District in response to increased pumping in 2011. Therefore, maintaining water levels above historical lows may not guarantee the cessation of subsidence. Also, periodic periods of high pumping rates can re-initiate subsidence. These facts complicate the analysis of ASR projects, in basins that have experienced significant regional subsidence.

There are limited publicly documented case studies of the impacts of ASR in subsidence-prone aquifers. Key case studies for ASR were the large-scale Las Vegas ASR and MAR project case study and the Antelope Valley, California ASR cycle test performed by the USGS. In both cases subsidence occurred in the vicinity of the ASR projects during their operation or testing. The observed subsidence rates are very small. However, it is uncertain how much of observed subsidence is the result of residual compaction versus the ASR projects. In the case of Las Vegas ASR and MAR, the subsidence rates have been significantly reduced in the basin and in some areas stopped. The data reviewed suggests that subsidence still occurs at very low rates even with the ASR project. What is not clear is how much of that observed subsidence is a result of residual compaction versus the response to ASR recovery. The subsidence rates increase during recovery. ASR and MAR have successfully mitigated earth fissuring and lowered subsidence rates in the valley and are an essential part of the Las Vegas Valley Water District's water portfolio.

8.1.2 Simulation of Compaction Associated with ASR

In Regulatory Area 1, the 2011 drought caused surface water scarcity and a resulting increased need for groundwater production. The 2011 drought also raised concerns regarding the vulnerability and long-term viability of the surface water resources of the Brazos River in Regulatory Area 1. As a result, industrial water users in Regulatory Area 1 have shown interest in ASR as a conjunctive water supply strategy. For this study, the base case hypothetical ASR project considered was a DOR water supply strategy for industrial water users in Regulatory Area 1 in the Texas City Industrial Complex. As the study progressed, it was suggested that the study also consider a municipal alternative water supply strategy based upon meeting an annual summer peak demands with ASR.

For the DOR industrial user ASR case, we performed an analysis of both water demand and surface water availability based upon the information provided by the Gulf Coast Water Authority and through use of the Brazos WAM, respectively. For the municipal summer peaking case the water demand and timing of that demand for the ASR simulation was based upon general characteristics of a project being considered by a municipality in the region. The base case DOR ASR wellfield was located in the Texas City Industrial Complex. To investigate variability from the base case, two other project locations were modeled, one on Galveston Island (downdip case) and one just southeast of Loop 610 in the area that comprises the Galena Park PRESS Site (updip site) in the far northwest edge of Regulatory Area 1.

The summer peaking municipal water user project was based upon the needs of a typical municipal water user going through groundwater reduction in response to the District Regulatory Plan and growth in demands as a result of projected increases in population. For this case, we also used site conditions representative of the Texas City, downdip and updip locations used for the DOR case above. The code that was used to simulate hydraulic response and compaction associated with ASR projects was MODFLOW-NWT (Niswonger and others, 2011), which is one of the family of MODFLOW codes developed by the USGS. MODFLOW-NWT supports the subsidence (SUB) package (Hoffman and others, 2003), which allows simulation of a compaction response to pressure change in the aquifer. The SUB package can simulate time-dependent compaction which is a key process to be simulated for ASR.

The important conclusion from the ASR simulations is that ASR is predicted to result in less compaction and potential subsidence as compared to an equal amount of groundwater pumping without a recharge cycle. This finding has been used to address the issue of subsidence neutral ASR. In the DOR case, the benefit of ASR versus straight pumping is approximately 3% less compaction at the end of a 5-year recovery period (see Figure 6-6). In the case of the summer peaking case, the benefit of ASR versus traditional groundwater pumping is greater than 30% after 20 years of operation (see Figure 6-13). The early time benefit for the DOR case (compared to traditional pumping) is largest in the first year (50%) and least at the end of recovery (3%). The converse is true for the summer peaking case. In that case, the maximum benefit (compared to traditional pumping) is after many cycles of recharge and recovery.

The simulations provide evidence that an ASR project can be designed and operated to serve as a valuable water management strategy while minimizing potential compaction. Simulations found that the key components of an ASR project from a compaction perspective are: (1) maximizing the well spacing; (2) decreasing the recovery rate(s); (3) increasing the time the project operator recharges water into storage relative to the time the operator recovers water; and (4) targeting high transmissivity, low clay content intervals as the storage formation(s).

As stated above, an ASR operator should maximize the recharge rate and duration of the recharge and storage periods relative to the recovery rate and duration of the recovery period. The ASR simulations performed for this study show that even short duration recharge and recovery cycles bring the most benefit compared to traditional groundwater production. The benefit of ASR from a drawdown perspective (and compaction) is that for a given volume of pumping, the effective drawdown (and compaction) is less. As the duration of recovery cycles increase, the effective drawdown approaches the drawdown that would occur without recharge, and the benefit of ASR correspondingly decreases.

While the simulations of the hypothetical projects are informative for a conceptual management framework, the simulations do not capture the permutations of potential ASR project designs that could be developed in the District.

8.1.3 Considerations for Regulation of ASR in the District

ASR projects are regulated under the TCEQ's Class V UIC ASR Well Program. The TCEQ modified its rules effective May 19, 2016 and established the process and the criteria to be considered during the permit review. In making its determination to issue an authorization for a Class V ASR Well for ASR purposes, the TCEQ considers: (1) whether the project complies with the SDWA; (2) the extent to which the cumulative volume of stored water can be successfully recovered from the formation, taking into account that the injected water may be comingled with native groundwater; (3) the effect of the ASR project on existing wells; and (4) whether injection of water will alter the physical, chemical or biological quality of the native groundwater to a degree that would: (i) render the groundwater harmful or detrimental; or (ii) require an unreasonably-higher level of treatment in order for the native groundwater to be suitable for beneficial use. Most of these considerations are shared objectives with the District. Much of the data collected in support of the TCEQ application process would be data that would be relevant, and in some cases required, for the District to evaluate the potential subsidence impact of a project and ASR Credit. Although the TCEQ regulates ASR injection wells that may be used for both recharge and recovery, the TCEQ does not have authority to permit production wells in the District, other than the regulatory authority applicable to public water supply wells standards. That authority resides with the District.

The conceptual ASR-related regulatory framework described in this report for consideration by the District is based upon the following assumptions or premises: (1) ASR projects require ASR well pumping and therefore have the potential to cause compaction and potentially subsidence; (2) with proper hydrogeologic data collected at a potential ASR wellfield site, ASR can be designed and operated to minimize compaction and the potential for subsidence; (3) production (recovery) associated with an ASR well could, under District rules be considered an alternative water supply within a GRP; and (4) the expectation is that, although surface water users within the District may use water from an ASR wellfield only during periods of severe drought, most groundwater users will seek to use ASR as an alternative water supply within a GRP only if it allows them to *increase* their percent of groundwater production relative to demand. The framework also seeks to use information required by the TCEQ to the degree possible to prevent unnecessary duplication of effort.

A concept proposed in this report is ASR Credits. An ASR Credit would be a fraction of the water stored in an ASR Project that would be subject to a credit to be added to an authorized withdrawal approved in the Regulatory Plan. The ASR Credit is a de facto subsidence neutral yield of the ASR Project. It does not imply that subsidence may not occur, it implies that the ASR Credit will not increase subsidence beyond that considered in the Regulatory Plan. The concept of an ASR Credit is similar to an over-conversion credit in that it expands the amount of groundwater one could pump within a GRP. Unlike an over-conversion credit, an ASR Credit could not be transferred. The regulatory challenge is in defining the ASR Credit fraction of the project total storage volume. The ASR Credit for an ASR project is dependent upon that project’s unique operation and the hydrogeology at the wellfield site. Given these contributing factors, defining a “rule-of-thumb” ASR Credit may not be possible. However, if the District wanted to support ASR as an alternative water supply strategy in GRPs, they could set a minimum ASR Credit as a policy that would incentivize the use of ASR so that the District could get experience in the aquifer response and changes in rates of compaction.

Permitting of ASR wells as an alternative water supply would require analysis, data collection and monitoring. It is recommended that the District meet with the TCEQ and develop a memorandum of understanding or some other type of agreement to allow for the timely flow of information from the TCEQ to the District. Although the TCEQ permitting process is entirely separate from the District’s process, an ASR operator will have to comply with the requirements of both agencies.

It will be important for the TCEQ to make the applicant aware of the regulatory authority of the District and who to contact at the District to understand how to apply for an ASR Production Well Permit. It is our understanding that the TCEQ prefers that the District attends the TCEQ pre-application meeting the TCEQ generally recommends to applicants.

The District will require a new ASR production well classification at the District to identify the well as a Class V ASR well. After an applicant registers the well(s), the District will require a Well Test Plan in addition to TCEQ's requirements. Once the applicant is authorized to drill, the District will provide the applicant a Class V ASR Well Drilling Permit. Based upon data collected and analyzed during the drilling and testing, the applicant will be required to provide the District two reports: (1) a Modeling Report; and (2) a Subsidence Management Plan. Based upon a review of the Modeling Report and a Subsidence Management Plan the District will consider the ASR project potential impacts, benefits and may define an ASR Credit. 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. An annual permitting process provides a process for the District to compare actual ASR performance data against predicted values and allows modifications to production limits or the ASR Credit if appropriate.

8.2 Limitations of the Study

This study is based upon theoretical calculations (modeling) of compaction resulting from the operation of two conceptual ASR projects. As is the case for any predictive modeling application, there are limitations or uncertainties in the calculations presented herein. These limitations do not undermine the conclusions and recommendations presented in this report but should be identified to better inform the District of the application of the analysis. The key limitations will be discussed below.

- While the study team set out to define what constitutes "subsidence neutral" yield of a "typical" ASR project, we have determined that theoretical modeling will always predict some compaction in the existence of clay interbeds under the assumptions herein. What the study has shown is that ASR provides an advantage over traditional groundwater pumping. Also, ASR projects can be optimized to minimize compaction and potential subsidence.
- All results and recommendations provided in this report are made to inform the District as they review policy and regulation for ASR. This report is for the consideration of the District Board of Directors and does not set policy. It should be noted that Texas statute requires that all ASR wells associated with a project must be located within one parcel of land, or within adjacent parcels under common ownership, lease, joint operating agreement or contract.
- The theoretical modeling has shown that pumping associated with an ASR project offers benefits over pumping without recharge. This is the concept behind the proposed ASR Credit discussed in Section 7.
- The conceptual regulatory approach provided in Section 7 is based upon the premise that to fully understand the potential impacts of ASR requires implementation of a few full-scale ASR projects. The required data collection and monitoring will inform future analyses of ASR and compaction.
- The conceptual regulatory approach presented for consideration is considered conservative and flexible.
- The modeling performed in this study is not exhaustive. It provides a good basis for informing the District regarding the potential for compaction from ASR projects. We have discussed the

many factors that control the compaction potential of an ASR project, but we have not modeled all permutations. For this reason, the regulatory framework recommends interpretation and decision-making based upon the specific attributes of each project.

- The literature documents that in large basins that have undergone regional subsidence, subsidence rates can increase significantly with water level declines, even when water levels are above historical lows. This is in part the result of historical transience in effective stress in the clay beds. This study does not account for the historical change in effective stress that has occurred and continues to occur across the District and could have an impact on future subsidence associated with an ASR project depending on the ASR project location. The modeling in this study assumes that we cannot accurately determine the current effective stress within clay interbeds at a specific location within the aquifer. As a result, we have assumed that any amount of drawdown represents an increase in effective stress above preconsolidation stress. This is a conservative, though realistic assumption. We recommend that the District continues studying the relationship of drawdown and subsidence rates across the District to continue to refine an understanding of patterns in how specific aquifers have responded and respond to pumping. This information is germane to the consideration of ASR in the District.
- This study only analyzes isolated ASR projects where recharge occurs locally and over a period similar in duration to the recovery cycle. Regional ASR or MAR could be considered in the District and could result in further increase in regional heads which would be a benefit to the region and continue to mitigate subsidence. This study has not contemplated large scale MAR or ASR projects which are operated with significantly greater recharge volumes than recovery volumes.
- In model simulations, each ASR project modeled was optimized to minimize compaction. Because of assumptions regarding the reduction of aquifer transmissivity with depth, associated drawdown for a given flow rate was greater the deeper the interval was located. Compaction properties of clays are conceptualized to decrease with depth (Section 2). As a result, from a hypothetical perspective, a deeper interval could be better or worse than a shallow interval depending upon several factors. From a practical perspective, if aquifer tests indicate that a comparable transmissivity can be accessed at a deeper depth, this would be more favorable from a compaction and subsidence perspective.
- The simulations performed herein predict compaction at depth in the aquifers. The study has not quantified how the compaction at depth may result in subsidence at land surface. Literature confirms that the amount of subsidence resulting from subsurface compaction in basins that have not undergone regional subsidence depends mainly on the ratio between depth of burial and the lateral extent of the aquifer radius being de-pressured and compacted (Geertsma, 1973). It is recommended that there be future analysis of the quantification of the relationship between subsidence and compaction based upon depth of burial and area of depressurization in the District.

The compaction modeling (using MODFLOW-SUB) in this report 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 District for the regulatory plan. There is inherent uncertainty in these properties.

9.0 REFERENCES

American Society of Civil Engineers (ASCE), 2001. Standard Guidelines for Artificial Recharge of Ground Water, EWRI/ASCE 34-01(ASCE Standard No. 34-01), Reston, VA.

Baker, E.T., Jr. 1979. Stratigraphic and hydrogeologic framework of part of the coastal plain of Texas: Texas Department of Water Resources Report 236, 43 p.

Bell, J.W., 1981a. Subsidence in Las Vegas Valley: Nevada Bureau of Mines and Geology Bulletin 95, 83 p., 1 plate, scale 1:62,500.

Bell, J.W., 1981b. Results of leveling across fault scarps in Las Vegas Valley, Nevada, April 1978–June 1981: Nevada Bureau of Mines and Geology Open-File Report 81-5, 7 p.

Bell, J.W., Amelung, F., Ramelli A.R., and Blewitt, G. 2002. Land Subsidence in Las Vegas, Nevada, 1935–2000: New Geodetic Data Show Evolution, Revised Spatial Patterns, and Reduced Rates, Environmental and Engineering Geoscience 8 (3): 155-174. DOI: https://doi.org/10.2113/8.3.155

Bell, J.W., and Price, J.G., 1991. Subsidence in Las Vegas Valley, 1980–91—Final project report: Nevada Bureau of Mines and Geology, Open-File Report 93-4, 10 sect., 9 plates, scale 1:62,500

Bell, J.W., and Ramelli, A.R., 1991. in Bell, J.W., and Price, J.G., eds., Subsidence in Las Vegas Valley, 1990-1991, final project report: unpublished Nevada Bureau of Mines and Geology Report, p. E1-E31.

Bell, J.W., Price, J.G., and Mifflin, M.D., 1992. Subsidence-induced fissuring along preexisting faults in Las Vegas Valley, Nevada: Proceedings, Association of Engineering Geologists, 35th Annual Meeting, Los Angeles, p. 66-75.

Bell, J.W., F. Amelung, A. Ferretti, M. Bianchi and F. Novali, 2008. Permanent scatter in nSAR reveals seasonal and long-term aquifer response to groundwater pumping and artificial recharge, Water Resour. Res. Vol. 44.

Binkley and Barfield, 2018. Final Drainage Reuse Initiative Feasibility Study, Prepared by Brinkley and Barfield, Inc., Texas A&M University and LBG-Guyton, January 2018, 170 p.

Borchers, J.W. and M. Carpenter, 2014. Land subsidence from groundwater use in California, Full Report of Findings, prepared for the California Water Foundation, 151 p.

Burbey T.J., 1995. Pumpage and water-level change in the principal aquifer of Las Vegas Valley, Nevada, 1980-1990, Nevada Department of Conservation and Natural Resources, Division of Water Resources.

Casagrande, A. 1936. The Determination of the Pre-Consolidation Load and Its Practical Significant, Discussion D-34, Proceedings of the First International Conference on Soil mechanics and Foundations Engineering, Cambridge, Vol III, p. 60-64.

Dillon, P., 2005. Future management of aquifer recharge. Hydrogeology Journal, Vol 13, pp. 313-316.

Domenico, P.A., and F.W. Schwartz. 1990. Physical and chemical hydrogeology: New York, NY, John Wiley & Sons, Inc., 824 p.

Faunt. C.C., (ed.), 2009. Ground-water availability in California's Central Valley Aquifer: Sacramento, California, U.S. Geological Survey Professional Paper 1766, 225 p.

Faunt, Claudia C., and Sneed, Michelle, 2015, Water Availability and Subsidence in California's Central Valley, Essay in San Francisco Estuary and Watershed Science: 13 (3).

Faunt, Claudia C., Sneed, Michelle, Traum, Jonathan A., and Brandt, Justin, 2015, Water availability and land subsidence in the Central Valley, California, USA, Hydrogeology Journal Hydrogeology Journal: Vol. 24, No. 3, p. 675-684. DOI: 10.1007/s10040-015-1339-x

Freese & Nichols (2014), Long Range Water Supply Study Detailed Evaluation of Selected Strategies, Prepared for the Gulf Coast Water Authority, September 2014, 378 p.

Freeze, R.A., and J.A. Cherry. 1979. Groundwater. Englewood Cliffs, NJ: Prentice-Hall, 604 p.

Fugro, Inc. 2013. Geotechnical Services – PRESS Model Runs – Work Order 7 – Houston-Galveston Subsidence District, Harris County, Texas.

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

Gabrysch, R.K., and C.W. Bonnet. 1976a. Land-surface subsidence in the area of Moses Lake near Texas City, Texas: U.S. Geological Survey Water-Resources Investigation 76-32, 42 p.

Gabrysch, R.K., and C.W. Bonnet. 1976b. Land-surface subsidence at Seabrook, Texas: U.S. Geological Survey Water Resources Investigation 76-31, 53 p.

Galloway, D., D.R. Jones, and S.E. Ingebritsen, eds. 1999. Land subsidence in the United States: U.S. Geological Survey Circular 1182, 177 p.

Garza, S, 1977. Artificial Recharge for Subsidence Abatement at the NASA-Johnson Space Center, : U.S. Geological Survey, Open File report 77-219, 82 p.

Geertsma, J., 1973. Land subsidence above compacting oil and gas reservoirs, Journal of Petroleum Technology, SPE 3730, June 1973, p. 734-744.

Gong, S., Li, C. and Yang S. (2009). The microscopic characteristics of Shanghai soft clay and its effect on soil body deformation and land subsidence. Environ Geol. (2009) 56:1051-1056. DOI 10.1007/s00254-008-1205-4.

Groundwater Geek, 2017. Las Vegas ASR, accessed in November 2017. http://www.groundwatergeek.com/asr-by-state/nevada/las-vegas

Harrill, James R., 1976. Pumping and depletion of Ground-Water Storage in Las Vegas Valley, Nevada, 1955 – 1974, U.S. Geological Survey, 1976.

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

Holzer, T.L. 1981. Preconsolidation Stress of Aquifer Systems in Area of Induced Land Subsidence, Water Resources Research, Vol 17, No. 3 p. 693-704.

Holzer, T.L. 1984. Ground failure induced by ground water withdrawal from unconsolidated sediment, in Holzer, T.L., ed., Man-induced land subsidence: Geological Society of American Review of Engineering Geology, V. 6, p. 67–105.

Ikehara, M.E., and Phillips, S.P., 1994, Determination of land subsidence related to ground-water-level declines using Global Positioning System and leveling surveys in Antelope Valley, Los Angeles and Kern Counties, California, 1992: U.S. Geological Survey Water-

Ingebritsen, S.E. and D.R. Jones, 1999. Santa Clara Valley, California – a case of arrested subsidence, in Galloway, Jones, and Ingebritsen ed. Land Subsidence in the United States, U.S. Geological Survey Circular 1182: pp 49-64.

Ireland, R.L., J.F. Poland, F.S. Riley, 1984. Land subsidence in the San Joaquin Valley, California, as of 1980: U.S. Geological Survey Professional Paper 437-I, 93 p.

Ireland, R.L., 1986. Land Subsidence in the San Joaquin Valley, California, as of 1983, U.S. Geological Survey Water-Resources Investigations Report 85-4196, 50p.

Jacob, C.E. 1940. On the flow of water in an elastic artesian aquifer. Trans-American Geophysical Union 21: 574-586.

Johnson, M., Cole, E., Brothers, K., 1997. Artificial recharge in the Las Vegas Valley: An Operational history. Available at: https://digitalscholarship.unlv.edu/water_pubs/74.

Kasmarek, M.C. 2013. Hydrogeology and Simulation of Groundwater Flow and Land-Surface Subsidence in the Northern Part of the Gulf Coast Aquifer System, Texas, 1891—2009. Prepared in cooperation with the Harris-Galveston Subsidence District, the Fort Bend Subsidence District, and the Lone Star Groundwater Conservation District: U.S. Department of the Interior, U.S. Geological Survey Scientific Investigations Report 2012-5154, Version 1.1, December 2013.

Kasmarek M.C., J.K. Ramage and M.R. Johnson, 2016. Water-Level Altitudes and Water-Level Changes in the Chicot, Evangeline and Jasper Aquifers and Compaction 1973-2015 in the Chicot and Evangeline Aquifers, Houston-Galveston Region, Texas, U.S. Geological Survey Scientific Investigations Map 3365, 2016.

Kelley, V.A., N. Deeds, S. Young and J. Pinkard, 2018. Subsidence Risk Assessment and Regulatory Considerations for the Brackish Jasper Aquifer, Report prepared by INTERA, Inc. for the Harris-Galveston Subsidence District, May 2018, 69 p.

Leake, S.A., and D.E. Prudic. 1991. Documentation of a computer program to simulate aquifer-system compaction using the modular finite-difference groundwater flow model: U.S. Geological Survey, Techniques of Water-Resources Investigations, Book 6, Chap A2, p. 68.

Leighton, D.A and S.P. Phillips, 2003. Simulation of ground-water flow and land subsidence in the Antelope Valley ground-water basin, California: Sacramento, California, U.S. Geological Survey, Water-Resources Investigations Report 03-4016, pp. 61-67.

Longwell, C.R., 1960. Interpretation of the leveling data, in Smith, W.O., Vetter, C.P., Cummings, G.B., and others, Comprehensive survey of sedimentation in Lake Mead, 1948-49: U.S. Geological Survey Professional Paper 295, p. 33-38.

Magara, K. 1978. Compaction and fluid migration – practical petroleum geology. Elsevier Scientific Publishing Company, New York. 350 pages.

Malmberg, G.T., 1964. Land Subsidence in Las Vegas Valley, Nevada, 1935-1963. Nevada Department of Conservation and Natural Resources Water Resources – Information Report 5, 10 p.

Maxey, G.B., and Jameson, C.H., 1948. Geology and water resources of the Las Vegas, Pahrump, and Indian Springs Valley, Clark and Nye Counties, Nevada: Nevada Department of Conservation and Natural Resources, Water Resources Bulletin 5, 128 p.

McMillan, J.F., 1973. Land Subsidence Antelope Valley area of Los Angeles County. County of Los Angeles, Department of County Engineer, Survey Division and Survey Division File Map No. 65-58.

Metzger, L.F., M.E. Ikehara and J.F. Howle, 2002. Vertical-Deformation, Water Level, Micro-Gravity, Geodetic, Water-Chemistry, and Flow-Rate Data Collected During Injection, Storage and Recovery Tests at Lancaster, Antelope Valley, California, September 1995 through September 1998, U.S. Geological Survey Open-File Report 01-414, p. 159.

Mifflin, M.D., Adenle, O.A., and Johnson, R.J., 1991. Earth fissures in Las Vegas Valley, 1990-91 inventory, in Bell, J.W., and Price, J.G., eds., Subsidence in Las Vegas Valley, 1990-91, final project report: unpublished Nevada Bureau of Mines and Geology Report, p. C1-C31.

Mindling, A.L., 1971. A summary of data relating to land subsidence in Las Vegas Valley: University of Nevada Desert Research Institute Publication, 55 p.

Nishikawa, T., D.L. Rewis and P.M. Martin, 2001. Numerical simulation of ground-water flow and land subsidence at Edwards Air Force Base, Antelope Valley, California, U.S. Geological Survey Water-Resources Investigations Report 01-4038, 111 p.

Niswonger, R.G., S. Panday, and M. Ibaraki. 2011. MODFLOW-NWT, A Newton formulation for MODFLOW-2005: U.S. Geological Survey Techniques and Methods 6-A37, 44 p.

Patt, R.O., and Maxey, G.B., 1978. Mapping of earth fissures in Las Vegas Valley, Nevada: University of Nevada Desert Research Institute Project Report 51, 19 p.

Pavelko, M.T., 2000. Ground-Water and Aquifer-System-Compaction Data from the Lorenzi Site, Las Vegas, Nevada, 1994-99, U.S. Geological Survey Open File Report 00-362: 20p.

Pavelko, M.T., 2004. Estimates of hydraulic properties from a one-dimensional numerical model of vertical aquifer-system deformation, Lorenzi Site, Las Vegas, Nevada. U.S. Geological Survey Water-Resources Investigations Report 03-4083, 36 p.

Pavelko, M.T., Hoffmann, J. and N. A. Damar 2006. Interferograms Showing Land Subsidence and Uplift in Las Vegas Valley, Nevada, 1992–99, U.S. Geological Survey Scientific Investigations Report 2006–5218, 17p.

Pavelko, M.T., Wood, D.B. and Laczniak, R.J., 1999. Las Vegas, Nevada, in Galloway, Jones, and Ingebritsen ed. Land Subsidence in the United States, U.S. Geological Survey Circular 1182: pp 49-64.

Poland, J.F., 1984. Case Study No. 9.14, Santa Clara Valley, California, USA, in Poland, J.F. editor, Guidebook to studies of land subsidence due to ground-water withdrawal" United Nations Educational, Scientific and Cultural Organization, 7 Place de Fontnoy, 75700, Paris, France, pp. 279-290.

Poland, J.F., and Davis, G.H., 1969. Land subsidence due to withdrawal of fluids, in Varnes, D.J., Reviews in engineering geology, v. II: Boulder Colorado, Geological Society of America, p. 187-268.

Poland, J.F. and R.I. Ireland, 1988. Land Subsidence in the Santa Clara Valley, California, as of 1982. U.S. Geological Survey Professional Paper 497-H. 70 pp.

Poland, J.F., B.E. Lofgren, R.L. Ireland, and R.G. Pugh. 1975. Land Subsidence in the San Joaquin Valley, California, as of 1972. U.S. Geological Survey Professional Paper 437-H. 78 pp.

Pyne, R.D.G., 2005. Aquifer Storage Recovery – A Guide to Groundwater Recharge Through Wells, Second Edition, ASR Press, 608 p.

Qu, F., Z. Lu, Q. Zhang, G.W. Bawden, J. Kim, C. Zhao and W. Qu, 2015. Mapping ground deformation over Houston-Galveston, Texas using multi-temporal InSAR, Remote Sensing of Environment, 169, p. 290-306.

Riley, F.S. 1969. Analysis of borehole extensometer data from central California, in Tison, L.J., ed., Land subsidence—Volume 2: International Association of Scientific Hydrology, Publication 89, p. 423–431.

SGEAEB (Shanghai Geological Environmental Atlas Editorial Board) (2002) Shanghai geological environmental atlas (in Chinese). Geological Publishing House, Beijing, 143 pp

Shanghai Hydrogeological Team. (1973). On the control of surface subsidence in Shanghai. Acta Geologica Sinica 1973, No. 2.

Sheng Z. (2005). An aquifer storage and recovery system with reclaimed wastewater to preserve native groundwater resources in El Paso, Texas, Journal of Environmental Management. 75(4): 367-377. (SCI IF: 4.005)

Sheng, Z. and X. Zhao, 2015. Special issue on managed aquifer recharge: powerful management tool for meeting water resources challenges. J. Hydrol. Eng. Vol. 20.

Sheng, Z., D.C. Helm, and J. Li. 2003. Mechanisms of earth fissuring caused by groundwater withdrawal: Journal of Environmental & Engineering Geoscience. IX (4): 313-324.

Shi L.X., Bao M.F. (1984). Case History No. 9.2 – Shanghai, China. In Poland, J.F. ed. Guidebook to studies of land subsidence due to groundwater withdrawal, UNESCO, Paris. http://unesdoc.unesco.org/images/0006/000651/065167eo.pdf

Shi, X., Jiang, S., Xu, H., Jiang, F., He, Z., and Wu J. (2016). The effects of artificial recharge of groundwater on controlling land subsidence and its influence on groundwater quality and aquifer energy storage in Shanghai, China, Environmental Earth Sciences, 2016, 75:195. DOI 10.1007/s12665-015-5019-x

Sneed, M and D.L. Galloway, 2000. Aquifer-system compaction and land subsidence: measurements, analyses and simulations – The Holly Site, Edwards Air Force Base, Antelope Valley, California, U.S. Geological Survey Water-Resources Investigations Report 00-4015, 65 p.

Swanson, A.A., 1998. Land subsidence in the San Joaquin Valley, updated to 1995, in: Borchers, J.W., ed., Land subsidence case studies and current research, Proceedings of the Joseph F. Poland Symposium on Land Subsidence, Sacramento, Calif., 4-5 October 1995, Association of Engineering Geologists, Special Publication no. 8, 75-79, 1998.

Terzaghi, K. 1925. Principles of soil mechanics: IV, Settlement and consolidation of clay, Eng. News-Rec., p. 874-878.

Terzaghi, K. and R.B. Peck. 1967. Soil mechanics in engineering practice. New York, John Wiley and Sons, Inc. 2d ed., 729 p.

Tolman, C.F. and J.F Poland, 1940. Ground-water, salt-water Infiltration, and ground-surface recession in Santa Clara Valley, Santa Clara County, California: American Geophysical Union Transactions, Part 1, pp. 23-35.

Turco, M. 2015. Science and Research Plan; Harris-Galveston Subsidence District, Harris-Galveston Subsidence District, Houston, TX.

Waichler, S.R., and Chochran, G.F., 1991, Modelling and prediction of land subsidence in Las Vegas Valley, Nevada: University of Nevada, Desert Research Institute, Water Resources Center Publication 41133, 30 p.

Wang, G. and T. Soler. 2014. Measuring Land Subsidence Using GPS: Ellipsoid Height vs. Orthometric Height, J. Surv. Eng., 141, 1– 12, 2014.

Wang, G., J. Welch, T.J. Kearns, J. Yang, and J. Serna. 2015. Introduction to GPS geodetic infrastructure for land subsidence monitoring in Houston Texas, USA. Proceedings, IAHS, 372. P. 297-303.

Wei ZX (2002) The stress-strain analysis of the 4th confined aquifer in Shanghai City. Hydrogeol Eng Geol 1:1–4 (in Chinese)

Xue YQ, Wu JC, Zhang Y et al (2008) Simulation of the regional land subsidence at south of Yangtze River delta. China Sci D Earth Sci 38(4):477–492 (in Chinese)

Yang G, Wei Z., Huang C. (2005). Advances and Challenge in Research on Land Subsidence in China, Volume 1: Proceedings of the 7th Symposium on Land Subsidence, Shanghai, PRC, October 2005, Shanghai Scientific & Technical Publishers, Vol.1, pp. 3- 9.

Young, S.C., and V. Kelley, eds., N. Deeds, P. Knox, T. Budge, and E. Baker. 2006. A Site Conceptual Model to Support the Development of a Detailed Groundwater Model for Colorado, Wharton, and Matagorda Counties: Lower Colorado River Authority, Austin, Texas.

Young, S.C., V. Kelley, T. Budge, N. Deeds, and P. Knox. 2009. Development of the LCRB Groundwater Flow Model for the Chicot and Evangeline aquifers in Colorado, Wharton, and Matagorda counties: LSWP Report Prepared by the URS Corporation, prepared for the Lower Colorado River Authority, Austin, TX.

Young, S.C., M. Jigmond, T. Jones, D. Lupton, T. Ewing, and B. Harden. 2017. Draft Report: Conceptualization, investigation, and sensitivity analysis regarding the effects of faults on groundwater flow in the Carrizo-Wilcox Aquifer in central Texas: prepared for the TWDB, 170 pp.

Zhang Y, Xue YQ, Wu JC, Ye SJ, Li QF (2007) Stress-strain measurements of deforming aquifer systems that underlie Shanghai, China. Environ Eng. Geosci. 13:217–228. doi:10.2113/gseegeosci.13.3.217

Zhang, M. and T. J. Burbey, 2016. Inverse modelling using PS-InSAR data for improved land subsidence simulation in Las Vegas Valley, Nevada, Hydrol. Process. 30, 4494–4516 (2016), DOI: 10.1002/hyp.10945.

Zhang, Y., Wu, J., Xue, Y., Wang, Z., Yao, Y., Yan, X., Wang, H. (2015). Land subsidence and uplift due to long-term groundwater extraction and artificial recharge in Shanghai, China, Hydrogeol J. (2015) 23:1851–1866 DOI 10.1007/s10040-015-1302-x

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APPENDIX A:
Harris-Galveston Subsidence District: Evaluation of ASR in the Gulf Coast Aquifer, Technical Memorandum.

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ARCADIS Design & Consultancy for natural and built assets

For INTERA Incorporated

HARRIS-GALVESTON SUBSIDENCE DISTRICT: EVALUATION OF ASR IN THE GULF COAST AQUIFER

Technical Memorandum

September 2017

HARRIS-GALVESTON SUBSIDENCE DISTRICT: EVAUATION OF ASR IN THE GULF COAST AQUIFER

Technical Memorandum

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ACRONYMS AND ABBREVIATIONS

AFY	Acre-feet per year
ASR	Aquifer storage and recovery
Authority	Gulf Coast Water Authority
BRA	Brazos River Authority
COA	Certificate of Adjudication (TCEQ)
CY	Calendar year
District	Harris-Galveston Subsidence District
DOR	Drought-of-record (1947-1957)
Dow	Dow Chemical Company
GCMUD	Galveston County Municipal Utility District
GCWA	Gulf Coast Water Authority
GCWCID	Galveston County Water Control & Improvement District
gpm	Gallons per minute
HGSD	Harris-Galveston Subsidence District
IPS	Industrial Pump Station (GCWA)
MG	Million gallons
MUD	Municipal utility district
mgd	Million gallons per day
SJ-B	San Jacinto-Brazos
TCEQ	Texas Commission on Environmental Quality
TSV	Target Storage Volume
WAM	Water Availability Model (TCEQ)
WTP	Water Treatment Plant

1 INTRODUCTION AND BACKGROUND

The Harris-Galveston Subsidence District (HGSD or the "District") was created in 1975 for the purposes of ceasing and preventing subsidence in Harris and Galveston Counties, Texas by regulating the use of groundwater. Since 1975, groundwater regulation by HGSD has increased aquifer water levels and slowed or stopped subsidence in areas closest to the Gulf of Mexico, within the District's Regulatory Area 1. Because of severe but short-term droughts in 2011 and 2012, industries in Regulatory Area 1 became concerned that their primary water source (the Brazos River) may lack long-term reliability.

As a result, the District decided to investigate aquifer storage and recovery (ASR) as a water management strategy. The HGSD believes that it is important for the use of ASR within the District to not create additional subsidence. Therefore, the HGSD engaged the INTERA team, composed of INTERA Incorporated, ASR Systems LLC and Arcadis U.S., Inc., to develop an understanding of the potential for "subsidence-neutral" ASR as a water supply strategy and to provide insight into what could be an acceptable ASR operating strategy within Regulatory Area 1.

This evaluation of ASR (the "Project") is based on a hypothetical ASR project within the industrial corridor of Regulatory Area 1. The objective of this Project is to determine how much excess water from existing sources can be reasonably stored for periods up to five years and recovered when necessary without creating subsidence. The evaluation also investigated water quality issues, including the potential geochemical reactions between the stored water from existing treated water sources and native groundwater.

1.1 Arcadis Scope of Work

As a member of the INTERA team, Arcadis U.S., Inc. (Arcadis) provided assistance with data collection and analysis, development and description of the hypothetical ASR project, and analysis of water quality data for the treated drinking water, which is the most feasible water source for ASR storage in Regulatory Area 1. In addition to project management and regular team communication through meetings and conference calls, the Arcadis scope of work included:

- Reviewing the regional water plan (Region H), and information provided by the District and others to develop a basic understanding of the sources of water supply and water supply availability for manufacturing (industrial) purposes, and the historical and projected water demands within Regulatory Area 1;
- Assisting in determining the most likely location for ASR storage;
- Providing this information to other members of the INTERA team so that estimates of storage volumes, and recharge and recovery rates can be made;
- Providing input into the description of the hypothetical ASR project;
- Reviewing treated water quality data, and providing input into potential treatment requirements for ASR storage, if required; and
- Reporting the information obtained and evaluated in previous tasks.

1.2 Purposes of Technical Memorandum

The purposes of this Technical Memorandum are to document the information gathered and analyzed during this Project, and to provide input into the description of the hypothetical ASR project.

2 DATA COLLECTION AND ANALYSIS

Arcadis evaluated both the total volume of ASR storage required and the quality of treated water that would be stored. The total volume of ASR storage required (2.4) was calculated by considering current industrial sources of water supply (2.1), current industrial water demand (2.2), potential volumes of water available for storage (2.3). Treated water quality (2.5) was also summarized. The potential compatibility of the source water with the aquifer's native groundwater was not evaluated by Arcadis.

2.1 Industrial Sources of Water Supply

Regulatory Area 1 is a highly urbanized area on the west side of Galveston Bay, including all or portions of the cities of Texas City, League City, Pasadena, La Porte and Baytown. The industries within the area that are most likely to implement ASR as a water management strategy are in the Texas City industrial complex and along the Houston Ship Channel. The 2016 Region H Water Plan documents that most of the municipal and manufacturing (industrial) water supplied to Regulatory Area 1 is untreated surface water from the San Jacinto-Brazos (SJ-B) and the Brazos River Basins supplied by the Gulf Coast Water Authority (GCWA or the "Authority").

The GCWA's water supply is governed by run-of-river Certificates of Adjudication (COAs) from the State of Texas through the Texas Commission on Environmental Quality (TCEQ), and stored water contracts with the Brazos River Authority (BRA). **Table 2-1** summarizes the Authority's COAs that can be used to supply water to GCWA's industrial customers in the area of interest for this evaluation, and the authorized maximum annual volume of water in acre-feet per year (AFY). For purposes of this study, the BRA contracts were not considered because they provide a firm supply from storage in upstream reservoirs and are not subject to curtailment. Additionally, in 2006, GCWA purchased the Chocolate Bayou Water Company (Juliff Canal System) and the associated water right (COA 12-5322). That water right is not included in **Table 2-1 (or Table 2-3)** but is discussed separately in the following paragraphs.

Table 2-1: Evaluated GCWA Certificates of Adjudication and Authorized Annual Volume

Certificate No.	Diversion Point	Authorized Annual Volume (AFY)
11-5169	Oyster Creek	12,000
11-5357	Chocolate Bayou	57,500
12-5171 SR	Brazos River	75,000
12-5171 JR	Brazos River	50,000
12-5168	Brazos River	99,932
Total		**294,432**

The water supplied to the industries by the GCWA is raw (untreated) water[1], primarily for cooling and process purposes. The industries typically treat their own water for potable purposes, or purchase treated water from local utilities. The GCWA has water supply contracts with each of the industrial customers. **Table 2-2** summarizes the contracted volume with each major industry in the Texas City area of Regulatory Area 1. The water is delivered through GCWA's Industrial Pump Station (IPS). The major customers supplied by the IPS include: Dow/Union Carbide Corporation; Marathon-Galveston Bay Refinery; Valero Refining Texas, LLP; Marathon Petroleum, LLC (Texas City Refinery); and Eastman Chemical Company. A much smaller industrial user (ISP Technologies/Ashland Chemical) is supplied directly from a GCWA terminal storage reservoir in the area and was not included in this analysis. **Table 2-2** also shows the percentage of the total volume contracted by each industry. The contract volumes are shown in both million gallons per day (mgd) and annual AFY.

Table 2-2: GCWA Major Industrial Customers and Contract Water Volume for Industries in the Texas City Area

Industrial Customer	Contract Water Supply Volume (mgd)	Contract Water Supply Volume (AFY)	Percent of Total Contracted Volume
Dow/Union Carbide Corporation	12.391	13,878	21%
Marathon-Galveston Bay Refinery	28.600	32,032	48%
Valero Refining Texas, LLP	6.510	7,291	11%
Marathon Petroleum, LLC (Texas City Refinery)	4.000	4,480	7%
Eastman Chemical Company	8.542	9,567	14%
Total	**60.043**	**67,248**	**100%**

2.2 Industrial Water Availability and Demand

Run-of-river water rights, such as the Authority's COAs, are subject to reduction or curtailment during periods of drought. In 2009, 2011, 2012 and 2013 dry conditions stressed water supplies in the lower Brazos River Basin. "Priority calls" were made to the TCEQ by the Dow Chemical Company ("Dow") in Freeport, Texas based on Dow's senior water rights. Other water rights holders, including the GCWA, were impacted for water rights junior to February 14, 1942. In response to the calls for water during these periods of drought, TCEQ appointed a Watermaster for the Brazos River Basin.

Arcadis reviewed the results of the TCEQ Water Availability Model (WAM) Run 3 to determine how much water might be available to the GCWA's industrial customers during a drought. The annual water availability using Run 3 of the WAM is predicated on full use by all senior water rights holders and no return flows, and is therefore the most conservative simulation. The results of the water availability

[1] Municipal water to local cities is supplied by the GCWA from its Thomas S. Mackey Water Treatment Plant (WTP). The Mackey WTP is in Texas City, just west of the industrial complex.

analysis for the Authority's COAs (excluding COA 12-5322) are summarized in **Table 2-3**. All volumes are reported in AF or AFY. The table provides:

- the maximum annual volume of water authorized by each COA;
- the mean annual volume of water that can be diverted from the creek, bayou or river under the COA during the period of record simulated in the WAM (1940 through 1997);
- the minimum annual volume of water available in the worst year of the 1950's drought-of-record (DOR);
- the mean volume of water available in the five worst years of the DOR; and
- the mean volume available in the four worst years of the DOR.

Table 2-3: Summary of Water Availability Under GCWA COAs (in AF or AFY)

Certificate No.	Diversion Point	Maximum Volume	1940-1997 Mean Volume	Minimum Volume	Percent of Maximum	1947-1957 5-Year Low Mean Volume	Percent of Maximum	1947-1957 4-Year Low Mean Volume
11-5169	Oyster Creek	12,000	10,533	0	0%	5,350	45%	6,687
11-5357	Chocolate Bayou	57,500	46,099	15,930	28%	32,173	56%	36,234
12-5171 SR	Brazos River	75,000	73,237	49,192	66%	58,193	78%	60,444
12-5171 JR	Brazos River	50,000	45,288	11,700	23%	22,746	45%	25,508
12-5168	Brazos River	99,932	99,775	94,943	95%	98,112	98%	98,904
Total		**294,432**	**274,932**	**171,765**		**216,575**		**227,777**
Percent of Max		**100%**	**93%**	**58%**		**74%**		**77%**
Percent Reduction				**42%**		**26%**		**23%**

As shown above in **Table 2-3**, in the worst year of the DOR, the COAs will be able to supply only 58 percent of the authorized annual amount (a reduction of 42 percent), and in the five worst years of the DOR, the availability will be on average about 74 percent of the authorized annual amount (a reduction of 26 percent).

Arcadis did not include COA 12-5322 in the evaluation for the Project because it is not clear that water diverted under that water right is currently available for treatment at the Mackey WTP and use in the Texas City industrial complex. Previous studies by GCWA consultants have either excluded COA 12-5322 from the analysis or have discussed it separately because the water may only be used in the Chocolate Bayou area or other portions of the GCWA canal system. Information in the GCWA's latest Long-Range Water Supply Study states that the total authorized diversion volume for COA 12-5322 is 155,000 AFY. The water right has three priority dates (1929, 1955 and 1983), only one of which is senior to 1942. The volume of water available under COA 12-5322 in the worst year of the DOR (i.e., the firm yield) is 68,531 AF (44 percent of the authorized amount). This is reasonably consistent with the analysis of the other GCWA COAs, as summarized in **Table 2-3**.

GCWA supplied the INTERA team with daily data on the actual raw water supplied to the five Texas City industries listed in **Table 2-2.** The data for calendar years (CY) 2011 through 2016 were evaluated, although the data for CY 2012 included only the months of January through June. It appears that the data are based on manual meter readings because there are typically no data for weekend days. The data for Mondays reflect water delivered on Saturdays and Sundays. Using these data, it is difficult to determine the maximum water delivered on any one day; however, in 2011 the maximum day industrial demand appears to be about 60 million gallons (MG). In 2016, the GCWA delivered a total of 48,693 AF to the five industries (which is an average of 43 mgd).

In addition, Arcadis reviewed the 2016 Region H Water Plan to evaluate the potential future demand for industrial customers supplied by the GCWA. The Regional Plan shows that GCWA's industrial water demand in Galveston County (location of Texas City industrial complex) will only increase 3 percent over the 50 years between 2020 and 2070, from 55,871 AFY to 57,587 AFY. This seems reasonable given the built-out conditions in the area.

Arcadis provided the INTERA team with a spreadsheet summarizing the daily industrial water demand for the period of record for the five major industries. The daily data were provided in MG and AF. A copy of the final version of that Excel spreadsheet is **Appendix A**.

2.3 Water Available for ASR Storage

During the kickoff meeting with the District, it was recommended that the source water for ASR storage be treated water from the Thomas S. Mackey WTP located in Texas City. The plant was acquired by the GCWA from Texas City in 1983. The Mackey WTP is a 49.7-mgd conventional surface WTP. The WTP currently serves 13 cities and water utilities in Galveston County. The treated water customers include the cities of Texas City, La Marque, Galveston, Hitchcock and League City; and Galveston County Water Control & Improvement District (GCWCID) #1, GCWCID #8, GCWCID #12, GCFWD #6, Galveston County Municipal Utility District (GCMUD) 12, Bacliff Municipal Utility District (MUD), Bayview MUD and San Leon MUD.

The GCWA supplied data on total treated water supplied by the Mackey WTP for the period from CY 2014 through CY 2016. For purposes of evaluating the treated water available for storage in an ASR wellfield, Arcadis added to its industrial demand spreadsheet formulas that calculate the difference between the Mackey WTP capacity (49.7 mgd) and the actual daily volume of water delivered from the WTP during the 2011-2016 period of record. That spreadsheet (**Appendix A**) was provided to the INTERA team for use in developing the ASR model.

During the three years of record, the maximum day treated water production was 42.9 MG (131.7 AF); the minimum day production was 10.8 MG (33.2 AF); and the average daily production was 30.7 mgd (94.2 AF/day). Therefore, the volume of water available for ASR storage on a daily basis during the period of record ranges from 6.8 MG (20.8 AF) to 38.9 MG (119.3 AF), and averages 19.0 mgd (58.3 AF/day).

2.4 Water Required from ASR Storage

Arcadis provided the INTERA team with an estimate of the volume of water required from ASR storage to meet the total demand of the five industries in the Texas City complex during a drought, with the understanding that the hypothetical ASR wellfield might be conceptually "designed" to supply less than that much water. To provide this daily estimate of water required from ASR storage, Arcadis modified its spreadsheet (**Appendix A**) to calculate the deficit in water availability using the information summarized in **Table 2.3** and the actual industrial water supplied by the GCWA during CYs 2011 through 2016.

Because CY 2011 was an extremely dry year and could be considered the worst year of a five-year drought, the water actually delivered to the five industries each day in 2011 was reduced by 42 percent. The reduction (deficit in supply) equals the volume of water required from ASR storage to meet the industrial demand on each day. For the remaining four years (CYs 2012 through 2016), the daily delivered water was reduced by 26 percent, and that deficit became the volume of water required from ASR storage to meet the industries' daily demands during those years.

2.5 Water Quality

Arcadis reviewed and summarized treated water quality data for the Thomas S. Mackey WTP. Data were collected from the GCWA's Annual Water Quality Reports[2] and through the TCEQ's Drinking Water Watch[3] database for Public Water System Number TX0840153. As limited data were available, all available data from 2002 through 2017 were reviewed. Data for the combined filter effluent, finished water (i.e., the entry point [EP001]), and distribution system are summarized in Table 2-4, Table 2-5, and Table 2-6, respectively. These tables summarize the minimum, average and maximum values measured for various parameters of interest to this Project. Although not shown in the tables, total coliform bacteria were reported as absent from all samples reported between July 2015 through May 2017. The complete tables of data are provided in **Appendix B**.

Table 2-4: EP001 Water Quality Results from 2002 - 2017

Parameter	Minimum	Average	Maximum
Total Alkalinity (TA) mg/L	97	126	156
Total Dissolved Solids (TDS) mg/L	210	358	733
Conductivity @ 25C UMHO/cm	432	682	1386
Specific Conductance mS/cm	328	559	1145
pH (field)	6.9	7.3	7.5
Chloride (Cl^-) mg/L	39	85	275
Fluoride (Fl^-) mg/L	0.18	0.5	0.95
Sulfate (SO_4^{2-}) mg/L	33	58	122
Carbonate Alkalinity (CO_3^{2-}) mg/L	<1	<2	<2
Bicarbonate Alkalinity (HCO_3^{1}) mg/L	118	154	190
Calcium (Ca) mg/L	37	48.2	67.6
Magnesium (Mg) mg/L	6.95	10.5	17.4
Sodium (Na) mg/L	36.6	60.4	163

[2] http://gulfcoastwaterauthority.com/reports-studies-data/water-quality-reports/

[3] http://dww2.tceq.texas.gov/DWW/JSP/WaterSystemDetail.jsp?tinwsys_is_number=1901&tinwsys_st_code=TX&wsnumber=TX0840153 &DWWState=TX

Parameter	Minimum	Average	Maximum
Potassium (K) mg/L	4.54	5.13	5.85
Iron (Fe) mg/L	<.01	<0.1	<0.46
Aluminum (Al) mg/L	<0.02	<0.03	<0.05
Copper (Cu) mg/L	0.0026	0.0149	0.0335
Manganese (Mn) mg/L	<0.001	<0.0036	<0.0127
Zinc (Zn) mg/L	0.0978	0.1356	0.224
Cadmium (Cd) mg/L	<0.001	<0.001	<0.0012
Selenium (Se) mg/L	<0.003	<0.0034	<0.0066
Total Hardness ($CaCO_3$)	121	163	240
Nitrate (NO_3^-) mg/L	0.09	0.63	1.48
Chloroform ($CHCl_3$) µg/L	1	4.9	12
Bromodichloromethane ($CHBrCl_2$) µg/L	1	9.9	16
Dibromochloromethane ($CHBr_2Cl$) µg/L	1	13.4	22
Bromoform ($CHBr_3$) µg/L	.7	5.7	17
Total Trihalomethanes (TTHM) µg/L	4	33.9	49.8

Table 2-5: Distribution System Water Quality Results from 2004 - 2016

Parameter	Minimum	Average	Maximum
Chloroform ($CHCl_3$) µg/L	2.9	9.2	17.6
Bromodichloromethane ($CHBrCl_2$) µg/L	11.2	16.7	23.1
Dibromochloromethane ($CHBr_2Cl$) µg/L	13.4	22.0	32.2
Bromoform ($CHBr_3$) µg/L	1.8	8.1	27.4
Total Trihalomethanes (TTHM) µg/L	39.5	56.0	75.3

Table 2-6: Combined Filter Effluent Water Quality Results from 2015 - 2017

Parameter	Minimum	Average	Maximum
Highest Measured Turbidity	0.07	0.19	0.90

Additional parameters of interest to this Project, which were not available in the data reviewed, include:

- Total Suspended Solids
- Color
- Temperature
- Dissolved Oxygen
- Eh
- Total Silica
- Non-Carbonate Hardness

- Calcium Hardness
- Phosphate
- Ammonia
- Hydrogen Sulfide
- Carbon Dioxide
- Total Halogenating Hydrocarbon
- Specific Gravity or Fluid Density

3 HYPOTHETICAL ASR PROJECT DESCRIPTION

Using the data collected and evaluated in previous tasks, Arcadis developed the following description of the hypothetical ASR project, subject to input from other members of the INTERA team on the required Target Storage Volume (TSV), and the required recharge and recovery rates (in gallons per minute [gpm]).

Location. The most likely location for the hypothetical ASR project is in the general area of the Mackey WTP and the Texas City industrial complex (see **Figure 3-1**). The proximity of the source water (i.e., the Mackey WTP) for ASR storage and the place where the stored water will be needed reduces the required infrastructure (e.g., pump stations and pipelines) for an ASR project.

Source of Supply. The source of supply for stored water is the 49.7-mgd Mackey WTP, using excess treatment capacity. Although the new ASR regulations in Texas provide for ASR storage with partially-treated water, from a practical standpoint it is best to assume in a conceptual study, such as this Project, that treated water will be used. The ASR project approach would be to: (i) operate the Mackey WTP at its maximum sustainable capacity; and (ii) store in the ASR wellfield any treated water not required by the GCWA's municipal customers.

ASR Wellfield. The wellfield could be located anywhere in the general area, but the most likely locations are at the Mackey WTP, the GCWA's administration property or near the industrial users (assuming that there are no environmental conditions that would preclude storage at or near the industrial plants).

Figure 3-1: Area Map

APPENDIX A

Daily Industrial Water Demand, Water Availability and Water Required from ASR Storage

APPENDIX B

Thomas S. Mackey WTP Treated Water Quality Data

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APPENDIX B:
A CONCEPTUAL FRAMEWORK FOR THE POTENTIAL GEOCHEMICAL CONSIDERATIONS OF ASR IN REGULATORY AREA 1, TECHNICAL MEMORANDUM.

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TECHNICAL MEMORANDUM

TO: David Pyne/ASR Systems/Gainesville, FL

FROM: Richard Glanzman/Glanzman Geochemical LLC/Lakewood, CO

SUBJECT: HGSD Geochemistry Report

DATE: June 18, 2018

SUMMARY

Groundwater analyses from the 152 wells in the Beaumont, Lissie and Willis Formations of the Chicot Aquifer indicate a relatively broad range of total dissolved solids but only two water chemistry types: sodium-bicarbonate and sodium-chloride. Essentially all well locations could be considered for ASR purposes but some are geochemically more readily acceptable than others. There are too few Beaumont and Willis wells to be representative but there are a sufficient number of Lissie wells with sufficient groundwater chemistry to rank 12 well locations by geochemical preference for ASR purposes along with geochemical questions each pose. The potential for calcite precipitation using system water from the Gulf Coast Water Authority Water Treatment Plant as the recharge source and the potential for iron sulfide (pyrite) and iron carbonate (siderite) oxidation and dissolution are two of the potential mineralogic problem issues identified by geochemical modeling. Calcite precipitation may present a plugging problem while oxidation of pyrite may mobilize arsenic and metals plus increase the total dissolved solids of the recovered water.

Lack of chemical parameter and mineralogical data is a major problem with the data set. There are neither arsenic nor uranium concentrations reported for the Chicot Aquifer, although very limited data from one well at Texas City confirms the presence of arsenic. Field parameters, temperature, pH and particularly oxidation reduction potential and dissolved oxygen are mostly missing. Total organic carbon, nitrogen and phosphorus speciation and concentrations are also largely missing. There is neither mineralogical data nor other physical characteristics available except for a few geophysical logs of the aquifer sediments. This severely restricts the ability to understand the geochemistry of the groundwaters and assess the potential of individual well locations for ASR. Acquisition of this information and data is recommended when an ASR well location is chosen, to minimize problems that could inhibit successful completion of the project.

Groundwater from two deep wells with an excellent suite of analytical data in the Jasper Aquifer contained an elevated arsenic concentration that exceeded the drinking water standard. The arsenic concentration exceedance is likely enhanced above the standard by adsorption onto iron oxyhydroxide colloids in and near the wellbore rather than dissolved in the groundwater.

There is insufficient physical characterization data on the aquifer sediments to assess the potential geochemical relationships that potentially relate to subsidence issues. However, the presence of elevated carbon dioxide gas and methane gas (Jasper Aquifer) at some well locations may be of concern. The actual total amount of gas and gas composition is unknown.

INTRODUCTION

This preliminary geochemistry study is a review of the available Chicot Aquifer groundwater chemistry from 152 well locations in Regulatory Area 1 of the Harris Galveston Subsidence District (HGSD), Texas

(Figure 1). The water quality database used in this analysis is included as part of the electronic project deliverables.

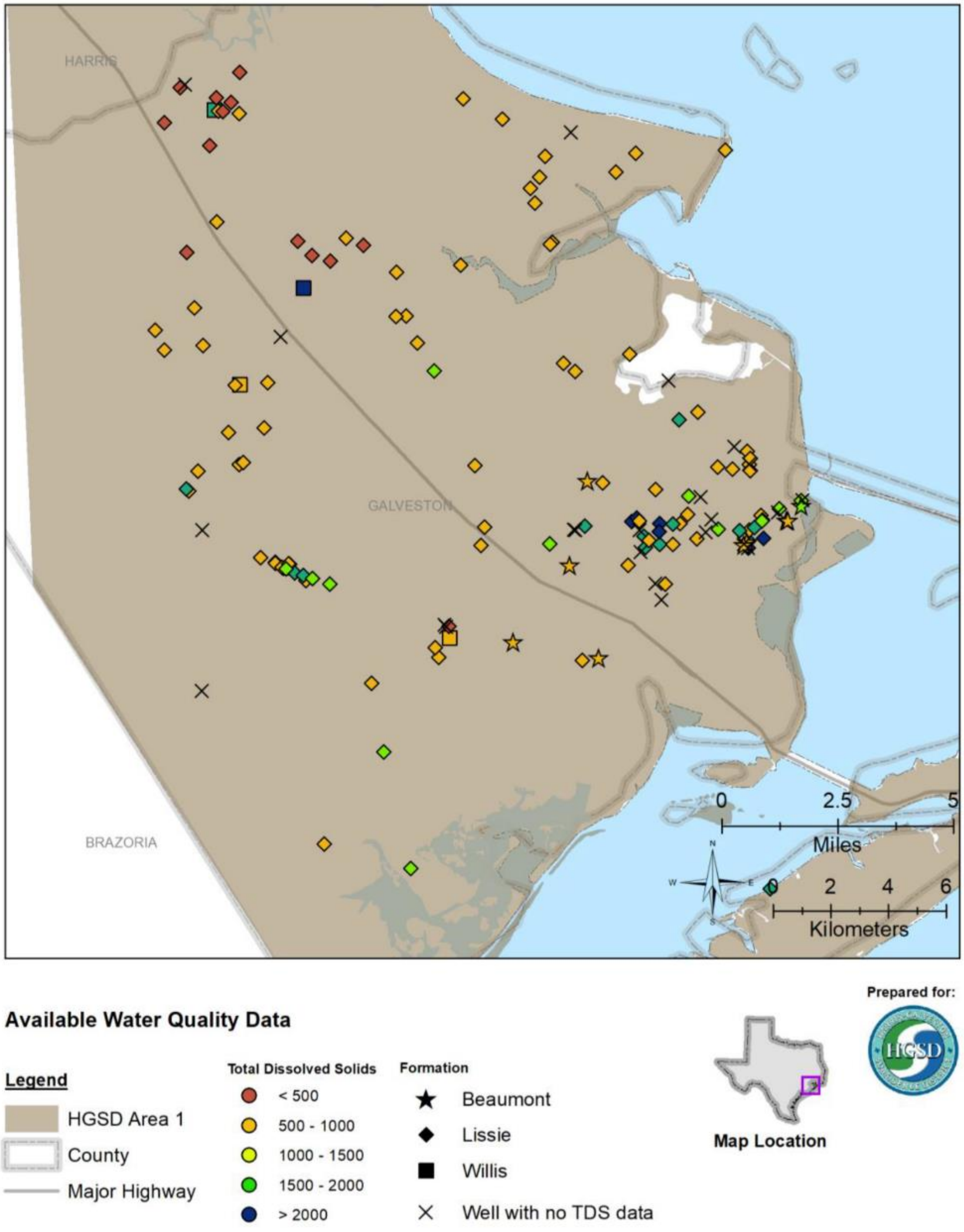

Figure 1. Distribution of wells with water quality data reviewed in this study.

INTERA et al. (2016) reported on the fresh, brackish and saline groundwater resources of the area using geophysical logs. The Chicot Aquifer has three formations, the Beaumont, Lissie and Willis, with sands comprising an average of 68 percent of the aquifer sediments. The groundwater volume in the sands of the three formations, assuming a void fraction based on specific yield, indicated that all three were dominated by fresh water (<1,000 milligrams per Liter (mg/L) Total Dissolved Solids (TDS)) in Harris County and slightly saline water (1,000 to 3,000 mg/L TDS) in Galveston County (INTERA, et al., 2016, p. 100).

During 2010 – 2011 there was an ASR demonstration project in Texas City, Texas by CH2M, however a final report is not available. Limited data provided by HGSD indicates that a slightly elevated concentration of arsenic (14.8 ug/l) was present in the recovered water at the end of recovery during a third cycle, however the recovery volume was 151% of the recharge volume. Experience in other states has demonstrated the viability of a simple approach to controlling arsenic concentrations in the recovered water, which is to initially form and maintain a buffer zone around the well, typically comprising about 30 to 50 percent of the Target Storage Volume. This procedure was not implemented at Texas City. Over-recovery of the small volumes of stored water during each cycle most likely contributed to the slightly elevated arsenic concentration. The U.S. Geological Survey published three reports on the geochemistry of arsenic and radionuclide occurrence in the Gulf Coast Aquifer System that includes the Chicot Aquifer in the Houston, Texas area (Oden and Szabo, 2015; Oden, Brown and Oden, 2011; and Oden, Oden and Szabo, 2010). The redox condition as defined by field measured dissolved oxygen (DO) and oxidation reduction potential (ORP) is the primary control on uranium mobility while pH, DO, and ORP are primary factors controlling arsenic mobility.

Uranium is mobile where the groundwater is under oxidizing conditions and immobile where groundwater is under reducing conditions. Arsenic is mobile under both oxidizing and reducing conditions but its mobility is considerably enhanced under reducing conditions. Furthermore, arsenic becomes increasingly mobile under oxidizing conditions when the pH of the groundwater is equal to 7.5 and higher values.

There are very limited available data on arsenic and no data on uranium in the Chicot data base developed for this study. However, the pH and redox condition of a ground water can be and is estimated by thermodynamic equilibrium modeling where the temperature, dissolved iron and major ions are available. Therefore, the above mobility characteristics of arsenic and uranium can be incorporated into a ranking of a groundwater being considered for an ASR project. The stability of iron sulfide (pyrite) and iron carbonate (siderite) minerals can also be assessed with modeling using the same parameters.

An accurate field pH of the native groundwater is also very important to assess the potential for the precipitation of calcium-carbonate (calcite), the most common plugging mineral in an ASR project. The alkaline pH and elevated bicarbonate concentration in the sodium-bicarbonate water type is particularly susceptible to an increase in calcium concentration in the recharge water or from cation exchange on the clays. Modeling the equilibrium status of calcite allows an accurate estimate of the pH of the native groundwater as well as for assessing the tendency for calcite precipitation where the recharge water and the native groundwater mix in the aquifer. Field measurement of temperature and pH along with the suite of major ion chemistry are necessary to model the calcite equilibrium.

The clay mineralogy of the aquifer sediments is a second common plugging factor in ASR projects. Silica, aluminum and the four major ion cations (calcium, magnesium, sodium and potassium) are necessary for model estimation of the clay mineralogy. The model estimate of clay mineralogy is no substitute for the laboratory determination of the aquifer mineralogy but it does provide an estimate of the mineralogy including clays controlling much of the groundwater chemistry. This clay mineralogy can be used to partially assess the potential impact of the recharge water on the clay stability. The cation exchange capacity is assumed to be dominated by sodium based on the dominance of sodium in the groundwater. Modeling is used where there is sufficient data to estimate the mineralogy since there is neither mineralogy nor other physical characteristics data available for this geochemical study. Such information would normally be derived from analysis of continuous wireline cores of the aquifer materials.

RECHARGE WATER

The Gulf Coast Water Authority Water Treatment Plant is the assumed recharge water source. Analytical data for 2002 through April, 2017 are listed and summarized in Table 1. Most of the data were collected during winter months, which is the most likely season for active recharge use. The average recharge water is a sodium-calcium-bicarbonate water chemistry type with a low TDS of 358 mg/L and near neutral pH of 7.3. TDS ranges from 210 to 733 mg/L and pH from 6.9 to 7.5. The water chemistry type ranges from calcium-sodium-bicarbonate at the lowest TDS to a sodium-chloride type at the highest TDS as shown on the trilinear diagram of Figure 2. Essentially all the maximum values on Table 1 are from a single sample with anomalously high reported values, collected on March 1, 2006.

With the exception of the single iron concentration of 0.46 mg/L for the March 1, 2006 sample, all the remaining iron concentrations are well within the 0.30 mg/L secondary drinking water standard for iron. All of the other inorganic parameter concentrations are also well within their respective drinking water standards.

Total organic carbon (TOC) has an average of 3.1 mg/L and ranges from 1.81 to 4.69 mg/L. These concentrations are elevated compared to the 1.0 or less TOC concentrations in groundwater. TOC can have a tendency to promote microbial bacteria in the subsurface, particularly in the wellbore when a well is idle. The ammonia-nitrogen concentration of the treated water is not reported but is also a potential source for microbial growth. It is recommended that the ammonia-nitrogen concentration of the recharge water be determined as part of the recharge water analytical schedule. It is also recommended that the recharged water in the wellbore receive a disinfectant equivalent to the potable level when the well is idled to control microbial growth in the wellbore environment. This “trickle flow” of disinfected drinking water is commonly implemented in ASR wells during extended periods of no recharge and no recovery, exceeding about a week.

Total trihalomethane and the four disinfection byproducts are within their drinking water concentrations. These concentrations will likely decline with storage time in the aquifers, resulting in a trace of chloride and bromide in the stored water at concentrations that would not be readily measurable.

Thermodynamic equilibrium modeling indicates that the recharge water is in equilibrium with the minerals estimated to be present in the aquifer sediments. Calcium carbonate precipitation is estimated to not be a potential problem at a pH equal to or less than 8.0 but precipitation will be increasingly probable at a pH at and above 8.2 to 8.5 in the recharge water chemistry. As shown in Table 1, pH values in the recharge water are less than 8.0.

Table 1. Recharge water chemistry ata - Gulf Coast Water Authority Water Treatment Plant.
(all units in milligrams per Liter except where otherwise indicated)

Parameter	Units	Qualifier	Minimum	Average	Maximum	Count
Temperature (field)	°C					
Specific conductance	µS/cm		328	559	1145	13
Conductivity @ 25C	µmhos/cm		432	682	1386	14
Total Dissolved Solids			210	358	733	9
pH (field)			6.9	7.3	7.5	13
Eh (field)	millivolts					
Oxygen, Dissolved						
Dissolved Silica						
Dissolved Aluminum	µg/l	less than	20	30	50	9
Dissolved Iron	µg/l	less than	10	100	460	9
Total Iron	µg/l					
Dissolved Manganese	µg/l	less than	1	3.6	12.7	9
Calcium			37	48.2	67.6	9
Magnesium			6.95	10.5	17.4	9
Sodium			36.6	60.4	163	12
Potassium			4.54	5.13	5.85	4
Phenolph-thalein Alkalinity						
Carbonate alkalinity	mg/l as HCO3	less than	1	2	2	10
Bicarbonate Alkalinity	mg/l as HCO3		118	154	190	14
Hydroxide Alkalinity						
Total alkalinity			97	126	156	14
Sulfate			33	58	122	14
Chloride			39	85	275	14
Fluoride			0.18	0.5	0.95	14
Dissolved Copper	µg/l		2.6	14.9	33.5	9
Dissolved Zinc	µg/l		97.8	135.6	224	9
Dissolved Cadmium	µg/l	less than	1	1	1.2	9
Dissolved Selenium	µg/l	less than	3	3.4	6.6	9
Dissolved Silver	µg/l					
Total hardness			121	163	240	9
Non-carbonate hardness						
Nitrate			0.09	0.63	1.48	17
Dissolved Phosphorus						
Ammonia						
Hydrogen Sulfide						
Total organic carbon			1.81	3.1	4.69	46
Total halogenating hydrocarbons						
Specific gravity or fluid density						
ORP	millivolts					

BEAUMONT FORMATION

There are 12 chemical analyses of groundwater from the Beaumont Formation of the Chicot Aquifer of Pleistocene age, ranging in depth between 461 and 850 feet (599 feet average). Of these, only groundwater from two public supply wells (6433710 and 6441103) had sufficient chemical parameters for comparative and modeling purposes. However, 10 of the 12 analyses have sufficient major ion chemistry to be able to be plotted on the trilinear diagram of Figure 3. Eight of the 10 groundwaters are a sodium-bicarbonate water chemistry type and only two are sodium-chloride. Even though the analysis with the highest TDS and chloride concentrations includes one of the two sodium-chloride type, the other has a TDS concentration well within the TDS range of the sodium-bicarbonate type. This means that neither the TDS nor the chloride concentration alone defines the water chemistry type. This is unusual and means that simple mixing of terrestrial native groundwater with sea water is not the defining factor in these groundwaters. Furthermore, depth does not appear to be a determining factor in the water chemistry type even though chloride concentrations typically increase with depth.

Only one Beaumont groundwater is equal to the secondary drinking water standard of 1,000 mg/L. All of the remaining TDS concentrations are less than this TDS standard. However, two sodium-bicarbonate water chemistry type groundwaters and one of the two sodium-chloride water chemistry types contain chloride concentrations that exceed the secondary chloride drinking water standard of 250 mg/L.

The average TDS of groundwater from the Beaumont is 861 mg/L and ranges between 567 and 1,289 mg/L The average temperature of the groundwaters is 27.0 degrees Celsius (°C) and ranges between 26.5 and 29.9 °C. The average pH is an alkaline 8.0 and ranges from 7.81 to 8.70, reflecting the sodium-bicarbonate water chemistry type. The average oxidation reduction potential (ORP) of the two measurements is minus 33 mv, ranging from minus 125 to plus 59 mv. However, adjusting for the reference electrode by adding 240 mv results in an average of plus 207 mv and ranging between plus 115 to plus 299 mv. Based on the ORP measurements the Beaumont groundwater is considerably oxidized at about what would be expected for an average oxidized shallow alluvial ground water.

The trilinear diagram on Figure 3 indicates that, counter to the U.S. Geological Survey Houston groundwater chemistry described in Oden, et al., 2010, 2011 and 2015, ion exchange is not a significant factor in the Beaumont Formation groundwater chemistry in this HGSD study area. Calcium and magnesium comprise less than 5 and 3 percent of the cation chemistry of these groundwaters, respectively. Calcium and magnesium may have significantly higher percentages in groundwaters upgradient of this area of interest but, if so, both of their respective concentrations have been significantly decreased by ion exchange and perhaps precipitation along the groundwater flow path upgradient of this area. The reason(s) for the sodium-bicarbonate dominance and prevalence in the Chicot Aquifer is not obvious.

The two dissolved iron concentrations average 0.253 mg/L and the three manganese concentrations average 0.023 mg/L. The iron and manganese concentrations are less than the respective iron and manganese secondary drinking water concentrations. The two copper, zinc, cadmium, selenium and silver concentrations are likewise less than their respective drinking water standards.

The two TOC concentrations of 2 mg/L and particularly 7 mg/L are elevated to considerably elevated for a relatively shallow groundwater. This elevated TOC may be at least partially responsible for the sodium-bicarbonate water chemistry type. It would be of considerable interest to understand what in the aquifer sediments is responsible for the elevated TOC. This level of TOC is usually associated with organic-rich debris incorporated within the aquifer matrix. However, a sufficient amount of organic-rich debris to alter the water chemistry type would also contain iron sulfide (pyrite). In an oxidized aquifer, the pyrite would create a significantly lower pH, and convert the ground water to a sodium-calcium-sulfate water chemistry type. Even though there are low dissolved iron and manganese concentrations in this groundwater they are likely sorbed within the TOC. Clearly the very low sulfate average of 9 samples of only 1.4 mg/L indicates that very little to no pyrite is being oxidized in this groundwater. The presence of ammonia with an average concentration of 0.61 mg/L supports this conclusion since it would be converted to nitrate if pyrite was being oxidized.

Thermodynamic Equilibrium Modeling

Thermodynamic equilibrium modeling estimates that albite feldspar (sodium-aluminosilicate), potassium feldspar (potassium-aluminosilicate), cristobalite, chalcedony, beidellite (aluminum-rich swelling clay), illite (potassium-rich non-swelling clay), calcite and rhodochrosite (manganese-carbonate) are under equilibrium conditions. Cristobalite and chalcedony are ephemeral silica minerals that ultimately become quartz. Beidellite is usually a mixed layer, montmorillonite-illite alteration mineral from the dissolution of feldspars. Illite is a common alteration product from the dissolution of potassium feldspar. Iron oxyhydroxide is supersaturated at the reported field pH and ORP values.

Minerals in equilibrium with the groundwater include only those that may be responsible for the water chemistry. They do not include the other common, minimally soluble minerals that form the aquifer mineralogy, for example, quartz. They do however partially explain minerals that may produce a problem for an ASR project. In this case, calcium and rhodochrosite are of interest.

Calcite is ubiquitous in sediments and it responds rapidly to the groundwater chemistry so it is inevitably in equilibrium. The most important changes are calcium and alkalinity (bicarbonate and carbonate) concentrations, pH, temperature and carbon dioxide gas. Assuming that the analytical data are accurate, calcite equilibrium is an excellent indicator of native groundwater pH. The field measured pH can be influenced by the pressure change between the groundwater in the aquifer and after passing through the well screens to atmospheric conditions as well as lifting pressure by the pump to the system pressure. These pressure changes commonly release carbon dioxide gas that causes the pH to rise, then the dissolved carbon dioxide gas in the groundwater further re-equilibrates in the sample bottle, also causing a rise in pH. Therefore the laboratory pH measurement is commonly slightly higher than that of the native groundwater in the aquifer.

Calcium is in equilibrium in the native groundwater but the alkaline to very alkaline pH of the Beaumont aquifer may result in calcite precipitation where the recharge water mixes with the native groundwater. Evaluation of chemical reactions with the aquifer mineralogy is not possible since there is no physical characterization of the aquifers, such as from analysis of cores.

The manganese-carbonate mineral rhodochrosite is also readily soluble, therefore may result in an increase in the manganese concentration of the recovered water from the Beaumont aquifer. Since there is no mineralogical data on the Beaumont aquifer, the potential impact of the possible presence of this mineral on the recovered water cannot be assessed or predicted.

Iron is similar to calcite in that its chemical reactions responding to water chemistry are rapid and similarly change between the native groundwater in the aquifer and its determination in the laboratory. The field pH, ORP and temperature are major factors involved in the precipitation of dissolved iron between the aquifer and the laboratory. The native groundwater would be expected to contain only dissolved iron since iron-oxyhydroxide is readily removed by sorption by the aquifer matrix. After modeling determines that the pH is accurate based on the calcite equilibrium, the iron oxyhydroxide equilibrium with ORP (Eh) can be estimated. In this case, the two laboratory-reported dissolved iron concentrations are supersaturated at the reported field ORP, the model-estimated pH and groundwater chemistry. The total iron concentration can include precipitated iron oxyhydroxide from the wellbore environment as well as that precipitated by changes in pH and ORP between sample collection and the laboratory determinations, so the dissolved iron is used as a conservative estimate of the native groundwater iron concentration. The Eh from the ORP measurement is adjusted during modeling until the dissolved iron is in equilibrium. The actual Eh of the native groundwater can be lower but not higher than the modeled value. The generally higher total iron than dissolved concentration would generally estimate significantly lower Eh than the dissolved iron.

The two field ORP measurements indicate an oxidized Eh of plus 115 and 181 mv, respectively (Table 2). Modeling estimates that the native groundwater Eh is slightly reduced at minus 40 and minus 10 mv, respectively, based on the dissolved iron and iron-oxyhydroxide equilibrium. In other words, these are the Eh values needed for the laboratory-reported dissolved iron concentrations to be present in the native groundwater. Therefore the Beaumont groundwater is likely under slightly reducing not oxidized conditions.

The oxidized recharge water will change the aquifer conditions from slightly reducing to moderately oxidized depending on the aquifer mineralogy. If iron-sulfide minerals are present and exposed to the recharge water, they will become oxidized, potentially resulting in a decrease in pH and increase in sulfate as well as dissolved iron, manganese and perhaps other associated metals and metalloids (i.e. arsenic). The extent of these changes to the recovered water chemistry depends on the amount of specific iron sulfide minerals and iron carbonate minerals present and exposed to the recharge water in the aquifer mineralogy. Since the actual physical aquifer mineralogy is unknown, the impact of these potential changes to the recovered water chemistry cannot be estimated.

Finally, the thermodynamic modeling estimates the equilibrium carbon dioxide concentration present in the native groundwater. This estimate is primarily based on the pH and laboratory-reported alkalinity concentrations. The actual carbon dioxide concentration in the groundwater can be higher but not lower since the model estimated carbon dioxide is the amount that is needed by the alkalinity concentration. The two modeled Beaumont groundwaters contain an estimated 7 and 6 mg/L carbon dioxide concentrations. Groundwaters typically contain less than 1 or 2 mg/L so these estimated concentrations are elevated. Carbon dioxide is likely being continuingly introduced into the Beaumont sands since its concentrations are usually considerably lower at the elevated pH of the Beaumont groundwaters.

Carbon dioxide is typically generated by microbial oxidation of methane that in turn is generated by microbial enzymatic reactions involving organic matter in the aquifer system. It could be generated in the Beaumont Formation or it could be generated in deeper sediments/formations/aquifers and migrated upward into the Beaumont. The nature of the type and amount of organic matter in the Beaumont are unknown therefore the reason(s) for the elevated carbon dioxide concentration in the Beaumont Formation groundwater cannot be assessed or addressed. However, the more highly elevated carbon dioxide concentrations in the underlying aquifers suggest that upward carbon dioxide leakage into the Beaumont is probable.

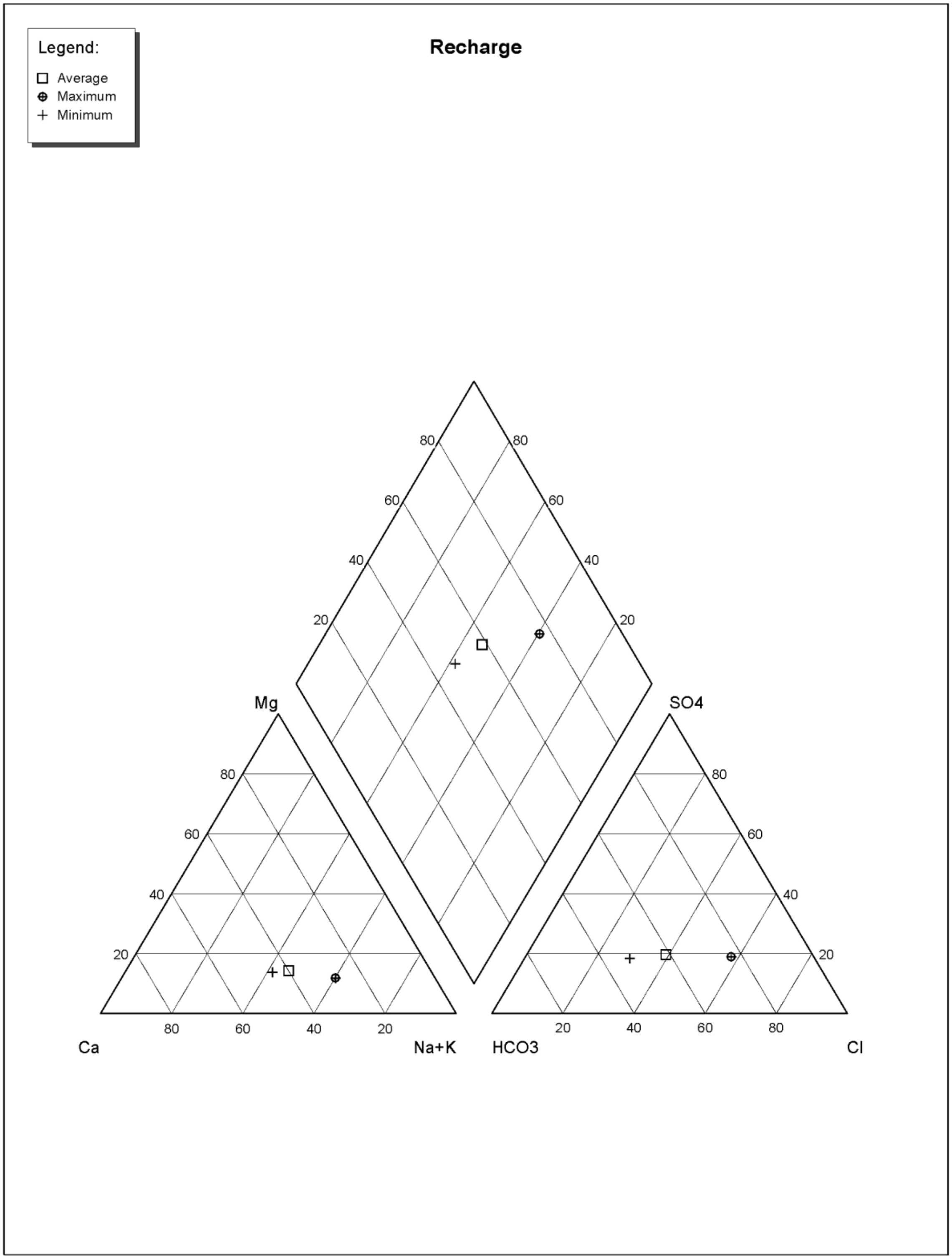

Figure 2. Trilinear diagram showing the major ion relationships between the range of recharge water chemistry.

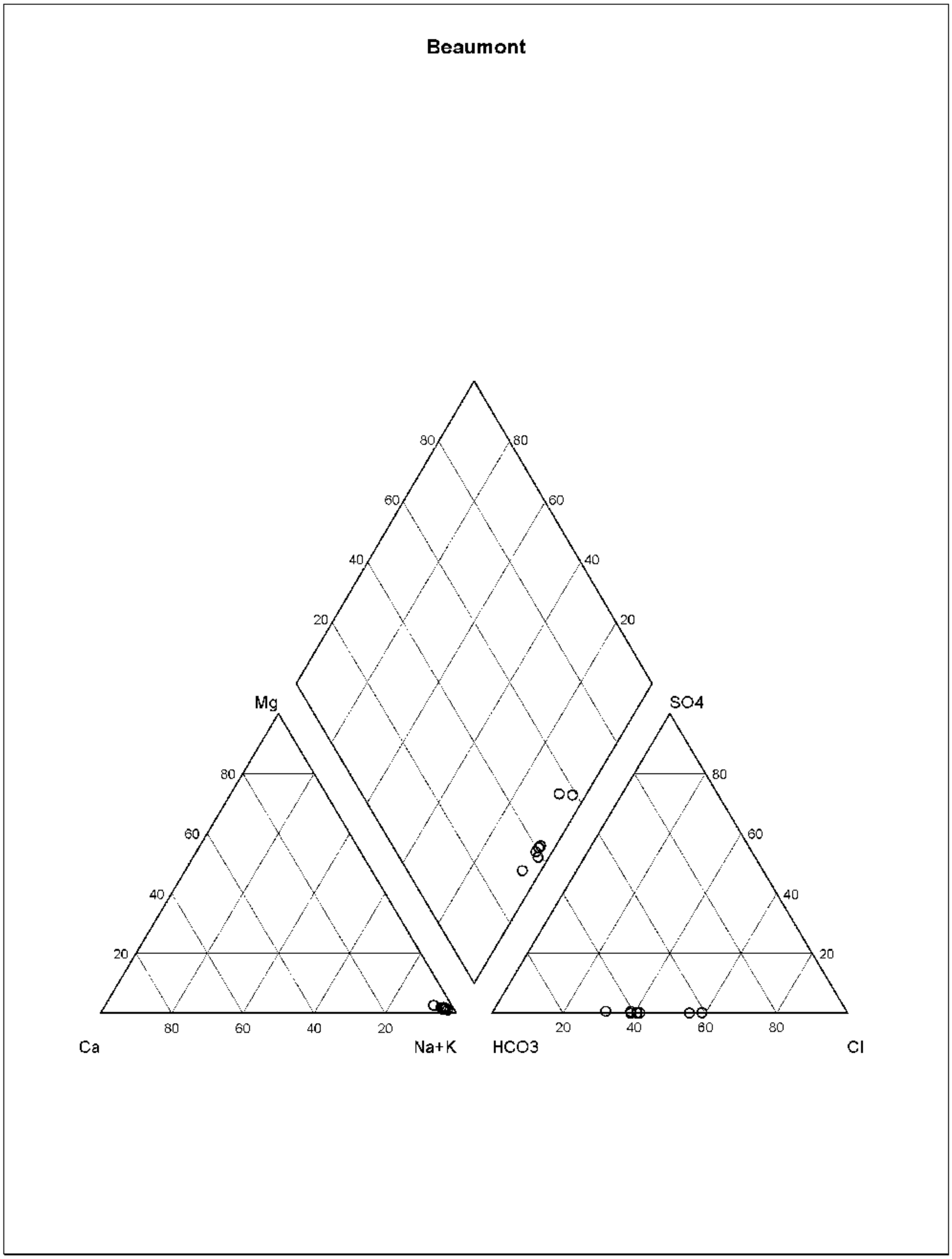

Figure 3. Trilinear diagram showing the major ion relationships of Beaumont groundwaters.

LISSIE FORMATION

Eighty-four percent (136 of the 152) of the chemical analyses of groundwater are from the Lissie Formation of the Chicot Aquifer. The formation is of Pleistocene age with wells having an average depth of 769 feet and ranging between 477 and 1,042 feet. Figure 1 shows the distribution of the Lissie wells within the District. The distribution is fairly well dispersed but almost 60 percent of the the wells are in within 10 miles north, south, east and west of the GCWA Mackey Water Treatment Plant.

The temperature of the groundwaters from the Lissie wells averages 27.0 °C and ranges between 23.0 and 34.5 °C for the 59 wells with a reported temperature. Temperature of groundwater typically has a high correlation with the well depth. However, the correlation coefficient of a linear relationship between the two is only 0.47. Therefore, the well depth is estimated to account for only about 22 percent of the total temperature variability. The remaining percentage may be due to either errors in measurement or the geothermal gradient has considerable variability across the area of interest.

Similar to the Beaumont groundwater, the Lissie ranges between a sodium-bicarbonate and sodium-chloride water chemistry type, as shown on the trilinear diagram in Figure 4. Unlike the Beaumont groundwaters, the Lissie groundwaters are a 50-50 mix of the two water chemistry types. The 46 chemical analyses with sufficient cation and anion values have an average mass balance error of minus 0.7 percent but range between plus 20 and minus 33 percent.

The 116 groundwaters with TDS concentrations have an average TDS of 939 mg/L and range between 377 and 2,644 mg/L. This average TDS approaches the secondary drinking water standard of 1,000 mg/L. The average pH of 77 samples is an alkaline 7.90 but ranges between a slightly alkaline 7.4 to a considerably alkaline 8.5. This suggests that almost 50 percent of the well locations may have calcium-carbonate precipitation where the native groundwater mixes with the recharge water.

The six ORP measurements suggest that there is considerable variability in the redox state of the Lissie groundwater. The ORP measurements have an average value of minus 65.9 mv and range from minus 257 to plus 89.4 mv. Adjusting the ORP readings for a calomel reference electrode to a hydrogen reference electrode, the average Eh is plus 179 mv, ranging from minus 13 to plus 329 mv. The Eh values indicate that the average Lissie groundwater is oxidized but ranges from slightly reducing to considerably oxidized. The two dissolved oxygen measurements of 1.5 and 3.4 mg/L are supportive of this redox condition.

All major ion concentrations increase with depth. Well depth accounts for 61 percent of the chloride variability, 52 percent of the sodium, 42 percent of the magnesium and 38 percent of the calcium variability.

Sodium dominates the cation chemistry of the Lissie groundwaters. The 118 sodium concentrations have an average of 352 mg/L and range between 116 and 1,165 mg/L. The 105 calcium concentrations have an average of only 18 mg/L and range between 3.2 and 61 mg/L. The 105 magnesium concentrations have an even lower average concentration of 6.5 mg/L and range between <1 to 27 mg/L. The 50 potassium concentrations are similarly quite low with an average of 2.0 mg/L and ranging between <1 to 5.4 mg/L.

These cation relationships suggest that ion exchange is minimal and that the cation exchange capacity of the clays in the aquifer matrix is likely to be dominated by sodium. Changes in the calcium concentration are probably dominated by the bicarbonate concentration.

Figure 5 indicates that bicarbonate is a dominant control on the calcium concentration. Bicarbonate averages 365 mg/L and ranges between 266 and 732 mg/L. Figure 5 indicates that the calcium concentration of the groundwater hits a “wall” at about 370 mg/L bicarbonate; essentially the mean bicarbonate concentration. The “wall” is likely the limit of calcium solubility when the pH, bicarbonate and temperature combine and lead to the precipitation of calcium-carbonate (calcite) at about 370 mg/L bicarbonate. Groundwaters with bicarbonate concentrations of 370 mg/l and higher bicarbonate concentrations are most certainly part of the sodium-bicarbonate water chemistry types but this water chemistry type also occurs at lower bicarbonate concentrations as well.

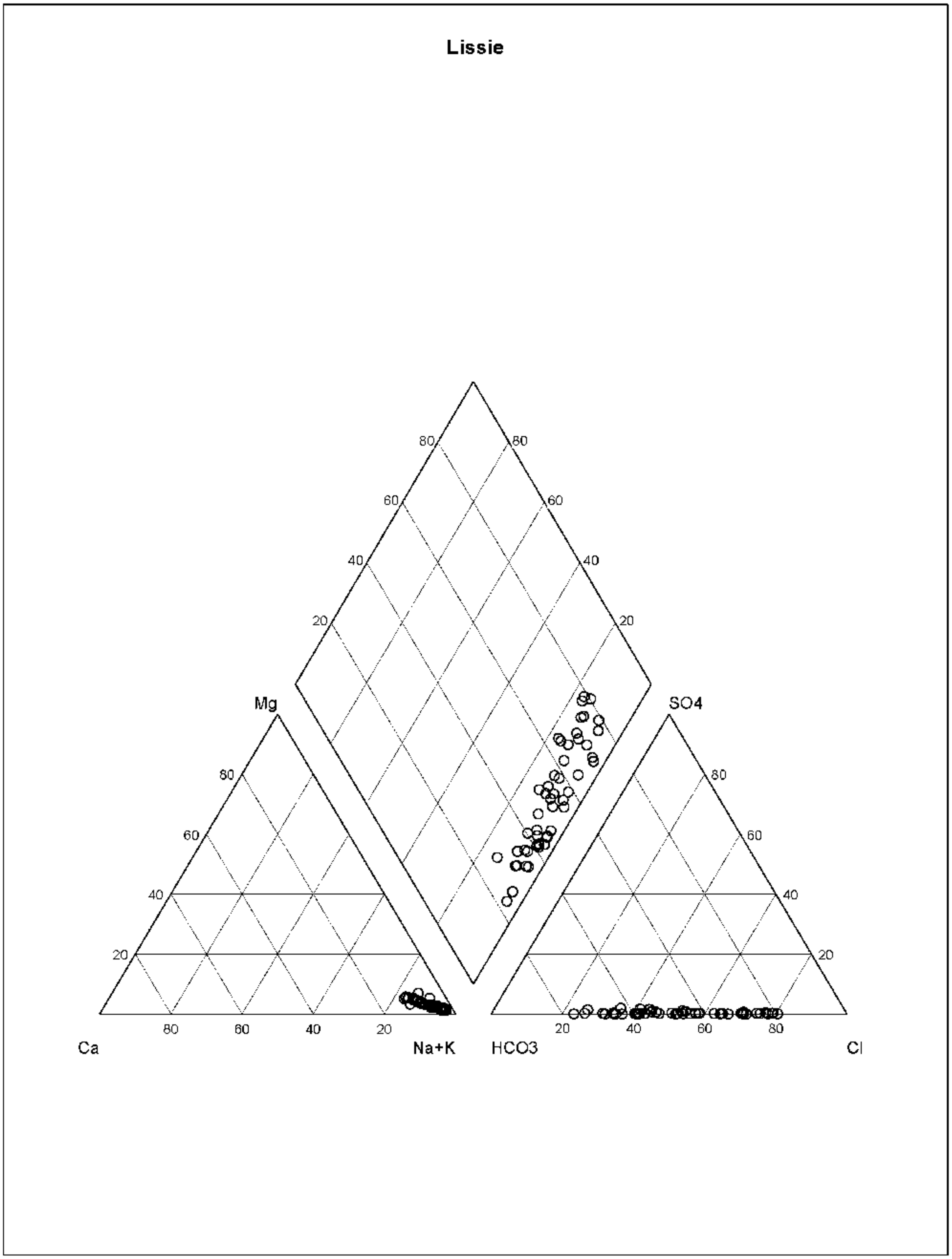

Figure 4. Trinlinear diagram showing the major ion relationships of Lissie groundwaters.

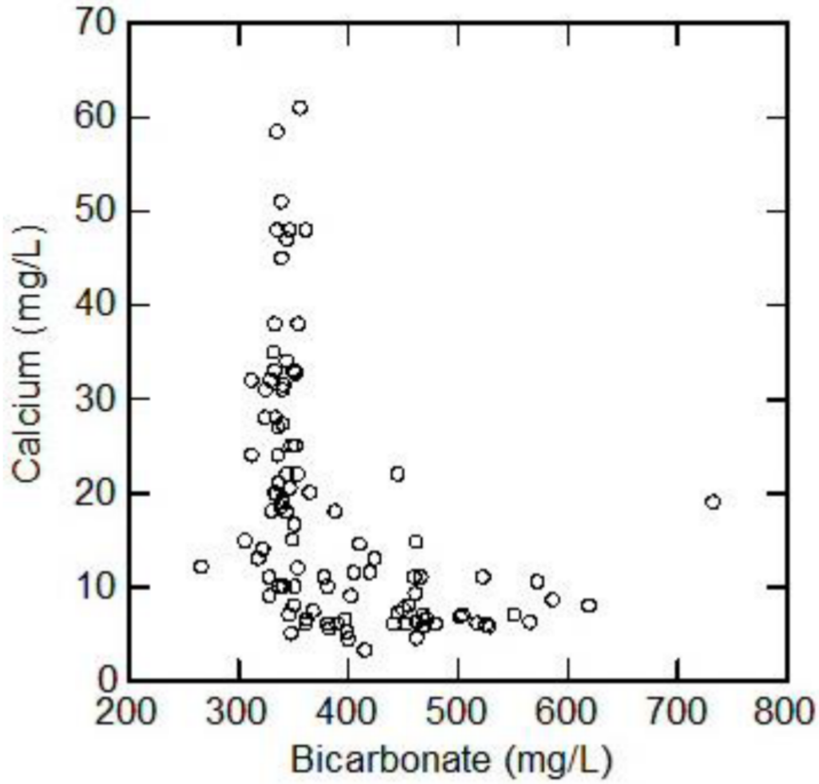

Figure 5. Calcium versus bicarbonate concentrations for Lissie Formation groundwaters.

Sulfate concentrations are quite low with an average of only 2.25 mg/L and ranging between less than 1 to 14 mg/L in the 115 analyses with sulfate concentrations. These low sulfate concentrations are anomalous for groundwaters with this TDS range. They suggest that there is little iron sulfide (pyrite) exposed to the oxidized Lissie groundwaters and/or the Eh is locally sufficiently reducing that pyrite is stable or being precipitated.

Chloride concentrations average 355 mg/L and range between 58 and 1,735 mg/L in the 136 analyses.

The average dissolved iron concentration is 0.15 mg/L and ranges between 0.0019 and 0.924 mg/L in the 13 analyses listing a dissolved iron measurement. Total iron concentration of 50 analyses has an average of 0.116 mg/L while ranging between 0.1 and 2.0 mg/L. More than half of the iron concentrations are less than the secondary drinking water standard of 0.30 mg/L.

The average manganese concentration is 0.046 mg/L and ranges between 0.0 and 0.106 mg/L in the 17 analyses listing a manganese concentration. This average manganese concentration approaches the secondary drinking water standard of 0.05 mg/L. This sampling number is insufficient to estimate the number of wells producing groundwater that exceeds the standard but suggests that the number is less than about half the total number of samples.

There are only four TOC analyses in Table 2 and all report one mg/L for the TOC concentration.

There are 85 analyses that include nitrate. Nitrate has an average of 5.5 mg/L and ranges between 1.0 and 10 mg/L. All nitrate concentrations are considerably less than the 45 mg/L drinking water standard for nitrate. There are only 6 analyses listing ammonia. Ammonia has an average of 0.279 mg/L but ranges between 0.13 and 0.735 mg/L.

The 8 to 10 analyses listing copper, zinc, cadmium, selenium and silver indicate that these metals concentrations are all well within their respective drinking water standards.

Thermodynamic Equilibrium Modeling

After reviewing the characteristics of the Lissie Formation groundwater chemistry, a suite of 12 wells were selected to be representative for thermodynamic equilibrium modeling. This suite specifically represents the observed variability in pH, Eh, temperature, and silica. The pH, as described in the Beaumont section, is a critical factor along with temperature and alkalinity for calcite equilibrium. The pH and Eh are critical factors for estimating the iron equilibrium status and, with sulfate, the potential exposure of iron sulfide minerals. The silica plus aluminum are critical parameters for estimating the clay mineralogy and feldspar stability.

The resulting 12 wells are referenced to their respective SWN on Table 3. Well use includes industrial (IND), Public Supply (PS), Irrigation (IRR) and unused (U). Well depths range from 587 to 894 feet. TDS ranges from 564 and 1,605 mg/L. Both the field measured pH (pH) and the model-estimated pH (EpH) are listed for comparative purposes. The single field measured Eh is compared with the model estimated Eh (EEh). The model-estimated values are estimated based on the iron concentrations (described in the Beaumont section). The model-estimated equilibrium dissolved carbon dioxide concentration (ECO2) is listed along with the water chemistry type (sodium-bicarbonate (HCO3) and sodium-chloride (Cl)). The resulting well locations are shown with their depth, TDS and well number in Figure 6.

Table 3. Modeling comparisons, estimated carbon dioxide gas and water chemistry types for Lissie Formation groundwaters.

SWN	Use	Depth (feet)	TDS (mg/L)	pH	EpH	Eh (mv)	EEh (mv)	ECO2 (mg/L)	Type
6433102	IND	666	564	7.90	7.90		10	7.5	NaHCO3
6433802	PS	715	1008	7.91	7.80		-25	10	NaCl
6433814	PS	894	1605	7.78	7.65		20	10	NaCl
6433903	PS	778	967	7.95	7.95		-15	7	NaCl
6433907	IND	857	839	8.36	8.20		-15	2.1	NaHCO3
6540214	PS	587	480	8.35	8.35		-50	2.6	NaHCO3
6540503	PS	810	633	8.00	8.00	-17	-10	5	NaHCO3
6548102	PS	776	726	7.70	7.70		0	10	NaCl
6548210	U	866	1566	7.80	7.40		200	18	NaCl
6548211	PS	873	1564	7.80	7.40		200	18	NaCl
6548501	IRR	865	1120	7.90	7.40		100	33	NaHCO3
6548502	PS	756	640	7.75	7.20		200	22	NaCl

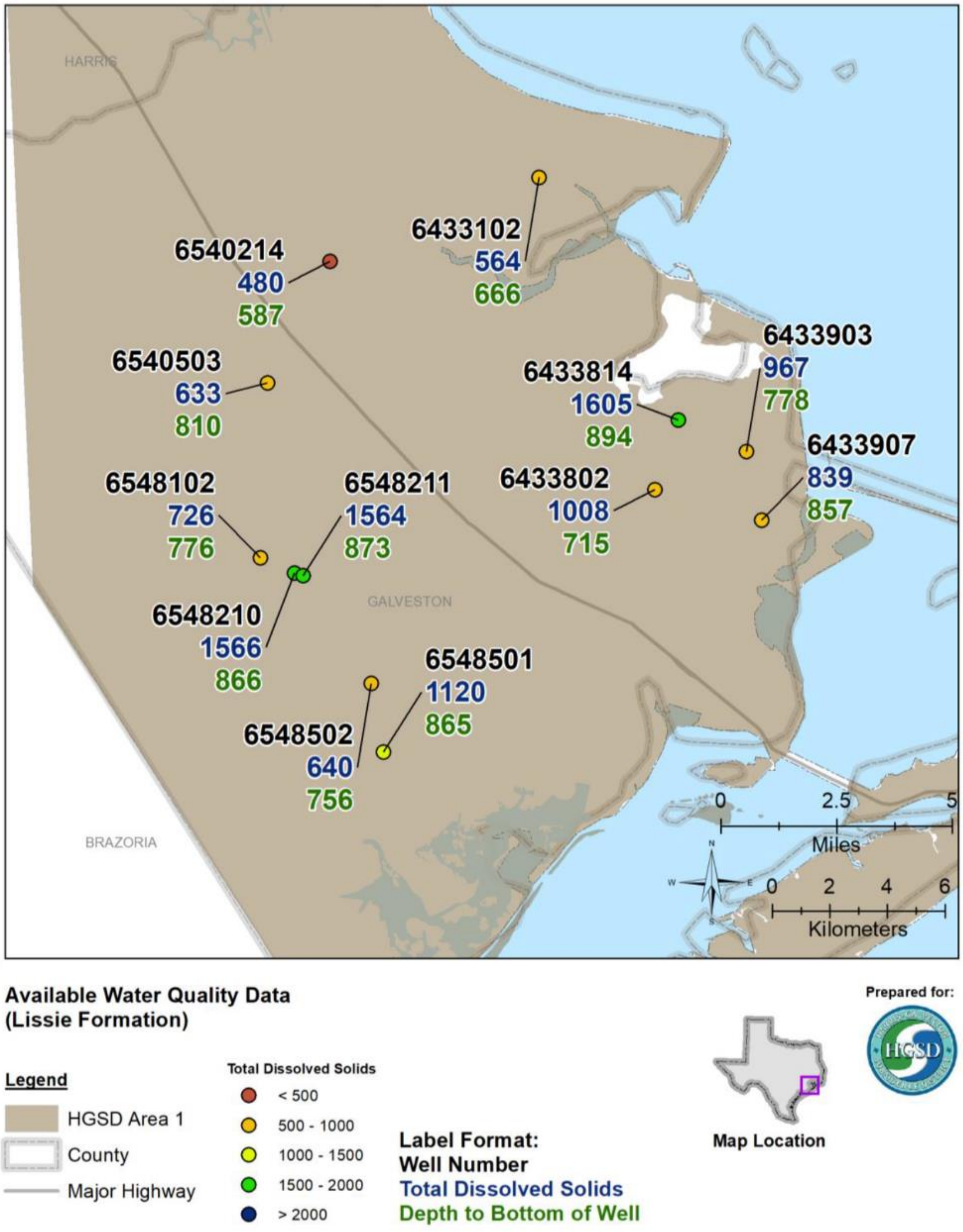

Figure 6. Lissie Formation wells with acceptable chemistry for thermodynamic modeling.

Thermodynamic equilibrium modeling estimates that albite, potassium feldspar, cristobalite, chalcedony, beidellite and saponite swelling clays are in equilibrium. Quartz is in equilibrium in groundwater 6540214 suggesting that the feldspars, particularly albite, are either not being dissolved or have been mostly converted to clay at this well location. Illite is in equilibrium in groundwater 6433102 suggesting that the feldspars have been considerably weathered and potassium feldspar is currently the dominant feldspar at this well location.

The ferrous iron carbonate mineral siderite is in equilibrium in groundwaters 6540214 and 6540503. These are two of the 5 groundwaters estimated to be under slightly to moderately reducing conditions based on the iron concentration of the groundwater. Even though siderite is undersaturated in the other 3 groundwaters under reducing conditions, its equilibrium status in these two groundwaters suggest that siderite could be present in all reduced Lissie groundwaters, particularly those that are sodium-bicarbonate water chemistry types.

The presence of siderite suggests that pyrite may be unstable and being slowly dissolved at these well locations, leading to the precipitation of siderite. Recharge water introduced into a siderite-bearing aquifer will tend to produce an elevated dissolved and colloidal iron oxyhydroxide in the recovered water. The severity of the impact on the recovered water chemistry is directly related to the amount of siderite exposed to the recharge water in the aquifer. Since there is no mineralogy available from Lissie Formation cores, this impact on the recovered water chemistry cannot be assessed. However, the potential presence of siderite is a negative on selecting a well location for an ASR well.

Groundwater 6540503 is in equilibrium with respect to siderite. It is also the only groundwater with a reported ORP measurement. Converted to Eh, it is minus 17 mv. Modeling using the dissolved iron concentration as a basis results is nearly the same EEh of minus 10 mv (Table 3). This lends some credibility to both the field measurement and the model's capability of estimating Eh.

Half of the 12 groundwaters are slightly to well oxidized with positive EEh values, one is neutral at zero mv and five are slightly to moderately reducing. Well locations producing neutral to reducing groundwaters may produce from parts of the aquifer in which pyrite is exposed to the groundwater or there is sufficient organic matter and methane at these locations to cause groundwater to be under reducing conditions. Given the very low sulfate concentrations of both the oxidized and reduced groundwaters, the latter condition is more likely. The relatively elevated estimated carbon dioxide gas, particularly for the oxidized groundwaters, would support this conclusion. Furthermore, the elevated estimated carbon dioxide concentrations are present in both water chemistry types. However, the shallowest groundwater 6540214 has the lowest EEh of minus 50 mv and the lowest estimated carbon dioxide concentration of 2.6 mg/L. The groundwater chemistry would be better understood and predictable if mineralogical data were available.

Rhodochrosite is in equilibrium with groundwater 6433802. Similar to siderite, this manganese-carbonate mineral is also readily soluble and therefore may result in an increase in the manganese concentration of the recovered water from an ASR well at this location. Also, since there is no mineralogical data on the Lissie aquifer, the potential impact of the possible presence of this mineral on the recovered water cannot be assessed. The potential presence of rhodochrosite is a negative factor when selecting this well location for an ASR well.

Calcite is under equilibrium status, tending to neither be dissolved nor precipitated, in only five of the 12 groundwaters. It is supersaturated in the other seven groundwaters, as indicated by the decrease in the modeled EpH compared to the measured field pH. Three of the seven indicate a slight change of 0.1 to 0.2 pH units. These are typical changes occurring in a water sample between when the field pH was measured and when it was analyzed in the laboratory or the use of a field pH meter that has variable standardization problems.

Changes in a field pH compared to the modeled pH greater than about 0.2 pH units usually involve groundwaters that contain elevated dissolved carbon dioxide concentrations. For example, the last four groundwaters with significant differences between the field and modeled pH on Table 3 have highly elevated estimated dissolved carbon dioxide concentrations of 18 to 33 mg/L. These highly elevated, dissolved carbon dioxide concentrations (ECO2) are typically present in groundwaters with visible production of gas in a glass of the groundwater sampled at or near the well. The groundwater in the glass becomes "cloudy" from the initial very small bubble formation. The bubbles coalesce forming large enough bubbles to move to the water surface and evolve into the atmosphere in less than about five minutes.

Discussion

ASR wells could successfully be completed at any of the well locations that hosted these 12 groundwaters. However, the groundwater chemistry of each of the 12 groundwaters pose questions of variable concern. Most of the questions can be answered when the aquifer mineralogy and physical characteristics are known. Others can be answered during a pilot test where the questions will be resolved by aquifer response to the recharge water.

Four of the 12 groundwaters appear to present the least apparent questions given the above groundwater chemistry and modeling results. Groundwater 6548502 is a highly oxidized, second lowest pH and lowest EpH, second-lowest TDS and is a sodium-chloride water chemistry type. These characteristics suggest that the potential for calcite and iron oxyhydroxide precipitation as well as increasing iron and other metals concentrations and particularly sulfate in recovered water, would appear to be minimal. Changes in the recovered water chemistry would appear to also be likely minimal and the volume of recoverable water is not a geochemical issue. This assumes that the estimated dissolved carbon dioxide gas does not increase with pumping.

Groundwater 6433814 is also a sodium chloride water chemistry type with similar characteristics but with higher TDS, slightly higher pH, but with a significantly lower but still oxidized EEh. The estimated dissolved carbon dioxide is significantly lower. The higher TDS of 1,605 mg/L will produce a mixing zone between the recharge water and native groundwater that will need monitoring and will likely somewhat limit the initial volume of recovered water. The mixing zone can be incorporated into a buffer zone that can be used to control and isolate the native groundwater and mixtures of recharge water and native groundwater from the recovered water volume. Once a buffer zone is established, subsequent ASR cycles can recover the total volume of recharged water.

Groundwater 6548102 is similar to that of 6433814 but has a lower TDS of 726 mg/L thereby reducing the need for monitoring based on a buffer zone. However, it has a neutral EEh that suggests that pyrite may be present and exposed to the oxidized recharge water. Oxidation of pyrite is one of the primary sources releasing arsenic to the recovered water along with other metals and metalloids if they are associated with pyrite. If that is the case, the impact on the recovered water chemistry is not assessable. Furthermore, formation of a buffer zone may or may not be a viable alternative if either pyrite or siderite are sufficiently prevalent, widely distributed and exposed to the recharge water. Buffer zone formation and maintenance has been shown to control arsenic to acceptable levels in some other states, but has not yet been clearly demonstrated in Texas. The Texas City data set is limited but is consistent with that from other states, showing acceptable arsenic in the recovered water from early samples but slightly elevated arsenic concentration (14.8 µg/l) in the recovered water when up to 151% of the stored water was recovered, thereby destroying any buffer zone. Had a buffer zone been initially formed and maintained at Texas City, it is likely that arsenic concentrations in the recovered water would have been acceptable.

Groundwater 6433102 is a slightly oxidized, sodium-bicarbonate water chemistry type, a low TDS of 564 mg/L, an alkaline pH of 7.90 and an estimated dissolved carbon dioxide of 7.5 mg/L. The combination of bicarbonate dominance and alkaline pH of just less than 8.0 suggests that even though the mixing of the recharge water and this native groundwater are within the equilibrium range, slight increases in calcium, bicarbonate or pH could precipitate calcite. The cation exchange capacity and cations in exchangeable positions are unknown. If calcium is a significant to dominant cation on the clays, recharge with a sodium-chloride water chemistry type could contribute calcium to the recharged water and potentially enhance calcite precipitation. If the carbon dioxide concentration increases, the recovered water may result in a slow buildup of calcite encrustation on the well screens.

WILLIS FORMATION

There are only four analyses representing the Willis Formation, the deepest formation of the Chicot Aquifer. It is Pliocene in age, dated at approximately 3.8 million years. The total depth averages 1,140 feet but ranges between 1,020 and 1,212 feet.

All four groundwaters are sodium-chloride type and cluster relatively closely on the trilinear diagram (Figure 7). The Willis groundwaters have an average TDS of 1,476 mg/L, ranging between 952 and 2,058 mg/L. Two of the four analyses exceed the 1,000 mg/L secondary drinking water standard. There is a single, moderately alkaline pH of 7.79, and a single ORP measurement of minus 306.9 mv. Converting the ORP to Eh indicates a reduced groundwater at minus 67 mv. The modeled Eh is estimated to be minus 20 mv using the dissolved iron concentration of 0.213 mg/L. This estimated value is less reduced than the measured Eh of minus 67 mv.

The average chloride concentration is 677 mg/L and ranges between 363 and 990 mg/L. All four chloride concentrations exceed the secondary drinking water concentration of 300 mg/L. With the exception of iron and perhaps manganese, all the remaining major, minor and trace concentrations are within their respective drinking water concentration.

The single total iron concentration of 0.167 mg/L is considerably lower than the dissolved iron concentration of 0.213 mg/L. The reason(s) for this condition is unknown but both iron concentrations are within the secondary drinking water standard of 0.30 mg/L. The single manganese concentration is 0.049 mg/L and is just slightly less than the secondary drinking water standard of 0.050 mg/L.

As expected from its reduced condition, nitrate in the Willis groundwater is marginally detectable in two analyses. A single ammonia concentration is only 0.27 mg/L

Thermodynamic equilibrium calculations indicate that the single Willis analysis is in equilibrium with respect to albite, potassium feldspar, cristobalite, chalcedony, swelling clays saponite and beidellite, calcite and siderite.

The groundwater is estimated to contain 7.5 mg/L dissolved carbon dioxide.

JASPER AQUIFER

The Jasper Aquifer is of Miocene age, dated at approximately 24.2 million years ago. There are three chemical analyses with an excellent analytical schedule from three depth intervals in an extensometer well sampled June 8 to June 22, 2015, and one production well (PW) at apparently the same location sampled on April 20, 2017. The three depth intervals for the extensometer well are 2,925 to 2,965 feet; 2,770 to 2,785 feet; and 2,450 to 2,954 feet, respectively. The PW has five screened intervals between 2,450 and 2,954 feet and a total depth of 2,964.

The two Jasper Aquifer wells are located at a latitude of 29°43’29” and longitude of 95°44’53” which is about 54 miles northwest of the GCWA Mackey Water Treatment Plant. However, groundwater from the wells may be representative of the groundwater beneath the Chicot Aquifer and not only include an arsenic concentration but may also provide an example of groundwater characteristics in which arsenic exceeds its drinking water standard.

The total arsenic concentration in groundwater from the shallowest depth interval is less than 0.002 mg/L and increases to only 0.006 mg/L in the intermediate and deep depth intervals. All three are less than the drinking water standard of 0.010 mg/L. However, the total arsenic concentration of the PW groundwater of 0.0261 mg/L is well above this standard.

All four groundwaters are sodium-chloride water chemistry types. The chloride concentration and anion percentage decreases with depth. TDS of 4,760 mg/L in the shallowest depth interval sample is considerably higher than the 3,131 and 3,274 mg/L of the two deeper depth intervals, respectively. All three are above the secondary drinking water standard. Likewise, the TDS of groundwater from the PW of 2,990 mg/L is also above the drinking water standard but significantly lower than all three depth interval samples.

A comparison of the PW and depth interval major ion relationships on a trilinear diagram (Figure 6) indicates that the PW groundwater appears to be a mixture of 60 percent deepest and 40 percent intermediate depth interval groundwater.

The pH of the shallowest depth interval is essentially neutral at 7.02 but alkaline 8.34 and 8.1 at the intermediate and deep depth interval, respectively. Groundwater from the PW has a field pH of 7.6 and laboratory pH of 8.00. Modeled pH values for the intermediate and deep groundwater approach a near neutral pH of 7.30 for both. The PW groundwater has a modeled neutral pH of 7.00.

The Eh is surprisingly oxidized for groundwater from more than 2,000 feet deep. The three depth intervals have a well oxidized Eh ranging between plus 333 (intermediate) and plus 358 mv (shallow). The PW groundwater is even more oxidized at plus 464 mv in both the field measured and the modeled Eh in equilibrium with the iron concentration. These groundwaters are more oxidized than those of the considerably shallower Beaumont Formation groundwater from an average depth of 599 feet.

The ferric iron concentration of the PW groundwater is 0.444 mg/L (total iron, 0.457 mg/L) well above the secondary drinking water standard of 0.30 mg/L while the total iron concentrations of the depth intervals range between 0.025 to 0.841 mg/L (shallow and deep depth interval, respectively). The dissolved iron is less than 0.025 mg/L and the ferrous iron of only 0.013 mg/L. The total manganese concentration is 0.0123 mg/L and dissolved manganese, 0.0118 mg/L.

This elevated total iron concentration suggests that the arsenic concentration may be arsenic adsorbed and enhanced by the iron oxyhydroxide colloid representing the total iron concentration. The very low dissolved iron and associated low manganese and sulfate concentrations are not indicative of pyrite oxidation of any significance occurring near this well location. A very minor amount of pyrite oxidation may be the source of the arsenic but the iron concentration may be from the oxidation and dissolution of siderite. Modeling indicates that the total arsenic is the oxidized (AsV) valence state, further supporting adsorption by iron oxyhydroxide.

Modeling indicates the same mineralogy suite as the groundwater in the shallower Chicot Aquifer. However, modeling estimates a very high carbon dioxide concentration of 104 mg/L for the PW groundwater.

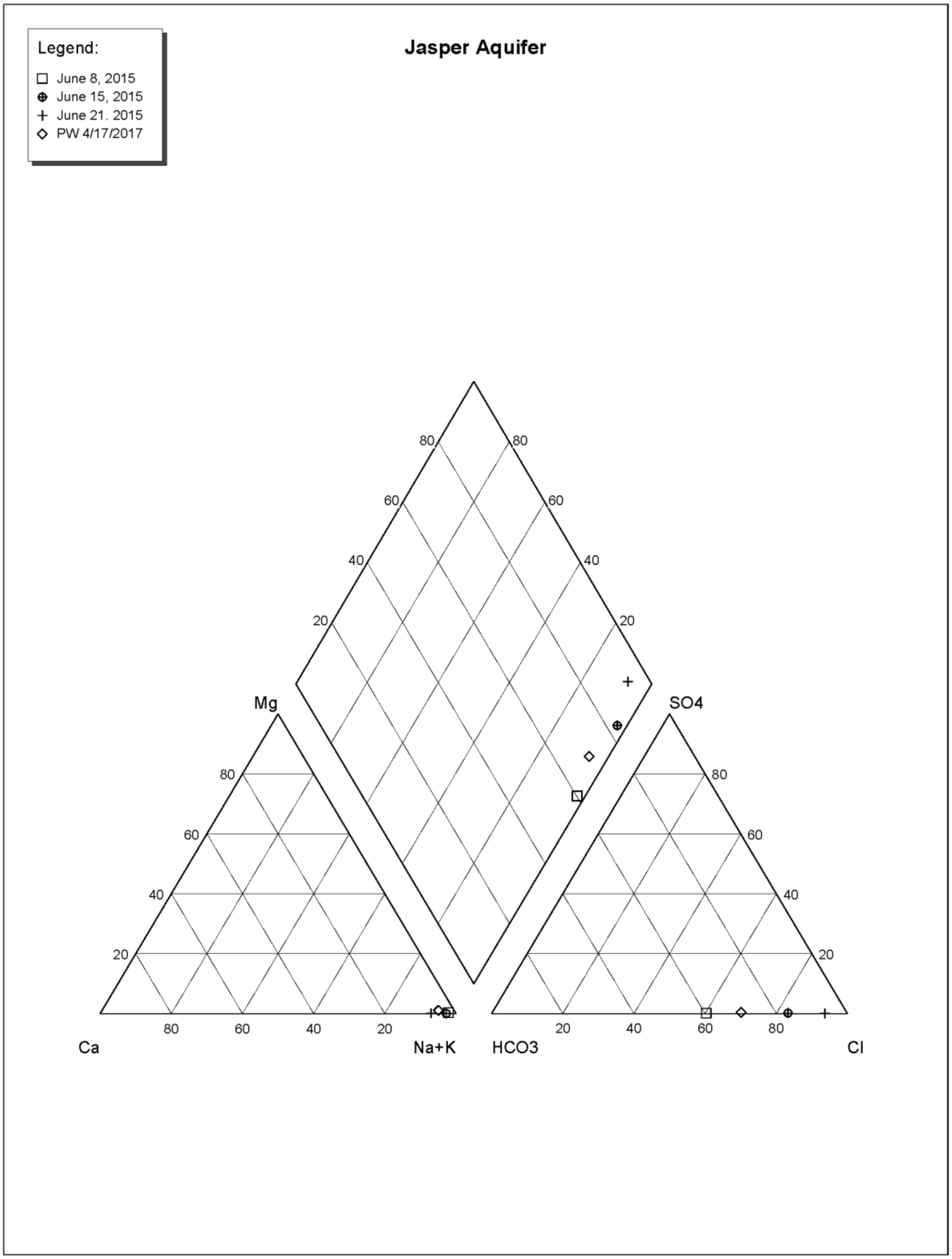

Figure 7. Trilinear diagram showing the major ion relationships between Jasper Aquifer depth interval groundwaters and Jasper 1 Production Well groundwaters.

CONCLUSIONS AND LIMITATIONS OF GEOCHEMICAL MODELING RELATIVE TO ASR

The potential key geochemical issues for proposed ASR storage within Regulatory Area No. 1 are as follows, in approximate order of importance:

- There are limited lithologic logs and no mineralogical data available for the aquifer sediments. Therefore, the geochemical issues can only reliably deal with recharge/native ground water chemistries mixing in a storage tank. Mineralogy was approximated from the geochemical modeling. Recovered water chemistry from a pilot test in one or more of the 10 recommended well locations would provide an estimate of what mineralogy may be the problem. However, cores should be recovered at each planned wellfield location to provide the necessary mineralogical data.

- Potential calcium carbonate precipitation in the ASR wells and surrounding aquifer, causing progressive well clogging. If recovered water from a pilot test indicates that this is an issue, this may require pH adjustment of the recharge water and/or periodic well rehabilitation such as about every five to ten years.

- Potential well clogging due to reaction of swelling clays when exposed to fresh water. If recovered water indicates that this is an issue, well conditioning to prevent the clays from swelling within a small radius around each well screen, such as a few tens of feet, may be necessary.

- Potential mobilization of arsenic. If recovered water indicates that this is an issue, a simple solution would be to form and maintain a buffer zone around each well or wellfield. All subsequently stored water could be fully recovered.

- Potential carbon dioxide in the recovered water. If the recovered water indicates that this is an issue, an issue related to potential calcium carbonate precipitation, the simplest solution would be to discharge recovered water to a small storage reservoir with a splash plate and a few minutes detention time for CO_2 release, then re-pump the water to the transmission/distribution system.

- Potential elevated concentrations of iron and/or manganese in the recovered water. If recovered water indicates that this an issue, select appropriate materials of construction to minimize rust formation from the well casing, and adjust the pH of the recharge water

- Potential elevated concentrations of total dissolved solids (TDS) in the recovered water. This is not expected to be a real issue since formation and maintenance of a buffer zone around each ASR well or wellfield is known to be a simple and effective solution and would likely be implemented anyway.

- Potential presence of H_2S in the groundwater. This is not expected to cause a problem since experience has consistently shown that H_2S is rapidly oxidized by oxygen and disinfectants in the recharge water and is therefore not present in the recovered water.

These potential issues are based on equilibrium geochemical modeling with limited available water quality data; no physical or mineralogic data from cores and core analysis; and experience at other ASR wellfields in brackish, unconsolidated aquifer systems. There are significant limitations in the available data. Relatively few wells in Regulatory Area 1 have sufficient data for the broad range of geochemical constituents necessary to guide an equilibrium geochemical model analysis. Almost all of these few wells are in the Chicot aquifer. Adequate water quality data for wells in the Evangeline aquifer is generally lacking in the study area. The absence of geochemical and geotechnical data from continuous wireline cores is a significant constraint upon modeling and conceptual design of an ASR wellfield to meet subsidence-neutral water supply reliability goals. If an ASR program moves forward, an initial task would be to obtain cores and to construct test/monitor wells at a selected site. Analysis of the data collected from these facilities would guide subsequent wellfield design and operation.

Approximately 140 ASR wellfields are operating nationwide in about 25 states. Many of these are storing fresh water in coastal alluvial geologic settings with alternating layers of sands and clays, similar to those found at HGSD Regulatory Area 1. Many are storing fresh water in brackish aquifers. Based upon available data, it would appear that ASR is viable in this area and is also cost-effective compared to other water management options that provide comparable levels of water supply reliability during droughts, floods and emergencies. Appropriate wellfield design and operation, based on adequate hydrogeologic, geochemical, geotechnical and water quality data, can achieve local "subsidence-neutral" goals. The general framework for phased development of an ASR demonstration program capable of supplying 5 MGD during a five-year drought is as follows:

- ASR feasibility study (this project)
- ASR demonstration site selection
- Continuous wireline core hole to about 2,000 feet; geophysical logging and detailed geochemical and geotechnical analysis of selected cores.
- Selection of up to five potential ASR storage intervals in the Chicot and upper Evangeline aquifers
- Construction and testing of monitor wells in up to five ASR storage intervals. These may be separate wells (one in each interval) or multiple-completion wells. Obtain water quality and hydraulic data for each storage interval, and geophysical logs
- Conduct geochemical and geotechnical modeling, updating the preliminary analysis completed in this report
- Design, construction and testing of approximately 10 to 12 ASR wells in up to five storage intervals. Recharge flow rate capacity will likely govern the number of ASR wells
- Equipping of ASR wells and construction of wellheads and wellfield facilities
- Startup and initial ASR wellfield operations to achieve the Target Storage Volume

Lessons learned from the 5 MGD ASR demonstration program would then support location, design, construction and operation of additional ASR wells and wellfields to meet broader regional goals for ensuring water supply reliability while managing subsidence.

REFERENCES

INTERA Inc., LBG-Guyton & Associates, Texas Bureau of Economic Geology, 2016, Draft Report on the Delineation of Fresh, Brackish and Saline Groundwater Resources Based on Interpretation of Geophysical Logs, Prepared for: Harris-Galveston Subsidence District and Fort Bend Subsidence District, November, 2016, 194 p.

Oden, J.H., and Szabo, Zoltan, 2015, Arsenic and Radionuclide Occurrence and Relation to Geochemistry in Groundwater of the Gulf Coast Aquifer System in Houston, Texas, 2007-11: U.S. Geological Scientific Investigations Report 2015-5017, 105 p.

Oden, J.H., Brown, D.W., and Oden, T.D., 2011, Groundwater Quality of the Gulf Coast Aquifer System, Houston, Texas, 2010: U.S. Geological Survey Data Series 598, 64 p.

Oden, J.H., Oden T.D., and Szabo, Zoltan, 2010, Groundwater Quality of the Gulf Coast Aquifer System, Houston, Texas, 2007-08: U.S. Geological Survey Data Series 548, 65 p. Revised July, 2011.

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