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Brackish Groundwater Comingling

Contract 2000012442

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1 Executive Summary

Comingling is defined in the Texas Water Well Drillers and Pump Installers Rules Texas Administrative Code (TAC) §76.10.10(16) as the "mixing, mingling, blending or combining through the borehole casing annulus or the filter pack of waters that differ in chemical quality, which causes quality degradation of any aquifer or zone." The Texas Water Well Drillers and Pump Installers Rule §76.100(c)(1) states that "All wells shall be completed so that aquifers or zones containing waters that differ in chemical quality are not allowed to commingle in the casing, borehole annulus or the filter pack and cause quality degradation of any aquifer or zone".

The definition of comingling includes several qualifiers that are not clearly defined in the TAC and thus are open to interpretation. One such qualifier is what constitutes "waters that differ in chemical quality"? Related to this question is what constitutes degradation, which is not defined in 16 TAC§76. These questions, as well as others, were the subject of a workgroup created by the Water Well Drillers Advisory Council to review potential issues raised regarding groundwater comingling and other concerns relevant to 16 TAC§76. The workgroup took input from the public and their work culminated in a workshop held on August 17, 2018, to give stakeholders the opportunity to provide verbal input on five issues defined by members of the workgroup. These issues were:

1. Define (groundwater) degradation. §76.10 (16) & (19) - §76.100 (c)(1) & §76.105 (b)(3);
2. Identify the amount of time and what conditions must be met for a test well to stay open. §76.100 (c)(6),
3. What is the minimum well construction standards to produce brackish water? §76.102,
4. Would mixing 20,000 milligrams per liter with 30,000 milligrams per liter total dissolved solids water be considered comingling?
5. Define aquifers and zones. §76.10 (16).

Because of the interest in comingling and the relevance of several of these issues to the development of brackish groundwater resources, the Texas Water Development Board (TWDB) funded a study of comingling with the intent of providing data and information which could inform future policy development.

This report documents a desktop study of comingling from the context of its definition in the Texas Water Well Drillers and Pump Installers Rules in the TAC. The study is organized into four major sections: a review of the statutes related to comingling, an interpretation of the definition of comingling, an assessment of the potential for comingling of brackish groundwater in Texas aquifers, and a summary of conclusions and recommendations.

The report begins with a review of the Texas Water Well Drillers and Pump Installers Rules in the TAC (Title 16, Chapter 76 [16 TAC§76]) and other relevant Texas Statutes. The review is focused on providing context to the potential meaning of comingling and is meant to help inform regulatory and regulated entities interpret 16 TAC§76. As recognized by the Water Well Drillers Advisory Council Workgroup, the rules neither define degradation nor the issue of mixing groundwater of differing quality but within the same salinity class. Through our review of the relevant statutes, we conclude that a consistent interpretation of degradation, as it relates to comingling, is to prevent contamination of useable water quality with water that is either a human or environmental health risk. It unclear whether preserving the current or future use of the groundwater encountered is a standard to be considered in evaluating degradation or impairment but groundwater use is explicitly considered in the definition of pollution which is found in 16 TAC§76.10(42). We conclude that the application of the meaning of degradation can be varied based upon the groundwater salinity level and if the following conditions are met; current groundwater uses are not impaired, potential groundwater uses are not impaired, a public health hazard is not created; and the quality of groundwater is restored if feasible.

The study presents a detailed conceptual model of the well and aquifer conditions that may result in comingling. Mixing of groundwater resulting in degradation of groundwater can occur under several conditions. First, it could occur during drilling and prior to well completion. Second, it could occur during a period when a well has been drilled but is left open prior to completion or plugging and abandonment. Finally, comingling can occur in wells that have been drilled and completed but allow for mixing of groundwater from one aquifer/zone to another during non-pumping periods. Intra-borehole groundwater flow can occur under non-pumping conditions if the hydraulic head within aquifers or zones co-completed by the well have different hydraulic heads. In this situation, one zone(s) will be of higher head than the other zone(s) creating a flow cell within the borehole from the high hydraulic head zone to the lower hydraulic head zones. For intra-borehole flow to be comingling, the zones or aquifers connected by the borehole must have differences between their water quality which would result in degradation of the zone or aquifer being recharged. While the mixing of groundwater of differing water quality can, and often does, occur in practice, it is rarely documented because of the characterization data requirements.

Using general physical aquifer conditions as indicators of the potential for comingling within an aquifer, this study assessed the potential for comingling in the aquifers in three regions of the state, the Gulf Coast Region, the Eagle Ford Region, and the Trans-Pecos Region. A review of these three regions found that the potential for comingling exists in all three regions, with the Gulf Coast Aquifer Region and the Eagle Ford Regions having the highest potential of the three. For each region, at least one case study was presented where detailed well-specific examples were evaluated to characterize the intra-borehole flow potential and zonal water quality. These case studies provide evidence of how comingling could occur, and they also provide insight into the types of detailed characterization data that must be collected to evaluate comingling.

To assess the potential for comingling of brackish groundwater across the state a ranking methodology was developed based upon metrics describing aquifer conditions important to the potential mixing of brackish groundwater. The assessment provides a hierarchical ranking of aquifer conditions that could be conducive to comingling through a well within a given aquifer. The assessment ranked all major and minor aquifers for their potential for comingling of brackish groundwater. Ten aquifers were ranked as having high potential for brackish groundwater comingling. The highest-ranking aquifers tend to be aquifers with distinct multi-aquifer architecture or aquifers that have a high occurrence of cross-aquifer completions.

Both the regional assessments and the statewide assessment document a framework for understanding the factors that impact the potential for comingling in brackish aquifers and freshwater aquifers, alike. The assessments provide an indication that many of Texas's aquifers have the potential to comingle brackish groundwater; however, the potential comingling occurring is a very site-specific, and borehole-specific condition. As the report will demonstrate, the potential for comingling to occur in a well is affected by multiple factors including the characteristics of the aquifer, zonal differences in water quality, zonal differences in hydraulic head, the well design, the well construction, the well operation, and by groundwater pumping. As a result, the statewide assessment of potential for comingling in brackish groundwater is a broad assessment of potential for comingling to occur and limited by its regional scope. The aquifer-wide assessments use available information to rank the relative potential for comingling of brackish groundwater within that aquifer. The fundamental aquifer data required to assess comingling is the zonal water quality and the zonal hydraulic head along the well screen. There is a general lack of this data collected and it is not required to be collected. Because of this general lack of information available regarding measured vertical profiles of hydraulic heads and water quality parameters in wells, the aquifer-wide assessments are limited by their reliance on hydraulic head predicted by groundwater models and salinity zones delineated by TWDB studies of brackish groundwater and should not be used as a substitute for well-specific evaluations. The regional and statewide assessments do not make determinations as to whether comingling is occurring at a given well because well-specific field data is generally lacking.

A nuance regarding the concept of comingling is that it addresses the mixing of groundwater from one zone or aquifer to another through the well bore such that the water quality within a co-completed zone or aquifer is degraded. Based upon the definition, it does not appear to consider the water quality measured at the wellhead from the mixing of two zones or aquifers. In practice, the degradation of water quality measured at the wellhead is the concern of the owner of a well. Most wells co-complete zones that are of slightly differing water quality and many times may co-complete zones where one zone has natural constituent concentrations above standards while the wellhead concentration complies with standards. Our interpretation of statute is that, if the use were maintained among other considerations described above, the mixing would be acceptable. In this hypothetical case, if the poor water quality zone recharged the better water quality zone in times of non-pumping, this would be comingling as per the definition. However, it is the opinion of the authors the impact of poorer water quality recharging a better water quality zone will be mitigated when the well is pumping in many real-world situations. The basis for that opinion is that in most cases zonal pumping rates will significantly exceed intra-borehole zonal flow rates. Comingling, except potentially in karst or fractured aquifers, will be local to the well bore. These facts do not minimize the need to protect potable water quality from injurious water, be their sources natural or anthropogenic.

The TWDB recently adopted brackish production zone rules amending Title 31 TAC§356 with a new Subchapter G to establish rules for persons interested in obtaining a permit from a groundwater conservation district. Of relevance to this topic, the proposed rule stipulates that brackish groundwater production zones are separated by hydrogeologic barriers sufficient to prevent significant impacts to water availability or water quality in any area of the same or other aquifers, subdivisions of aquifers, or geologic strata that have an average total dissolved solids level of 1,000 milligrams per liter or less at the time of designation of the zones. The proposed rule recognizes that mixing of variable water quality occurs in wells. Future compliance with these rules will require a minimum level of characterization data to evaluate the potential for comingling. We recommend that the TWDB work with conservation districts and other stakeholders on defining minimum standards of characterization that can be the basis for statewide regulation. The science developed as part of this guidance would be very useful to future policy considerations for comingling.

The meaning of the term degradation is central to the question of whether comingling occurs. An interpretation of the statutes would suggest that some degree of groundwater mixing can occur that may not be considered comingling while being consistent with the State’s groundwater protection policies. In the case of brackish groundwater aquifers, we recommend that the Groundwater Protection Committee, which includes the Water Well Drillers and Pump Installers Program, provide some guidance for application of the concept of comingling in brackish aquifer settings.

2 Introduction

Comingling is defined in the Texas Water Well Drillers and Pump Installers Rules Texas Administrative Code (TAC) §76.10.10(16) as the "mixing, mingling, blending or combining through the borehole casing annulus or the filter pack of waters that differ in chemical quality, which causes quality degradation of any aquifer or zone." The Texas Water Well Drillers and Pump Installers Rule §76.100(c)(1) states that "All wells shall be completed so that aquifers or zones containing waters that differ in chemical quality are not allowed to commingle in the casing, borehole annulus or the filter pack and cause quality degradation of any aquifer or zone".

The definition of comingling includes several qualifiers that are not explicitly defined in the TAC and thus are open to interpretation. One such qualifier is what constitutes "waters that differ in chemical quality". Related to this question is what constitutes degradation which is not defined in 16 TAC§76. These questions, as well as others, were the subject of a workgroup created by the Water Well Drillers Advisory Council to review potential issues raised regarding groundwater comingling and other concerns relevant to 16 TAC§76.

Since formation of the advisory council, the TWDB has met with Texas Department of Licensing and Regulation to discuss groundwater comingling issues, especially as they relate to brackish groundwater. To support the discussion of comingling as it relates to brackish groundwater, the TWDB funded a study to assess brackish groundwater comingling issues statewide with focus on the Gulf Coast Aquifer, Eagle Ford Shale Region, and Trans-Pecos Region. The TWDB Brackish Resources Aquifer Characterization System Program defines brackish groundwater as groundwater with 1,000 to 10,000 milligrams per liter total dissolved solids. This report documents that study.

This report documents a desktop study of comingling from the context of its definition in the Texas Water Well Drillers and Pump Installers Rules in the TAC. The study is organized into five major sections. Section 3 reviews the meaning of comingling of brackish groundwater from the perspective of the Texas Water Well Drillers and Pump Installers Rules in the TAC (Title 16, Chapter 76 [16 TAC§76]) and other relevant Statutes. The review is focused on providing context to the potential meaning or definition of comingling.

Section 4 provides a conceptual physical framework for understanding the aquifer conditions that may contribute to commingling. This section provides a discussion of physical aquifer conditions that may contribute to commingling and develops a physical framework for aquifer and borehole conditions that could result in commingling.

Section 5 performs a desktop assessment of the potential for comingling of brackish groundwater in three select regions of Texas: the Gulf Coast Aquifer, the Eagle Ford Region and the Trans-Pecos Region. The three regions are of significant areal extent; we used consistent data sources between all three regions. Conditions assessed to characterize the potential for comingling include characterization of wells completed across multiple aquifers, maximum head differences projected to exist at each multi-aquifer completed well and aquifer water quality. To augment the regional assessments, case studies were presented in each region. Each case study described an actual field condition where well completion data, interval water quality and intra-borehole flow rates could be characterized. These case studies provide evidence of how comingling could occur, and the types of data required to evaluate comingling.

Section 6 documents a statewide assessment of the relative potential for brackish groundwater comingling to occur for all major and minor aquifers in the State. The assessment is based upon development of a relative ranking process that is informed by metrics that attempt to characterize natural aquifer conditions required to for comingling to occur. The aquifers of the state are ranked for their potential for comingling to occur as high potential, medium potential and low potential. Comingling is a well-aquifer specific issue and as a result, aquifers that are ranked low in this assessment will have wells where comingling may occur.

Section 7 of the report details study conclusions, recommendations and discussed limitations of the study. Sections 8 and 9 provide a list of citations refenced in the report and acknowledgements to those who have supported the report. Section 10 provides an appendix listing of the Geographic Information System Datasets used and developed as part of this report. These datasets are a deliverable to the TWDB. Section 11 provides an appendix with the basis and references for the Statewide Aquifer Metrics and Section 12 provides an appendix with TWDB comments on the draft report with responses.

3 Review of Applicable Statutes and Codes

This section reviews issues related to comingling as it is defined in statute and in context of other relevant statutes and codes to support a statewide discussion of policies. This section includes a review of the Texas Water Well Drillers and Pump Installers Rules in the TAC (Title 16, Chapter 76 [16 TAC§76]) and other relevant Statutes. This review is focused on providing context to the potential meaning or definition of comingling and has been completed by a professional geoscientist and does not include legal opinions regarding code or statute. However, the review is meant to help inform regulatory entities.

In Texas, enacted legislation is codified in the Texas Statutes. State agencies in turn enact regulations, or administrative law, which interprets statute and is codified in the TAC. As a result, this review is focused on the TAC because that is the applicable source for rules on well completions and groundwater protection. A significant exception to this is rules developed by groundwater conservation districts. While both the Texas Commission on Environmental Quality and the TWDB have regulatory authorities over groundwater conservation districts, each district has been given rule-making authority in Chapter 36 of the Texas Water Code to enact their own unique set of rules. Additionally, the Water Well Driller Rules (16 TAC§76) also references the Texas Occupations Code. As a result, both sources are included in this review. Finally, the Texas Water Code, Chapter 26 – Water Quality Control was included for completeness. Table 3-1 provides a summary of Administrative Code reviewed and provides a summary of Statutes reviewed.

Table 3-1. Administrative Code Reviewed.

Administrative Code Title	Part	Chapter / Subchapter
TAC Title 16 - Economic Regulation	Part 1 – Railroad Commission	Chapter 3 - Oil and Gas Division
	Part 4 – Texas Department of Regulation and Licensing	Chapter 76 – Water Well Drillers and Pump Installers Rules
TAC - Title 30 - Environmental Quality	Part 1 – Texas Commission on Environmental Quality	Chapter 3 - Definitions Chapter 293 C – Requirements for Groundwater Conservation Districts Chapter 290 D - Rules and Regs Public Water Supply Systems Chapter 290 F - DW Standards and Reporting for Public Water Systems Chapter 331 - Underground Injection Control
TAC - Title 31 - Natural Resources	Part 10 – Texas Water Development Board	Chapter 356 - Groundwater Management
	Part 18 - Texas Groundwater Protection Committee	Chapter 601 - Groundwater Contamination Report

Table 3-2. Statutes Reviewed.

Statute Title	Chapter	Subject
Occupations Code	Subtitle A, Chapters 1901 and 1902	Water Well Drillers and Pump Installers
Texas Water Code	Chapter 26	Water Quality Control
Texas Water Code	Chapter 36	Groundwater Conservation Districts

3.1 Texas Department of Licensing and Registration

The Texas Department of Licensing and Regulation regulates Water Well Drillers and Pump Installers. Title 16, Chapter 76 of the TAC are the administrative rules for the Water Well Drillers and Water Well Pump Installers. The purpose of these rules is to provide the procedures and requirements for licensing, handling of complaints, continuing education, and technical standards for well drillers and pump installers such that the quality of the State's groundwater is ensured. This section will review comingling in the context of 16 TAC§76 and will summarize the key inputs received from the Well Drillers Advisory Committee Summit on Commingling.

3.1.1 Title 16, Chapter 76 of the Texas Administrative Code

Comingling is defined in TAC §76.10.10(16) as the "mixing, mingling, blending or combining through the borehole casing annulus or the filter pack of waters that differ in chemical quality, which causes quality degradation of any aquifer or zone." Under this definition, two conditions must be met for comingling: the mixing occurs between waters of different chemical quality and the subsequent mixing causes degradation to an aquifer or a zone. According to this definition, the mixing of waters of different chemical quality within a well or borehole is not sufficient by itself to be comingling. For example, although the mixing of two differing quality waters within a borehole may occur, that mixing may not cause degradation and therefore may not constitute comingling.

This definition of comingling includes several qualifiers that are not clearly defined in the TAC and thus are open to interpretation. One such qualifier is what constitutes "waters that differ in chemical quality". A fundamental question that is not addressed by the TAC is what water quality parameters should be considered. Are these differences to be based upon basic water quality parameters such as total dissolved solids and pH; specific constituents such as iron or drinking water standards; or salinity classes, or a combination of these metrics?

The second and most important qualifier open to interpretation is the definition of degradation, which is not defined in 16 TAC§76. The most representative definitions for degrade in the dictionary are "to lower to an inferior or less effective level" and "to impair in respect to some physical property" (Merriam-Webster Online Dictionary, 2021). These two dictionary definitions imply a reduction in quality that would make the groundwater inferior or less effective.

A reasonable interpretation is that Code 16 TAC§76 intends to prevent contamination of useable water quality with water that is either a human health or environmental health risk. It is not clear in 16 TAC§76 whether preserving the current or future use of the groundwater encountered is a standard to be considered in evaluating degradation or impairment. The consideration of groundwater use, or its ultimate usefulness, is explicitly considered in the definition of pollution which is found in 16 TAC§76.10(42). Pollution is defined as the "*The alteration of the physical, thermal, chemical, or biological quality of, or the contamination of, any water that renders the water harmful, detrimental, or injurious to humans, animals, vegetation, or property, or to public health, safety, or welfare, or impairs the usefulness or the public enjoyment of the water for any or reasonable purpose.*" Injurious water is defined in 16 TAC§76.10(33) as *"water that is harmful to vegetation, land or other water as set forth in §1901.254(a) and §1902.252(a) of the Code."* This reference is to the Occupations Code and in that code "*injurious water*" is not defined but is referred to as "*injurious to vegetation, land, or other water.*" It can be reasonably assumed that injurious water and pollution are interrelated.

Code 16 TAC§76 rules intend to ensure that wells be completed in a manner to prevent completion into an aquifer or zone containing "*injurious water or constituents*" (see 16 TAC§76.10(33), §76.62, §76.71, §76.72, §76.101, §76.102, §76.103 and §76.104). The water well drillers and pump installers rules also intend to ensure that wells be completed in a manner to prevent injury or pollution (see 16 TAC§76.10(16), §76.10(42), §76.101, §76.107, §76.109). As discussed above, the definition of injurious waters and pollution are interrelated in the code.

There appears to be some inconsistency in the rules as to whether comingling is meant to prevent comingling of injurious water with fresh groundwater, or any groundwater deemed to be non-injurious. According to the Texas Department of Licensing and Regulation staff, the intention of the rules is the latter. Code 16 TAC§76.100(c)(1), which covers requirements for locating and completing wells, states that all wells shall be completed so that "*aquifers or zones containing waters that differ in chemical quality are not allowed to commingle in the casing, borehole annulus or the filter pack and cause degradation of any aquifer of zone*." Code 16 TAC§76.103 regarding well re-completions states that the landowner shall have the "*continuing responsibility of ensuring that a well does not allow the commingling of injurious water with fresh water through the wellbore to other porous strata*." Code 16 TAC§76.105(a)&(c) covering standards for wells drilled prior to June 1, 1983, seeks to prevent *"…commingling of aquifers or zones of different water quality."* Code 16 TAC§76.105(c) requires that a well be plugged that allows "*commingling of aquifers or zones of different water quality and causing degradation of any water including groundwater."*

Based on a review of 16 TAC§76 and the terms used to define comingling, there is room for interpretation in what constitutes comingling. The regulations could be clearer by providing a definition of degradation and perhaps setting some criteria for water quality differences that may rise to the standard of comingling. It seems likely that the latter would be context specific.

The next section will discuss the work of the Texas Department of Licensing and Regulation Water Well Drillers Advisory Council which was convened in 2018 to provide input to the Texas Department of Licensing and Regulation on issues related to comingling in addition to other issues.

3.1.2 Texas Water Well Drillers Advisory Committee Summit

On January 5, 2018, the Water Well Drillers Advisory Council created a workgroup to review potential issues that had been raised regarding groundwater comingling and other concerns relevant to 16 TAC§76. The workgroup discussed the issues related to the current code regarding the definition of comingling. Based upon their review and input from the public, some members of the workgroup developed five areas of concern on which the workgroup sought input from the public. These were:

1. Define (groundwater) Degradation. §76.10 (16) & (19) - §76.100 (c)(1) & §76.105 (b)(3);
2. Identify the amount of time and what conditions must be met for a test well to stay open. §76.100 (c)(6);
3. What are the minimum well construction standards to produce brackish water? §76.102;
4. Would mixing 20,000 milligrams per liter with 30,000 milligrams per liter brackish water be considered comingling?;
5. Define aquifers and zones. §76.10 (16).

On August 17, 2018, the Water Well Drillers Advisory Council held a summit to give stakeholders the opportunity to provide verbal input on the five issues defined by the workgroup. A video of the summit is available at the Texas Department of Licensing and Regulation YouTube Channel (Water Well Drillers Advisory Council Summit. 2018). Many stakeholders also provided written testimony. Table 3-3 provides a summary of the stakeholders who provided written and/or verbal comments.

Table 3-3. Stakeholders who provided comments to the Water Well Drillers Advisory Council

Organization / Individual	Verbal or Written Comments
Texas Oil and Gas Association	Written and Verbal
Texas Alliance of Groundwater Conservation Districts	Written
Texas Groundwater Association	Written and Verbal
Texas Groundwater Protection Committee	Written
Texas Commission on Environmental Quality	Written
Texas Water Development Board	Written
Texas Desalination Association	Written
Panola Co. Groundwater Conservation District	Verbal
Rusk Co. Groundwater Conservation District	Verbal
Independent PG	Verbal

There was a consistent opinion in the stakeholder group that the Texas Department of Licensing and Regulation should not make modifications to the rules before additional stakeholder input and a clear articulation of the objectives of any modifications.

Because the five questions sought clarification regarding several definitions (i.e., comingling, degradation, aquifer, and zone), stakeholders referenced several codes and rules from both state statutes and administrative code as well as some federal regulations. Most input simply referred to the current water well drillers and pump Installers rules. Other state regulations cited by stakeholders will be briefly introduced in a summary of feedback for each of the five issues.

Define (groundwater) Degradation – As introduced above, the term degradation is the important qualifying term in the definition of comingling and is not defined in 16 TAC§76. It was the opinion of several stakeholders that degradation should be equated to the definition of pollution which is found in the well drillers' rules (16 TAC§76.10(42)) and provided in Section 3.1.1.

Comingling under the paradigm pollution would be the mixing of groundwater that is detrimental or injurious to humans or the environment or impairs a reasonable use. Another stakeholder referred to the Texas Water Code, Chapter 26.401-408, Subchapter J – Groundwater Protection. TWC§26.401(c) states:

> *(c) It is the policy of this state that: (1) discharges of pollutants, disposal of wastes, or other activities subject to regulation by state agencies be conducted in a manner that will maintain present uses and not impair potential uses of groundwater or pose a public health hazard; and (2) the quality of groundwater be restored if feasible. (d) The legislature recognizes the important role of the use of the best professional judgment of the responsible state agencies in attaining the groundwater goal and policy of this state.*

This portion of the water code emphasizes the objective to maintain and protect current and potential uses as well as not be a health hazard, which one can assume means to be protective of human and environmental health.

Time and Conditions a Test Borehole Can Stay Open – No additional statutes or codes were introduced by the feedback. It was the opinion of Texas Department of Licensing and Regulation that the current rules are adequate because they allow a variance process (16 TAC§76.109(a)) for all types of water wells, including test wells. That variance process allows modification to requirements found in 16 TAC§76.100-105 if the change will not allow injury and pollution. The current rule, 16 TAC§76.100(c)(6), allows a test well drilled for exploring for groundwater to remain non-completed, or open for up to six months. Many suggested that the timing should be shorter than six months if the mixing is causing mixing of injurious water with non-injurious water.

Minimum Construction Standards for Production of Brackish Groundwater – Texas Department of Licensing and Regulation recognized no definition of brackish groundwater is in 16 TAC§76; however, they noted there is a definition of injurious water, which includes brackish water, included within the definition of pollution. Therefore, completion standards defined in code 16 TAC§76.101 require that brackish water must be confined to the zone of origin.

The Texas Commission on Environmental Quality provided a detailed response to this question. They stated that the well should be drilled with a properly weighted mud to prevent borehole or interval mixing. The well should be completed to ensure that the brackish groundwater is isolated to the zone of origin. TWDB and Texas Commission on Environmental Quality suggested that all wells and pump components in contact brackish groundwater should be composed of materials compatible with brackish conditions. Both agencies also stated that if brackish groundwater wells were to be used for public water supplies then they should also comply with 30 TAC§290.

Would Mixing 20,000 milligrams per liter with 30,000 milligrams per liter Brackish Water be Considered Comingling? – There was a difference of opinion on this issue. Texas Department of Licensing and Regulation, as well as several others, suggested that this example would be comingling. Others, including the Texas Groundwater Protection Committee did not consider this comingling because both total dissolved solids levels are within the same salinity class. Several groups suggested that comingling consider degradation in context of the proposed use. That is, if mixing of 20,000 milligrams per liter with 30,000 milligrams per liter maintains the proposed use, it would not be considered comingling. Still others, including TWDB, stated that both use and aquifer of origin should be considered.

Define Aquifers and Zones – Both of the terms aquifers and zones appear in the definition of comingling. Most stakeholders who responded suggested that the Texas Department of Licensing and Regulation and Regulation use TWDB definitions for these concepts. The TWDB recognizes 11 major aquifers and 22 minor aquifers in the state which are defined in the State Water Plan and in George and others (2011). Chapter 36.001(7) of the TWC defines a groundwater reservoir as a subsurface water bearing reservoir that has ascertainable boundaries containing groundwater. Section §36.001(7) defines a subdivision of a groundwater reservoir in which the groundwater supply will not be appreciably affected by withdrawing water from any other part of the reservoir.

Others referenced the Code of Federal Regulation (CFR) for definitions of aquifers and zones. Specifically, 10 CFR 40, Appendix A, 10 CFR 960.2, 30 CFR Part 710.5 and 30 CFR Parts 710.5,146.03, 260.10, 270.2 and 257.3-4. Others referenced the definition of an aquifer from the United States Geological Survey (Lohman and others, 1972) as a formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells or springs.

3.2 Review of Selected Texas Administrative Code

The review of TAC focused on three Titles (see Table 3-1):

- Title 16 – Economic Regulation (Texas Department of Licensing and Regulation and the Railroad Commission)
- Title 30 – Environmental Quality (Texas Department of Environmental Quality)
- Title 31 – Natural Resources (TWDB and Groundwater Protection Committee)

The review of these administrative codes used as selective key word search. These words were selected to provide insight into how other portions of the TAC, or statutes, define terms relevant to comingling as defined in 16 TAC§76.10(16). These terms are:

- Comingling
- Degradation
- Injurious
- Pollution
- Beneficial Use

The use of key words is efficient given the volume of the code which is relevant to this study. Comingling and degradation are direct terms to search given the definition of comingling. Comingling is only found in two other portions of the code; the Underground Injection Control code (30 TAC§331) and the Texas Railroad Commission Oil and Gas Division Code (Title 16, Part 1, Chapter 3). The term injurious, generally used in conjunction with water, is used throughout the 16 TAC§76 with the intention of preventing injurious waters from mixing with fresh water. It has also been suggested by Texas Department of Licensing and Regulation, that the term pollution could replace degradation as used in the definition of comingling. Pollution is defined in the well drillers code and includes protection from injurious water. Finally, because maintaining the intended use of water should logically be considered when evaluating degradation or pollution, the term beneficial use was added. All these terms focus on what may constitute degradation which is a qualifying trait of comingling.

3.2.1 Title 16, Part 1-Railroad Commission, Chapter 3-Oil and Gas Division

The Texas Railroad Commission regulates oil and gas activities within the state, including Class II wells which inject waste fluids produced during the drilling or production of oil and gas. Of the five terms searched on, only the term degradation was not found in this code. The remaining four terms will be briefly discussed below.

Comingling – The term comingling is used in several places in two contexts. The first context is not relevant to this study as it refers to the surface comingling of oil and gas from two different strata in surface facilities. The second context is more relevant as it deals with the comingling of oil and gas from different strata. Under 16 TAC§3.10 comingling of fluids from different strata may be allowable "*if commingling production will prevent waste or promote conservation or protect correlative rights*." The focus of these rules is to protect correlative rights of oil and gas lease holders.

Injurious and Pollution – The term injurious is found throughout this code. However, it is never defined but rather used in the definition of pollution or pollutants. Water Protection Rule 16 TAC§3.8(a)28 defines pollution of surface or subsurface water as "*the alteration of the physical, thermal, chemical, or biological quality of, or the contamination of, any surface or subsurface water in the state that renders the water harmful, detrimental, or injurious to humans, animal life, vegetation, or property, or to public health, safety, or welfare, or impairs the usefulness or the public enjoyment of the water for any lawful or reasonable purpose.*" This definition is identical to that found in 16 TAC§76.10(42).

These regulations are meant to protect freshwater strata (16 TAC§3.46). An example can be found in the rules for brine mining injection wells (16 TAC§3.81) which states that the commission will issue a brine mining permit only if it determines that the operation will not result in pollution of freshwater. Brine injection permits can be terminated, or renewal denied if the commission determines that the injection endangers "*human health or the environment, or that pollution of fresh water is occurring or is likely to occur as a result of the permitted injection; or (E) fluids are escaping from the permitted injection zone.*"

Beneficial Use – The relevant use of the term beneficial in this code is in the definition of fresh water which is defined in numerous places. These definitions are the same in all locations within the code. The definition in 16 TAC§3.81(a)(7) is "*water having bacteriological, physical, and chemical qualities that make it suitable for beneficial use for any lawful purpose*." This definition of fresh water is quite different from one defined strictly by salinity class (that is, greater than 1,000 milligrams per liter total dissolved solids).

The method used to ensure the protection of fresh or usable water quality for wells regulated by the Texas Railroad Commission is through a process called Groundwater Protection Determination. A Groundwater Protection Determination defines zones that should be protected because of their water quality. The Groundwater Protection Unit of the Railroad Commission makes these determinations as required by code. These determinations are made for new oil and gas wells, re-entries, and salt-water disposal wells. For oil and gas wells the Groundwater Protection Unit determines the top and bottom of fresh-water zones (they define as generally less than 1,000 milligrams per liter total dissolved solids), and the Base of Usable-Quality Water (generally 3,000 milligrams per liter total dissolved solids). The Groundwater Protection Unit will also identify for the operator other subsurface waters known to be used or identified as sources of desalinization water. For saltwater disposal wells (Class II) they also provide the base of the Underground Source of Drinking Water (less than 10,000 milligrams per liter total dissolved solids) and verify geologic isolation from the Base of Usable-Quality Water (3,000 milligrams per liter) and the Underground Source of Drinking Water (10,000 milligrams per liter).

3.2.2 Title 30, Part 1-Texas Commission on Environmental Quality

The Texas Commission on Environmental Quality is the environmental regulatory agency for the state and is tasked with protecting the state's public health and natural resources. They regulate three programs of potential interest to this review: Chapter 290-Public Drinking Water; Chapter 293C-Water Districts; and Chapter 331-Underground Injection. Groundwater Conservation Districts fall under Chapter 293. Chapter 293C is not relevant to this review because it deals with Groundwater Conservation District process and requirements. Chapter 290F – Drinking Water Standards and Reporting for Public Water Systems is included in our review for completeness. While this section is relevant because it defines the drinking water and water quality reporting requirements for Public Water Systems, the code does not offer any insight to the discussion of commingling.

Chapter 290 – Public Drinking Water, Subchapter D – Rules and Regulations for Public Water Systems

Title 30, Part 1, Chapter 290 documents the rules and regulations for public water systems including Public Water Supply wells (30 TAC§290.41(c)). Public Water Supply wells must comply with the Water Well Drillers and Pump Installers Rules (16 TAC§76) in addition to any other requirements found in Chapter 290. The terms commingling, injurious and beneficial use are not found in these rules. The terms degradation and pollution occur in these rules, but in context of anthropogenic pollution hazards.

Contamination is defined in these rules (§290.38(17)) as the "*presence of any foreign substance (organic, inorganic, radiological, or biological) in water which tends to degrade its quality so as to constitute a health hazard or impair the usefulness of the water.*" Most discussion of contamination as it applies to Public Water Supply wells in these rules relates to protecting the well from shallow and surficial anthropogenic contamination. In §290.41(c), which discusses rules for groundwater sources, it states that the casing shall extend to the shallowest water formation to be developed and deeper, if necessary, "in order to eliminate all undesirable water-bearing strata." Completion standards can be found in Chapter 290, Subchapter F for Public Water Supply wells.

Chapter 331 – Underground Injection

Chapter 331 documents the rules and procedures to implement the regulations of the Injection Well Act, Chapter 27 of the Water Code. In §331.1(a) it states that the implementation shall be consistent with the policy of this state to: "*maintain the quality of fresh water in the state to the extent consistent with the public health and welfare and the operation of existing industries, taking into consideration the economic development of the state; prevent underground injection that may pollute fresh water; and require the use of all reasonable methods to implement this policy*."

Subchapter A provides the general provisions for Chapter 331 which includes relevant definitions: pollution and fresh water. Section §331.2(86) defines pollution as *"the contamination of water or the alteration of the physical, chemical, or biological quality of water: (A) that makes it harmful, detrimental, or injurious: i) to humans, animal life, vegetation, or property; or (ii) to public health, safety, or welfare; or (B) that impairs the usefulness or the public enjoyment of the water for any lawful and reasonable purpose."*

Chapter 331 is structured to protect fresh water and to protect Underground Sources of Drinking Water. Section §331.2(49) defines fresh water as water *"having bacteriological, physical, and chemical properties which make it suitable and feasible for beneficial use for any lawful purpose. (A) For the purposes of this chapter, it will be presumed that water is suitable and feasible for beneficial use for any lawful purpose only if: (i) it is used as drinking water for human consumption; or (ii) the groundwater contains fewer than 10,000 milligrams per liter milligrams per liter) total dissolved solids; and (iii) it is not an exempted aquifer."* The commission can consider water with total dissolved solids greater than 10,000 milligrams per liter if an affected person can show that water can be put to beneficial use.

An Underground Source of Drinking Water is defined in §331.2(115) as an aquifer, or its portions, *"(A) which supplies drinking water human consumption; or (B) in which the groundwater contains fewer than 10,000 milligrams per liter total dissolved solids; and (C) which is not an exempted aquifer."* Class I wells (Hazardous Waste) must be designed, constructed, and completed to prevent movement of fluids that could result in the pollution of an Underground Source of Drinking Water. Class III (In-Situ Mining) wells rules are found in Subchapter E and are also focused on protecting Underground Sources of Drinking Water.

Class V wells (Miscellaneous) rules are found in Subchapters H and O, which pertain to wells used in Aquifer Storage and Recovery Projects. In Subchapter H, §331.132 (Construction

Standards) other protection measures called out different than the other requirements are related to commingling and undesirable groundwater. Subsection §331.132(g)(1) states that commingling is prohibited. This code states *"All wells, especially those that are gravel packed, shall be completed so that aquifers or zones containing waters that are known to differ significantly in chemical quality are not allowed to commingle through the borehole-casing annulus or the gravel pack and cause quality degradation of any aquifer containing fresh water."* This language is consistent in meaning to that in 16 TAC§76. Subsection §331.132(g)(2) which states that "*When undesirable groundwater, which is water that is injurious to human health and the environment or water that can cause pollution to land or other waters, is encountered in a Class V well, the well shall be constructed so that the undesirable groundwater is isolated from any underground source of drinking water and is confined to the zone(s) of origin*."

Aquifer storage and recovery wells, are a special class of Class V wells and have additional requirements codified in Chapter K. In Section 331.183 (Construction Standards) it requires that aquifer storage and recovery wells be "*designed, constructed, completed, and closed to prevent commingling, through the wellbore and casing, of injection waters with other fluids outside of the authorized injection zone; mixing through the wellbore and casing of fluids from aquifers of substantively different water quality; and infiltration through the wellbore and casing of water from the surface into ground water zones*." Like 16 TAC§76, these rules also seek to prevent comingling. In these rules an objective is to prevent mixing of fluids of substantively different water quality. The term substantive is open to interpretation.

A relevant section of code can be found in §331.186 (Additional Requirements Necessary for Final Project Authorization) which discusses acceptable mixing of a recharge water with the native groundwater. This section of code requires the commission to consider whether the injection of the recharge water will comply with the Safe Drinking Water Act. These rules also allow comingling, within the aquifer, if the recovered groundwater maintains its beneficial use allowing for some comingling with the native groundwater. In aquifer storage and recovery. the recharge water must also comply with water quality standards of the Safe Drinking Water Act and must not endanger drinking water sources.

3.2.3 Title 31, Part 10-Texas Water Development Board

The only section reviewed in Title 31 Part 10 was Chapter 356 which is Groundwater Management. A review of the current code did not provide any insight relative to clarification of the definition comingling. In addition to this section, the proposed brackish production zone rules amending Title 31 TAC§356 with a new Subchapter G were reviewed. The new proposed rules were issued in August of 2020 and were developed to establish rules for persons interested in obtaining a permit from a groundwater conservation district to authorize producing from a brackish groundwater production zone for a municipal supply or for electric generation.

Section §356.70 of the Subchapter G provides rules for brackish groundwater production zone designation. This section stipulates that brackish groundwater production zones are "*separated by hydrogeologic barriers sufficient to prevent significant impacts to water availability or water quality in any area of the same or other aquifers, subdivisions of aquifers, or geologic strata that* *have an average total dissolved solids level of 1,000 milligrams per liter or less at the time of designation of the zones.*" This proposed code seeks to isolate brackish groundwater from fresh water as defined by the salinity classifications used by the TWDB. The code does not discuss more complicated issues such as the protection of water of differing chemical quality or the standard of degradation. One interpretation of "significant impacts" in this proposed code is that degradation would be anything that increased the total dissolved solids concentration of fresh groundwater to above the Texas Commission on Environmental Quality secondary drinking water standard of 1,000 milligrams per liter.

3.2.4 Title 31, Part 18-Texas Groundwater Protection Committee

This section documents the implementation of rules and duties to the Groundwater Protection Committee concerning the maintenance of public files containing documented cases of groundwater contamination by member agencies. The focus of this committee has historically been anthropogenic contamination of groundwater. The relevant portion of code for this review is the definition of contamination in §601.3(7): "*the detrimental alteration of the naturally occurring physical, thermal, chemical, or biological quality of groundwater. Except for an underground source of drinking water granted an aquifer exemption by the commission..., groundwater contamination, for purposes of inclusion of cases in the public files and the joint groundwater monitoring and contamination report, is limited to contamination reasonably suspected of having been caused by activities or by entities under the jurisdiction of the member agencies identified in §601.2 of this title (relating to Applicability) and affecting groundwater that contains a concentration of: (A) less than or equal to 10,000 milligrams per liter (milligrams per liter) of dissolved solids; or (B) greater than 10,000 milligrams per liter of dissolved solids if it is: (i) currently extracted for beneficial use such as domestic, industrial, or agricultural purposes; or (ii) hydrologically connected with, and with the potential for contaminant movement to, a surface waterbody or another zone of groundwater that has a concentration of less than or equal to 10,000 milligrams per liter of dissolved solids.*"

Member agencies include TWDB and Texas Commission on Environmental Quality and therefore groundwater contamination from comingling could be interpreted to be relevant to this code. Also, this definition is specific to the joint groundwater monitoring and contamination report required under this code. It is also relevant to this discussion that the committee defines contamination occurs to waters less than 10,000 milligrams per liter with the exception that one could show the groundwater at greater than 10,000 milligrams per liter could be put to beneficial use. This is consistent with the protections allowed under the 30 TAC§331, Underground Injection Rules.

3.3 Review of Selected Texas Statutes

The review of Texas Statutes will focus on three Titles (see) and used the same selective key word search as in Section 3.3:

- Occupations Code – Title 12, Subtitle A – Occupations Related to Water
- Texas Water Code, Chapter 26 – Water Quality Control
- Texas Water Code, Chapter 36 – Groundwater Conservation Districts

3.3.1 Occupations Code, Chapters 1901 and 1902 – Water Well and Pump Installers

The occupations code only has reference to the term injurious. The Water Well Drillers and Pump Installers code (16 TAC§76.10(33)) defines injurious water as "*Water that is harmful to vegetation, land or other water as set forth in §1901.254(a) and §1902.252(a) of the Code*." The citation is the occupations code.

The context of Sections §1901.254(a) and §1902.252(a) is for providing notice of encountering injurious water during well repair or completion and plugging. The code does not further define the term injurious but rather uses it in the context of requiring notification to the department on "*encountering water injurious to vegetation, land, or other water.*" Recall that 16 TAC§76 completion standards are predicated on the objective to prevent the mixing of injurious water with "good water". From the definition of comingling, one would expect that such mixing would have to meet the degradation standard.

3.3.2 Texas Water Code, Chapter 26 – Water Quality Control

Protection of the State's groundwater resources from degradation or waste is an explicit policy which can be found in the Texas Water Code in numerous places including TWC §26.401 and TWC §36.101. TWC §26.401 establishes the state's groundwater protection policy regarding non-degradation of groundwater resources for all state programs (Texas Groundwater Protection Committee, 2020). TWC §26.401(a) states that the legislature finds that: *"(1) in order to safeguard present and future groundwater supplies, usable and potentially usable groundwater must be protected and maintained; (2) protection of the environment and public health and welfare requires that groundwater be kept reasonably free of contaminants that interfere with present and potential uses of groundwater".*

In this section TWC §26.401(c) the legislature determines that "*it is the goal of groundwater policy in this state that the existing quality of groundwater not be degraded. This goal of nondegradation does not mean zero-contaminant discharge. (c) It is the policy of this state that: (1) discharges of pollutants, disposal of wastes, or other activities subject to regulation by state agencies be conducted in a manner that will maintain present uses and not impair potential uses of groundwater or pose a public health hazard; and (2) the quality of groundwater be restored if feasible.*"

This statute puts degradation in the context of a balance between human and environmental health, economics, and the preservation of present and potential uses of the groundwater. This section recognizes that certain contamination is within the bounds of maintaining human and environmental health.

3.3.3 Texas Water Code, Chapter 36 – Groundwater Conservation Districts

Groundwater Conservation Districts in the State of Texas are authorized under Article 16, Section 59 of the Texas Constitution. The Texas Water Code (TWC) specifies the organization, authorities, and rules for conservation districts. TWC §36.0015(b) states that groundwater conservation districts are the State's preferred method of groundwater management.
TWC §36.101 defines the rulemaking powers of groundwater conservation districts and states

that a "*district may make and enforce rules, including rules limiting groundwater production based on tract size or the spacing of wells, to provide for conserving, preserving, protecting and recharging of the groundwater or of a groundwater reservoir or its subdivisions in order to control subsidence, prevent degradation of water quality, or prevent waste of groundwater.*"

The terms comingling and injurious are not used in Chapter 36. Pollution is referenced in the definition of waste as well as referenced in portions of the code as a condition to be avoided. The terms degradation and beneficial use occur in the code and will be discussed in this section. We will start with a review of key definitions. TWC §36.001(8) provides a multi-faceted definition of waste which includes "*pollution or harmful alteration of groundwater in a groundwater reservoir by saltwater or by other deleterious matter admitted from another stratum or from the surface of the ground.*"

TWC §36.001(9) defines beneficial use as: "*use for a beneficial purpose means use for: (A) agricultural, gardening, domestic, stock raising, municipal, mining, manufacturing, industrial, commercial, recreational, or pleasure purposes; (B) exploring for, producing, handling, or treating oil, gas, sulphur, or other minerals; or (C) any other purpose that is useful and beneficial to the user.*"

TWC §36 defines terminology that is relevant to the terms aquifer and zone used in the definition of comingling. Section §36.001(6) defines a groundwater reservoir as "*a specific subsurface water-bearing reservoir having ascertainable boundaries containing groundwater*." This could be equated to a major or minor aquifer defined by TWDB or it could be conceptualized as a particular formation within an aquifer that has clear boundaries such as the Simsboro Formation in the Carrizo-Wilcox Aquifer. TWC §36.001(7) further refines a groundwater reservoir by subdivision which is defined as "*a definable part of a groundwater reservoir in which the groundwater supply will not be appreciably affected by withdrawing water from any other part of the reservoir, as indicated by known geological and hydrological conditions and relationships and on foreseeable economic development at the time the subdivision is designated or altered*." An example of a subdivision of a reservoir may be a groundwater production zone.

It can be concluded from a review of TWC §36 that a primary role of groundwater conservation districts is to prevent degradation of water quality and to prevent waste. Degradation is not defined, but the definition of waste includes the harmful alteration of groundwater in a groundwater reservoir by saltwater or other deleterious matter admitted from another stratum or from the surface of the ground. Saltwater is not defined within the code, but TWDB delineates aquifers based on the presence of freshwater, defined as a total dissolved solids level less than 1,000 milligrams per liter. Deleterious is also not defined, but a standard dictionary definition equates it to being harmful, often in a subtle or unexpected way.

3.4 Groundwater Protection Committee's Groundwater Classification System

The Groundwater Protection Committee was created by the legislature in 1989. The Groundwater Protection Committee includes members of ten state agencies and organizations. These are:

- Texas Commission on Environmental Quality;
- The TWDB;
- Railroad Commission of Texas;
- Texas Department of State Health Services;
- Texas Department of Agriculture;
- Texas State Soil and Water Conservation Board;
- Texas Alliance of Groundwater Districts;
- Texas A&M AgriLife Research;
- Bureau of Economic Geology; and
- The Water Well Drillers and Pump Installers Program at the Texas Department of Licensing and Regulation.

The purpose of the Groundwater Protection Committee is to implement the State's groundwater protection policy by identifying opportunities to improve existing groundwater quality programs and promoting agency coordination (Groundwater Protection Committee, 2020). One of the committee's responsibilities is publishing an annual groundwater monitoring and contamination report.

In Appendix 3 of the 2019 Annual Report, which includes the Texas Department of Licensing and Regulation as a member agency, they define a groundwater classification system to be used as a tool for groundwater protection consistent with groundwater policy contained in TWC §26.401. 4 provides the classification system from the 2019 Joint Groundwater Monitoring and Contamination Report. The classification seeks to categorize water quality which would then define the appropriate degree of protection or restoration which would be applied to that class. The Groundwater Protection Committee states that this classification applies to all groundwaters in the state.

The report states that all usable and potentially usable groundwater be subject to the same protection afforded the non-degradation policy goal of the TWC §26.401. The report states that protection, or restoration, can be varied based upon the response level provided in the classification system if the following conditions are met:

- Current groundwater uses are not impaired;
- Potential groundwater uses are not impaired;
- A public health hazard is not created; and
- The quality of groundwater is restored if feasible.

The groundwater classification system also speaks to the question of aquifers versus zones raised by Texas Department of Licensing and Regulation in 2018. Specifically, the report states that the "*suitability of a zone for use as a human drinking water supply can be based on the quality and quantity of the water it contains as well as its ability to produce enough water to meet its intended use*."

In Appendix 3 of the 2019 Joint Groundwater Monitoring and Contamination Report, the Groundwater Protection Committee states that the following.

> *This classification system is intended to be implemented by member agencies as an integral part of their groundwater quality programs. In addition to its response setting*

> *function, the classification system can also serve as a common basis among the various programs to foster consistency.*

The 16 TAC§76 rules could consider addressing comingling, degradation, injurious and pollution in a manner consistent with this classification.

Table 3-4. Groundwater Classification System of the Texas Groundwater Protection Committee.

Class	Quality* (total dissolved solids concentration)	Examples of Use	Agency Response
Fresh	0 – 1,000 milligrams per liter	Drinking and all other uses	Level I: Protection or restoration measures based on current use as a human drinking water supply.
Slightly Saline	greater than 1,000 – 3,00 milligrams per liter	Drinking if fresh water is unavailable, livestock watering, irrigation, industrial, mineral extraction, oil and gas production	Level I:
Moderately Saline	Greater than 3,000 to 10,000 milligrams per liter	Potential/future drinking and limited livestock watering and irrigation if fresh or slightly saline water is unavailable; industrial, mineral extraction, oil and gas production.	Level I:
Very Saline to Brine	Greater than 10,000 milligrams per liter	Mineral extraction, oil and gas production.	Level II: Protection or restoration measures based on indirect exposure or no human consumption.

* "Quality" refers to the concentration range of total dissolved solids in milligrams per liter of water.

3.5 Summary of Findings

This section provides a review of select Administrative Codes and Texas Statutes relevant to the concept of comingling as it is denoted in the Water Well Drillers and Pump Installers Rules (16 TAC§76). This review focused on terminology and attributes of groundwater protection from the other codes and statutes that may provide guidance in interpreting comingling as set forth in 16 TAC§76.10(16). Table 3-5 provides a summary of findings from the review.

Table 3-5. **Summary Characteristics of Groundwater Protection.**

CODE / STATUTE TITLE	PART	CHAPTER / SUBCHAPTER	Groundwater Protection Considers				
			Human Health	Environmental Health	Use	Total Dissolved Solids Limits (milligrams per liter)	Constituent Based
TAC Title 16 - Economic Regulation	Part 1 - RRC	Chapter 3 - Oil and Gas Division	Yes	Yes	Yes	1000, 3000, 10,000(1,2)	No
	Part 4 - Texas Department of Licensing and Regulation	Chapter 76 – Water Well Drillers & Pump Installers Rules	Yes	Yes	Yes(3)	No	No
TAC - Title 30 - Environmental Quality	Part 1 - Texas Commission on Environmental Quality	Chapter 290 D - Rules and Regs Public Water Supply Systems	Yes	Yes	Yes	No(4)	No(3)
		Chapter 290 F - Drinking Water Standards	Yes	Yes	Yes	1,000	Yes
	Part 1 - Texas Commission on Environmental Quality	Chapter 331 - Underground Injection Control	Yes	Yes	Yes	1,000, 3,000, 10,000(2)	No
TAC - Title 31 - Natural Resources	Part 10 - Texas Water Development Board	Chapter 356 - Groundwater Management	No	No	No	1000(5)	No
	Part 18 - Texas Groundwater Protection Committee	Chapter 601 - Groundwater Contamination Report	No(6)	No(6)	No	10,000	No

CODE / STATUTE TITLE	**PART**	**CHAPTER / SUBCHAPTER**	**Groundwater Protection Considers**				
			Human Health	**Environmental Health**	**Use**	**Total Dissolved Solids Limits (milligrams per liter)**	**Constituent Based**
Occupations Code	Subtitle A; Chp. 1901 & 1902	Water Well Drillers and Pump Installers	Yes(7)	Yes(7)	Yes(7)	No	No
Texas Water Code	Chapter 26	Water Quality Control	Yes	Yes(8)	Yes	No	No
Texas Water Code	Chapter 36	Groundwater Conservation Districts	Yes(9)	Yes(9)	Yes(9)	No(10)	No

(1) The definition of fresh water 16TAC381(a)(7) is based upon beneficial use, not total dissolved solids

(2) Objective is to protect Underground Sources of Drinking Water - Less than 10,000 milligrams per liter total dissolved solids

(3) The concept of considering use occurs in the definition of Pollution (16TAC76.10(42))

(4) References compliance with 16TAC76 and refers to Drinking Water Standards in 30TAC290, Subchapter F

(5) In reference to the Brackish Production Zone Rules 31TAC356 proposed in August of 2020

(6) This code is in reference to the Groundwater Contamination Report, 18TAC601.10 of Subchapter B to may imply consideration of health effects

(7) Implied through use of the term "injurious" which occurs in the definition of pollution in 16 TAC 76 to include human and environmental health and use

(8) Protection is focused on maintaining current and future use and protecting public health which is interpreted to include environmental health

(9) Through the definition of waste, Chapter 36 includes pollution which is interpreted to consider human and environmental concerns as well as use

(10) TWC 36.001(8) does define waste to include alteration of groundwater by saltwater which could be interpreted to be protecting less than 1,000 milligrams per liter total dissolved solids

We can conclude from Table 3-5 that most of these regulations consider both human and environmental health in their paradigm for groundwater protection. The majority reference consideration or preservation of the groundwater use when considering degradation. Half of them have defined total dissolved solids-based protection limits. Most do not explicitly consider constituent specific standards.

It is reasonable to assume, though not directly stated, that 16 TAC§76 was written to protect fresh water generally accepted to be 1,000 milligrams per liter total dissolved solids or less. The code seeks to protect human health and the environment which is consistent with the Public Supply Well program (30 TAC§290). This implies that the objective is not to degrade fresh water nor have comingling result in degradation of fresh water such that it will not meet the primary and secondary drinking water standards (30 TAC§290.104 and §290.105). Many parts of the state regularly utilize slightly brackish groundwater as drinking water. As a result, it would not meet the spirt of 16 TAC§76 to have comingling degrade slightly saline groundwater such that its quality could no longer meet the intended purpose. As a result, 16 TAC§76 would extend to brackish groundwater if that comingling deters use. The Underground Injection Control Program seeks to protect Underground Sources of Drinking Water which have a character of less than 10,000 milligrams per liter. As stated earlier in this document, Texas Department of Licensing and Regulation staff consider the intent of 16 TAC§76 to protect waters even if neither is considered injurious.

A valid question that arises from this review is, should 16 TAC§76 seek to protect groundwaters above a certain water quality standard? For example, the Texas Department of Licensing and Regulation question of whether mixing 20,000 milligrams per liter with 30,000 milligrams per liter total dissolved solids is comingling. A case can be made, based upon the administrative code and statutes reviewed, that mixing of poor water qualities which have no expected beneficial use for human consumption and could not reasonably be expected to discharge into the environment would not be considered degradation and therefore not considered comingling. The concept of groundwaters use should be considered when defining protective measures. Issues such as these could be addressed by defining degradation and providing guidance regarding what constitutes a significant difference in water quality.

4 Physical Framework for Comingling

As discussed in Section 3, comingling as defined in 16 TAC§76 is the result of mixing through a borehole casing annulus or filter pack of waters that differ in chemical quality, causing water quality degradation of any aquifer or zone. Mixing of groundwater resulting in degradation of groundwater can occur under several conditions. First, it could occur during drilling and prior to well completion. Second, it could occur during a period when a well has been drilled but is left open prior to completion or plugging and abandonment as might occur in a test borehole. Finally, comingling can occur in wells that have been drilled and completed but allow for mixing of groundwater from one aquifer or zone to another during non-pumping periods. The inter-aquifer or zonal flow that may occur during non-pumping periods in water supply wells is episodic and likely would not result in the permanent degradation. This is because the water supply well production flow rate is generally much greater than the ambient interflow occurring in a borehole during non-pumping. If a well is abandoned or not pumped for large periods of time the inter-aquifer flow rates will decrease over time but the potential for degradation is higher. For pumping wells, the most common groundwater degradation likely occurs during groundwater pumping when mixing of deleterious water quality within the wellbore causes a water quality concern in the water sampled at the wellhead. This situation does not technically classify as comingling because the water quality in a zone of aquifer is not being degraded from that borehole mixing. This condition typically is addressed when a water supply well fails to comply with drinking water standards or treatment costs become too costly. Direct field evidence of the conditions which could cause comingling is generally documented in wells post well completion when wellhead water quality becomes an issue.

The section will discuss a conceptual physical framework for understanding the aquifer conditions that may contribute to comingling. The discussion focuses on physical aquifer conditions conducive to comingling if poor aquifer characterization and well completion standards are used. We do not identify the multiple combinations of aquifer conditions and well completion conditions that could lead to comingling.

4.1 Background

It is not uncommon for a well to be completed into multiple aquifers or zones having different transmissivities and static hydraulic heads. Flow to a well under these conditions is significantly more complicated than for a well completed into a single hydrogeologic unit. The estimation of the amount of flow originating from each aquifer gets quite complex, especially for unsteady (transient) flow. There is a mature body of literature presenting analytic or numerical solutions to predict flow rates from zones of different transmissivity as well as the composite well hydraulic head in a pumped well (e.g., Hantush, 1967; Motz, 1978; Reilly and others 1989; Neville and Tonkin, 2004). The study of intra-borehole flow between zones within a well that may cause comingling is less common.

Comingling, per its definition, requires a borehole or filter pack to be the conduit through which water quality mixing results in degradation in any aquifer or zone. While mixing will occur within the borehole during pumping conditions, the potential for flow between aquifers through the borehole under non-pumping conditions is the primary mechanism for degradation of water quality because flow will occur between aquifers/zones if a vertical hydraulic gradient exists in the well/borehole.

The potential for interflow between aquifers or zones through a borehole has been recognized as a source for cross-contamination for many decades. Johnson (1961) published an article in the Johnson Well Driller Journal on the problems posed by dual-aquifer wells which includes the potential of degrading water quality from flow to one zone to another. In 1977, the United States Environmental Protection Agency published a handbook on the impacts of abandoned wells on groundwater which included a chapter on case studies of cases where groundwater was polluted from abandoned wells (Gass and others, 1977). Since that time, many studies have been performed both theoretically simulating or documenting cases of groundwater quality degradation from wells completed in multiple aquifers or zones. Silliman and Higgins (1990) published an analytic solution for predicting steady-state flow rates between aquifers through an open borehole. Konikow and Hornberger (2006) modeled the impacts of inter-borehole flow on contaminant transport using the MODFLOW multi-node package. More recently, Gailey (2017) documented tens of case studies where inactive supply wells served as conduits for contaminant migration.

The fact that flow rate to a well's screen can vary with elevation has resulted in many field characterization methods to measure the inflow, and outflow, that may occur across a long screen under certain hydrogeologic conditions. These methods have included traditional interval packer testing to a host of indirect and direct borehole logging methods. Most borehole logging methods determine the vertical distribution of flow within a well by estimating the flow velocity within the borehole during pumping or non-pumping conditions and from that infer interval inflows and outflow. Typical types of logging tools include the spinner flow meter, the packer flow meter, the heat pulse flow meter, electromagnetic flowmeter, and various methods for in borehole tracing of a conservative tracer (Molz and others, 1994; Tsang and others, 1990; Loew and others, 1994; Izbicki and others, 1999; Paillet and others, 2002; Young and Pearson, 1995).

The methods of borehole profiling using tracers to determine vertical flow rates and water quality along a well screen have advanced significantly over the past two decades through the development of dynamic flow profiling combined with downhole water sampling techniques originally developed by the United States Geological Survey (Izbicki and others, 1999, Izbicki, 2004, Izbicki and others, 2005). These methods have been further developed and employed by BESST, Inc. across the country (https://besst-inc.com/). These methods have been used in Texas to characterize inter-borehole flow rates during ambient and pumping well conditions in both the Gulf Coast and Edwards aquifers. These methods are well suited to isolate and screen intervals in water supply wells that are degrading the wellhead water quality above standards. Through selective recompletion of the well, water quality and treatment costs have been improved.

A nuance of the concept of comingling is that it addresses the mixing of groundwater from one zone or aquifer to another through the well bore such that the water quality within a co-completed zone or aquifer is degraded. Based upon the definition, it does not appear to consider the water quality measured at the wellhead from the mixing of two zones or aquifers. In practice, the degradation of water quality measured at the wellhead is the concern of the owner of a well. All wells co-complete zones that are of slightly differing water quality and many times may co-complete zones where one zone has natural constituent concentrations above standards while the wellhead concentration complies with standards. Is this comingling? Our interpretation of statute is that, if the use were maintained, among other considerations described above, the mixing would be acceptable. In this hypothetical case, if the poor water quality zone recharged the better water quality zone in times of non-pumping, this would clearly be comingling as per the definition. However, it is the opinion of the authors the impact of poorer water quality recharging a better water quality zone will be mitigated when the well is pumping in most real-world situations.

4.2 Physical Aquifer Conditions Contributing to Comingling

The Texas Department of Licensing and Regulation definition of comingling requires a borehole or filter pack to be the conduit through which water quality mixing results in degradation in any aquifer or zone. Therefore, the presence of a borehole within an aquifer is a requirement for comingling. However, there are physical aquifer conditions that are also required: groundwater quality variability that could result in degradation if mixing occurs and vertical hydraulic gradients to allow for that mixing under ambient (that is, non-pumping conditions). This section will discuss natural water quality in fresh and brackish aquifers and will also discuss vertical hydraulic gradients which are the driving force for the aquifer-to-aquifer mixing to occur.

4.2.1 Evolution of Macro-chemistry of Fresh and Brackish Aquifers Along a Groundwater Flowpath

Water is subject to multiple geochemical processes (Figure 4-1) as rainwater infiltrates the land surface, becomes groundwater, and begins moving from a recharge to a discharge location. As groundwater passes through the subsurface, its chemical signature is modified by processes which includes dissolution/precipitation, ion exchange processes, oxidation, and reduction. These chemical reactions vary spatially and temporally, depending on the chemical nature of the initial recharge water, aquifer deposits, and residence time. In Figure 4-1, the processes affecting the water chemistry are distinguished between open and closed groundwater systems. The distinction between an open and closed system is based upon the aquifer's accessibility to atmospheric gases (oxygen and carbon dioxide). Open systems are typically shallow and unconfined to semi-confined, whereas closed systems are deeper and confined.

The initial quality of the recharge that enters a groundwater flow system is determined by the chemical composition of the source water, which is typically precipitation or surface water, and by chemical reactions in the unsaturated zone. The occurrence and intensity of the chemical reactions in the unsaturated and saturated zones depend on the initial water's disequilibrium with minerology of the aquifer deposits. Minerals that comprise the aquifer matrix will completely or partially dissolve in water according to the resistance of chemical weathering. Table 4-1 lists the resistance to chemical weathering of rock types, and their associated mineralogy, that commonly comprise aquifers. Generally, groundwater increases in mineral content with residence time because the equilibration of the groundwater with the aquifer matrix can require many years.

Because chemical reactions are groundwater-flow-path-dependent, the groundwater entering a well from different depths will have variable chemical composition.

As a result of being modified by geochemical processes, the signature of groundwater macro-chemistry, which is defined by the composition of its major anions and cations, evolves along a groundwater flow path. An example of the evolution of chemical signature are the changes in anionic composition of groundwater observed by Chebotarev (1955), which reviewed more than 10,000 chemical measurements from water wells in Australia and concluded that groundwater tends to evolve chemically toward the composition of seawater and that this evolution typically includes the following regional changes in dominant anion species:

Travel along flow path: ---▶

$HCO_3^- \rightarrow HCO_3^- + SO_4^{2-} \rightarrow SO_4^{2-} + HCO_3^- \rightarrow SO_4^{2-} + Cl^- \rightarrow Cl^- + SO_4^{2-} \rightarrow Cl^-$

Increasing Age: ---▶

where:

HCO_3^- = Bicarbonate ion
SO_4^{2-} = Sulfate ion
Cl^- = Chloride ion

Table 4-1. Common rock types and resistance to chemical weather (modified from Elango-Lashmanan and Kannan, 2007).

Type of Rock	Dominant Minerals Present in Rock	Resistance to Chemical Weathering
Quartz-cemented sandstone	Quartz and K-Feldspar	High
Calcite-cemented sandstone	Quartz, K-Feldspar, and clays	Low
Siltstone	Quartz, K-Feldspar, and clays	High
Shale	Quartz and clays	High
Limestone	Calcite	Low
Rock salt	Halite	Low
Rock gypsum	Gypsum	Low
Slate	Quartz, Biotite, and Muscovite	High
Phyllite, schist	Quartz, K-Feldspar, Biotite and/or Muscovite and Amphibole	High
Gneiss	Quartz, K-Felspar, Plagioclase, Biotite, and Amphibole	High
Marble	Calcite	Moderate
Quartzite	Quartz	Very high
Granite	Quartz and K-Feldspar	High
Basalt	Olivine, Pyroxene	Moderate

For large aquifer systems, Chebotarev (1955) suggests that salinity should generally increase: with depth, with distance from the recharge area, with proximity to the sea (where applicable), and with duration of contact with aquifer minerals, which can also be referred to as residence time. The anion-evolution sequence described by Chebotarev (1955) can be described by three main zones, which correlate with general depth (Domenico, 1972; Freeze and Cherry, 1979).

> The Upper Zone – characterized by active groundwater flushing through the relatively well-leached rocks. Water in this zone has bicarbonate as the dominant anion and is low in total dissolved solids.
>
> The Intermediate Zone – characterized by less active groundwater circulating and higher total dissolved solids. Sulfate is normally the dominant anion.
>
> The Lower Zone – characterized with very slow groundwater velocities. Highly soluble minerals are commonly present in this zone because very little groundwater flushing occurs. High chloride concentrations and high total dissolved solids are characteristic of this zone.

Ophori and Toth (1989) and Back (1966) are among the notable studies that document the anion-evolution sequence and the gradual increase in total dissolved solids concentrations that occurs along a groundwater pathway as described by Chebotarev (1955), Domenico (1972), and Freeze and Cherry (1979). Some hydrogeologic studies that document the evolution of ionic composition and total dissolved solids concentration along groundwater flow paths in Texas aquifers include: Haile and Fryar's (2017) study of the Wilcox Aquifer; Khan and others (2016) and Young and others (2016a) study of the Gulf Coast Aquifer System; Kreitler and others (2013a) study of the aquifers of Groundwater Management Areas 11, 12 and 13; Kreitler and others (2013b) study of aquifers in Groundwater Management Areas 3 and 7; Fryar and others, (2001) study of the southern High Plains Aquifer; Potratz's (1980) study of the Ogallala Aquifer; Sharp and Banner's (1997) study of the Edwards Aquifer; Fisher and Mullican's (1997) study of the Rio Grande Alluvium; Uliana and Sharp's (2001) study of the Pecos Valley Aquifer; and Jones and others (1977) study of the Trinity Aquifer.

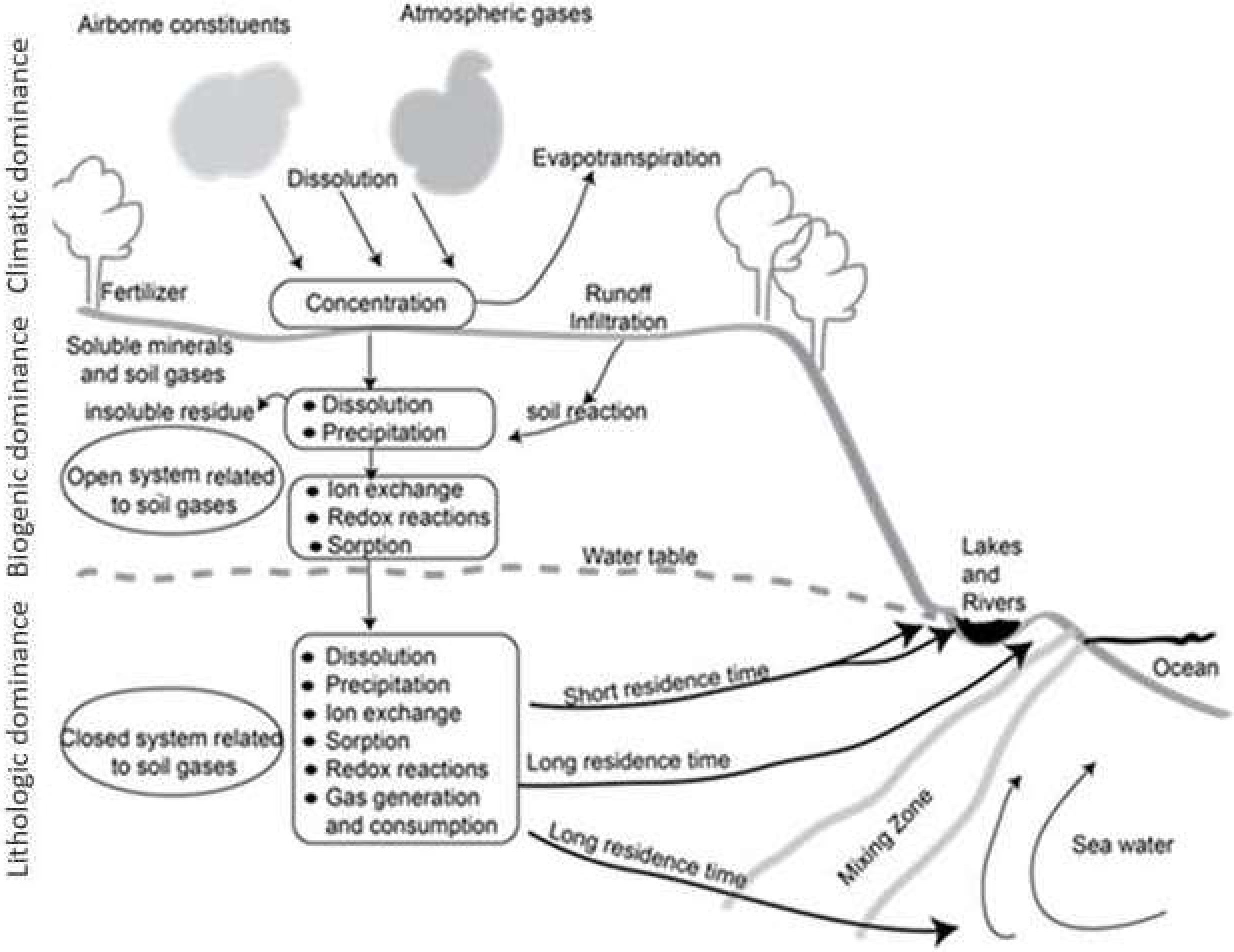


Figure 4-1. **Conceptualized groundwater flow system incorporating hydrochemical processes that affect reactions and transport involving major ions (modified after Back and others, 1983; Herczeg and Edmunds, 2000).**

4.2.2 Factors Influencing Spatial Variability in Groundwater Quality

Table 4-2 lists the major factors that determine the spatial variability of water quality. The combination of these factors can produce significant changes in total dissolved solids concentration, the macro-chemistry (regional), and micro-chemistry over vertical distances of a few feet to tens of feet. Among the nine factors, the first three exert the most influence on the spatial and regional variability of groundwater quality. In general, the addition of clays and clayey deposits to a sandy aquifer will increase the spatial variability of groundwater quality for two reasons: an increased mineralization of the groundwater in sandy units adjacent to clays and clayey deposits and a decreased hydraulic interconnectivity among the sand units throughout the aquifer. Consequently, a thick sandy deposit form the Carrizo Aquifer will have considerably less spatial variability in water quality than does an equally thick sandy-clayey deposit from the Chicot Aquifer.

Table 4-2. Factors that Influence the Spatial Variability in Groundwater Quality.

Factor		Influence on Water Quality
#	Description	
1	Hydraulic Properties of Sands and Clays Sequences	Hydraulic properties exert a primary control on the rate, orientation, and mixing of three-dimensional flow and the degree to which the aquifer is hydraulic interconnected throughout its thickness.
2	Mineralogy of the bulk aquifer deposits	Determines the evolution of macro-chemistry of the groundwater along its flow path.
3	Clayey deposits containing high concentrations of arsenic, radio-nuclides and metals	Geochemical reactions involving these clayey deposits can cause exceedances of MCLs within a vertically localized groundwater zone.
4	Geologic Structure Including Faults	Structure can provide direct hydraulic connection between aquifers zones that are vertically separated and can hinder horizontal flow increasing residence times.
5	Groundwater Pumping	Pumping changes the flow rate, the flow direction, and amount of vertical mixing of groundwaters in the vicinity of a well.
6	Leakage from Surface Water Bodies	Leakage from surface waters may change the chemical composition of water recharging a groundwater system.
7	Bedded Halite, Bedded Evaporites and Salt Domes	Dissolution of salts from evaporites or from carbonates will increase the total dissolved solids concentration of the groundwater.
8	Non-point source Anthropogenic Contamination	Use of fertilizers, herbicides, insecticides, and irrigation will affect water quality beneath agricultural lands; runoff from paved areas will affect water quality beneath urban areas.
9	Point source Anthropogenic Contamination	Leakage from landfills, gasoline storage tanks, industrial waste facilities, and oil & gas operations will affect underlying groundwater.

As a rule, the chemistry of groundwater is controlled by minerology of the aquifer materials and the time the groundwater is in contact with those materials (residence time). Clearly, aquifer properties, and their juxtaposition, impact flow path geometry and as a result both the minerology to react with and residence time.

Factors 8 and 9 are anthropogenic factors that alter water quality. Although not the subject of this report, they have been added to Table 4-2 for completeness. Anthropogenic sources generally impact shallow aquifer settings as most sources derive from surface activities. However, poorly completed or abandoned wells are often a mechanism for vertically transporting contamination deeper into aquifers.

4.2.3 Exceedances of Maximum Contaminant Levels in Texas Aquifers

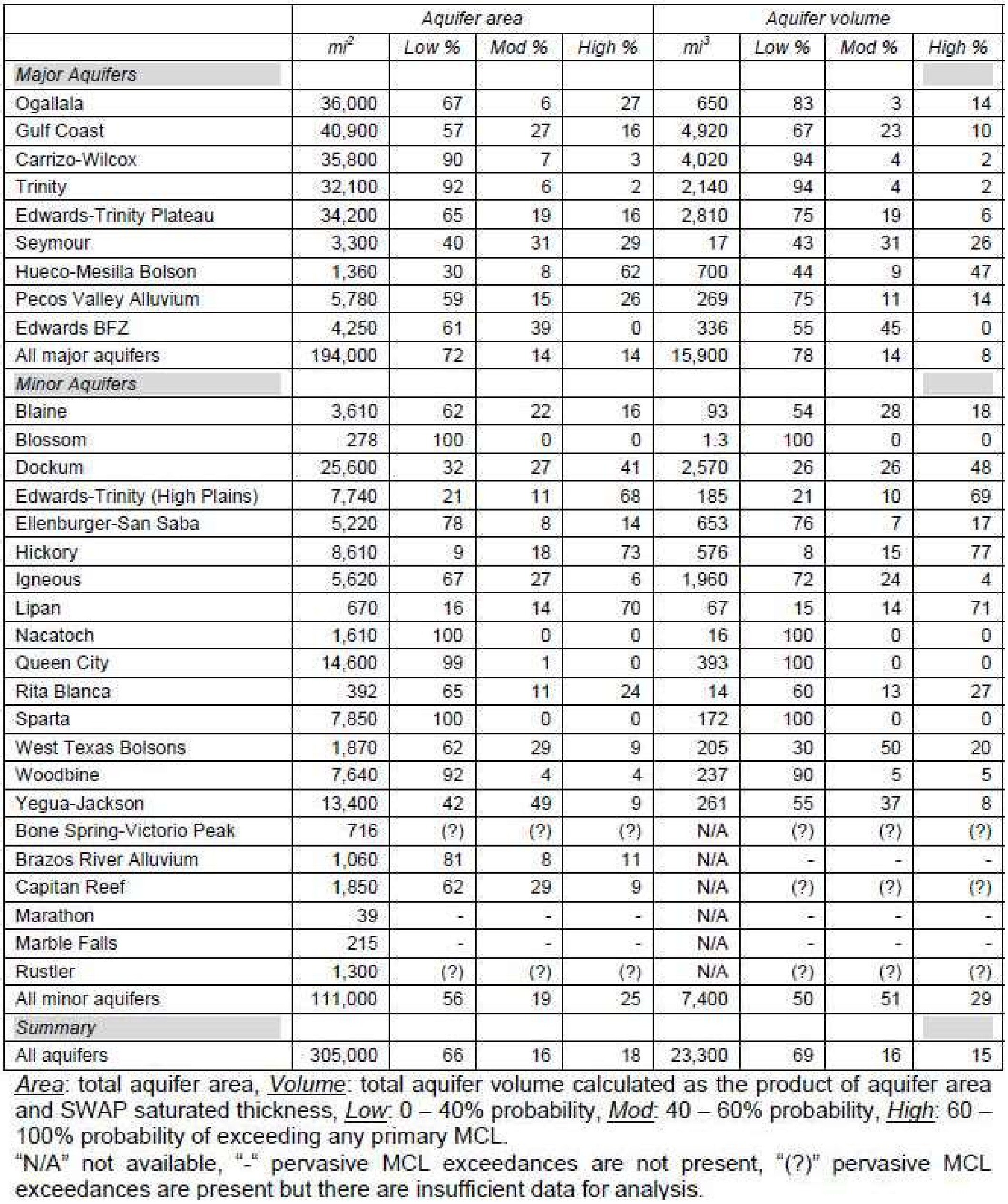
Over time, groundwater interacts with more and more aquifer deposits along its flow path from its point of origin to its point of discharge. In some areas along its flow path, groundwater may interact with minerals to such a degree that groundwater quality is degraded beyond its suitability for human consumption or potential use. In some cases, the degradation of water quality may occur because the aquifer deposits have high mineralogic content of a potential contaminant. In other cases, the aquifer deposits contain average concentrations of potential contaminants, but some particular feature of the water or the aquifer, such as pH or redox conditions, allows contaminant concentrations to reach undesirable levels. Texas roll-front uranium deposits in the Gulf Coast Aquifer are such a phenomenon.

Reedy and Scanlon (2011) have developed Texas statewide maps showing the distribution of sampled groundwater concentrations of naturally occurring constituents exceeding their primary and secondary maximum concentration levels. The highest EPA primary maximum concentration level percent exceedance throughout all Texas aquifers is gross alpha radiation representing 11.6 percent of all gross alpha radiation analyses and combined radium-226/ radium-228 (11.4 percent of all combined radium analyses). These are followed by arsenic (7.9 percent), nitrate-N (7.0 percent), fluoride (4.3 percent), uranium (3.0 percent), selenium (1.4 percent), and gross beta radiation (1.1 percent). The remaining primary maximum concentration level percent exceedances represent less than 0.4 percent of analyses for those chemical constituents in the state. Secondary maximum concentration limit percent exceedances in all aquifers are dominated by total dissolved solids (21.5 percent of all total dissolved solids analyses), fluoride (19.5 percent), chloride (17.2 percent), sulfate (15.6 percent), iron (13.8 percent), manganese (10.8 percent), pH (9.8 percent), and aluminum (2.3 percent).

Reedy and Scanlon (2011) also developed the probability, or risk, of exceeding any primary maximum concentration limit for all major and minor aquifers. As shown in Table 4-3, these probabilities were subdivided into low (0 to 40 percent), moderate (40 to 60 percent) and high (60 to 100 percent) risk categories by both aquifer area and aquifer volume. Both areal and volume calculations were performed to account for the varying thickness of the aquifers. A key assumption used in determining the volume percentages is that the areal spatial distribution of concentrations derived from the well data can be projected with depth to the base of the aquifer.

Primary maximum concentration limit exceedances in the high probability category for major aquifers are greatest for the Hueco-Mesilla Bolson, Seymour, and Ogallala aquifers and lowest for the Edwards (Balcones Fault Zone) Aquifer by both aquifer area and volume. Primary maximum concentration limit exceedances in the high probability category for minor aquifers are greatest for the Hickory, Lipan, and Edwards Trinity (High Plains) aquifers and lowest for the Nacatoch, Queen City, and Sparta aquifers by both aquifer area and volume.

Table 4-3. **Probability of exceeding any primary maximum concentration limit by aquifer (from Reedy and Scanlon, 2011).**



	Aquifer area				*Aquifer volume*			
	mi^2	*Low %*	*Mod %*	*High %*	*mi^3*	*Low %*	*Mod %*	*High %*
Major Aquifers								
Ogallala	36,000	67	6	27	650	83	3	14
Gulf Coast	40,900	57	27	16	4,920	67	23	10
Carrizo-Wilcox	35,800	90	7	3	4,020	94	4	2
Trinity	32,100	92	6	2	2,140	94	4	2
Edwards-Trinity Plateau	34,200	65	19	16	2,810	75	19	6
Seymour	3,300	40	31	29	17	43	31	26
Hueco-Mesilla Bolson	1,360	30	8	62	700	44	9	47
Pecos Valley Alluvium	5,780	59	15	26	269	75	11	14
Edwards BFZ	4,250	61	39	0	336	55	45	0
All major aquifers	194,000	72	14	14	15,900	78	14	8
Minor Aquifers								
Blaine	3,610	62	22	16	93	54	28	18
Blossom	278	100	0	0	1.3	100	0	0
Dockum	25,600	32	27	41	2,570	26	26	48
Edwards-Trinity (High Plains)	7,740	21	11	68	185	21	10	69
Ellenburger-San Saba	5,220	78	8	14	653	76	7	17
Hickory	8,610	9	18	73	576	8	15	77
Igneous	5,620	67	27	6	1,960	72	24	4
Lipan	670	16	14	70	67	15	14	71
Nacatoch	1,610	100	0	0	16	100	0	0
Queen City	14,600	99	1	0	393	100	0	0
Rita Blanca	392	65	11	24	14	60	13	27
Sparta	7,850	100	0	0	172	100	0	0
West Texas Bolsons	1,870	62	29	9	205	30	50	20
Woodbine	7,640	92	4	4	237	90	5	5
Yegua-Jackson	13,400	42	49	9	261	55	37	8
Bone Spring-Victorio Peak	716	(?)	(?)	(?)	N/A	(?)	(?)	(?)
Brazos River Alluvium	1,060	81	8	11	N/A	-	-	-
Capitan Reef	1,850	62	29	9	N/A	(?)	(?)	(?)
Marathon	39	-	-	-	N/A	-	-	-
Marble Falls	215	-	-	-	N/A	-	-	-
Rustler	1,300	(?)	(?)	(?)	N/A	(?)	(?)	(?)
All minor aquifers	111,000	56	19	25	7,400	50	51	29
Summary								
All aquifers	305,000	66	16	18	23,300	69	16	15

Area: total aquifer area, *Volume*: total aquifer volume calculated as the product of aquifer area and SWAP saturated thickness, *Low*: 0 – 40% probability, *Mod*: 40 – 60% probability, *High*: 60 – 100% probability of exceeding any primary MCL.

"N/A" not available, "-" pervasive MCL exceedances are not present, "(?)" pervasive MCL exceedances are present but there are insufficient data for analysis.

Note: % = percent, mi^2 = square miles, mi^3 = cubic miles, mod = moderate

4.2.4 Hydraulic Head and Vertical Head Differences and Gradients

The driving force that makes groundwater mix within a borehole under non-pumping conditions is the vertical head differences, sometime referred to as vertical hydraulic gradient, that exist between the aquifers or zones co-completed by the well. To discuss these concepts requires an understanding of hydraulic head.

Water well owners and hydrogeologists commonly measure the depth to water in a well. The depth is generally measured from ground surface or some common measuring point at the well head and is typically referred to as a water level. While depth to groundwater has practical importance when it comes to understanding well performance and energy costs, it does not provide information required by hydrogeologists to understand groundwater flow. Hydraulic head is the elevation of the groundwater level in an aquifer and is measured in a groundwater well. Hydraulic head is generally determined from a measurement of depth to groundwater, measured at the well head. The depth to water is easily converted to an elevation using a known elevation of where the depth was recorded (generally the top of casing). Depth to groundwater is generally reported in feet below ground surface from a fixed measuring point. Hydraulic head is generally expressed in terms of feet above mean sea level, which provides a common datum.

Hydraulic head is a direct measure of the potential energy of groundwater. Analogous to atmospheric flow or electrical flow, groundwater flows from high to low hydraulic heads (potential). The process of pumping is based upon developing a head difference between the wellbore and the adjacent aquifer. The difference between the original water level and the water level at some time after pumping is termed drawdown and is generally measured in feet. Drawdown serves as the driving force for inducing groundwater to flow towards and into a well.

If a well screen is completed across an aquifer, or aquifers, that have significantly different static hydraulic heads, there is potential for groundwater to flow from the aquifer with a high head through the well to the aquifer with the lower head. The driving force for the flow between aquifers is the difference between the two hydraulic heads which is measured in units of length. The higher the head difference, the higher the driving force between the two aquifers and the higher the intra-borehole flow. If one divides the head difference between two points in an aquifer by the length between the measurements, you get a hydraulic gradient which is dimensionless and is analogous to a topographic gradient. The higher the gradient, the greater the difference in heads over a given distance.

Vertical head differences within aquifer can be because of natural aquifer hydrodynamics or can be the result of aquifer development (pumping). Natural hydraulic gradients result from a complex interplay between recharge rates, area for recharge, elevation of recharge zones, relative hydraulic conductivity of the aquifer materials, area for groundwater flow and aquifer discharge boundaries. Because perceptible groundwater flow occurs in nearly all economically developed groundwater basins, all groundwater basins have measurable hydraulic gradients. Development of a basin and associated groundwater pumping can significantly alter, and in most cases, increase vertical gradients within aquifers as we have seen documented in the Texas Gulf Coast Aquifer.

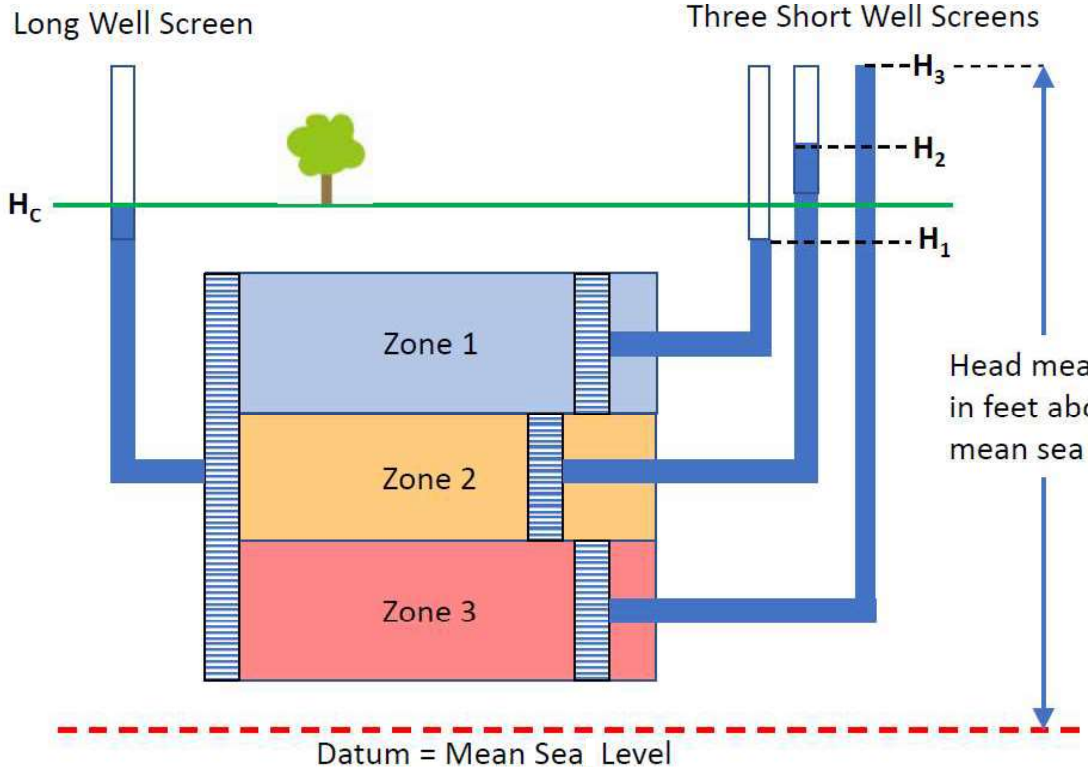
4.3 Conceptual Model for Borehole Comingling

This section develops a conceptual case study based upon representative field conditions to characterize the conceptual understanding of how the comingling would occur, what would control the degree of mixing that within the borehole and within the aquifer. The discussion also identifies the factors controlling comingling.

4.3.1 Conceptual Model

The following describes a conceptual groundwater well that is drilled into an aquifer that encounters zones of differ water quality, which when mixed in the borehole could result in comingling. Hydraulic heads within the aquifer zones encountered define vertical hydraulic gradients capable of causing intra-borehole flow and mixing of groundwater within the borehole under static (unpumped) and pumped conditions.

Figure 4-2 shows a schematic of an aquifer that has three hydrogeologic zones which possess different hydraulic heads. On the right side of the diagram, three wells are depicted, each completed into one of the aquifer zones (1, 2, and 3). Each of these wells measure the hydraulic head in the individual zone. The zones are numbered 1 through 3 from the top to the bottom. The heads for each zone reflect the elevation the water will rise to in the well and these are depicted to the right of each screen. The green horizontal line is meant to depict ground surface. From Figure 4-2, one can observe that the head in zone 3 (H_3) is higher than the head in zone 2 (H_2) and that H_2 is higher than the head in zone 1 (H_1). Also, both H_3 and H_2 rise above ground surface so both wells would flow without pumping. The left side of the figure depicts a well with a screen completed across all three zones. The hydraulic head that would be measured in that well is product of the individual zone heads as well as each zones transmissivity. This combined head representing the integration of all three zones is typically referred to as a composite head as it does not equal the head in any of the three zones. This situation is a common occurrence in the Northern Trinity Aquifer.



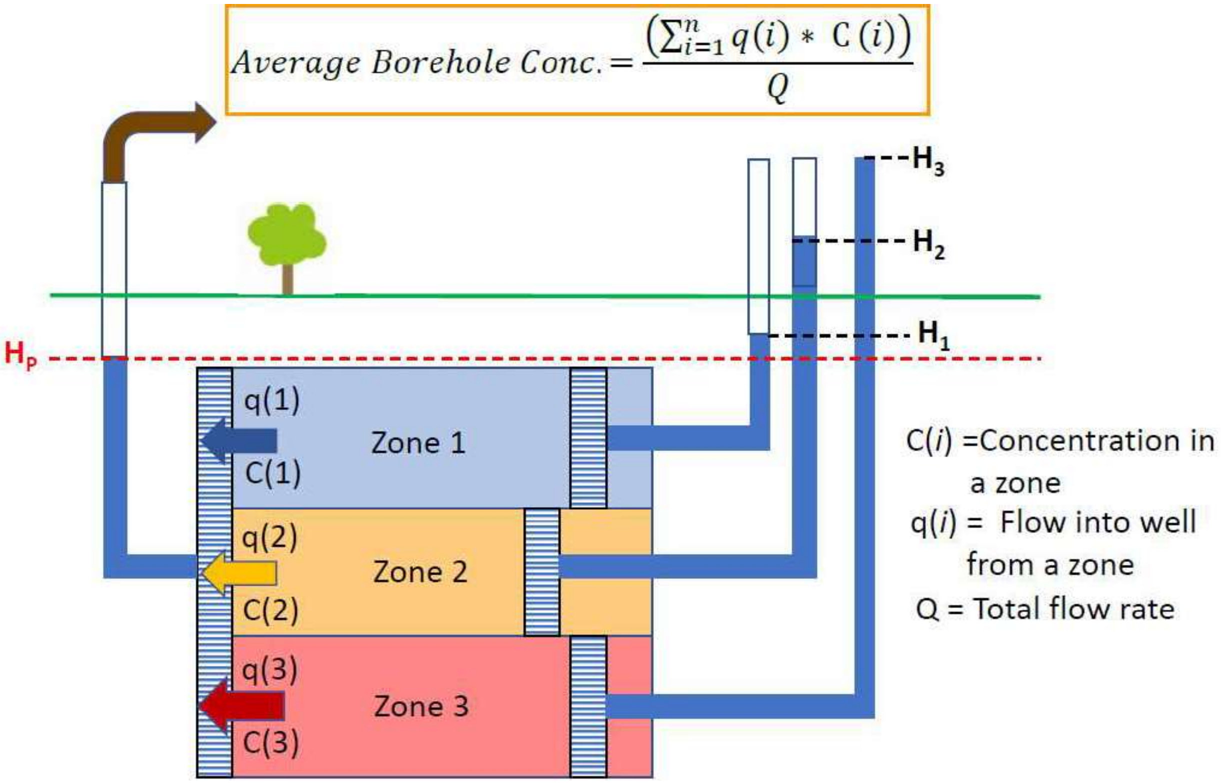
Note: H_1 = Zone 1 Head, H_2 = Zone 2 Head, H_3 = Zone 3 Head, H_c = composite head

Figure 4-2. Schematic representation of three aquifer/zones with different hydraulic heads being completed using three individual well screens or one long well screen.

We will use this hypothetical example to look at what occurs during pumping of a well completed across all three zones such as that shown in this figure and then we will look at the case of non-pumping conditions. This would be conditions in the well prior to a borehole being completed or during extended period of no pumping.

4.3.2 Pumping Conditions

In a well that has been completed into an aquifer with zones with significantly different heads, each zone contributes to the total well flow rate non-uniformly. Figure 4-3 reproduces Figure 4-2 but represents pumping conditions. In our hypothetical example, we assume that each zone has identical transmissivity but each zone has different water quality. First, we will look at total flow contribution from each zone. As we said earlier, the water flows into the well because of pumping because we have induced a hydraulic gradient into the well. The drawdown imposed in the well will be the difference between the pumped head in the well (depicted here as head during pumping and denoted in red) and the head in any given aquifer zone. Because we have assumed that each zone has identical transmissivity, the variability in flow contributed by each zone is proportional to the head difference for that zone. In this example, the head difference between the pumped head level and zone one is very small. In contrast, the head difference between the pumped head level and zone three is large by comparison. In this case, the total borehole flow rate will predominantly be supplied by zone 3 and very little flow will originate from zone 1.



Note: H1 = Zone 1 Head, H_2 = Zone 2 Head, H_3 = Zone 3 Head, Hp = Head during pumping

Figure 4-3. **Schematic representation of a well co-completed with one long screen across three aquifer/zones with different hydraulic heads under pumping conditions.**

Because groundwater has associated quality characteristics, this can have ramifications on the water quality measures at the wellhead. The water quality measured at the wellhead is equal to:

$$Average\ Borehole\ Concentration\ \frac{\sum_{i=1}^{n} q(i)* C(i)}{Q} \qquad \text{(Equation 1)}$$

Equation 1 is a simple mass balance equation and assumes perfect mixing within the borehole or at the wellhead. If zone 3 is contributing most of the flow, the water quality at the wellhead will be disproportionally defined by the water quality in zone 3. Zone 1 may have excellent water quality but minimal impact on the wellhead concentration.

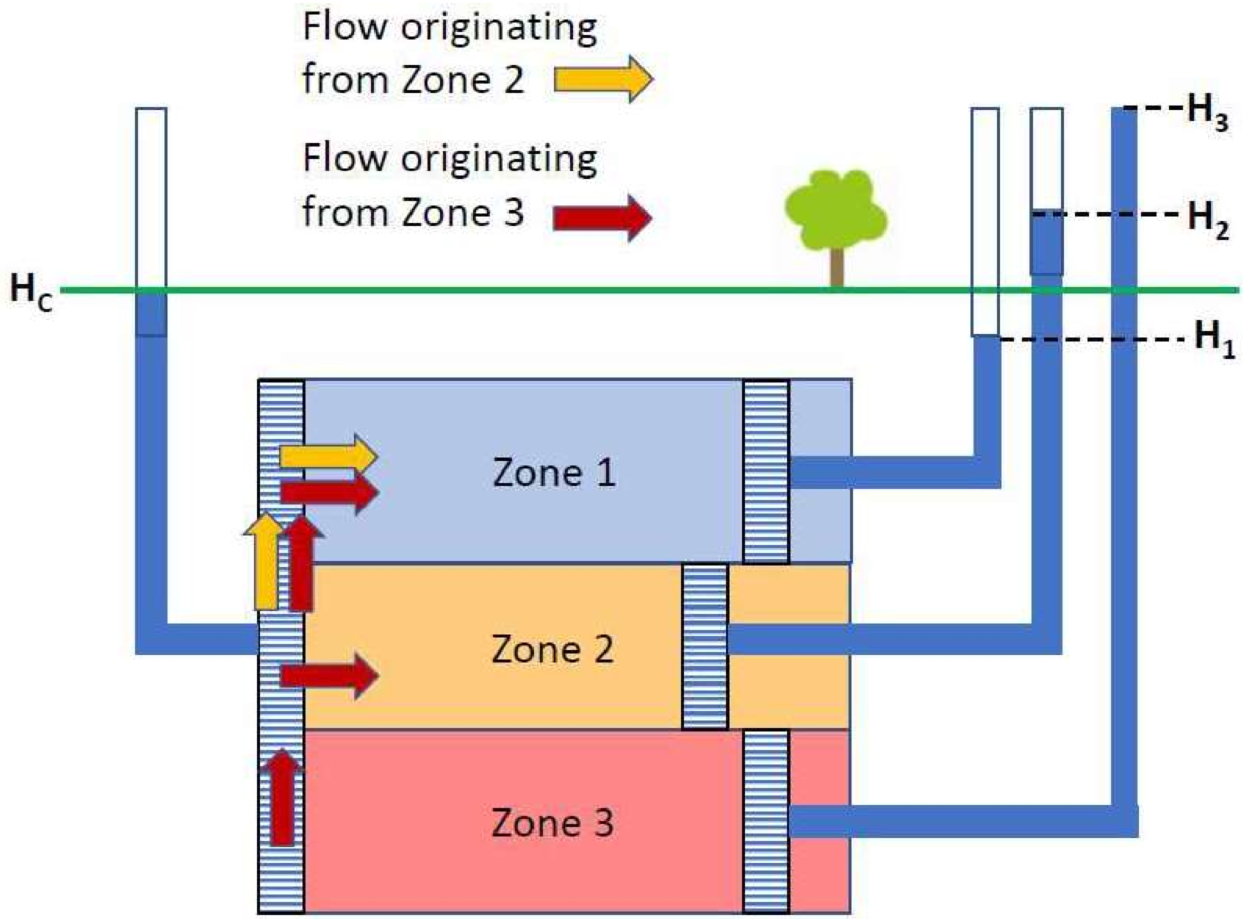
In the pumped well scenario, the potential for comingling through the well screen or filter pack from zone to zone is minimal compared to the comingling that occurs under non-pumping conditions. In the pumped case, the borehole acts as the integration cell to define the well head concentration. So, while one may be having deleterious effect on wellhead water quality, there is little potential for zone-to-zone water quality degradation.

4.3.3 Non-Pumping Conditions

Non pumping conditions provide the opportunity for comingling to occur. We will use the same hypothetical example to investigate non-pumping conditions. We will also review the results from an actual example based upon the dynamic profiling of an Edwards Aquifer well in Comal County under non-pumping conditions.

Figure 4-4 shows our hypothetical well under non pumping conditions. In this case, our well measured a wellbore head that we will refer to as the composite head. As discussed earlier, the composite head is not equal to the head in either of the three zones (shown on right of figure). Even though a pump has not been used to induce vertical head difference from the well to the zones, the head differences exist naturally within the groundwater system. These head differences drive flow from one to the next zone. In Figure 4-4, the head in zone 3 is significantly higher that the zone 1 head and is also higher than the zone 2 head. As a result, even under non-pumping conditions, groundwater will flow from zone 3 to zone 2 and zone 1. Groundwater will also flow from zone 2 to zone 1 but there is no vertical gradient to induce flow from zone 2 to zone 3 or zone 1 to zone 2 or zone 3. If in this example, zone 3 has very poor water quality, it could lead to degradation of groundwater quality in zone 1 and possibly zone 2. This would meet the definition of comingling. While this example is illustrative, the hydrodynamics of wells intersecting zones or aquifers with large head differences is complex and varies with time.

We will now quickly look at a field study where inter-borehole flow and water quality was documented in an Edwards Aquifer well in Comal County. This data is used with permission of Paul Bertetti of the Edwards Aquifer Authority. The flow estimates and interval water quality were collected by BESST, Inc and interpreted by INTERA. Figure 4-5 shows a plot of the well with flow rate (gallons per minute) on the x axis and depth on the y axis. The flow rates are shown in bar chart format and a red bar indicates downward flow (negative) within the well and a blue bar indicates upwards flow (positive). By estimating flow rate differences along the well depth, one can infer flow loss or gain which are indicative of flow out or flow into the well, respectively.

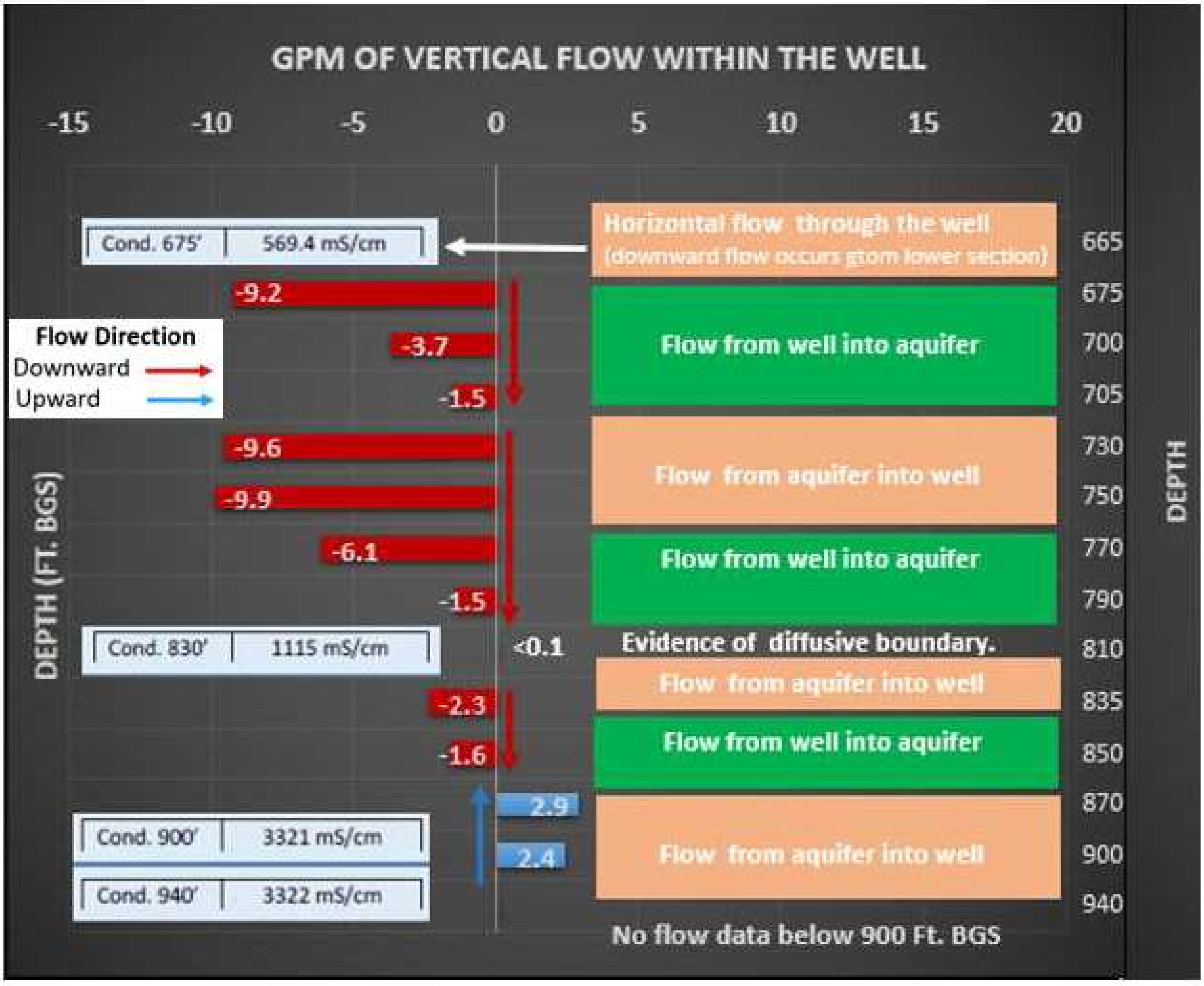


Note: H_1 = Zone 1 Head, H_2 = Zone 2 Head, H_3 = Zone 3 Head, H_c = composite head

Figure 4-4. **Schematic representation of a well co-completed with one long screen across three aquifer/zones with different hydraulic heads under no pumping conditions.**

From a review of Figure 4-5, one can see that at the top of the interval, there is evidence of horizontal flow through the well. At a depth of approximately 675 feet, inflow occurs of approximately 9.2 gallons per minute and starts flowing down the borehole. Between 675 and 705 feet of depth, the groundwater flows from the well to the aquifer. At a depth of approximately 800 feet, there is little flow in the borehole and the water quality has increased in specific conductance. Below a depth of 810 feet, inflows occur and start flowing down the well and back into the aquifer to a depth of approximately 870 feet. At this depth, there a convergence of flow occurring. Approximately 2.9 gallons per minute is coming from the bottom of the interval and combining with 1.6 gallons per minute flowing down the well and both flows are exiting the borehole. The inflows occurring below a depth of 870 feet are of the highest specific conductance measured in the borehole.

These data demonstrate, with actual field data, how comingling may occur in a well with conditions conducive to intra-borehole flow and water quality capable of degradation. The next section of the report will build off these concepts and look at the potential for comingling in three select areas of the state.



Note: ' = feet, bgs = below ground surface, ft = feet, Cond. = electrical conductance, mS/cm = milliSiemens per centimeter

Figure 4-5. **Plot of inter-borehole flow rates determined from Dynamic Well Profiling within an Edwards Aquifer well in Comal County under non-pumping conditions (courtesy of the Edwards Aquifer Authority and BESST, Inc.)**

5 Assessment of Brackish Groundwater Comingling in Select Aquifer/Regions

The TWDB identified three areas to assess the potential for comingling of groundwater to occur. These three aquifer/regions are the Gulf Coast Aquifer System, the Eagle Ford Region, and the Trans-Pecos Region. This assessment will discuss the aquifer(s) in each area, describe well completion conditions with an emphasis on potential for comingling of brackish groundwater and will review select case studies at well(s) where relevant data is available to directly provide evidence of comingling potential.

5.1 Approach and Data Sources

While the analysis of comingling is restricted to three select regions of Texas, these three regions are of significant areal extent. As a result, we chose to use a method that used consistent data sources and accepted aquifer structure and water quality data. The objective of the analysis is to characterize the potential for comingling both within and between aquifers in each region. As we discussed in earlier sections, comingling as defined in 16 TAC 76 occurs through a borehole or the adjacent borehole filter pack or anulus. The approach is based upon the following steps:

- Develop a groundwater wells database with well screen data in each of the three select study regions,
- Develop surfaces for all the aquifers in the select study regions,
- Identify multi-completed wells by aquifer in each study area by intersection structure with well screens,
- Identify vertical head differences at select wells in the select study regions,
- Develop a water quality database of total dissolved solids for each of the select study regions,
- Assess the potential for brackish groundwater comingling on a regional scale in the select aquifer regions,
- Identify individual wells where aquifer and well water quality data demonstrate typical potentially comingling conditions in each of these select aquifer regions.

Various types of data required collection and organization to perform these steps. The data sources for these data will be summarized below.

The initial data source that had to be developed was a well completion database in each of the regions. The database was developed using the TWDB groundwater database (TWDB, 2020a) and the Texas Well Report Submittal and Retrieval System Database managed by the TWDB and the Texas Department of Licensing and Regulation (TWDB, 2020b). The data were downloaded and integrated into a wells database and was inspected for errors in the data. When complete, the well completion database contained 102,699 wells within the Gulf Coast Aquifer System, 35,580 wells in the Eagle Ford Region and 5,815 wells in the Trans-Pecos Region.

The next step was to intersect the well screens with the aquifer structure. We used the TWDB Groundwater Availability Model layers to define the aquifer stratigraphy consistent with the process used in the Statewide Aquifer Storage and Recovery Survey Study (Shaw and others, 2020). We used the Groundwater Availability Model layers as they were defined in the

Statewide Aquifer Storage and Recovery Survey Study database. The rules used for making screen assignments are defined below:

- At least 50 percent of the interval screened by a well is contained in a model layer (aquifer),
- For a well to be completed in multiple layers, it must have a minimum percent (3 percent) within the layer.

These rules would discard any well without screen information and whose screen does not intersect a model layer. Secondly, if a screen was 97 percent or greater in one model layer, it is coded as a single-layer completion.

The next step in the process required the estimation of hydraulic heads at specific wells that are completed in multiple aquifers to assess maximum vertical head difference at a given well which could provide the hydraulic driving force for borehole comingling. Again, the heads are derived from the Groundwater Availability Models which again is consistent with the Aquifer Storage and Recovery Survey Study (Shaw and others, 2020). Consistent with the approach used in the Aquifer Storage and Recovery Survey Study, we used aquifer head surfaces from the last historic stress period (end of calibration period) for each Groundwater Availability Model to calculate vertical head differences. Most Groundwater Availability Model grids are at the scale of one-square mile. We did not interpolate head surfaces to individual wells but rather used the grid centered head the well fell in.

For water quality, data were compiled from two sources. In aquifers where we had Brackish Resources Aquifer Characterization System project developed salinity class surfaces expressed in terms of elevation, we used that data. An example would be the total dissolved solids salinity class boundaries developed in the Gulf Coast Brackish Resources Aquifer Characterization System report (Young and others, 2016a). For most of the aquifers, we had to develop water quality distributions by aquifer. The source data for them was the TWDB groundwater database (TWDB, 2020a).

The regional assessment will follow the steps outlined above. The key products of the regional assessment are characterization of: (1) well completions with an emphasis on identifying multi-aquifer completions; (2) maximum head differences between aquifers at the location of multi-completed wells; and (3) water quality within the aquifers. The characterization of well completions provides insight into the relative numbers and magnitude of groundwater wells completed in multiple aquifers and therefore describes the potential for borehole comingling to occur at that well. As described in Section 4, the risk of significant crossflow of groundwater between co-completed aquifers, or formations, is highest when the borehole is left under no pumping conditions either after drilling or during significant periods of nonuse. The driving force that makes borehole comingling of groundwater possible is head differences between co-completed aquifers or zones. In the final analysis step, the difference in water quality of the aquifers is characterized to provide an indication of borehole comingling potential. Because of the size of the area being analyzed, we use total dissolved solids as a general proxy of water quality. Through inference, one can then make conclusions on the potential for mixing across salinity classes and the potential for comingling. The regional assessment does not determine if comingling is occurring as defined in 16 TAC 76 because, (1) individual well water quality is not matched to individual wells and (2) judgement regarding degradation is not made. Instead, these regional assessments determine the potential for comingling to occur in that region. In contrast, the cases studies presented for each region brings the analysis down to the scale of individual wells and in some cases, degradation could be concluded.

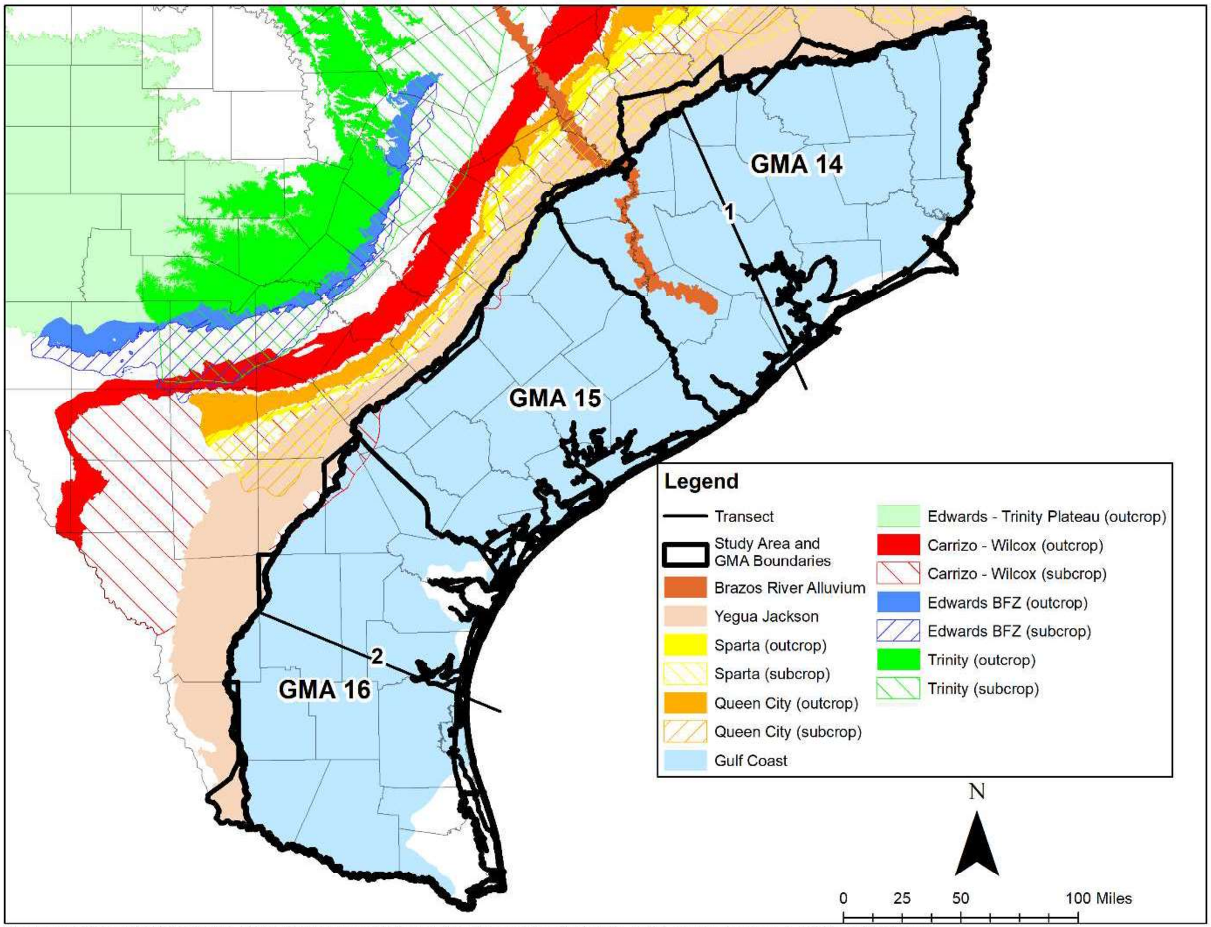
5.2 Gulf Coast Aquifer

This section provides an assessment of the potential for borehole comingling within the Gulf Coast Aquifer System. The section will begin with a description of the aquifers followed by a regional assessment of the potential for comingling of brackish groundwater. Next, the section will look at specific wells where the assessment of the potential for comingling can be based upon direct evidence at that specific well. These will be termed case studies.

5.2.1 Description of Gulf Coast Aquifer System

The Gulf Coast Aquifer System parallels the Gulf of Mexico on its southern border and extends across Texas from the Sabine to the Rio Grande. This belt generally coincides with the Tertiary aquifers of the Lower Coastal Plain (Figure 5-1).

The Texas Gulf Coast borders the Gulf of Mexico, which is a small, semi-enclosed ocean basin surrounded by continental shelves and coastal plains (Bryant and others, 1991). Sediments of the Gulf Coast Aquifer System were deposited in a fluvial-deltaic or shallow-marine environment (Sellards and others, 1932). Repeated sea level changes and basin subsidence caused the development of cyclic sedimentary deposits comprised of discontinuous sand, silt, and gravel. Inland, closer to the sediment source areas, coarser fluvial and deltaic sand, silt, and clay sediments predominate, while in offshore areas sediments grade into finer-grained brackish and marine environment sediments. These deposits tend to progressively thicken toward the gulf because of subsidence of the Gulf Coast Aquifer System basin, which is caused by the weight of the sediment load, and a sequential rise of the land surface.



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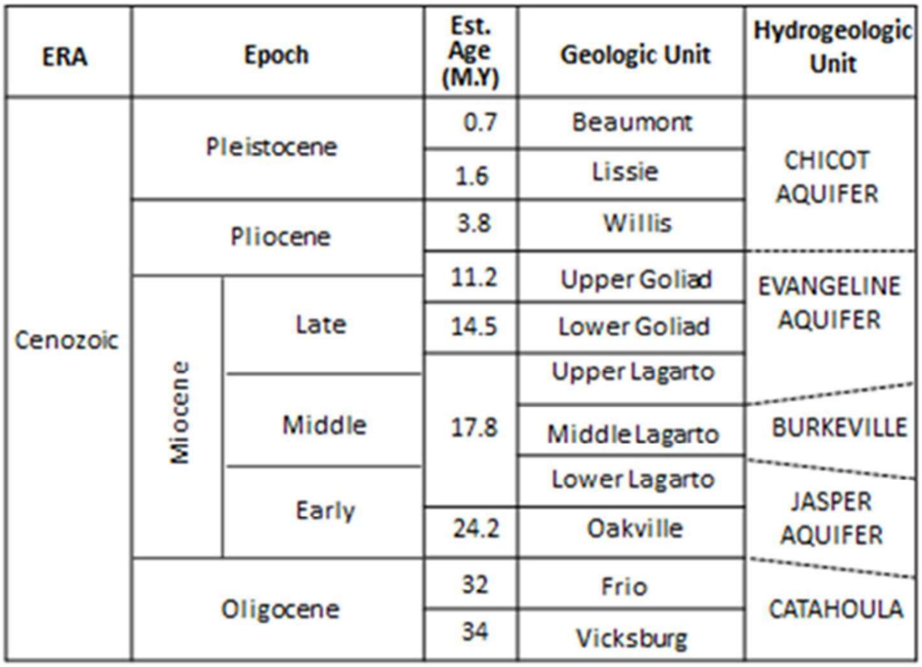
Note: GMA = groundwater management area

Figure 5-1. Gulf Coast Aquifer Region and the locations of Transects 1 and 2, which are shown in Figure 4-3.

Gulf Coast Aquifer System Stratigraphy

As shown in Figure 5-2, the Gulf Coast Aquifer System can be described using five hydrogeologic units: (1) the Chicot Aquifer, (2) the Evangeline Aquifer, (3) the Burkeville Confining System, (4) the Jasper Aquifer, and (5) the Catahoula Confining System. (Baker, 1979; Kasmarek, 2012). The groundwater models used by the Groundwater Management Areas which overlie the Texas Gulf Coast include individual model layers to represent the Chicot Aquifer, the Evangeline Aquifer, the Burkeville Unit, and the Jasper Aquifer.



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	

Note: M.Y. = million years

Figure 5-2. **Geologic and hydrogeologic units of the Gulf Coast Aquifer System (from Young and others, 2018).**

The Texas Gulf Coast Aquifer System groundwater is managed in three Groundwater Management Areas. These are from the north to the south Groundwater Management Areas 14, 15, and 16 (see Figure 5-1). For simulating future pumping scenarios, Groundwater Management Area 14 uses the Houston Area Groundwater Model (Kasmarek, 2012). Groundwater Management Area 15 uses the Central Gulf Coast Groundwater Availability Model (Chowdhury and others, 2004). Groundwater Management Area 16 uses the Groundwater Management Area 16 Alternative Groundwater Model (Hutchison and others, 2011). Among these three groundwater models, only the Houston Area Groundwater Model includes the Catahoula confining system, but it is not represented as a separate model layer. Instead, the Catahoula confining system is combined with the Yegua-Jackson Aquifer and the Cook Mountain Formation to represent a model layer that underlies the Jasper Aquifer.

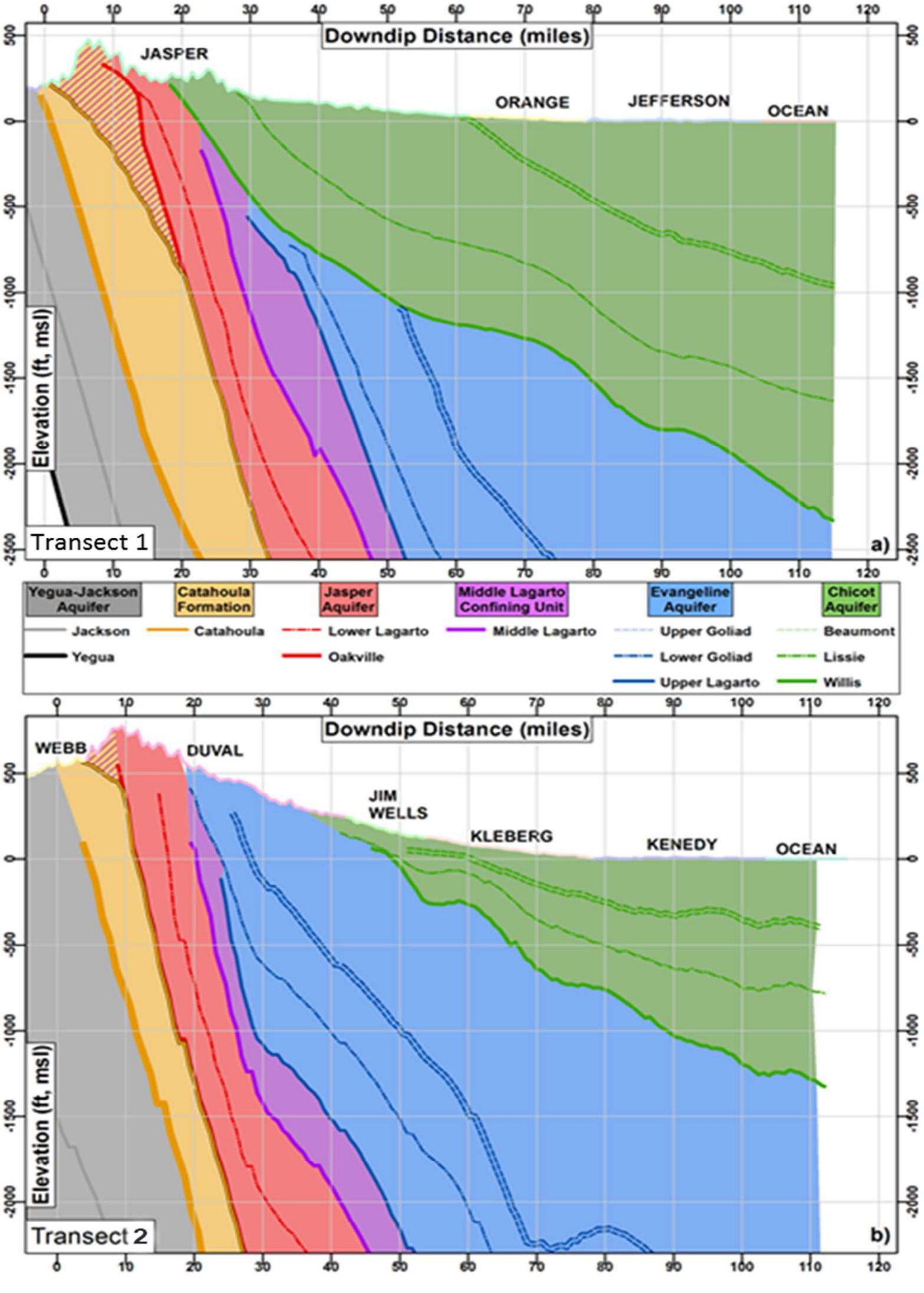
The stratigraphy used to construct the groundwater models currently used by Groundwater Management Areas 14, 15, and 16 is based on the United States Geologic Survey Source Water Assessment and Protection Program that was conducted in the 1970s and documented by Strom and others, (2003a, 2003b, 2003c). To provide a more comprehensive understanding of the Gulf Coast stratigraphy and structure, the TWDB-funded studies (Young and others, 2010; 2012) to divide the four youngest hydrogeologic units in Figure 5-2 into the nine geologic units listed in Figure 5-2. These TWDB studies relied on the sequence stratigraphic concepts used by Gulf Basin Depositional Synthesis Project (Galloway, 1989a,b; Galloway and others, 2000; Galloway, 2005). A key feature of the approach used by the TWDB studies is identification of clay-dominated flooding surfaces, which were deposited during relative sea-level maximum, to represent boundaries between the nine geologic units.

Figure 5-3 shows cross sections of the Gulf-Coast stratigraphy along Transects 1 and 2 in Figure 5-1. The cross sections show that both the Chicot and Evangeline aquifers average more than 1,000 feet thick in all three Groundwater Management Areas. There is considerable variation in the relative thickness between the two aquifers: in the north, the Chicot Aquifer is the much thicker aquifer whereas, in the south, the Evangeline Aquifer is much thicker.

The Brazos River Alluvium Aquifer is designated as a minor aquifer by the TWDB and occurs in parts of Austin, Bosque, Brazos, Burleson, Falls, Fort Bend, Grimes, Hill, McLennan, Milam, Robertson, Waller, and Washington counties. This aquifer parallels the Brazos River, and the aquifer overlies the Gulf Coast Aquifer in several counties in the region. The Brazos River Alluvium Aquifer consists of recent unconsolidated fluvial sediments that range in thickness up to about 100 feet in the study area (thicker sequences are observed downstream). Wells in the Brazos River Alluvium Aquifer are used for irrigation, domestic, stock and industrial purposes. Saturated thicknesses of up to 50 to 60 feet are observed locally across the study area (Cronin and Wilson, 1967). The Brazos River Alluvium Aquifer is comprised of Quaternary sediments that were deposited much more recently than any of the other aquifers previously discussed. As such, this aquifer lies across the top of the outcrops of all the Tertiary-aged aquifers and interacts with these aquifers through cross-formational flow (Ewing and others, 2016). The GAM used to assess this aquifer is documented in Ewing and others (2016).

Gulf Coast Aquifer Groundwater Flow System

Figure 5-4 shows a simplified conceptual model of groundwater flow system that is valid for the Chicot and Evangeline aquifers where the Texas Gulf Coast System is thicker than a few hundred feet. This conceptual model’s premise is that basinal flow can be subdivided into local, intermediate, and regional flow regimes as described by Toth (1963). The major driver for the local, shallow flow system is the difference in topography between adjacent hills and valleys. Recharge to local flow regimes occurs in topographically high areas, and discharge occurs in nearby low areas, such as stream valleys. Intermediate flow paths are longer and deeper than local flow paths and underlie several local flow regimes. An example of an intermediate flow path would be the migration of groundwater from the perimeter of a watershed of one Texas’s major rivers to a discharge location near the river. Regional flow regimes extend from regional recharge areas such as outcrops and discharge to near the coastline. A consequence of the hierarchical and nested flow regimes is that vertical hydraulic gradients can be created under naturally flow conditions without pumping. In fact, maps of the Gulf Coast area show that prior to 1900, the entire Gulf Coast area was underlain by aquifers with artesian pressures meaning that there was sufficient upward vertical gradient to causes wells to flow at and surface without pumping (Hill, 1901). It would also mean that heads are expected to increase with depth in predevelopment and areas with historically limited development.



Note: ft, msl = feet mean sea level

Figure 5-3. **Geologic cross-section along Transects 1 and 2 in Figure 5-1 that shows the differences in the differences in the Gulf Coast stratigraphy between the northern and southern regions of the Gulf Coast Aquifer system, (from Young and others, 2014).**

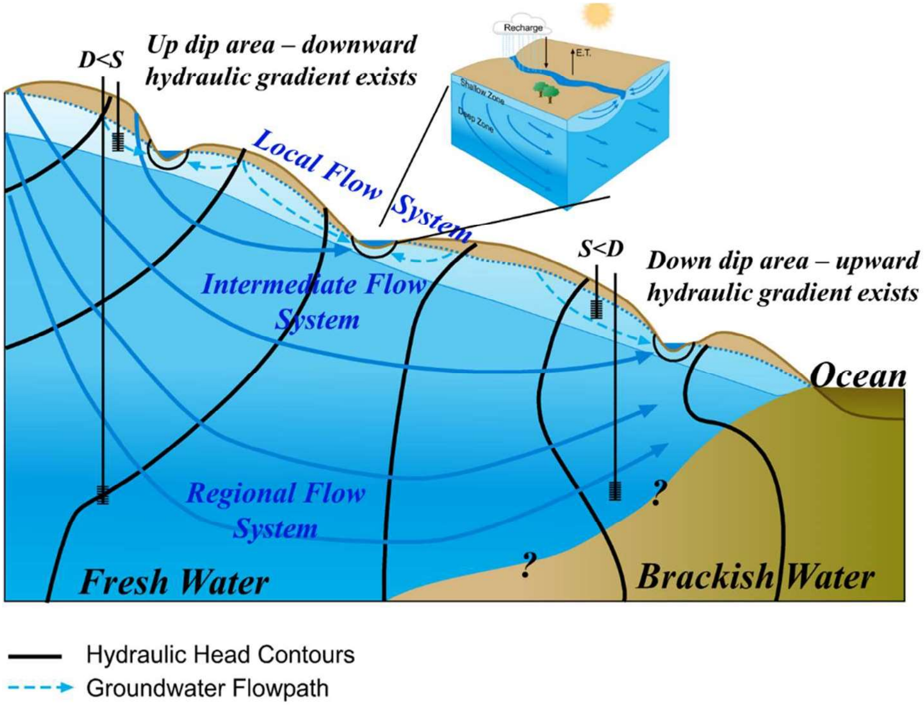
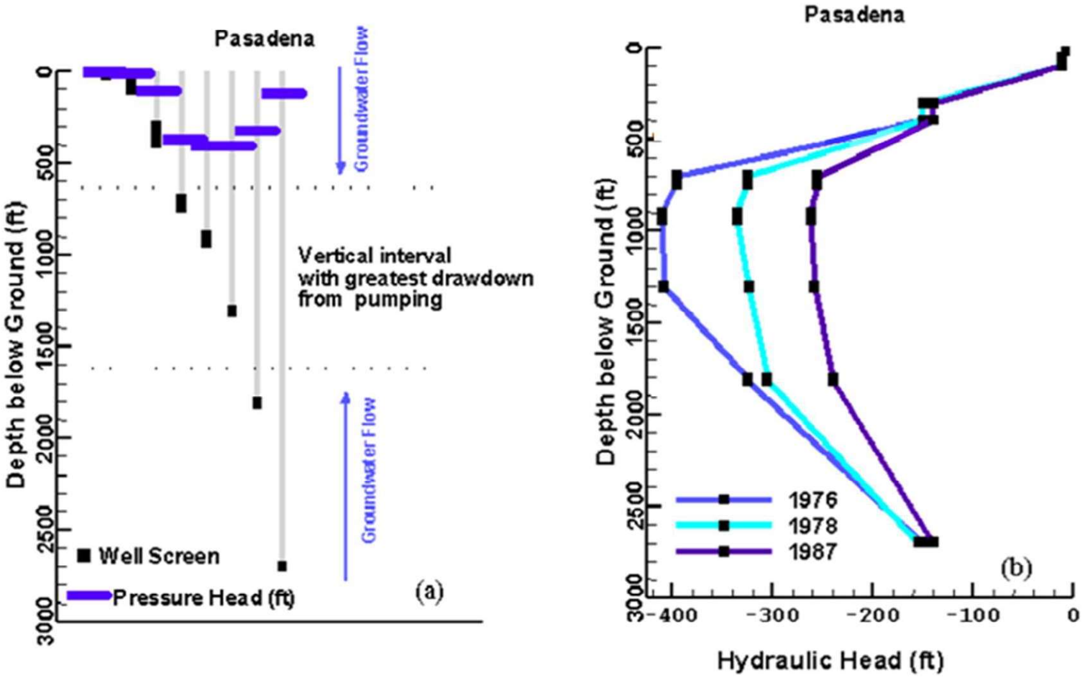


Figure 5-4. **Conceptual flow model of gravity driven groundwater flow in the Texas Gulf Coast Aquifer System based on the local, intermediate, and regional flow systems.**

Since the 1900s, the pumping in the Gulf Coast aquifer has caused significant changes in vertical gradients over time. In the Houston area, nested piezometers have been used to document how the reduction in pumping from the 1970s to the 1980s has affected the hydraulic heads at different elevations in the aquifer. Figure 5-5 shows the screened intervals of eight collated piezometers in Pasadena, Harris County, Texas. The piezometer nest is designed to characterize vertical gradients by using short well screens installed relatively close to each other at different elevations. The measured hydraulic heads show groundwater pumping has created significant vertical hydraulic gradients and that these gradients are greatest above and below the zone of pumping. The changes in the measured hydraulic heads suggest that the presence of low permeability layers in the Gulf Coast Aquifer help to keep the reduction in hydraulic head caused by pumping confined to the vertical zones where pumping is occurring. The hydraulic head measurements indicate that the downward vertical flow in a non-pumping well would likely occur if the well were screened from a depth of 300 to 700 feet.



Note: ft = feet

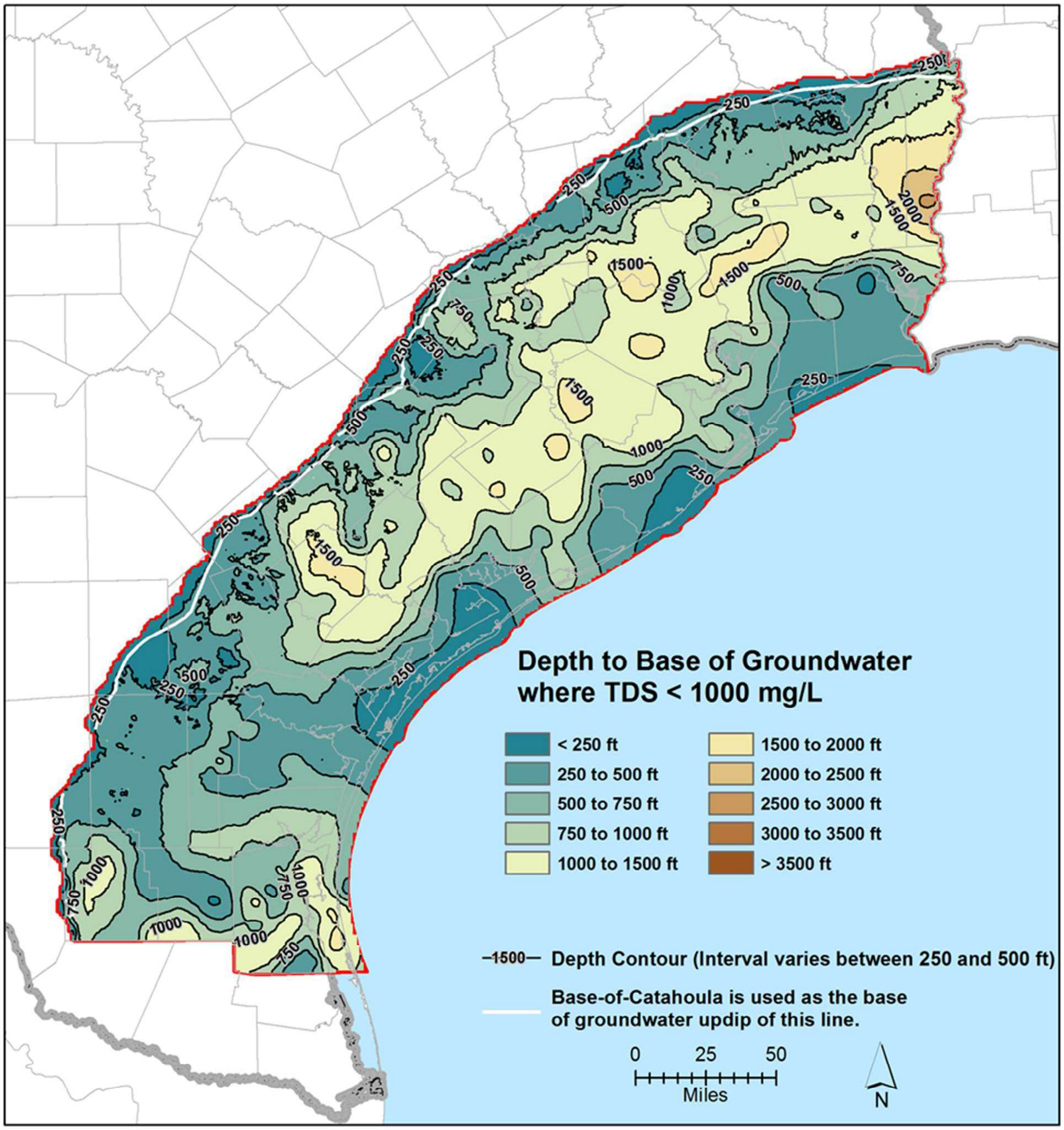
Figure 5-5. **Schematic of the nested piezometers at (a) the Pasadena site and (b) changes in the measured vertical hydraulic head profile over time (after Young and others, 2009).**

Gulf Coast Aquifer Brackish Groundwater

As part of the TWDB Brackish Resources Aquifers Characterization System program, the brackish groundwater of the entire Gulf Coast Aquifer was mapped by Young and others (2016a). This project integrated total dissolved solid concentrations estimated from 600 geophysical logs with measured total dissolved solids concentrations from 9,000 water wells to map salinity zones. Locally focused brackish groundwater studies have also been completed in the Corpus Christi vicinity (Meyer, 2012) and in the Lower Rio Grande Valley (Meyer and others, 2014).

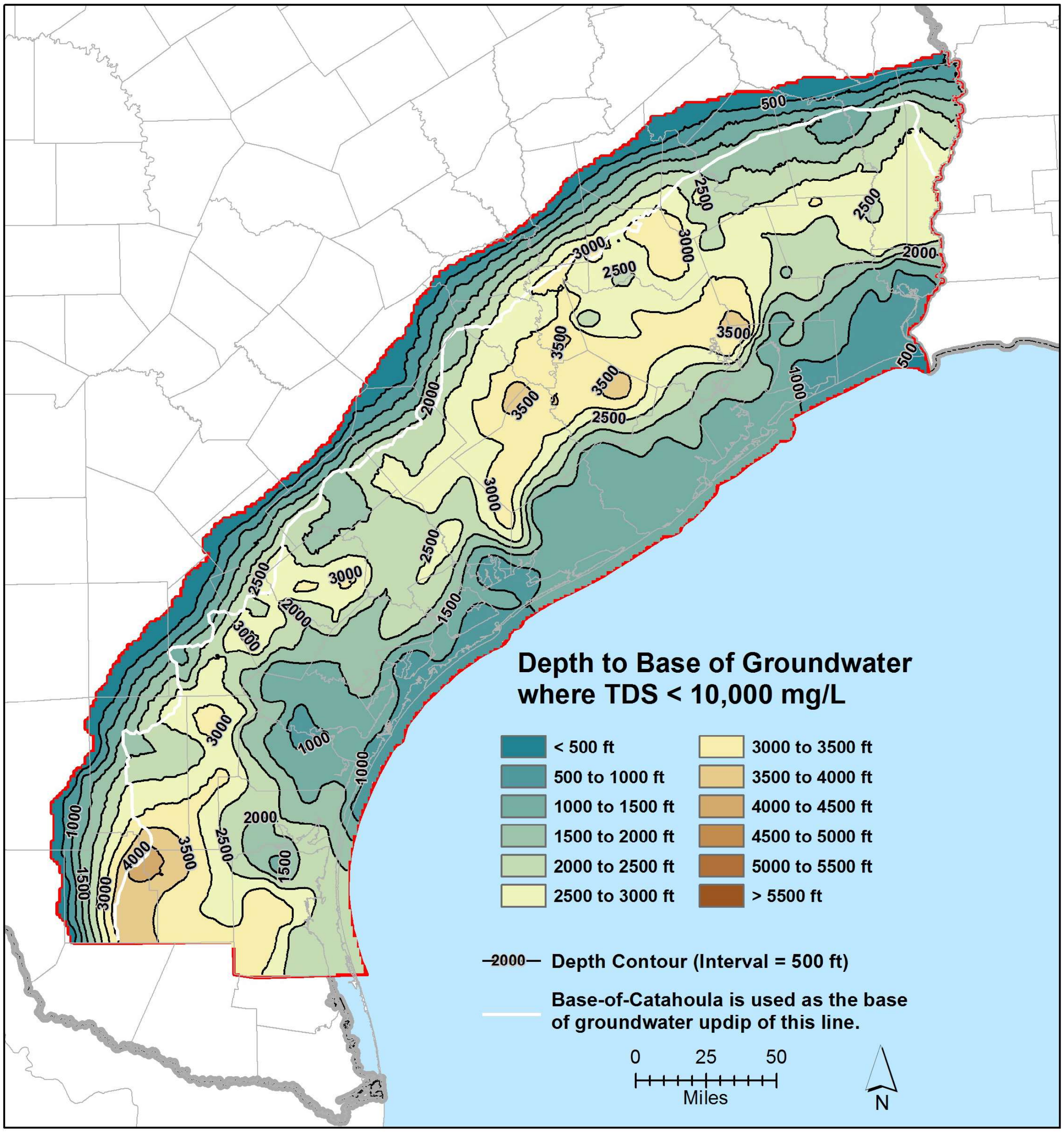
Figure 5-6 shows the depth to the base of fresh water in the Gulf Coast Aquifer, which is defined as a total dissolved solids concentration less than 1,000 milligrams per liter as defined in Young and others (2016a). Figure 5-6 shows a deepening of the fresh-water zones to depths greater than 1,500 feet below ground surface toward the middle vicinity of Groundwater Management Areas 14 and 15. In the southern Gulf Coast region in Groundwater Management Area16 in San Patricio, Nueces, Bee, Aransas and Calhoun counties, the fresh-water zone thins to between 250 and 500 feet. The thicker fresh-water zone in the north is attributed to higher recharge rates and a more permeable aquifer. The brackish mapping project found areas along the coast where there was a thin freshwater zone beneath more saline water indicating a complex salinity profile. This observation was also documented in Meyer (2012), Meyer and others (2014) and most recently by Meyer and others (2020) in the Upper Coastal Plains aquifer systems of Central Texas.

Figure 5-7 shows the depth to the base of brackish water, which is defined as a total dissolved solids concentration of between 1,000 and 10,000 milligrams per liter. Within 50 miles of the coastline, the depth to the brackish groundwater is typically less than 1,500 feet below ground surface. Along the mid-section of the Gulf Coast Aquifer is where the greatest depths to the base of the brackish water occurs. This depth is typically between 3,000 and 4,000 feet below ground surface.



Note: ft = feet, mg/L = milligrams per liter, TDS = total dissolved solids

Figure 5-6. **Depth to the base of fresh water, as defined by a total dissolved solids concentration less than 1,000 milligrams per liter (from Young and others, 2016a).**



Note: ft = feet, mg/L = milligrams per liter, TDS = total dissolved solids

Figure 5-7. **Depth to the base of brackish water, as defined by a total dissolved solids concentration less than 10,000 milligrams per liter (from Young and others, 2016a).**

5.2.2 Regional Assessment of Comingling

The regional assessment follows the steps outlined in Section 5.1 above. The key products of the regional assessment are characterization of: (1) well completions with an emphasis on identifying multi-aquifer completions; (2) maximum head differences between aquifers at the location of multi-completed wells; and (3) water quality within the aquifers.

Aquifer Completions

The first step is to characterize the well completions within the aquifers and formations represented in the Gulf Coast Aquifer Region. As described in Section 5.1 above, to perform this step, a validated database of groundwater wells and their screen information was developed. Next, the well screens were intersected with aquifer structure to produce tabulations of both single-aquifer completed wells and multi-aquifer completed wells.

Table 5-1 lists the well completions for 65,917 wells in the area covered by Houston Area Groundwater Model, which is the groundwater model currently used by Groundwater Management Area 14 for joint planning in the northern aquifer region. More than 60 percent of the wells are completed solely in the Chicot Aquifer, which is the shallowest aquifer. The percentages of wells solely completed in the Evangeline Aquifer, Burkeville Formation, and Jasper Aquifer are about 24, 54, and 3 percent, respectively. Multi-aquifer completed wells comprise less than 4 percent of the total wells. The relatively low percent of multi-aquifer completed wells is attributed to the relative thickness and good productivity of the Chicot Aquifer. In the northern Gulf Coast region, most of the Chicot Aquifer is greater than 800 feet thick and thickens to greater than 1,800 feet near the coastline. About 5 percent of the wells intersect either the Burkeville Formation or the Jasper Aquifer. The fact that many of these wells are completed in one aquifer does not mean that long-screens within an aquifer could not contribute to comingling. As demonstrated in the case studies, water quality and vertical head differences within the aquifers are significant.

Figure 5-8 plots the multi-aquifer completed wells in the northern portion of the Gulf Coast Aquifer. Superimposed on the well locations is the outline of the aquifers as represented in the Houston Area Groundwater Model. Because of the relatively large thickness of the Chicot Aquifer, there are no multi-aquifer completed wells closer than about 35 miles from the coastline. The highest density of the multi-aquifer completed wells occur in Harris and Montgomery counties, and near the up-dip boundary of the Burkeville Formation. An interesting feature in Figure 5-8 is the large number of wells completed across both the Jasper Aquifer and Burkeville Formation in Montgomery County.

Table 5-1. **Well Completions in the Houston Area Groundwater Model.**

Aquifer(s)	Number of Wells
Chicot	44,111
Evangeline	14,747
Burkeville	2,647
Jasper	2,198
Chicot & Evangeline	1,429
Chicot, Evangeline, Burkeville	13
Chicot to Jasper	3
Evangeline & Burkeville	440
Evangeline, Burkeville, Jasper	21
Evangeline & Jasper	1
Jasper & Burkeville	307
Total single aquifer	**63,703**
Total multi aquifer	**2,214**
Percent Multi-Completed	**3.4 percent**

Table 5-2 lists the well completions for 23,611 wells in the area covered by the Central Gulf Coast Groundwater Availability Model. About 60 percent of the wells are completed solely in the Chicot Aquifer, which is the shallowest aquifer and covers most of the central portion of the Gulf Coast Aquifer. The percentages of wells solely completed in the Evangeline Aquifer, Burkeville Formation, and Jasper Aquifer are about 23, 5, and 9 percent, respectively. Multi-aquifer completed wells comprise 4 percent of the total wells. The relatively low percent of multi-aquifer completed wells is again attributed to the relatively large thickness and good productivity of the Chicot Aquifer.

Figure 5-9 plots the multi-aquifer completed wells in the Central portion of the Gulf Coast Aquifer. Superimposed on the well locations is the outline of the aquifers as represented in the Central Gulf Coast Groundwater Availability Model. Because of the relatively large thickness of the Chicot Aquifer, there are few multi-aquifer completed wells closer than about 20 miles from the coastline. The highest density of the multi-aquifer completed wells occurs within 15 miles of the up-dip extent of the Chicot Aquifer and within about 10 miles of the Burkeville Formation.

Table 5-2. Well Completions in the Central Gulf Coast Aquifer Groundwater Availability Model.

Aquifer(s)	Number of Wells
Chicot	13,712
Evangeline	5,519
Burkeville	1,115
Jasper	2,073
Chicot & Evangeline	870
Chicot, Evangeline, Burkeville	13
Evangeline & Burkeville	8
Evangeline, Burkeville, Jasper	2
Jasper & Burkeville	299
Total single aquifer	**22,419**
Total multi aquifer	**1,192**
Percent Multi-Completed	**5.1 percent**

Table 5-3 lists the well completions for 2,190 wells in the area covered by the Southern Gulf Coast Groundwater Availability Model. About 70 percent of the wells are completed solely in the Chicot Aquifer, which is the shallowest aquifer and covers most of the southern portion of the Gulf Coast Aquifer. The percentages of wells solely completed in the Evangeline Aquifer, Burkeville Formation, and Jasper Aquifer are about 20, less than 1, and 2 percent of the total number of wells, respectively. Multi-aquifer completed wells comprise four percent of the total wells.

Figure 5-10 plots the multi-aquifer completed wells in the southern portion of the Gulf Coast Aquifer. Superimposed on the well locations is the outline of the aquifers as represented in the southern Gulf Coast Groundwater Availability Model. Because of the base of the Chicot Aquifer is deeper than base of fresh water (see Figure 5-6) near most of the coastline, there are few multi-aquifer completed wells closer than about 40 miles from the coastline. The highest density of the multi-aquifer completed wells occurs withing the southeast portion of Hidalgo County and the eastern region of Starr County.

Table 5-3. **Well Completions in the Southern Gulf Coast Aquifer Groundwater Availability Model.**

Aquifer(s)	Number of Wells
Chicot	1,567
Evangeline	447
Burkeville	58
Jasper	41
Chicot & Evangeline	54
Evangeline & Burkeville	4
Jasper & Burkeville	19
Total single aquifer	**2,113**
Total multi aquifer	**77**
Percent Multi-Completed	**3.5 percent**

Table 5-4 lists the well completions for 8,311 wells for the Yegua-Jackson Aquifer and the Catahoula Aquifer in the study area. Approximately 33 and 24 percent of the wells are completed only in the Catahoula Aquifer and only in the Shallow Yagua-Jackson Aquifer, respectively. Twenty-eight percent of the wells are completed in solely in the Upper Jackson, Lower Jackson, Upper Yegua, or Lower Yegua, respectively. Fourteen percent of the wells are multi-aquifer completed wells. Table 5-4 lists fourteen aquifer combinations where multi-aquifer wells completions have occurred. More than 50 percent of the multi-aquifer completed wells occur across the Shallow Aquifer-Upper Jackson boundary, the Catahoula-Upper Jackson boundary, and the Shallow Aquifer-Lower Jackson boundary. The Yegua-Jackson is a less productive aquifer than the Gulf Coast Aquifer and water quality degrades quicker with depth. As a result, wells tend to be shallower and lower capacity.

Figure 5-11 lists the multi-aquifer completed wells for the Yegua-Jackson Aquifer and the Catahoula Aquifer in the study area. Because of the length of the aquifer system, the figure is divided into a northern, central and southern panel. The highest density of the multi-aquifer completed wells occur within 16 miles of the updip extend of the Lower Yegua Aquifer in the following five counties: Karnes, DeWitt, Lavaca, Fayette, and Washington counties.

Table 5-4. Well Completions Between the Yegua-Jackson Aquifer and the Gulf Coast Aquifer.

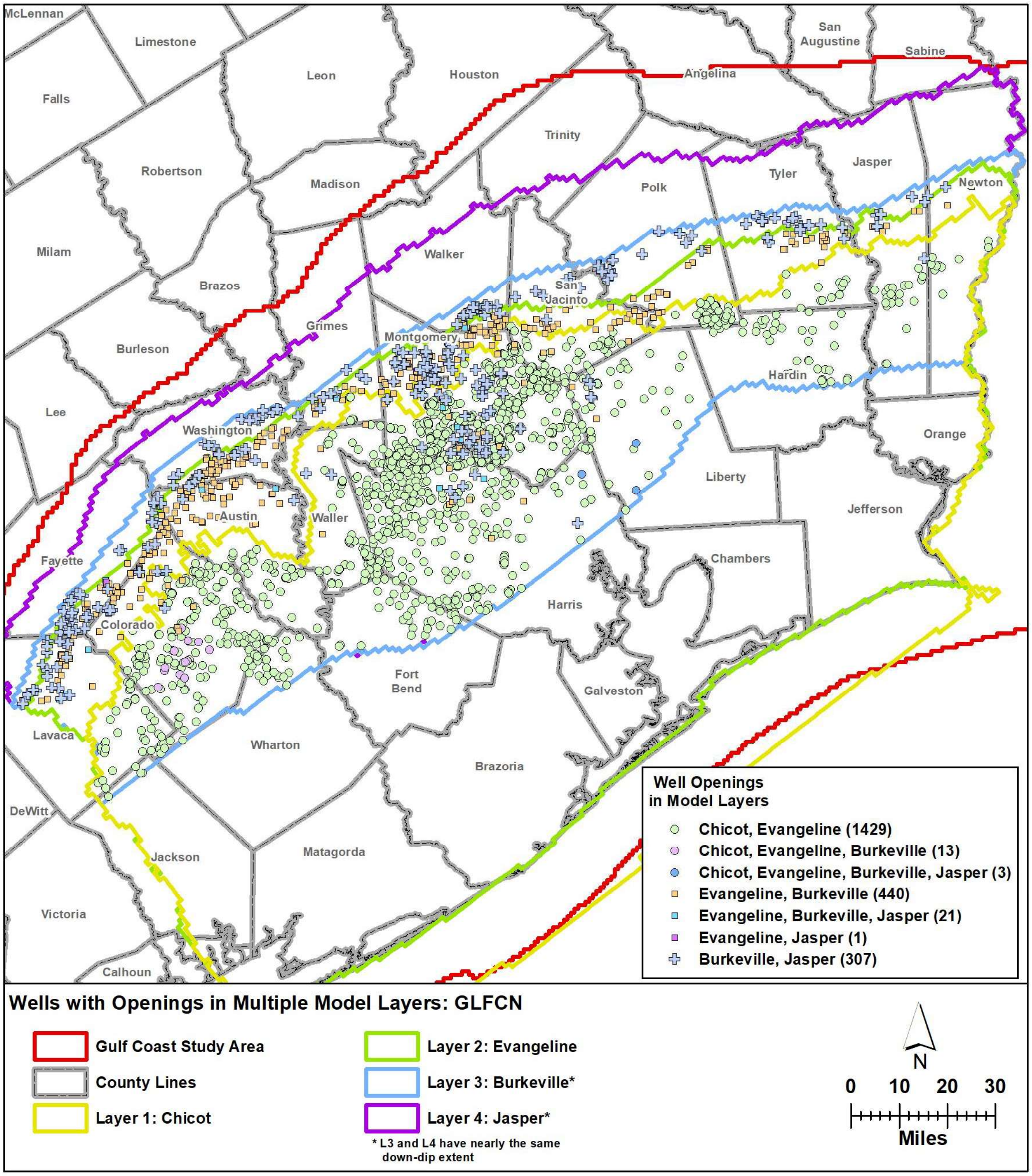
Aquifer(s)	Number of Wells
Catahoula	2,803
Shallow Yegua-Jackson	1,996
Upper Jackson	967
Lower Jackson	494
Upper Yegua	742
Lower Yegua	116
Catahoula/Upper Jackson	196
Catahoula/Jackson	1
Shallow / Upper Jackson	355
Shallow / Lower Jackson	134
Shallow / Upper Yegua	88
Shallow / Lower Yegua	2
Shallow / Upper & Lower Jackson	32
Shallow / Lower Jackson / Upper Yegua	27
Shallow / Upper & Lower Yegua	15
Upper & Lower Jackson	120
Upper & Lower Jackson/Upper Yegua	5
Jackson/Yegua	1
Lower Jackson/Upper Yegua	113
Upper Lower Yegua	104
Total single aquifer	**7,118**
Total multi aquifer	**1,193**
Percent Multi-Completed	**14.4 percent**

Table 5-5 lists the well completions for 111 wells in the Brazos River Alluvium Aquifer in the area covered by the Central Gulf Coast region. Multi-aquifer completed wells comprise 68 percent of the total wells. Forty-six percent of these wells are completed in the both the alluvium and Gulf Coast aquifer. Thirty of these wells are completed in the lower alluvium and the Gulf Coast aquifer.

Figure 5-12 plots the multi-aquifer completed wells in the in the Brazos River Alluvium Aquifer and the underlying Gulf Coast Aquifer. The location of the multi-aquifer completed wells are spatially distributed in all counties adjacent to the Brazos River. Most of the multi-aquifer completed wells are in Brazos County.

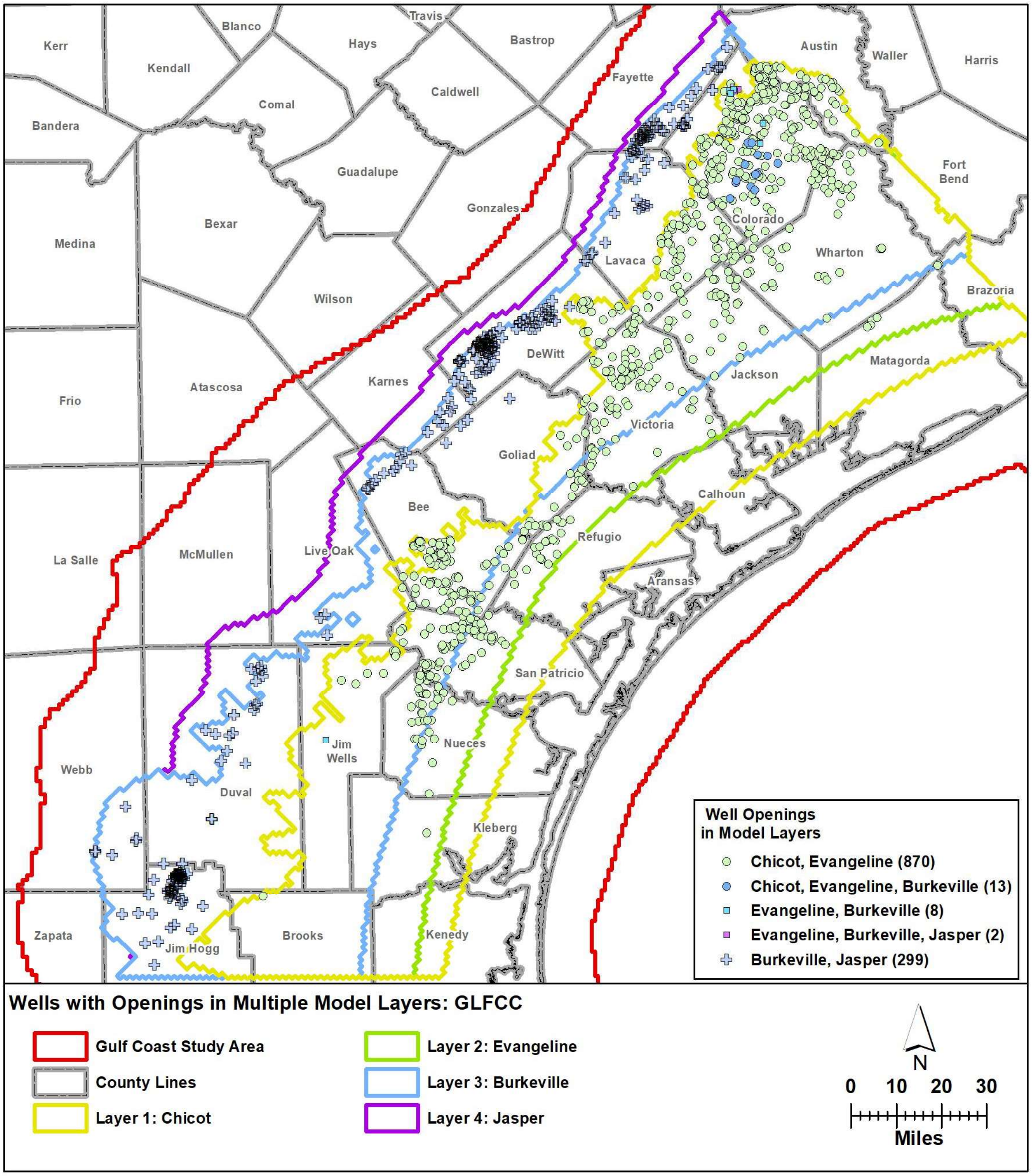
Table 5-5. Well Completions in the Brazos River Alluvium Aquifer.

Aquifer(s)	Number of Wells
Upper Alluvium	17
Lower Alluvium	4
Upper & Lower Alluvium	14
Alluvium and Gulf Coast Aquifer	46
Lower Alluvium and Gulf Coast Aquifer	30
Total single layer	**35**
Total multi-layer	**76**
Percent Multi-Completed	**68.4 percent**



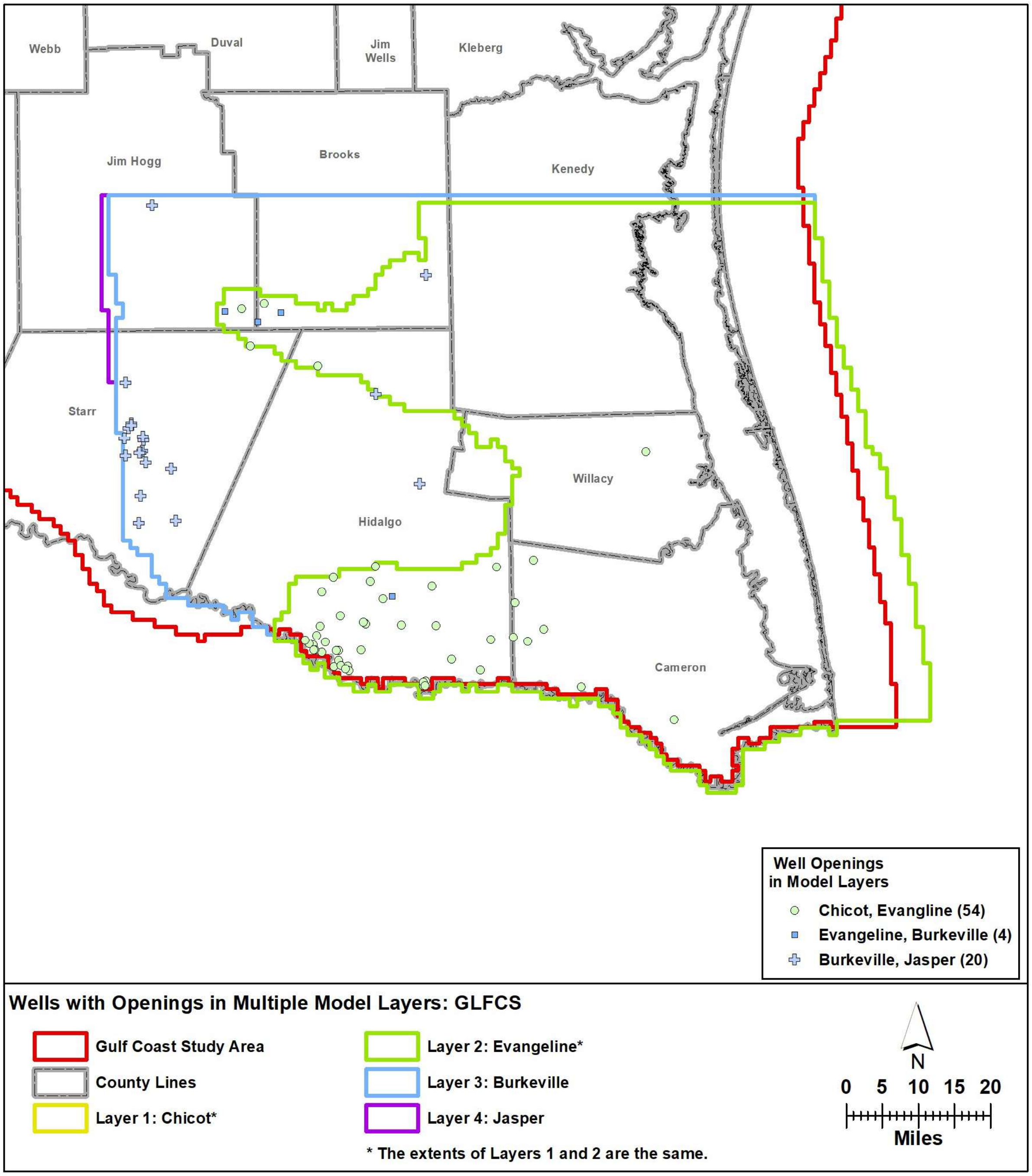
Note: GLFCN = Northern Gulf Coast Groundwater Availability Model

Figure 5-8. **Location of wells completed in two or more aquifers in the Northern Gulf Coast Groundwater Availability Model.**



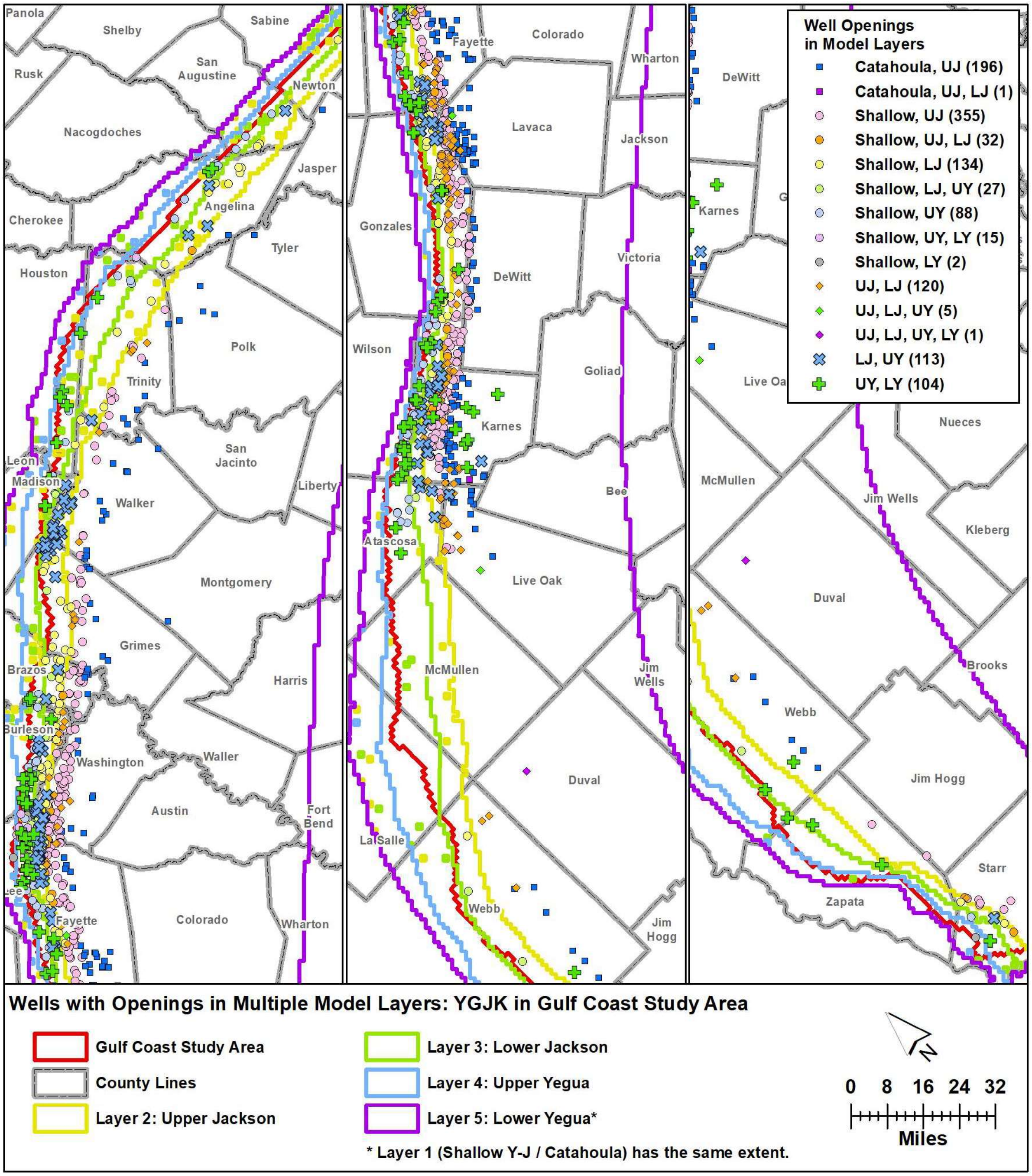
Note: GLFCC = Central Gulf Coast Groundwater Availability Model

Figure 5-9. **Location of wells completed in two or more aquifers in the Central Gulf Coast Groundwater Availability Model.**



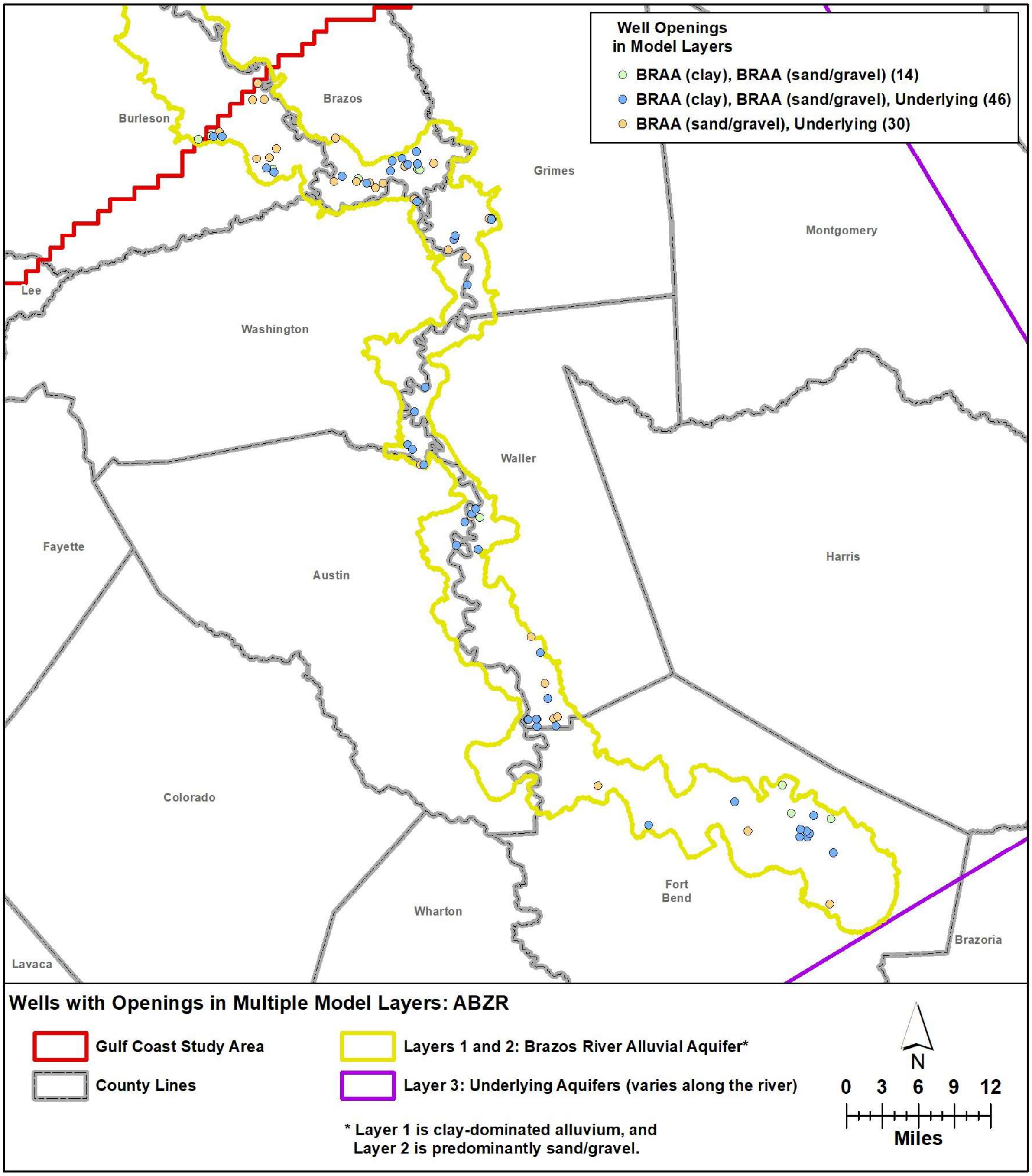
Note: GLFCS = Southern Gulf Coast Groundwater Availability Model

Figure 5-10. **Location of wells completed in two or more aquifers in the Southern Gulf Coast Groundwater Availability Model.**



Note: LJ = Lower Jackson, UJ = Upper Jackson, YGJK = Yegua-Jackson Groundwater Availability Model

Figure 5-11. **Location of wells completed in two or more aquifers in the Yegua-Jackson Groundwater Availability Model.**



Note: ABZR = Brazos River Alluvium Aquifer Groundwater Availability Model; BRAA = Brazos River Alluvium Aquifer

Figure 5-12. **Location of wells completed in two or more aquifers in the Brazos-River Alluvium Aquifer Groundwater Availability Model.**

Maximum Head Differences

As discussed in Section 4, flow within a well or filter pack occurs from head differences between aquifers and zones co-completed by the well. Vertical hydraulic head differences and resulting vertical gradients within the aquifers in the Gulf Coast Aquifer region have been documented by the United States Geological Survey since the early 1970s. As a result of concerns with land subsidence in the Houston Area, the United States Geological Survey began a major initiative to measure water levels to better understand the relationship between declines in water levels and land subsidence (Gabrysch, 1975, 1982; Gabrysch and Bonnet, 1975, 1976a, 1976b; Gabrysch and Coplin, 1990). These studies continue today in the form of annual reports by the United States Geological Survey on measured water levels in approximately 900 wells over a seven-county region to generate water contour maps for the Chicot, Evangeline, and Jasper aquifers (Kasmarek and Ramage, 2017). These reports document differences of up to 200 feet in hydraulic head have occurred between the aquifers for the last 20 years.

In parallel with their efforts to understand land subsidence, the United States Geological Survey has been modeling the regional groundwater flow within the Gulf Coast Aquifers since the 1970s in support of their projects to model groundwater flow and land subsidence in the Houston area (Jorgensen, 1975; Meyer and Carr, 1979; Carr and others, 1985). In addition, the United States Geological Survey modeling of the Gulf Coast regional Gulf Coast flow system began in the mid-1980s with their Regional Aquifer-System Analysis of the Gulf Coast Aquifer (Grubb, 1986; Williamson and Grubb, 2001) that included all states that border the Gulf Coast. Along with the Regional Aquifer-System Analysis models, the United States Geological Survey developed a series of groundwater availability models that included modeling the relationship between water level decline and land subsidence in the Northern Gulf Coast Region (Kasmarek and Strom, 2002; Kasmarek and Robinson, 2004; Kasmarek, 2012).

In the mid-2000s, the TWDB developed groundwater availability models for the central (Chowdhury and others, 2004) and southern (Chowdhury and Mace, 2003) regions of the Gulf Coast Aquifer. These two Groundwater Availability Models provided maps and hydrographs of hydraulic head differences over time and correlated these the change in water levels with change in pumping. Since the 2000s, several groundwater models of the Gulf Coast have been developed by the TWDB and other state agencies. Notable models include the Groundwater Management Area 16 Alternative model (Hutchison and others, 2011) in south Texas and the Lower Colorado River Basin Model (Young and others, 2006c; 2010) in central Texas.

All Gulf Coast groundwater models document that significant vertical head differences (vertical head gradients) occur in the Gulf Coast from groundwater pumping. Areas of high pumping in the Texas Gulf Coast include the Houston Area (municipal use), Colorado, Wharton, and Matagorda counties (agricultural use) and municipal use near the cities of Victoria in Victoria County and in Kingsville in Kleberg County.

Because the groundwater models are calibrated to match historical measured groundwater elevations on the aquifer scale, the results of the Groundwater Availability Models have been used to estimate vertical head differences potentially encountered by wells. A primary reason for using model results is a lack of closely spaced wells monitoring water levels in different aquifers.

For this report, we also use the results of the State Groundwater Availability Models to estimate head differences within multi-completed wells.

Table 5-6 through Table 5-8 provide a statistical summary of the highest absolute value head difference in multi-aquifer completed wells in the Northern Gulf Coast Groundwater Availability Model (Houston Area Groundwater Model), the Central Gulf Coast Groundwater Availability Model, and the Southern Gulf Coast Groundwater Availability Model, respectively. All multi-aquifer completed wells with a common uppermost layer were grouped together in a common bin, and the head difference for each possible pair of model layers in each bin was calculated. The highest magnitude of these head differences was determined for each well, and the table and figure are a summary of these values. So, for the column labelled Chicot in Table 5-6 below, all wells completed in the Chicot and another lower aquifer, and all such permutations, were considered in the calculation. A negative head difference is an upward gradient indicating upward flow potential and a positive difference is a downward gradient indicating downward flow potential.

Table 5-6 shows that significant head differences are simulated by the Houston Area Groundwater Model between aquifers at the location of the multi-aquifer completed wells (Kasmarek, 2012). For all aquifers, the range of head difference is several hundred feet, with the largest difference indicating downward vertical hydraulic gradients. Recall that head differences are calculated at the last historic stress period for the Groundwater Availability Model and therefore flow potential accounts for historical impacts to aquifer heads. Plots of the location and magnitudes of the maximum head difference provide useful information of the spatial differences across the Gulf Coast. Figure 5-13 shows that for the Chicot Aquifer, the vertical hydraulic gradients are predominantly downward and the largest head differences occur in Harris, Montgomery, and Waller counties where head differences between the Chicot and Evangeline aquifers greater than 100 feet are prevalent. Figure 5-14 shows that, for the Evangeline Aquifer, the head differences are typically less than 50 feet and that head differences greater than 100 feet only occur in Montgomery and Harris counties. Figure 5-15 shows that, for the Burkeville Aquifer, the head differences are typically less than 50 feet.

Table 5-7 shows that large head differences are simulated by the Central Gulf Coast Groundwater Availability Model between aquifers near multi-aquifer completed wells. For the Chicot and Burkeville aquifers, the range between the minimum and maximum head difference is about one hundred feet. The range for the Evangeline Aquifer is considerably less at about 23 feet. Figure 5-16 through Figure 5-18 plot the magnitude and direction of the vertical head differences at individual wells using the Chicot, Evangeline, and Burkeville as the uppermost unit in the calculation. Figure 5-16 shows that, for the Chicot Aquifer, the vertical hydraulic gradients are predominantly downward except for in Refugio, San Patricio, and Nueces counties where the hydraulic gradients are predominantly upward. Figure 5-17 plots the maximum head difference between any wells multi-completed with and below the Evangeline Aquifer in the Central Gulf Coast Groundwater Availability Model. Because the Evangeline Aquifer is such a prolific aquifer, few wells are cross completed between it and lower aquifers. For those that are, the gradient is dominantly upward. Figure 5-18 plots the maximum head difference between any wells multi-completed in the Burkeville and the underlying Jasper Aquifer in the Central Gulf

Coast Groundwater Availability Model. Gradients are dominantly downward from the Burkeville to the Jasper Aquifer.

Table 5-8 shows maximum head differences simulated by the Southern Gulf Coast Groundwater Availability Model for multi-aquifer completed wells. The mean and median head differences for all model aquifers are negative indicating upward flow potential, significantly so from the Burkeville to the Evangeline. Figure 5-19 through Figure 5-21 plot the magnitude and direction of the vertical head differences at individual wells using the Chicot, Evangeline, and Burkeville as the uppermost unit in the calculation and the Southern Gulf Coast Groundwater Availability Model. Head differences and resulting flow potential is dominantly upward in the southern region.

Table 5-6. **Maximum Head Difference Between Aquifers at Wells in the Houston Area Groundwater Model.**

Uppermost Aquifer Considered	Chicot	Evangeline	Burkeville
Count	1445	462	307
Min (ft)	-19.0	-153.5	-132.2
Max (ft)	371.2	187.6	213.9
Mean (ft)	43.6	4.2	70.6
Median (ft)	**12.2**	**0.2**	**64.1**
St. Dev. (ft)	70.9	23.8	77.9

Note: ft = feet

Table 5-7. **Maximum Head Difference Between Aquifers at Wells in the Central Gulf Coast.**

Uppermost Aquifer Considered	Chicot	Evangeline	Burkeville
Count	883.0	10.0	299.0
Min (ft)	-20.8	-8.8	-23.6
Max (ft)	93.0	15.0	84.5
Mean (ft)	15.4	0.4	15.1
Median (ft)	**9.5**	**-1.5**	**11.7**
St. Dev. (ft)	19.8	8.8	17.3

Note: ft = feet

Table 5-8. **Maximum Head Difference Between Aquifers at Wells in the Southern Gulf Coast.**

Uppermost Aquifer Considered	Chicot	Evangeline	Burkeville
Count	54	4	20
Min (ft)	-16.3	-57.7	-34.4
Max (ft)	2.4	-31.4	0.9
Mean (ft)	-3.5	-39.6	-3.2
Median (ft)	**-3.5**	**-34.6**	**-0.1**
St. Dev. (ft)	3.0	12.4	8.5

Note: ft = feet

Table 5-9 provides a statistical summary of the highest absolute value of the head differences between aquifers in the Yegua-Jackson and Catahoula aquifers in the study area. All five aquifers have significant positive and negative head differences with the greatest values being downward hydraulic gradients. Positive head difference ranges from 30 to 150 feet for the five aquifers. Figure 5-22 shows the magnitude and direction of the vertical head differences in wells using the shallow outcrop or Catahoula as the uppermost aquifer in the calculation. Downward hydraulic gradients are more prevalent than upward gradient across the study area. However, upward hydraulic gradients are dominant in portions of Starr, Karnes, Burleson, Brazos, and San Augustine counties. Figure 5-23 through Figure 5-25 plot the magnitude and direction of the vertical head differences using the Upper Jackson, Lower Jackson and Upper Yegua as the uppermost layer in the calculation, respectively. On average, vertical head differences are greatest between the Upper Jackson and the underlying Lower Jackson and Upper Yegua.

Table 5-9. **Maximum Head Difference Between Aquifers at Wells in the Yegua-Jackson Aquifers.**

Uppermost Aquifer Considered	Catahoula	Shallow Yegua-Jackson	Upper Jackson	Lower Jackson	Upper Yegua
Count	197	653	126	113	104
Min (ft)	-76.4	-79.1	-37.6	-33.9	-18.0
Max (ft)	150.0	125.1	66.5	43.3	30.7
Mean (ft)	20.0	8.5	12.8	5.6	-0.6
Median (ft)	**23.1**	**2.7**	**13.1**	**5.8**	**-0.5**
St. Dev. (ft)	34.7	34.4	16.1	14.5	7.8

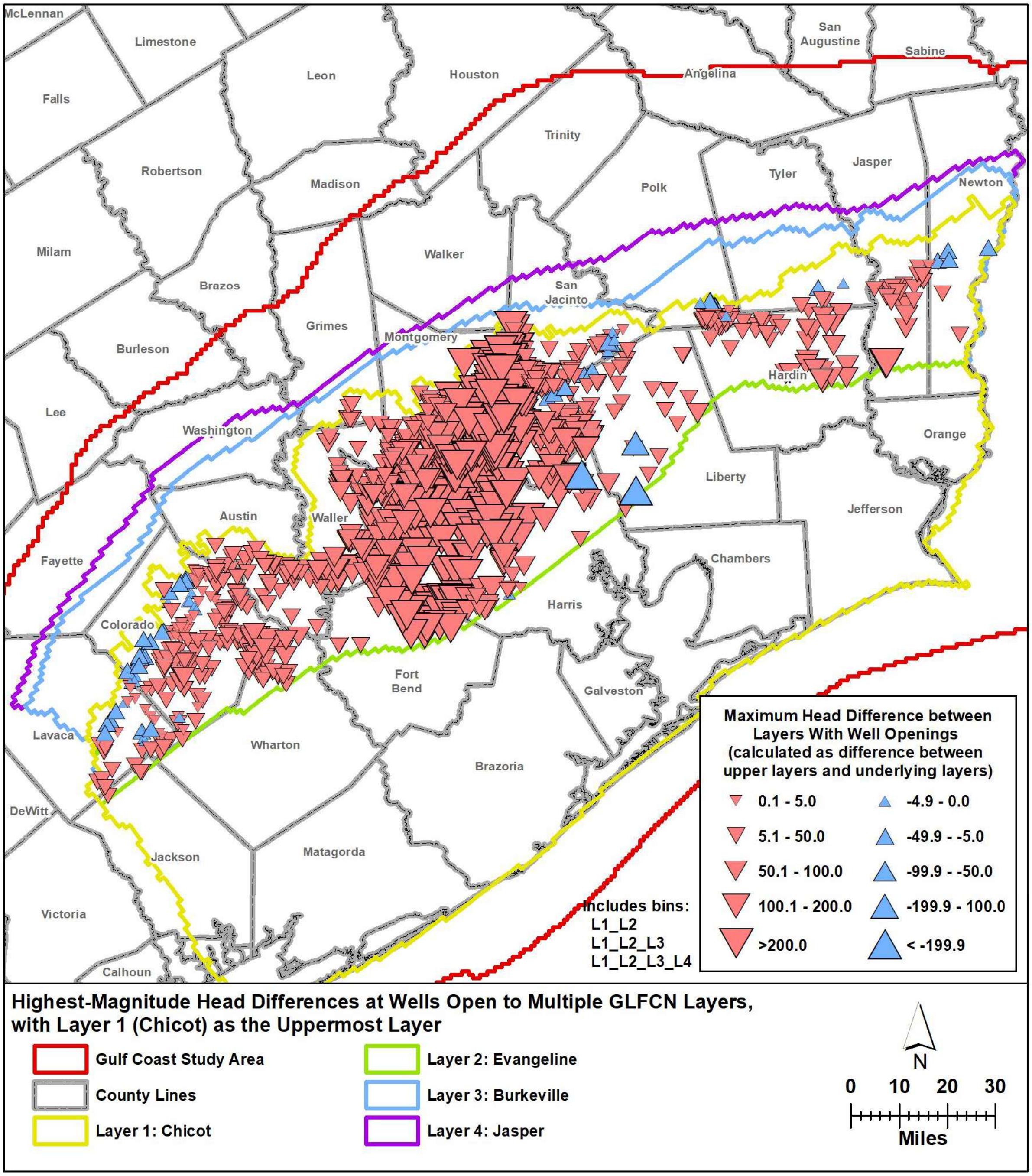
Note: ft = feet

Table 5-10 provides a statistical summary of the highest absolute value of the head differences between an upper and lower portion of the Brazos River Alluvium Aquifer. The two aquifer layers have maximum positive head differences between 1 and 5 feet and have minimum negative head differences between -16 and -18 feet. The magnitude of the differences is significantly less than the other aquifers which is expected given the thinner deposits compared to other aquifer units and the stabilizing influence of the Brazos River on hydraulic heads in the shallow deposits within a flood plain. Figure 5-26 shows that upward hydraulic gradients are more prevalent than downward hydraulic gradients except for within Waller County.

Table 5-10. Maximum Head Difference Between Aquifer Layers at Wells in the Brazos River Alluvium.

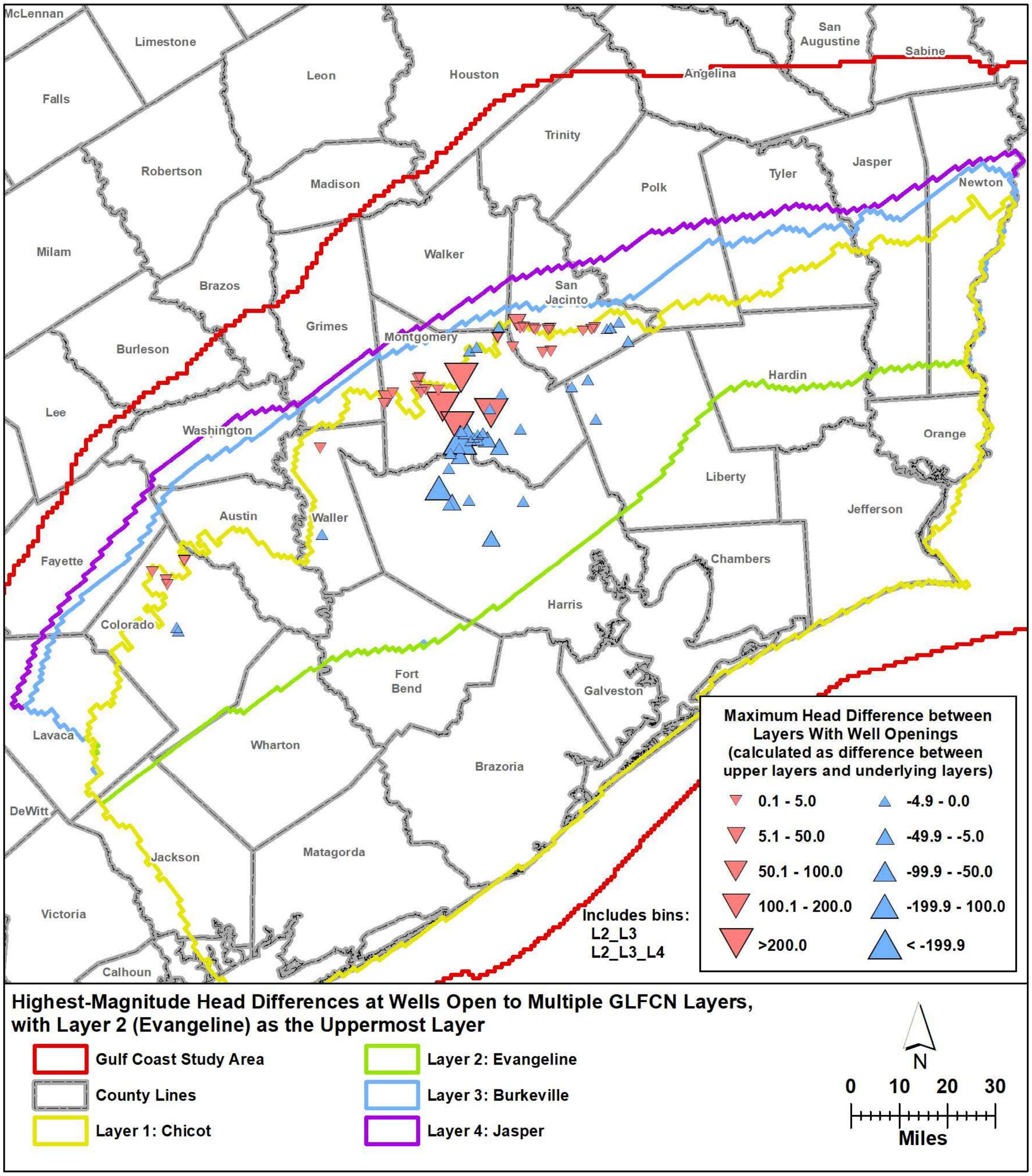
Uppermost Aquifer Considered	Upper Alluvium	Lower Alluvium
Count	60	30
Min (ft)	-17.1	-16.8
Max (ft)	1.3	4.5
Mean (ft)	-2.8	-3.5
Median (ft)	**-0.9**	**-2.0**
St. Dev. (ft)	4.2	4.5

Note: ft = feet



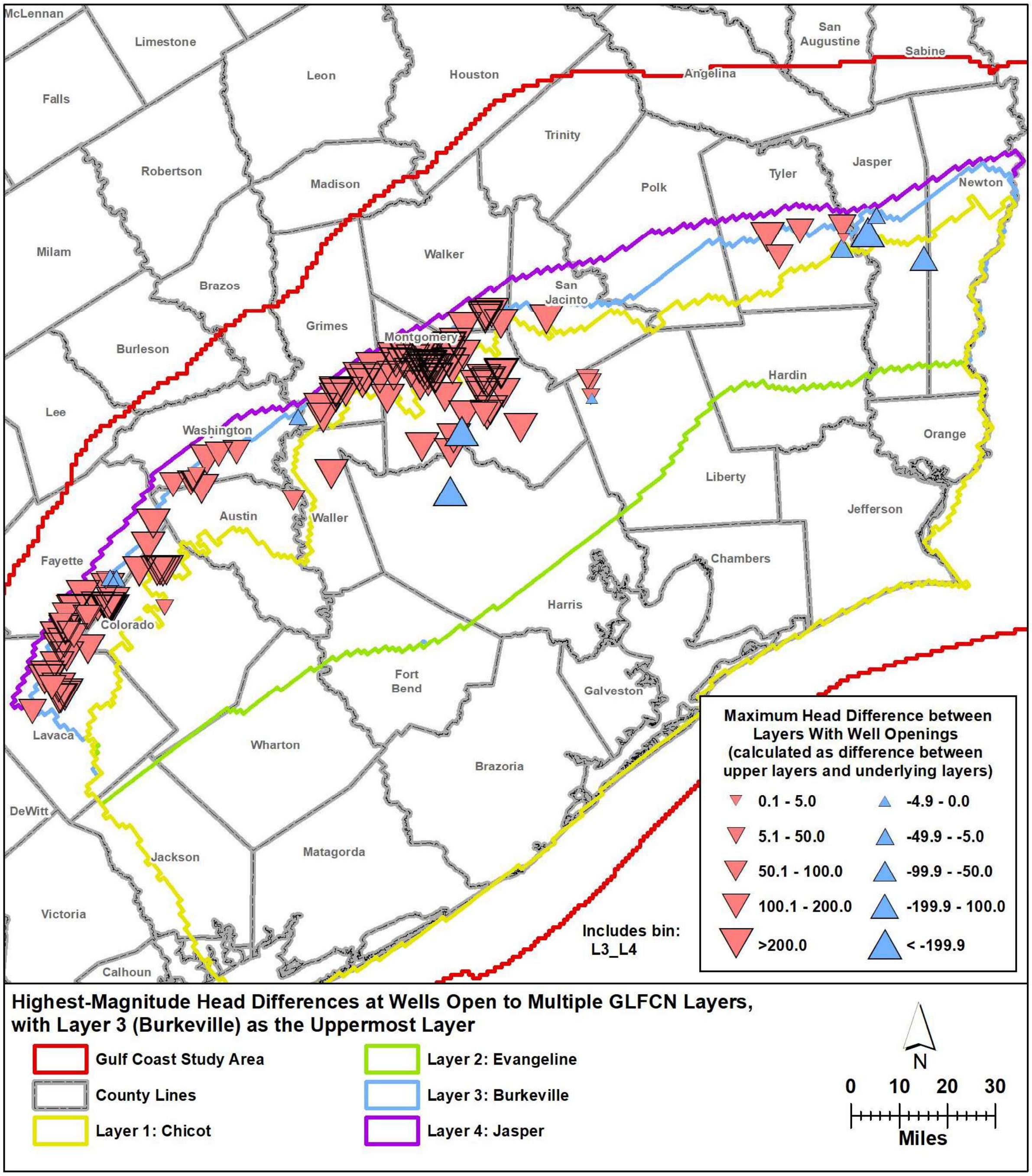
Note: GLFCN = Northern Gulf Coast Groundwater Availability Model

Figure 5-13. **Maximum head difference at each well completed in the Chicot and any underlying aquifer – Houston Area Groundwater Water.**



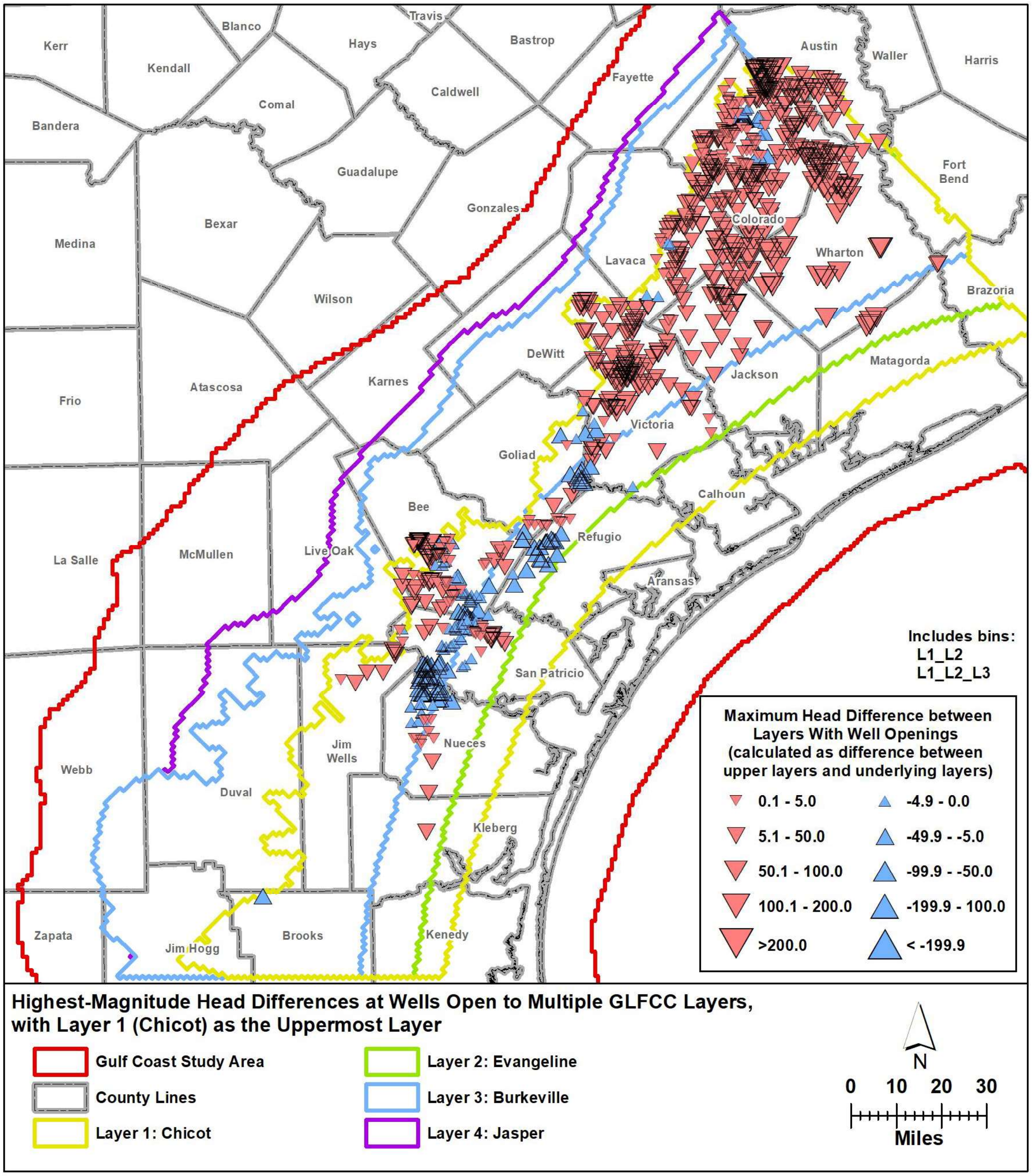
Note: GLFCN = Northern Gulf Coast Groundwater Availability Model

Figure 5-14. **Maximum head difference at each well completed in the Evangeline and any underlying aquifer – Houston Area Groundwater Water.**



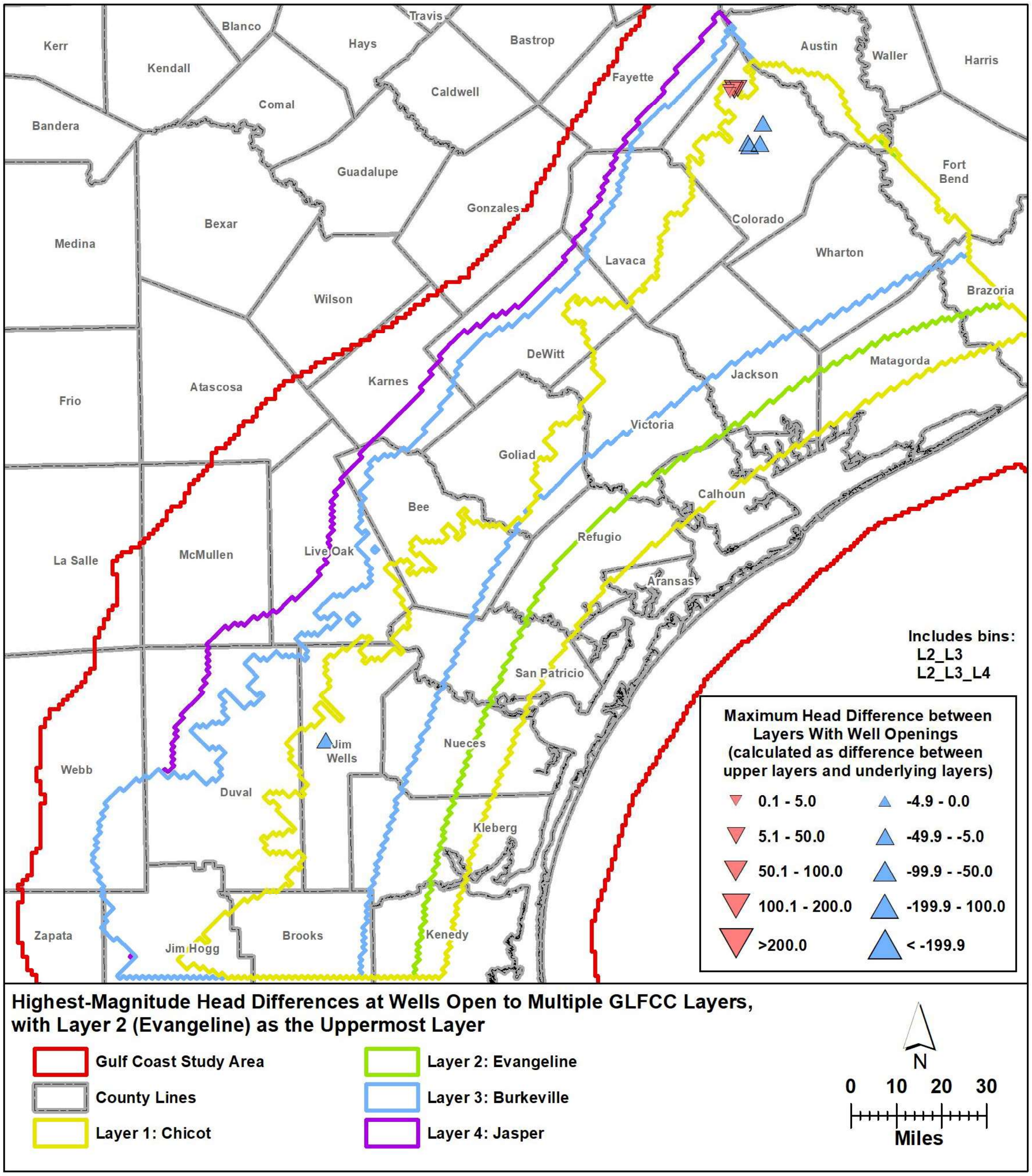
Note: GLFCN = Northern Gulf Coast Groundwater Availability Model

Figure 5-15. **Maximum head difference at each well completed in the Burkeville and the Jasper aquifer – Houston Area Groundwater Water.**



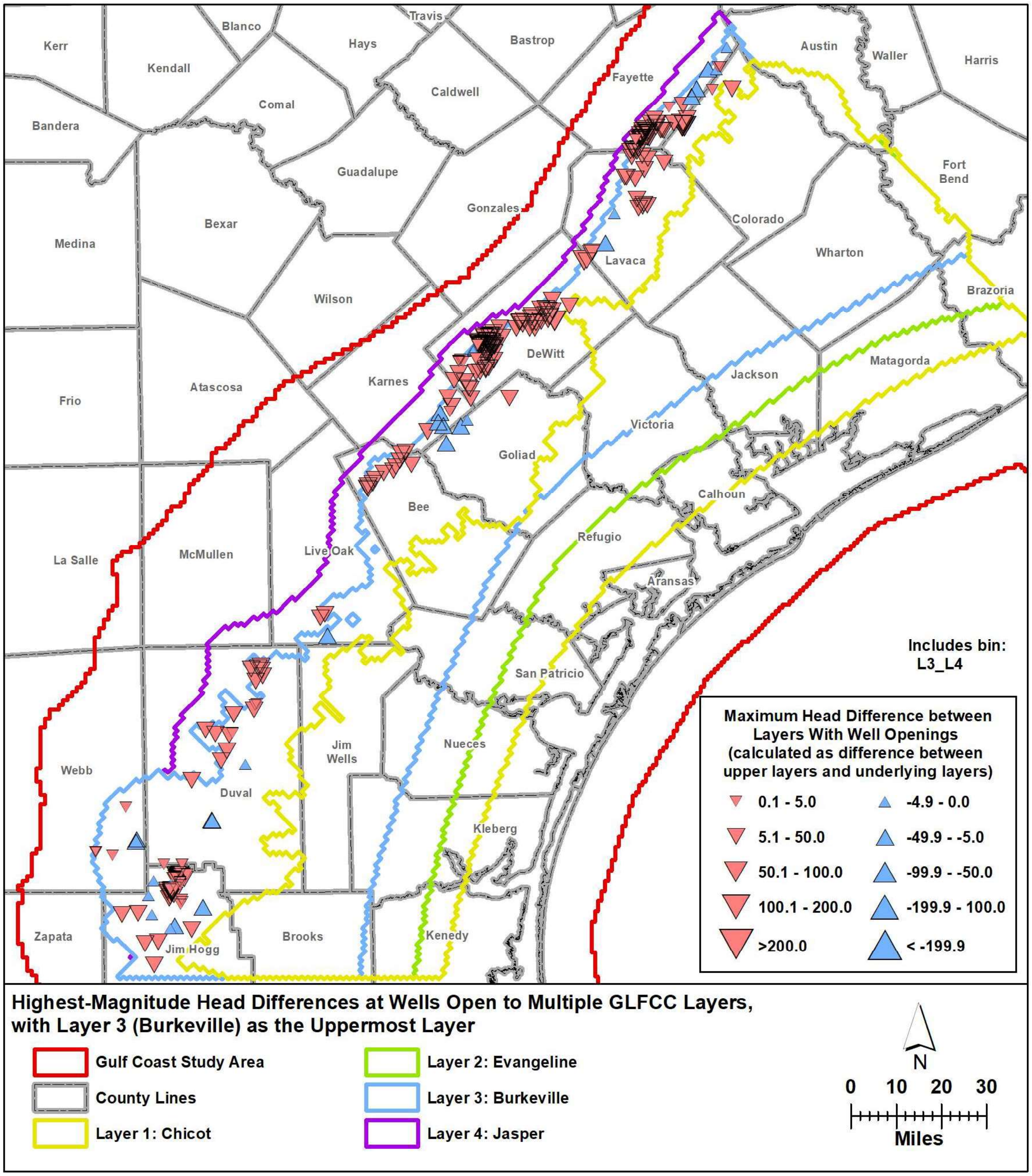
Note: GLFCC = Central Gulf Coast Groundwater Availability Model

Figure 5-16. Maximum head difference at each well completed in the Chicot and any underlying aquifer – Central Gulf Coast Groundwater Availability Model.



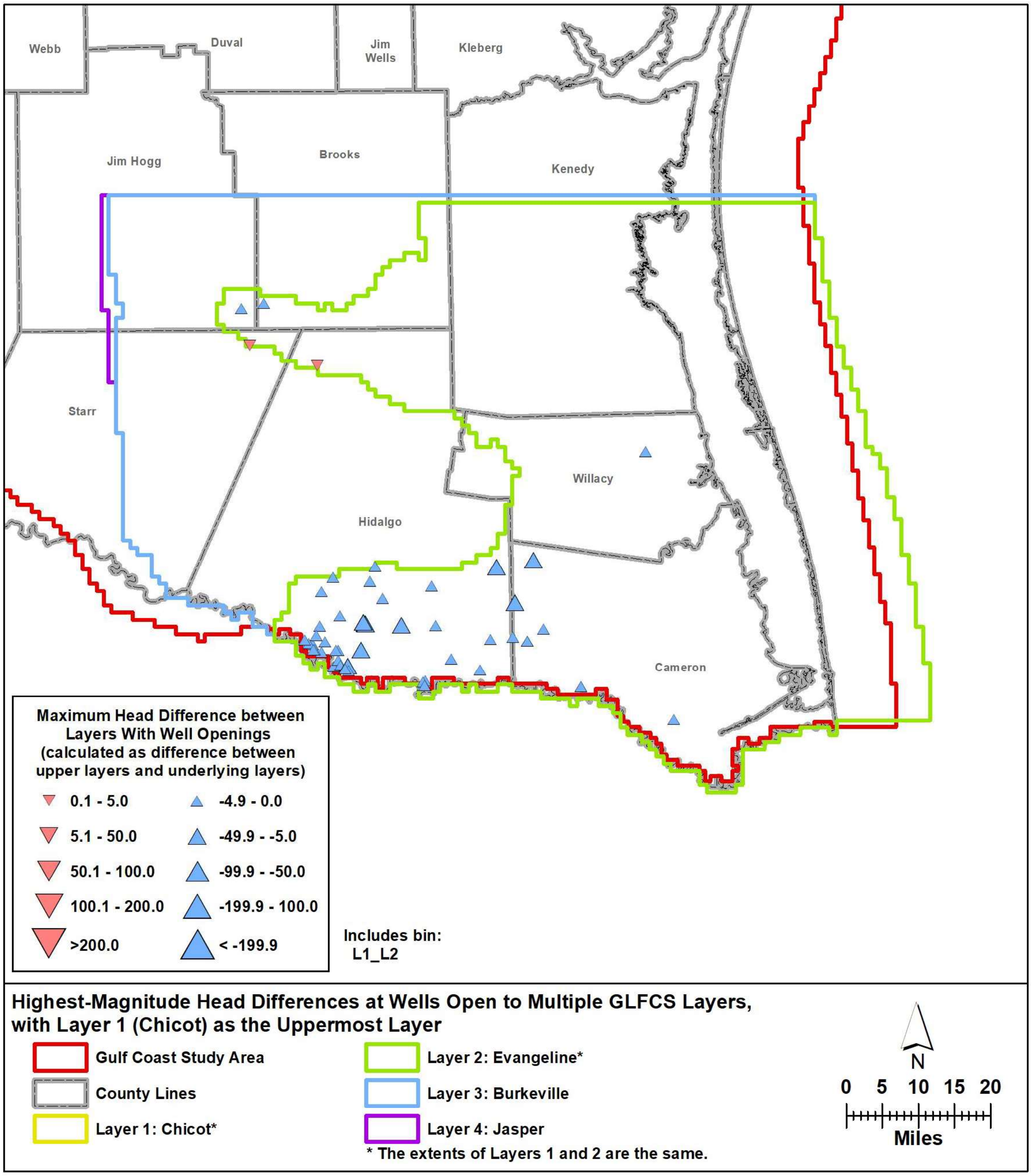
Note: GLFCC = Central Gulf Coast Groundwater Availability Model

Figure 5-17. **Maximum head difference at each well completed in the Evangeline and any underlying aquifer – Central Gulf Coast Groundwater Availability Model.**



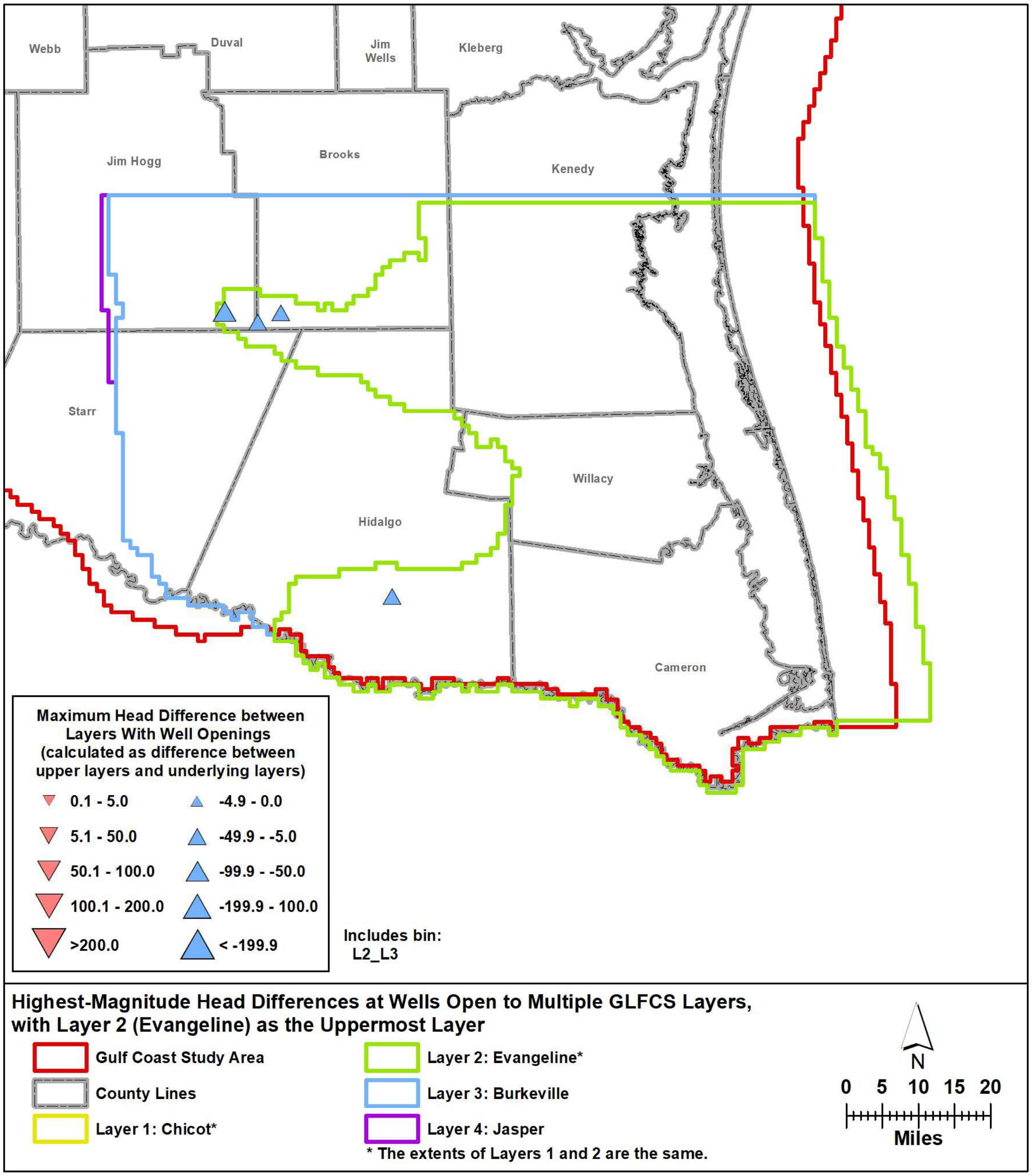
Note: GLFCC = Central Gulf Coast Groundwater Availability Model

Figure 5-18. Maximum head difference at each well completed in the Burkeville and Jasper Aquifer – Central Gulf Coast Groundwater Availability Model.



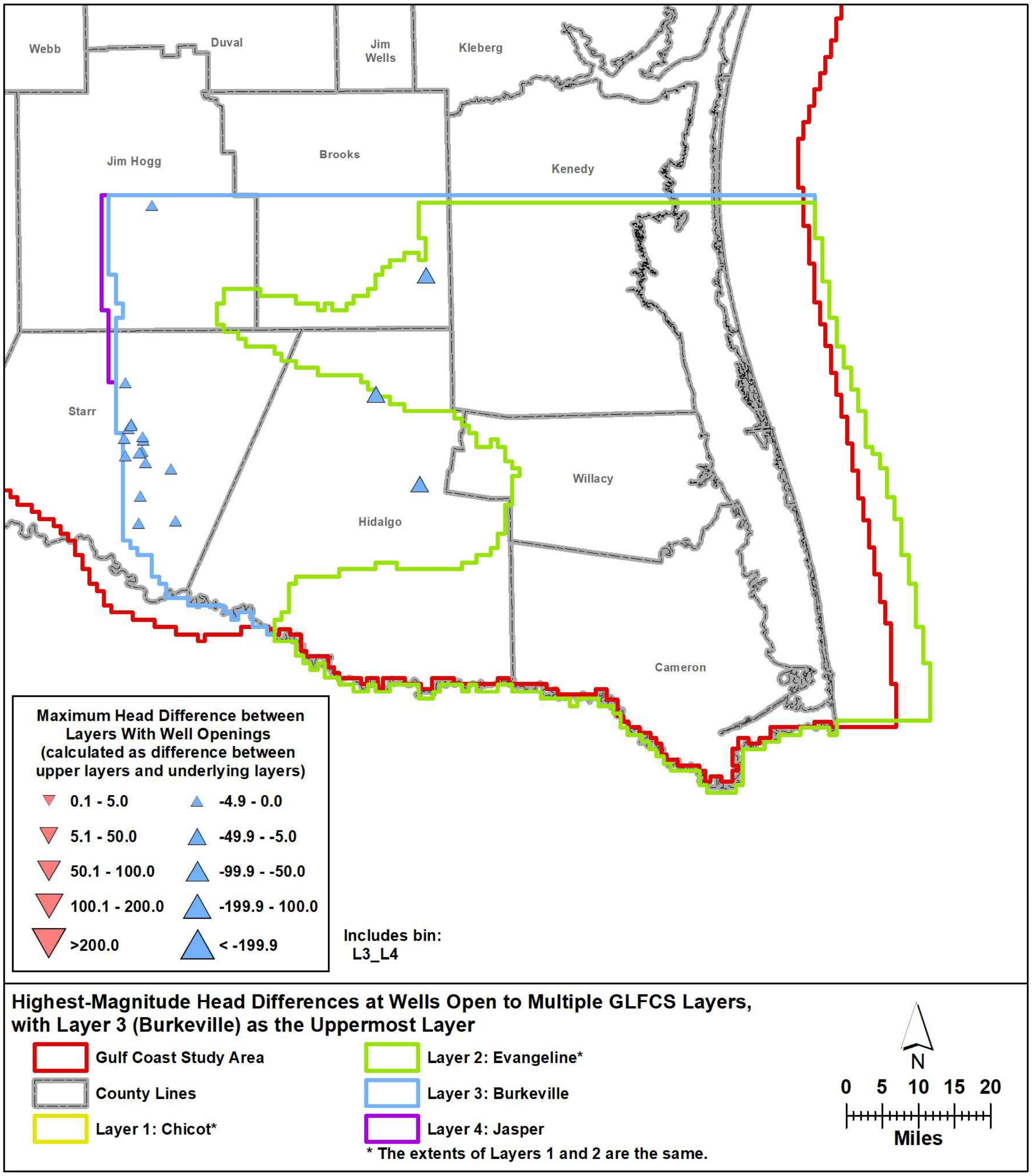
Note: GLFCS = Southern Gulf Coast Groundwater Availability Model

Figure 5-19. **Maximum head difference at each well completed in the Chicot and any underlying aquifer – Southern Gulf Coast Groundwater Availability Model.**



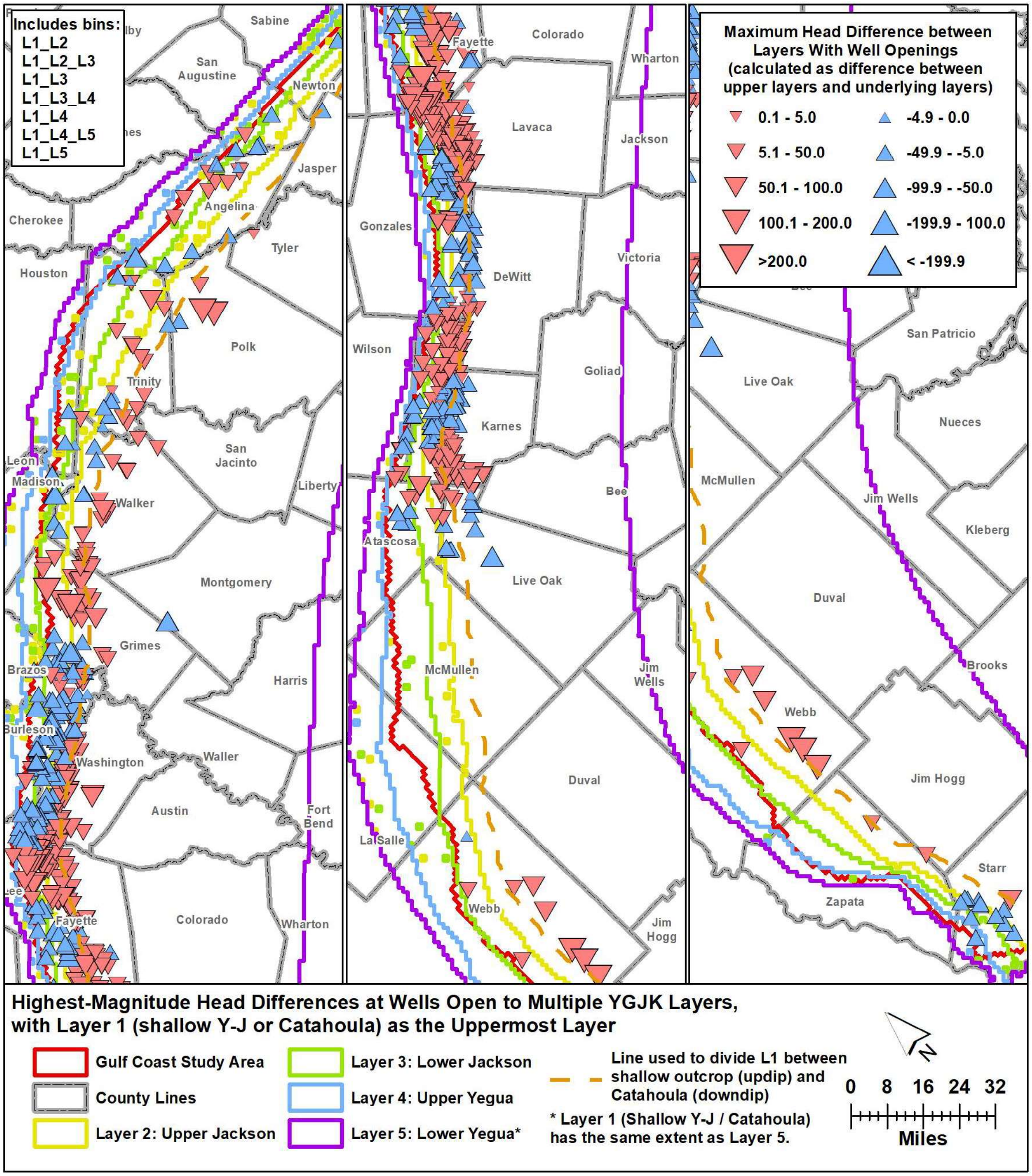
Note: GLFCS = Southern Gulf Coast Groundwater Availability Model

Figure 5-20. **Maximum head difference at each well completed in the Evangeline and any underlying aquifer – Southern Gulf Coast Groundwater Availability Model.**



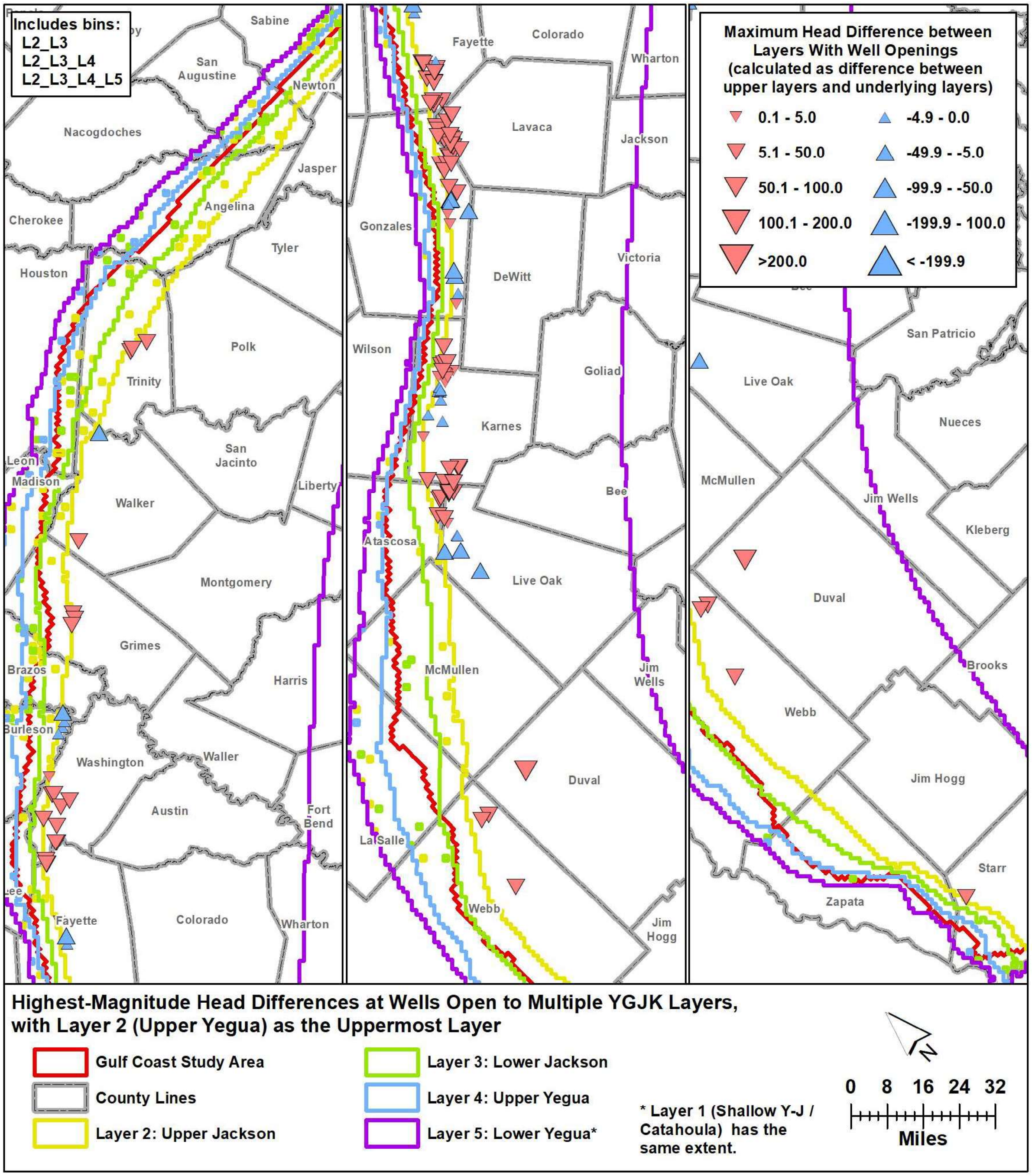
Note: GLFCS = Southern Gulf Coast Groundwater Availability Model

Figure 5-21. **Maximum head difference at each well completed in the Burkeville and Jasper Aquifer – Southern Gulf Coast Groundwater Availability Model.**



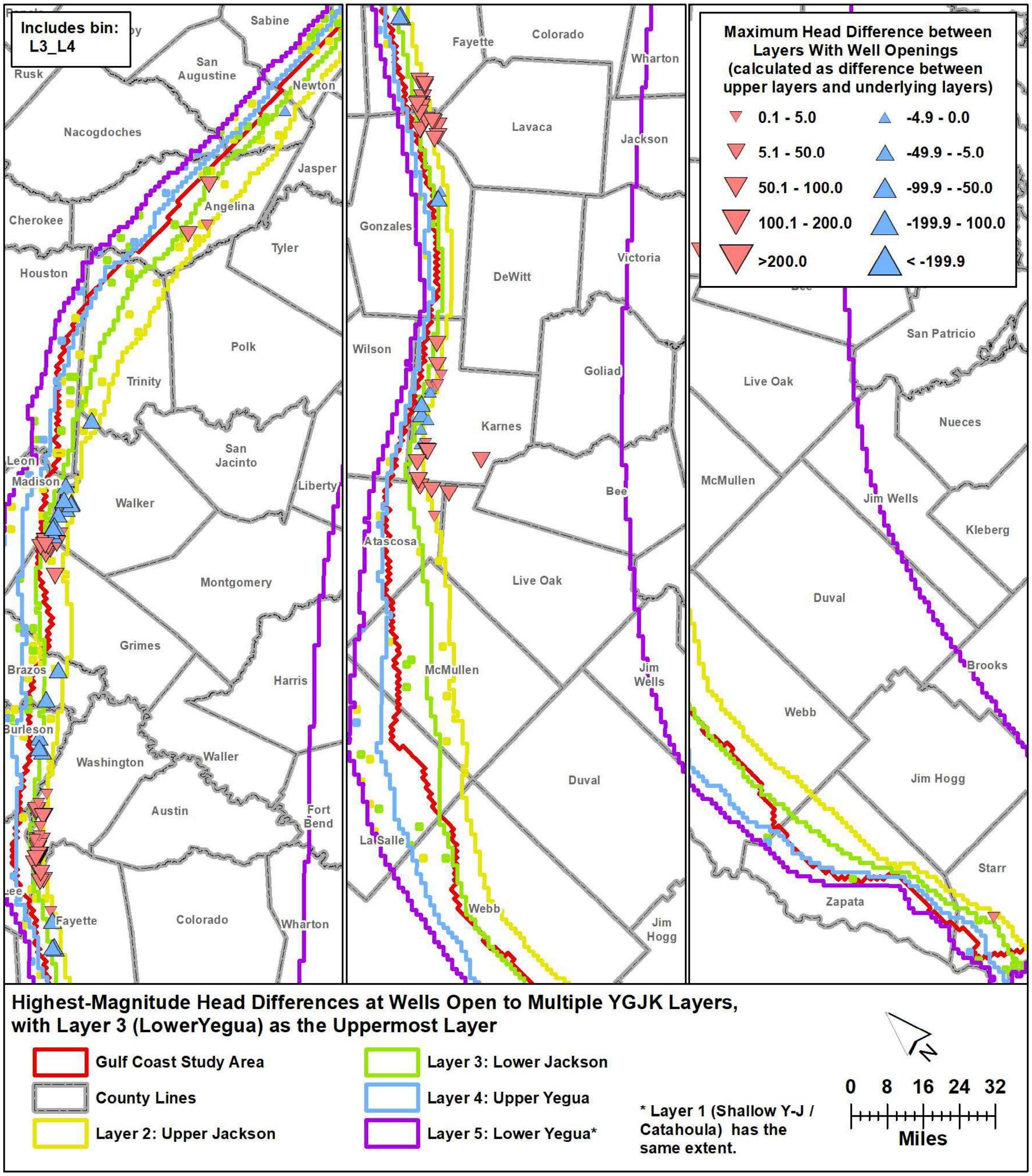
Note: YGJK = Yegua Jackson Groundwater Availability Model

Figure 5-22. **Maximum head difference at each well completed in the Shallow Outcrop or Catahoula and the underlying aquifers – Yegua-Jackson Groundwater Availability Model.**



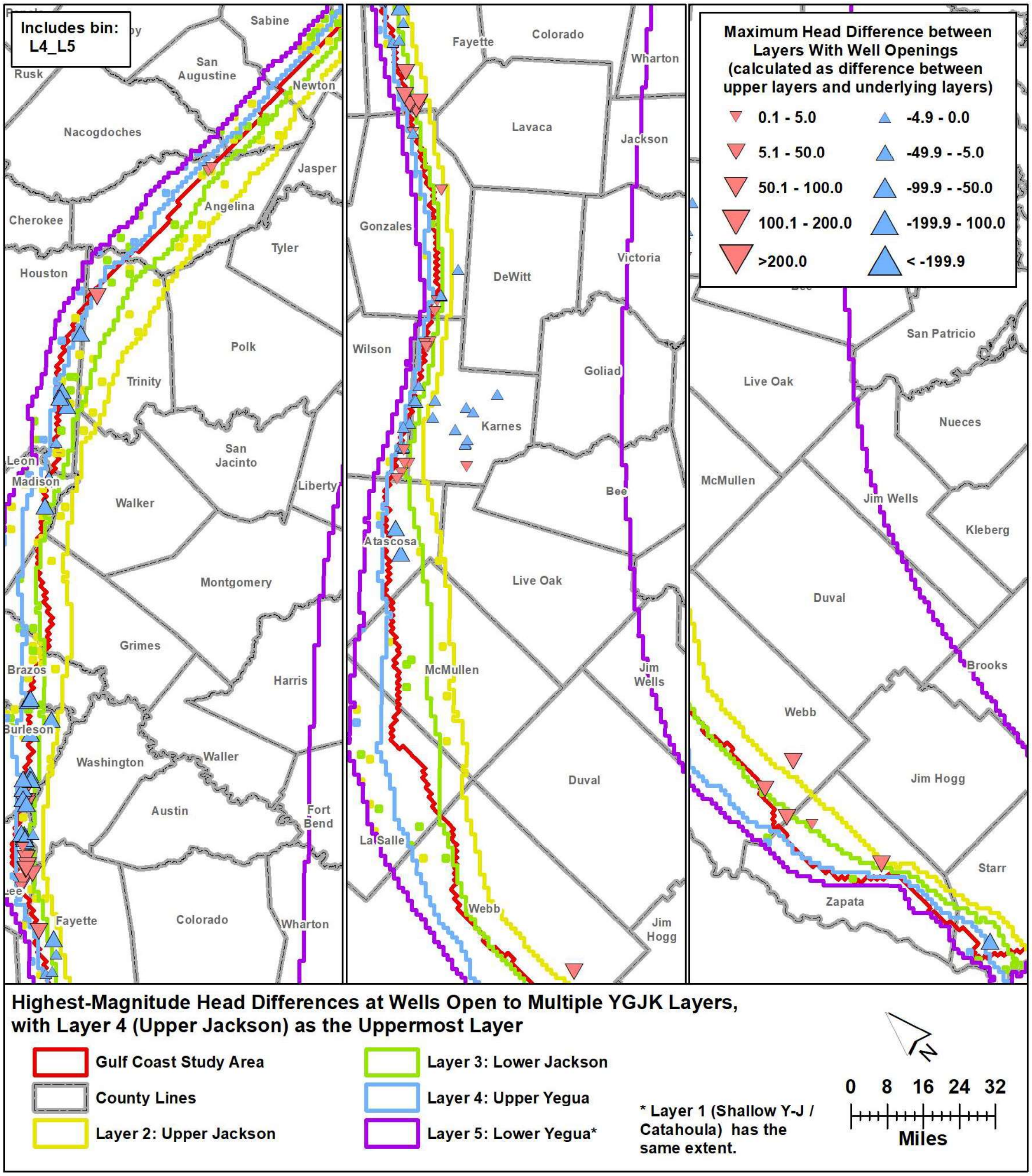
Note: YGJK = Yegua Jackson Groundwater Availability Model

Figure 5-23. **Maximum head difference at each well completed in the Upper Jackson and underlying aquifers – Yegua-Jackson Groundwater Availability Model.**



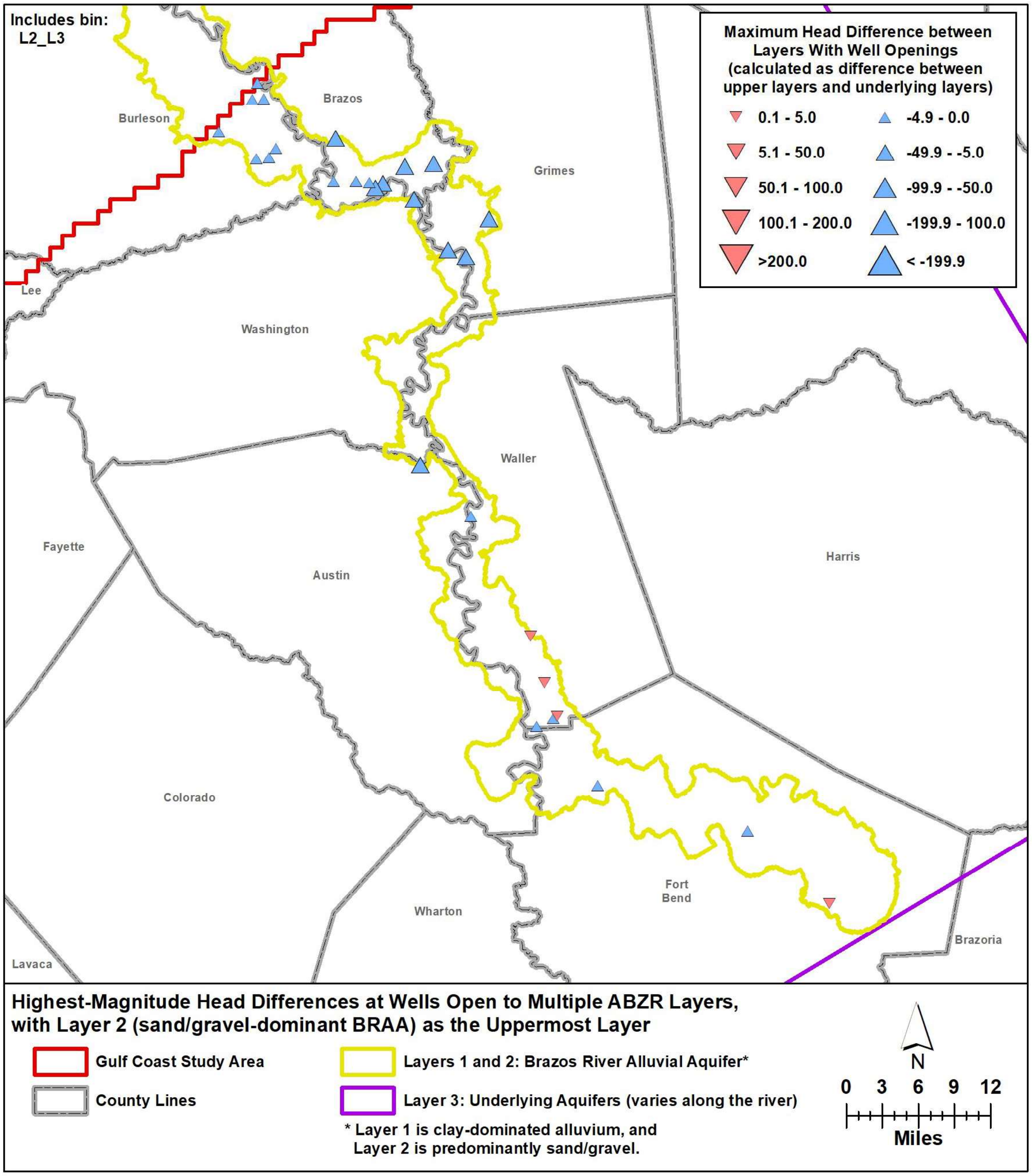
Note: YGJK = Yegua Jackson Groundwater Availability Model

Figure 5-24. **Maximum head difference at each well completed in the Lower Jackson and underlying aquifers – Yegua-Jackson Groundwater Availability Model.**



Note: YGJK = Yegua Jackson Groundwater Availability Model

Figure 5-25. **Maximum head difference at each well completed in the Upper Yegua and the Lower Yegua aquifers – Yegua-Jackson Groundwater Availability Model.**



Note: ABZR = Brazos River Alluvium Aquifer Groundwater Availability Model; BRAA = Brazos River Alluvium Aquifer

Figure 5-26. Maximum head difference at each well completed in the Lower Brazos River Alluvium and underlying aquifers – Brazos Aquifer Alluvium Aquifer Groundwater Availability Model.

Water Quality

A primary indicator of water quality is total dissolved solids concentrations. In the Gulf Coast Aquifer, brackish water is defined as water with a total dissolved solids concentration between 1,000 and 10,000 milligrams per liter. Figure 5-27 shows the spatial distribution of total dissolved solids for depth intervals of 0 to 200, 200 to 500, and 500 to 1,000 feet for the Gulf Coast Aquifer System. The maps of total dissolved solids concentrations were generated by interpolating approximately 11,000 measured total dissolved solids concentration from the TWDB groundwater database (Young and others, 2014). The location and thickness of fresh water in Figure 5-27 is consistent with the results shown in Figure 5-6, which is based on the analysis of geophysical logs.

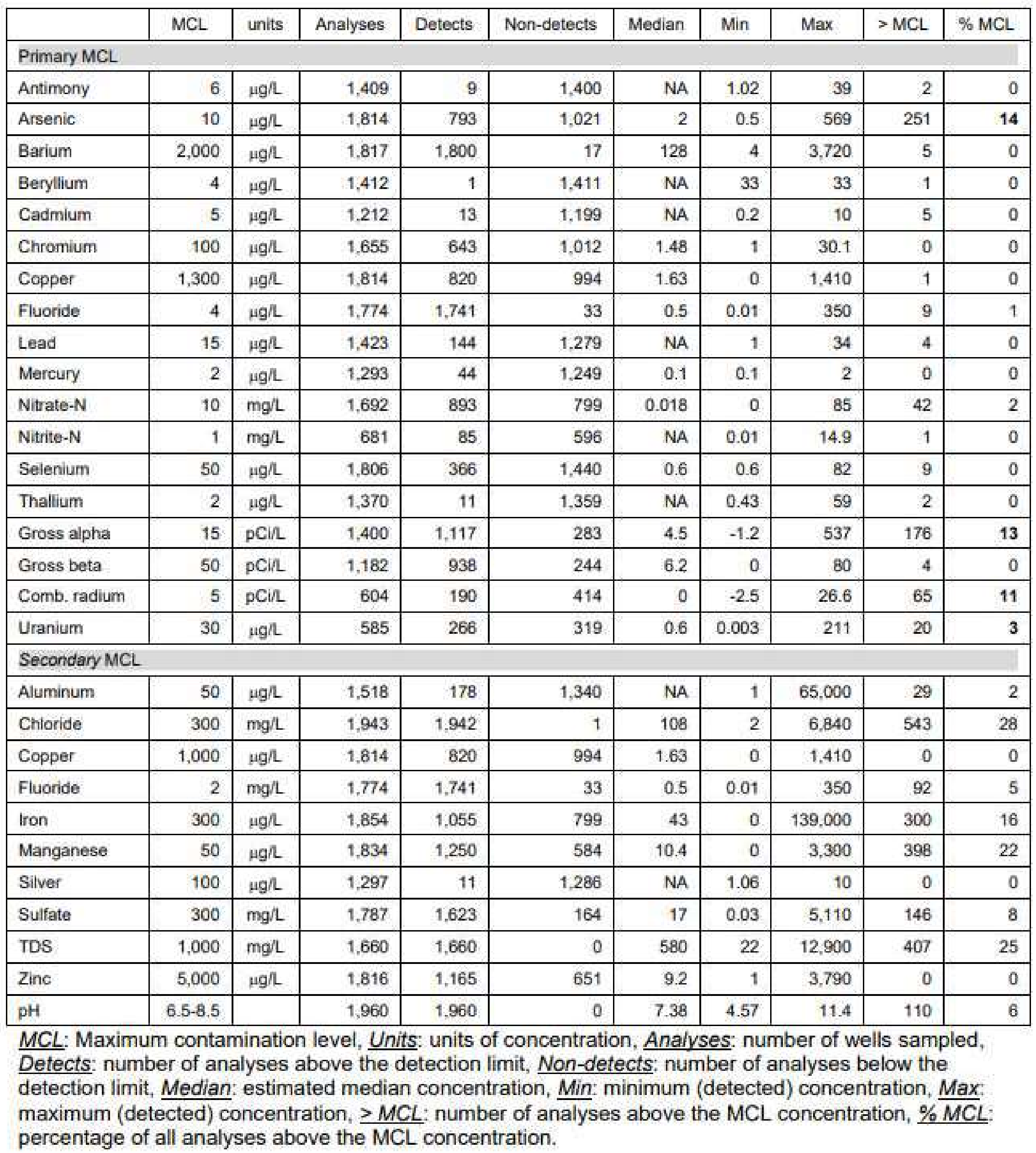
Figure 5-6 and Figure 5-27 show that the deepest fresh water in the northeast portion of the study area and becomes shallower toward the southwest. In the northern and central portion of the Gulf Coast Aquifer, the depth to the base of fresh water is generally between 1,500 and 2,000 feet below ground surface and thins to about 300 feet below ground surface in the south. The significantly higher ion concentrations in the south are consistent with higher residence times for the infiltration caused by higher evaporation rates and possibility lower permeability soils (Young and others, 2014; Reedy and others 2010). The higher evaporation rates cause the concentrations of the ions in rainwater to increase, and the slower groundwater flow rates promotes mineralization.

Figure 5-28 shows the Gulf Coast Aquifer wells that are completed across the base of freshwater shown in Figure 5-6. Except for the wells located in Harris and Montgomery counties, the well locations in Figure 5-28 are in three general areas where the depth to the base of fresh water is less than 400 feet. These three areas can be described as: (1) near the coast where the ocean and bays interact with groundwater, (2) near the updip boundary of the Gulf Coast where the fresh water in the Catahoula and Jasper aquifers are above the higher total dissolved solids waters in the Jackson Aquifer; and (3) in the south where evaporation rates and groundwater migration is slower than in the north. In Harris and Montgomery counties, most of the well locations shown in Figure 5-28 are associated with relatively deep high-capacity wells.

Among the potential concerns on degradation of water quality is that total dissolved solids concentrations not only affect the suitability of water for industry and agriculture, but also for human consumption. The Texas Commission on Environmental Quality's secondary maximum contaminant level for total dissolved solids is 1,000 milligrams per liter. Table 5-11 lists other compounds that have either a maximum contaminant level or a secondary maximum contaminant level and provide the number of analyses performed for each compound and the number of violations of either maximum contaminant level or maximum contaminant level in the Gulf Coast Aquifer (Reedy and others, 2010).

Figure 5-29 is a map that shows the probability of exceeding a primary maximum contaminant level (Reedy and others, 2010). The highest levels of primary maximum contaminant level exceedances occur in the southern part of the aquifer and in a zone in the northern part of the aquifer. The only constituent with high primary maximum contaminant level percent exceedance in the north is combined radium; all other primary maximum contaminant level exceedances are focused in the south. Figure 5-30 shows the spatial distribution of measured radium concentrations in the Gulf Coast Aquifer. The high combined radium concentrations are correlated to radon-222 in public water wells because radon-222 is derived from radium-226 through radioactive decay. The percentage of uranium maximum contaminant level exceedances in the Gulf Coast Aquifer (three percent) is much lower than that of gross alpha radiation or combined radium, and uranium exceedances are mostly restricted to the south.

Table 5-11. **Summary of maximum contaminant level violations in Gulf Coast Aquifer groundwater wells (reproduced from Reedy and others, 2010).**



	MCL	units	Analyses	Detects	Non-detects	Median	Min	Max	> MCL	% MCL
Primary MCL										
Antimony	6	µg/L	1,409	9	1,400	NA	1.02	39	2	0
Arsenic	10	µg/L	1,814	793	1,021	2	0.5	569	251	**14**
Barium	2,000	µg/L	1,817	1,800	17	128	4	3,720	5	0
Beryllium	4	µg/L	1,412	1	1,411	NA	33	33	1	0
Cadmium	5	µg/L	1,212	13	1,199	NA	0.2	10	5	0
Chromium	100	µg/L	1,655	643	1,012	1.48	1	30.1	0	0
Copper	1,300	µg/L	1,814	820	994	1.63	0	1,410	1	0
Fluoride	4	µg/L	1,774	1,741	33	0.5	0.01	350	9	1
Lead	15	µg/L	1,423	144	1,279	NA	1	34	4	0
Mercury	2	µg/L	1,293	44	1,249	0.1	0.1	2	0	0
Nitrate-N	10	mg/L	1,692	893	799	0.018	0	85	42	2
Nitrite-N	1	mg/L	681	85	596	NA	0.01	14.9	1	0
Selenium	50	µg/L	1,806	366	1,440	0.6	0.6	82	9	0
Thallium	2	µg/L	1,370	11	1,359	NA	0.43	59	2	0
Gross alpha	15	pCi/L	1,400	1,117	283	4.5	-1.2	537	176	**13**
Gross beta	50	pCi/L	1,182	938	244	6.2	0	80	4	0
Comb. radium	5	pCi/L	604	190	414	0	-2.5	26.6	65	**11**
Uranium	30	µg/L	585	266	319	0.6	0.003	211	20	**3**
Secondary MCL										
Aluminum	50	µg/L	1,518	178	1,340	NA	1	65,000	29	2
Chloride	300	mg/L	1,943	1,942	1	108	2	6,840	543	28
Copper	1,000	µg/L	1,814	820	994	1.63	0	1,410	0	0
Fluoride	2	mg/L	1,774	1,741	33	0.5	0.01	350	92	5
Iron	300	µg/L	1,854	1,055	799	43	0	139,000	300	16
Manganese	50	µg/L	1,834	1,250	584	10.4	0	3,300	398	22
Silver	100	µg/L	1,297	11	1,286	NA	1.06	10	0	0
Sulfate	300	mg/L	1,787	1,623	164	17	0.03	5,110	146	8
TDS	1,000	mg/L	1,660	1,660	0	580	22	12,900	407	25
Zinc	5,000	µg/L	1,816	1,165	651	9.2	1	3,790	0	0
pH	6.5-8.5		1,960	1,960	0	7.38	4.57	11.4	110	6

MCL: Maximum contamination level, *Units*: units of concentration, *Analyses*: number of wells sampled, *Detects*: number of analyses above the detection limit, *Non-detects*: number of analyses below the detection limit, *Median*: estimated median concentration, *Min*: minimum (detected) concentration, *Max*: maximum (detected) concentration, *> MCL*: number of analyses above the MCL concentration, *% MCL*: percentage of all analyses above the MCL concentration.

Note: % = percent, MCL = maximum contaminant level, mg/L = milligrams per liter, TDS = total dissolved solids, ug/L = micrograms per liter

Table 5-11 shows that the primary maximum contaminant level with the highest percent exceedance is arsenic (22 percent), followed by gross alpha (13 percent) and combined radium (11 percent); and the secondary maximum contaminant levels with the highest percent exceedance is chloride (28 percent), total dissolved solids (25 percent), manganese (22 percent), and iron (16 percent). These seven constituents are also the only constituents in Table 5-11 that have a percent violation greater than 10 percent. With respect to comingling, an important concern is the how a constituent is distributed vertically (stratified) between and within the deposits intersected by a well screen. Among the seven constituents described above, the spatial vertical variability for chloride and total dissolved solids has been observed to be less that for the other five constituents, which can be very isolated vertically to small zones. Chloride and total dissolved solids concentrations are primarily caused by the mineralization of the components of the host aquifer by groundwater as it migrates though different formations. Generally, significant changes in total dissolved solids values do no occur over vertical distance of 50 feet or less unless there are nearby isolated sources of salts such as salt domes, faults, abandoned disposal pits, waters enriched by salt spray, or salt-water intrusion. However, significant changes in concentration can occur over vertical distances of 50 feet or less for the other five constituents. The concentrations of the other five constituents can be vertically stratified in an aquifer because their concentration is tied to specific minerals and/or geochemistry associated with a particular deposit rather than the bulk mineralogy of the deposits. For instance, volcanic ash is likely a primary source of arsenic (Scanlon and others, 2005; Glenn and Lester, 2010; Gates and others, 2009), and the leachate from volcanic ash migration oxidizing conditions is likely an important source of radioactive compounds (Reedy and others, 2010). Reedy and others (2010) report that the Brazos River Alluvium Aquifer has seven constituents that have a water quality standard exceedance in greater than 10 percent of the analyzed samples. These include nitrate-N, gross alpha, chloride, iron, manganese, sulfate and total dissolved solids.

Because this study focused on the potential for brackish groundwater comingling and brackish groundwater is classified by total dissolved solids concentration, we will use total dissolved solids as a bulk indicator to assess potential for comingling to occur and to assess the difference in water quality among aquifers.

Table 5-12 through Table 5-14 and Figure 5-31 through Figure 5-33 tabulate and plot total dissolved solids concentrations within the Gulf Coast Aquifer in the northern, central, and southern regions, respectively. Based on the median total dissolved solids concentration values in each table, the total dissolved solids concentration in all aquifers in the Gulf Coast increases toward the south. In the northern Gulf Coast (Table 5-12), all four aquifers have median total dissolved solids concentrations less than 500 milligrams per liter. In the central Gulf Coast (Table 5-13), the median total dissolved solids concentrations for the four aquifers range between 498 and 931 milligrams per liter. In the southern Gulf Coast (Table 5-14), the median total dissolved solids concentrations for the four aquifers range is between 1,333 and 1,895 milligrams per liter. Combining the tabulated and graphical data with the information in Figure 5-6, Figure 5-27 and Figure 5-28, the potential for mixing fresh and brackish water in a well should be based more on the well's geophysical log than on the surface boundary used by the Groundwater Availability Models to model to represent the different aquifers.

Table 5-15 and Figure 5-34 tabulate and plot total dissolved solids concentrations within the Yegua-Jackson Aquifer and the underlying Catahoula Formation. For five of the six aquifers, the measured total dissolved solids values have a range that is greater than 5,000 milligrams per liter and a standard deviation greater than1,000 milligrams per liter. The Lower Jackson Aquifer shows less variability in the measured total dissolved solids, but its statistics are based on only 12 measurements. Based on these data, our analysis is the same as for the Gulf Coast aquifer: an evaluation of the potential for mixing fresh and brackish water in a well should be based on more characterization data than a well's geophysical log and aquifer layering at the scale of Groundwater Availability Model layers.

Similar tables and plots were not developed for the Brazos River Alluvium Aquifer because our process worked with wells that had defined screen data. There were only two wells with screen data that indicate that the well screen is completed in the Brazos River Alluvium Aquifer, therefore summary statistics were not developed nor a histogram were completed. In Section 4.7 of the Brazos River Alluvium Aquifer Groundwater Availability Model report, they report that the mean total dissolved solids in the aquifer is 959 milligrams per liter (Ewing and others, 2016). In the footprint of the Brazos River Alluvium Aquifer Groundwater Availability Model in the Gulf Coast Aquifer, the average total dissolved solids is 438 milligrams per liter, indicating that groundwater discharging as base flow from the Gulf Coast Aquifer to the Brazos River Alluvium Aquifer would generally be of better quality.

Table 5-12. Total dissolved solids Measurements in the Northern Gulf Coast (milligrams per liter).

Model Aquifer	Chicot	Evangeline	Burkeville	Jasper
Num	649	289	36	65
Min	57	44	174	43
Max	7,090	1,007	1,159	1,024
Mean	622	349	443	431
Median	**487**	**325**	**355**	**377**
StDev	554	148	236	215

Table 5-13. Total dissolved solids Measurements in the Central Gulf Coast (milligrams per liter).

Model Aquifer	Chicot	Evangeline	Burkeville	Jasper
Num	315	265	23	66
Min	82	174	459	368
Max	3,590	3,357	1,174	2,327
Mean	628	901	834	1,059
Median	**498**	**827**	**853**	**931**
StDev	444	419	227	462

Table 5-14. **Total dissolved solids Measurements in the Southern Gulf Coast (milligrams per liter).**

Model Aquifer	Chicot	Evangeline	Burkeville	Jasper
Num	199	85	7	2
Min	584	395	794	1,174
Max	9,072	9,321	2,534	2,616
Mean	1,984	2,257	1,443	1,895
Median	**1,603**	**1,807**	**1,333**	**1,895**
StDev	1,297	1,510	597	--

Table 5-15. **Total dissolved solids Measurements in the Yegua-Jackson Aquifers (milligrams per liter).**

Model Aquifer	Catahoula	Shallow Yegua-Jackson	Upper Jackson	Lower Jackson	Upper Yegua	Lower Yegua
Num	86	52	33	12	28	18
Min	83	45	155	414	384	377
Max	10,200	5,772	5,592	2,568	7,849	11,710
Mean	1,120	1,134	864	1,270	1,106	1,930
Median	**612**	**650**	**590**	**1,288**	**715**	**630**
StDev	1,740	1,110	1,011	708	1,455	2,762

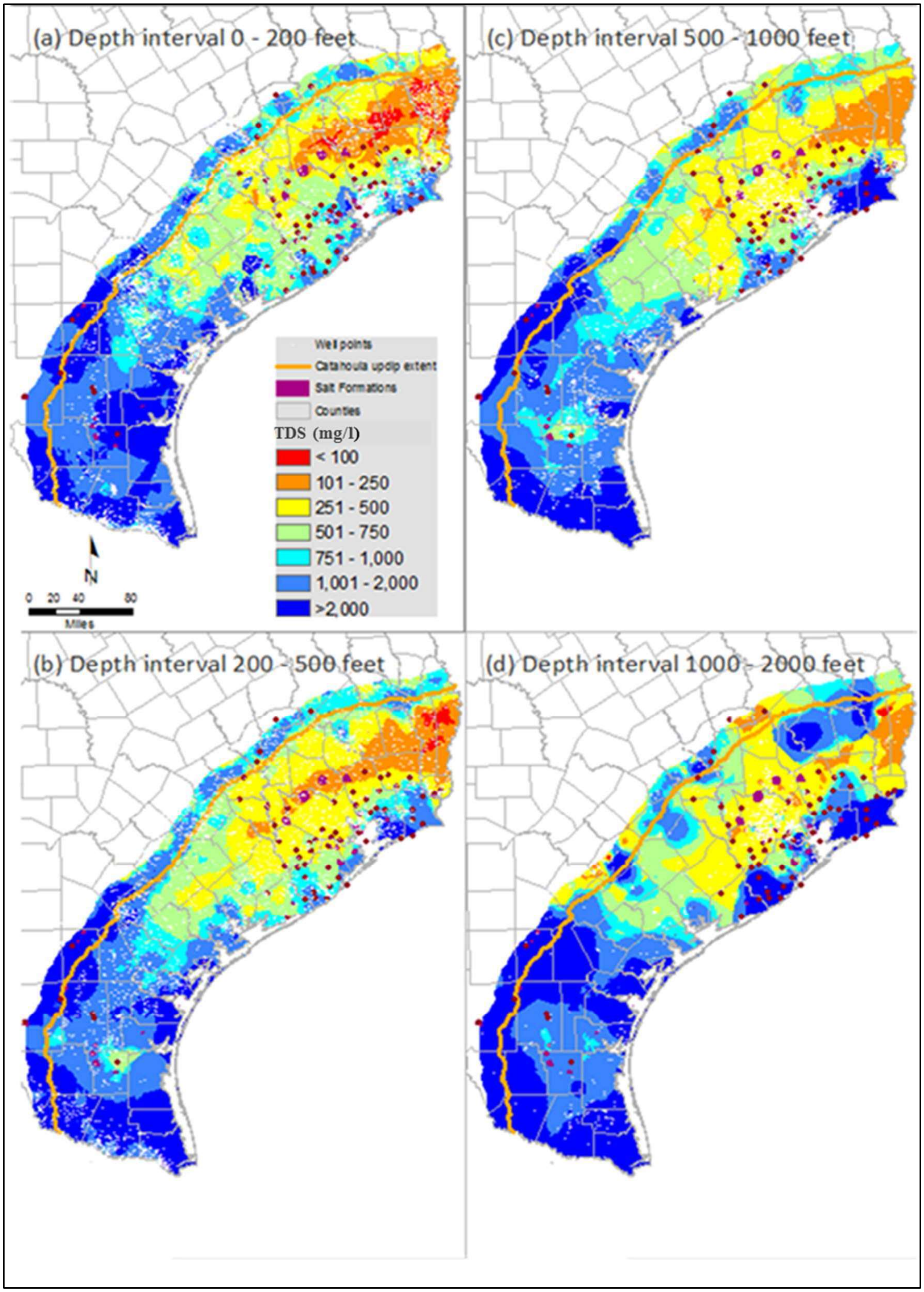
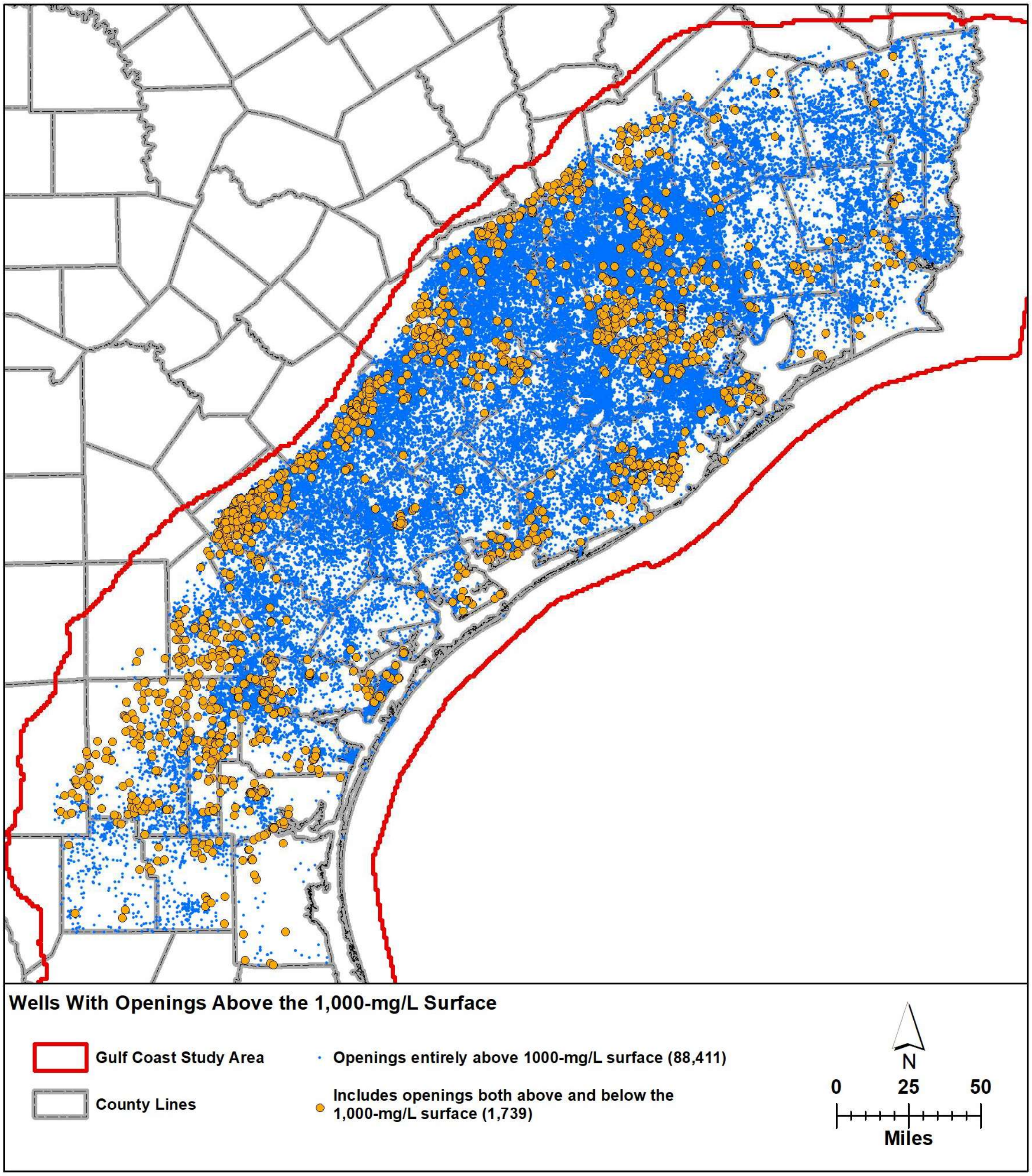
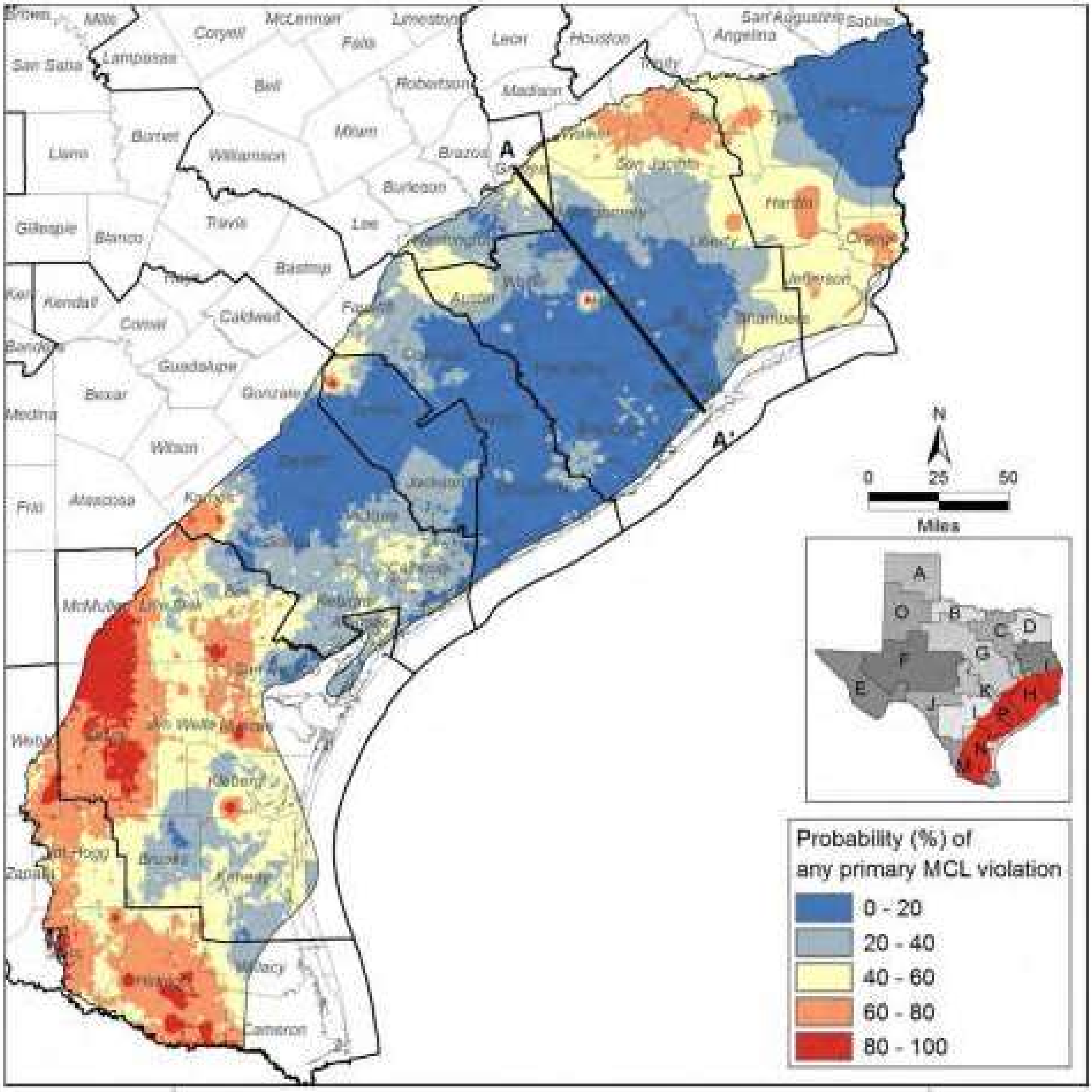


Figure 5-27. **Total Dissolved Solids concentrations as a function of depth estimated by kriging point measurements from the Texas Water Development Board groundwater database (from Young and others, 2014).**



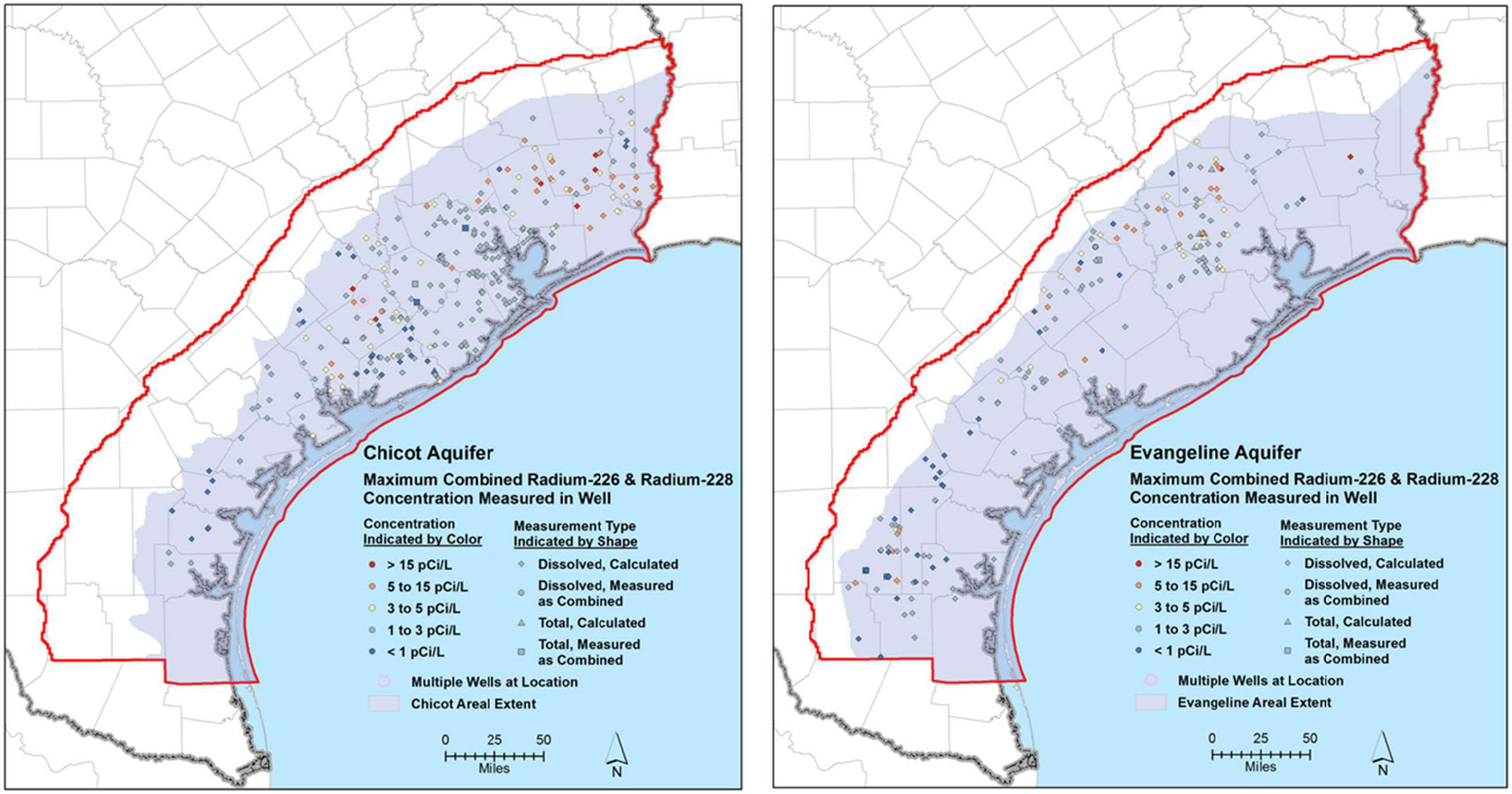
Note: mg/L = milligrams per liter

Figure 5-28. **Gulf Coast Aquifer wells that are completed across the 1,000 milligrams per liter surface as reported in Young and others (2016a).**



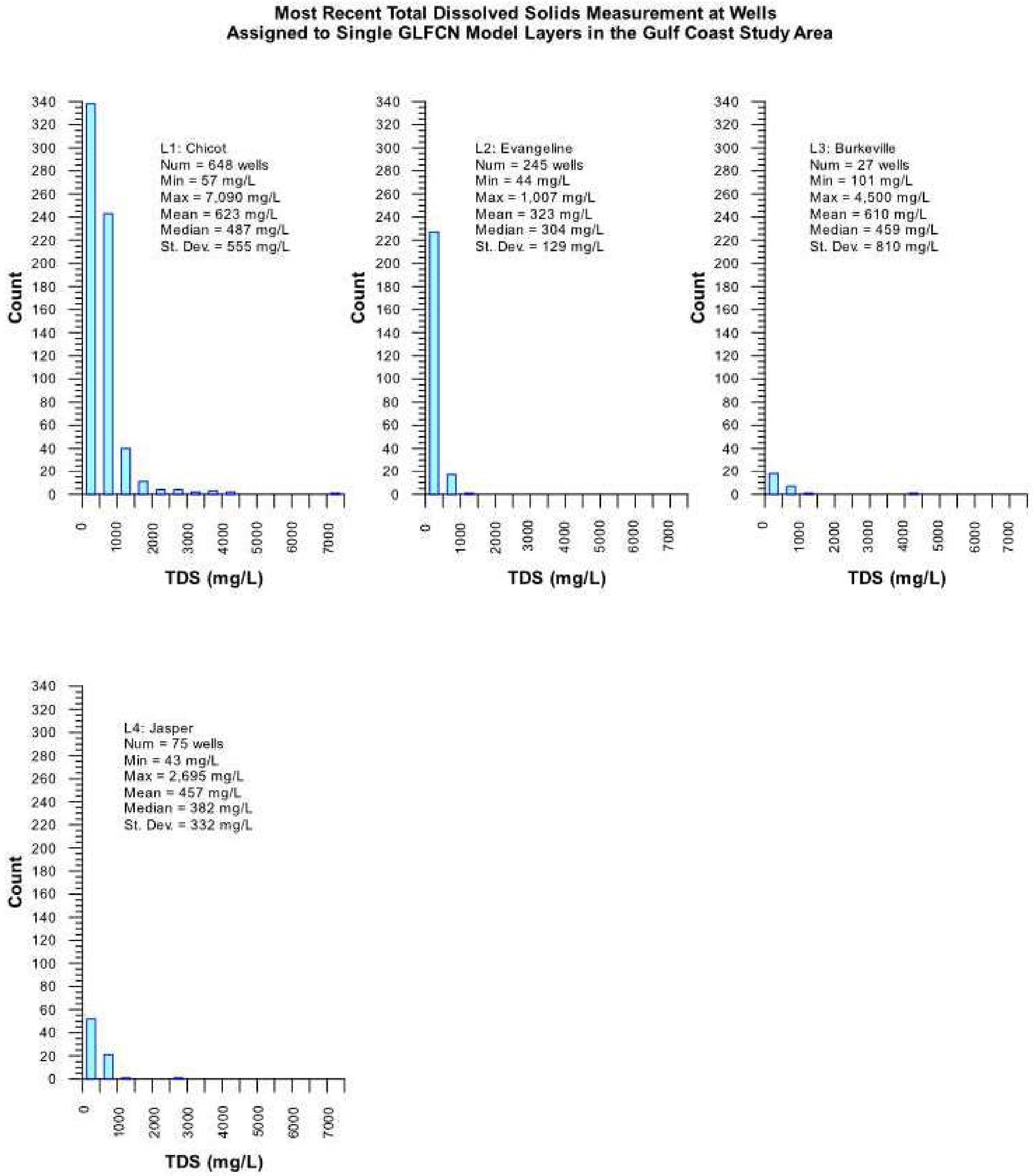
Note: % = percent, MCL = maximum contaminant level

Figure 5-29. **Probability of violation of any primary maximum contaminant level (maximum contaminant level) in the Gulf Coast Aquifer (from Reedy and others, 2010).**



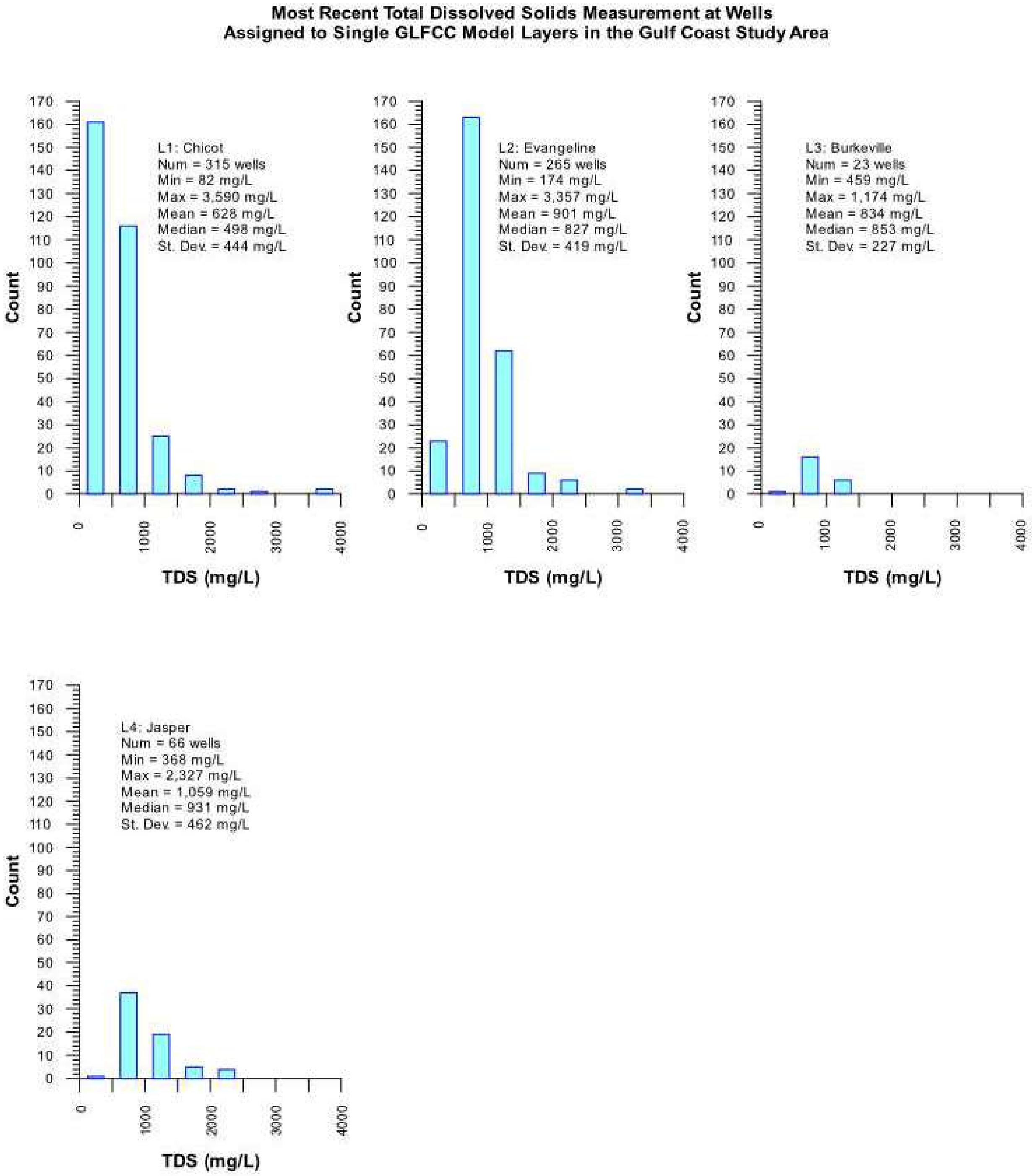
Note: pCi/L = picocuries per liter

Figure 5-30. **Maximum Combined Radium-226 and Radium -228 concentration in the Chicot Aquifer and Evangeline Aquifer (from Young and others, 2016).**



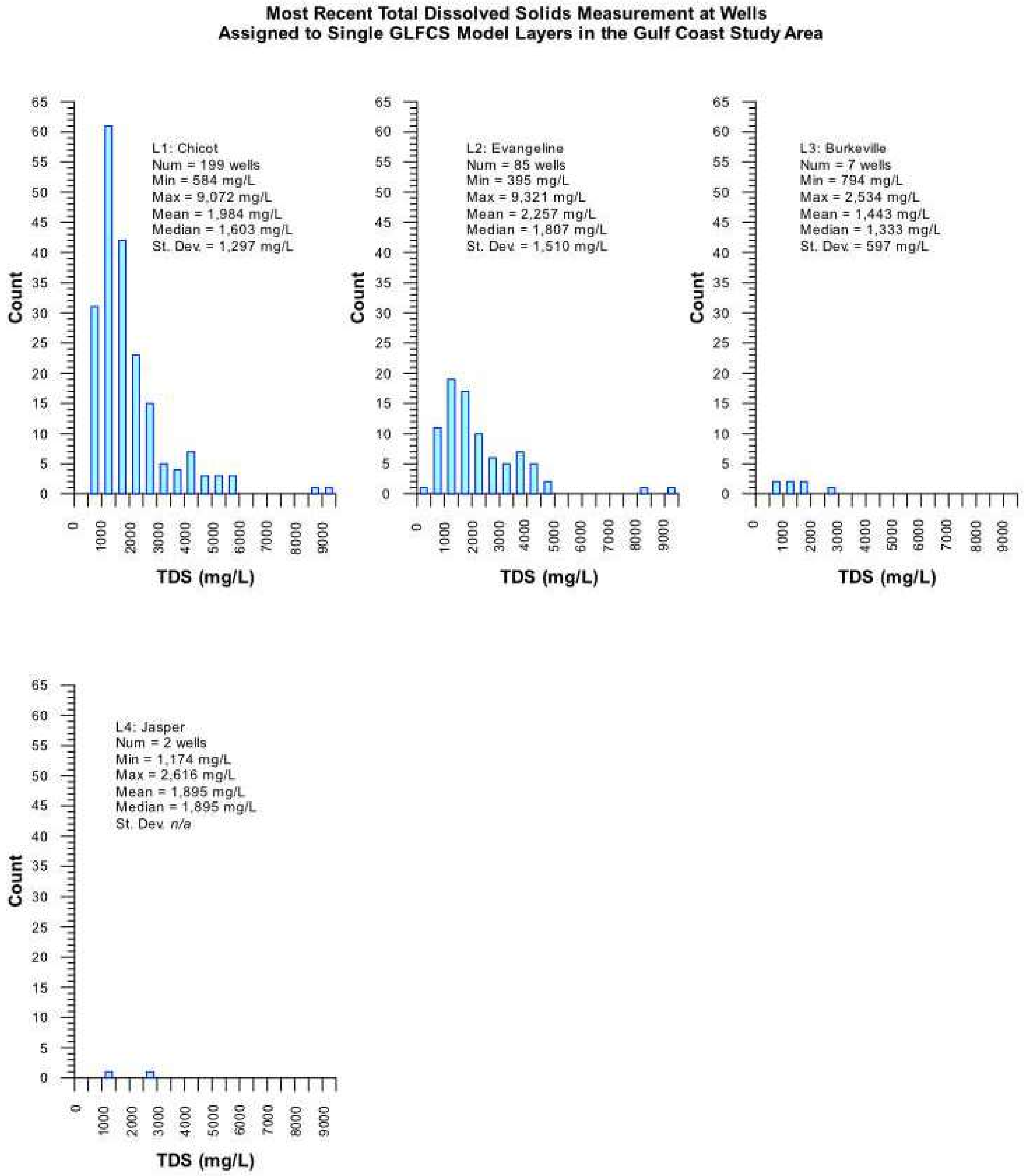
Note: GLFCN = Northern Gulf Coast Aquifer Groundwater Availability Model, mg/L = milligrams per liter, TDS = total dissolved solids

Figure 5-31. **Total dissolved solids (milligrams per liter) measurements from Texas Water Development Board (2020a) for wells completed in the Northern Gulf Coast Aquifer.**


Most Recent Total Dissolved Solids Measurement at Wells Assigned to Single GLFCC Model Layers in the Gulf Coast Study Area

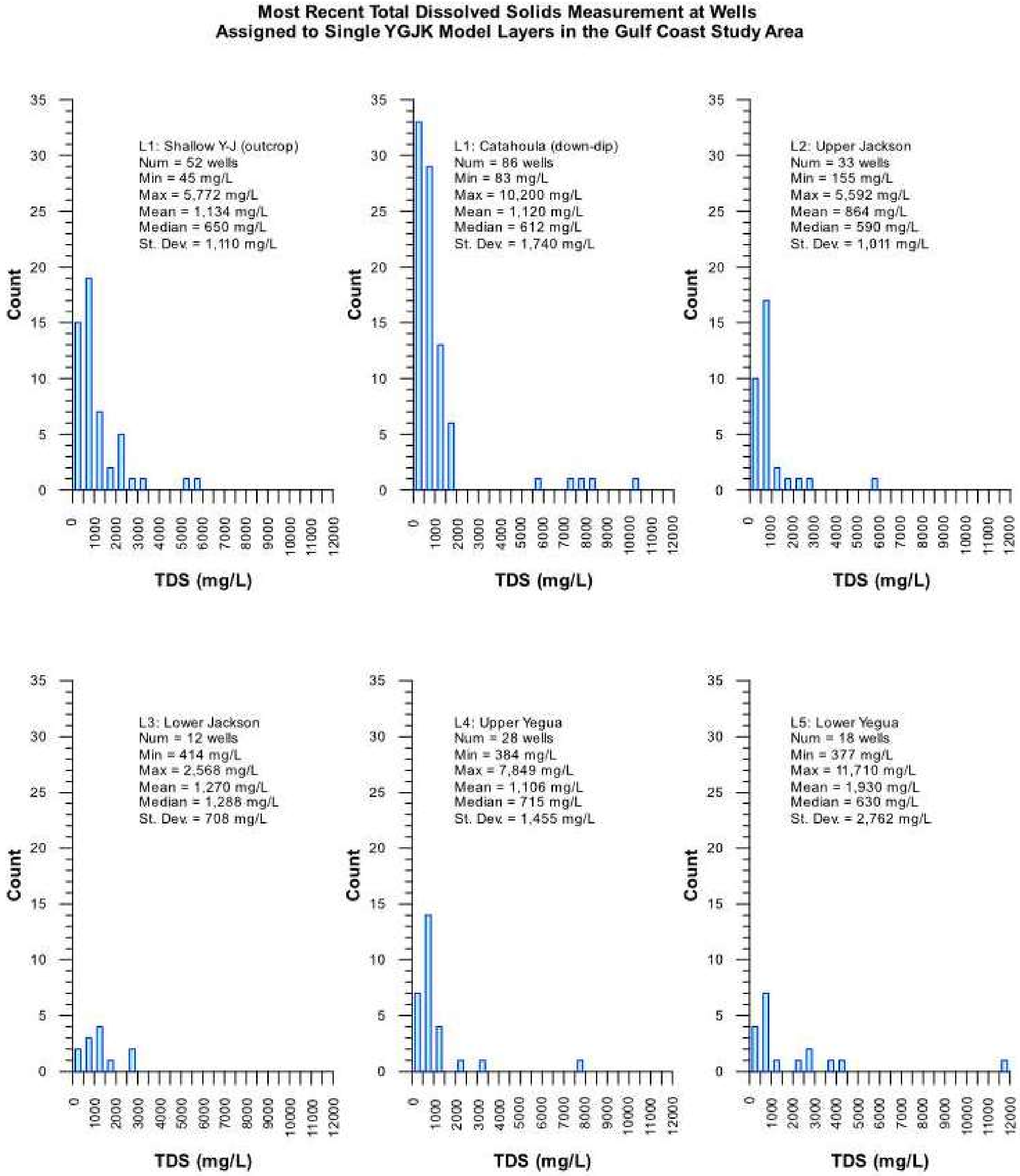
Note: GLFCC = Central Gulf Coast Aquifer Groundwater Availability Model, mg/L = milligrams per liter, TDS = total dissolved solids

Figure 5-32. Total dissolved solids (milligrams per liter) measurements from Texas Water Development Board (2020a) for wells completed in the Central Gulf Coast Aquifer.



Note: GLFCS = Southern Gulf Coast Aquifer Groundwater Availability Model, mg/L = milligrams per liter, TDS = total dissolved solids

Figure 5-33. **Total dissolved solids (milligrams per liter) measurements from Texas Water Development Board (2020a) for wells completed in the Southern Gulf Coast Aquifer.**



Note: YGJK = Yegua-Jackson Groundwater Availability Model, mg/L = milligrams per liter, TDS = total dissolved solids

Figure 5-34. **Total dissolved solids (milligrams per liter) measurements from Texas Water Development Board (2020a) for wells completed in the Yegua-Jackson Aquifer.**

5.2.3 Case Study(s)

In this section, we will take a more granular approach and look at specific wells and direct and indirect evidence of possible comingling. These case studies present field data that demonstrate the necessary hydrogeological conditions exist to facilitate groundwater mixing between zones of different water quality that are hydraulically connected through unpumped well screen in the Gulf Coast Aquifer. The field data have been organized into three discussion areas: measured vertical hydraulic gradients, measured vertical flow in an unpumped well, and measured zonal flow rates and zonal water quality in a well.

Figure 5-35 shows the location of wells associated with the case studies. At six of the well locations, there are nested piezometers that have been used to measure vertical hydraulic gradients. At the location of the flowmeter test, a spinner log was used to measure the direction and rate of vertical flow in a unpumped well. At the locations of the four dynamic profiles, depth-specific tracer tests and water sampling were performed to measure the differences in the flow rates and water quality among the different vertical zones along the well screen in a pumped well.

Measured Vertical Hydraulic Gradients

In the late 1970s, the United States Geological Survey performed extensive hydrogeological studies of land subsidence in the Houston area. These studies included the installation of nested piezometers. Figure 5-35 shows the location of six of the piezometer nests. Each piezometer nest includes between five and nine piezometers. A schematic of the eight piezometers that comprise the piezometer nest at Site NP-5 is shown in Figure 5-5. Four key features of each piezometer nest are that the piezometers are located close to each other, each piezometer is screened over a relatively small vertical length, each piezometer is screened at different depths, and no pumping occurs from any of the piezometers.

Figure 5-36 shows the measured hydraulic heads in 1978 at the six piezometer nests. All six piezometer nests have locations where the hydraulic heads differ more than 50 feet over vertical interval of a few hundred feet or less. As discussed in Section 4, only a difference of a few tenths of a foot in the hydraulic head at the top and bottom of the well screen is needed to cause sufficient vertical flow to cause comingling in a borehole or well.

The data from each piezometer nest shows that large differences in hydraulic head occur both between the Chicot and Evangeline aquifers and within an individual aquifer. In their analysis of the data in Figure 5-36 and other similar hydraulic head data, Young and Kelley (2006) conclude that pumping is the primary reason for the large difference in hydraulic heads and that layers of clayey deposits act to vertically limit the low hydraulic heads to the zone of pumping. With respect to conceptualizing of the groundwater flow system, the field data in Figure 5-36 confirms that the significant differences in simulated hydraulic heads between aquifers that are generated by the Houston Area Groundwater Model (Kasmarek, 2012) in the Houston area are reasonable.

Measured Vertical Flows in Unpumped Wells

Results from two studies are presented to demonstrate that vertical flow can occur in unpumped wells in the Gulf Coast Aquifer. One study is from a study performed as part of the Lower

Colorado River Authority-San Antonio Water System Water Project (Young and others, 2006a,b). The other study is from a project characterizing the zonal contribution of groundwater flow and water quality into a municipal well (BESST, 2012a)

Lower Colorado River Authority-San Antonio Water System Water Project Study

Young and others (2006a) measured the vertical flow in Lakeside Irrigation District Well #8 under both non-pumping and pumping conditions in March 2005 prior to the start of the first flooding of the rice fields. The well is located on the northside of Wharton County is numbered as FT-1 in Figure 5-35. The well was installed in 1973.

Analysis of the aquifer pumping test data indicates that positive skin effects existed at the well, the aquifer had a transmissivity of 6,700 square feet per day, and that the most permeable deposits exist above a depth of 300 feet below ground surface. The analysis of measured water and simulated water levels from a groundwater flow model indicated that during the field testing the hydraulic head at Well #8 was about 50 feet greater at the top of the well screen than at the bottom of the well screen. The Well #8 well screen exists from a depth of 240 to 700 feet below ground surface. The well screen diameter is 20 inches above 400 feet depth and 12 inches at 400 feet depth and below.

An impeller meter was used to measure vertical flow rates in Well 8 well screen under non-pumping conditions. No vertical flow was accurately measured above 400 feet depth because the flow velocity was below the flowmeter’s measurement threshold. At a depth of 400 feet, the ambient vertical groundwater flow was downward at a rate of 50 gallons per minute.

Figure 5-37 shows the downward flow rate in the well and where water is entering or leaving the well screen. The flow rates in Figure 5-37 show that the groundwater that entered the well above a depth of 400 feet and primarily exited between the depths of 500 feet and 675 feet below ground surface. This is demonstrated by the distinct but small decrease in vertical flow that occurred from 450 to 500 feet depths (48.4 to 43.4 gallons per minute, respectively), followed by larger incremental decreases in vertical flow velocity from 500 to 675 feet depths (Figure 5-37).

The motivation for measuring the ambient flow rate at Well #8 was to validate predictions of the rate of ambient vertical flow in the irrigation wells in Colorado, Wharton, and Matagorda counties during periods of non-pumping predicted by numerical groundwater modeling. The ambient rates were simulated using an advanced wellbore sub-model package called FLW5, which is a part of the MODFLOW-SURFACT (HGL, 2012) groundwater modeling code. The groundwater model simulations that used FLW5 package predicted an average ambient flow rate of 100 gallons per minute in the irrigation wells during the winter when the wells are not pumping (Young and others, 2006b). Field testing validated this borehole flow process.

Dynamic Profiling of a Municipal Well

In 2012, BESST Inc was hired by a Harris County Municipal Utility District to provide comprehensive qualitative flow and chemistry data for Well #1 and Well #3 (BESST, 2012a). As part of their field investigation at Well #1, which is identified as Site DP-2 in Figure 5-34, BESST measured vertical flow under non-pumping conditions.

Well #1 includes eight screened intervals that are located between 920 feet and 1,280 feet below ground surface. The vertical flow rate in the well is measured by performing a series of tracer tests that have a significantly lower velocity measurement threshold compared to the impeller meter used at the Lower Colorado River Authority wells discussed above. As a result, much lower flow rates can be measured. Figure 5-38 shows measured ambient flow rates along the well screen. The figure shows that groundwater enters Well #1 at the bottom of the screen near depth 1,230 feet (8.59 gallons per minute) and moves upward (zero flow at a depth of 1,270 feet). At a depth of 1,150 feet, the ambient flow achieves its largest flow rate of 22.6 gallons per minute. Between a depth of 1150 feet and 910 feet below ground surface, the 22.6 gallons per minute leaves the well and enters the aquifer. As will be shown later in the report, the vertical flow in Well #1 serves as a mechanism for mixing of differing water quality within the borehole from different zones in the aquifer.

Measured Zonal Flow Rates and Zonal Water Quality in a Well

Results from three field investigations are presented to demonstrate that significant differences in water quality can occur across the vertical zones intersected by wells in the Gulf Coast Aquifer. BESST collected data for all three investigations by a process called dynamic profiling.

Dynamic profiling consists of performing tracer tests and groundwater sampling at specific depths within and above the well screen and from that data calculating flow rates and concentration values for vertical intervals in a well. Figure 5-39 provides a schematic to help illustrate the data collecting and analyses associated with a typical dynamic profiling test. A typical dynamic profiling consists of the following four steps.

Step 1 - Prior to testing a well, establish a steady flow rate in the well by pumping it at a constant rate.

Step 2 - As the well is pumping, use miniaturized equipment to perform tracer tests and depth-dependent groundwater sampling at the same depth locations (Figure 5-39a).

The tracer tests consist of injecting dye at different depths in the well, measuring the time required to the dye to exit the well, and then calculating the average flow rate of the pumped water.

Step 3- Compile the results from tracer tests and sampling events at different depths to construct a vertical profile of total flow and average concentration (Figure 5-39b).

Step 4 - Calculate a vertical flow profile by using the measured flow amount and average concentration of groundwater entering the well through specific aquifer zones, as determined by multiple measurement intervals (Figure 5-39c).

All three of the field investigations were performed at municipal wells that had poor water quality motivating the well and aquifer characterization. The dynamic profile tests were conducted to identify the vertical zones where incoming groundwater had chemical concentrations exceeding maximum contaminant levels or secondary maximum contaminant levels for drinking water. The zonal flow combined with concentration data would then be used to determine if the well screen could be modified to reduce or eliminate the water quality problem by blocking poor quality groundwater from entering the well by using either an installing a packer or well screen patch.

The technology is a proven technology having been employed by BESST for over 800 dynamic profile tests to help address water quality problems in California alone. In Texas, as in California, the main water quality constituents of concern for a dynamic profile tests are iron, manganese, radioactive constituents, and arsenic that can accumulate in specific types of sedimentary deposits (especially in sands with higher clay content). As a result of preferential deposition, the variability in the concentration compounds such as iron or manganese along a well screen can be much greater than the variability in total dissolved solids concentrations.

Wells #1 and #3 in a Brazoria County Municipal Utility District

Figure 5-40 shows the results from geophysical logs and dynamic profiles at a Municipal Utility District Wells #1 and #3 (BESST, 2012a). Figure 5-35 shows the location of the two wells (Site DP-1 & DP-2), which are approximately 1 mile apart. In Figure 5-40, the geophysical log data present the tracks for spontaneous potential and resistivity. These data were used to develop a lithology profile that was compared to the lithology provided in the driller's report.

The results of the dynamic profiles provide zonal values for flow rates and total dissolved solids concentrations correspond to the well screen intervals. The well screens at Well #1 span a vertical interval of about 300 feet. The well screens at Well #3 span about 200 feet. At Well #1, the total dissolved solids concentration at the pump discharge is 840 milligrams per liter and the zonal concentrations range is from 419 to 1,393 milligrams per liter. At Well #3, the total dissolved solids concentration at the pump discharge are 810 milligrams per liter and the zonal concentrations range from 513 to 1,204 milligrams per liter. The vertical distribution of the total dissolved solids concentrations does not show any discernable trends or pattern in total dissolved solids values and there are not readily discernable correlations between information in the geophysical logs or the lithology logs with the zonal total dissolved solids concentrations. What is evident, however, is that the groundwater that is pumped is comprised of a wide range of total dissolved solids concentrations across the well screen interface.

Figure 5-41 shows zonal values for flow rates and total dissolved solids concentrations for non-pumping conditions. The zonal flow profiles indicate that, when the well is not pumped, groundwater enters the well between the depths of 1,175 and 1,250 feet below ground surface and flows upward and outward from the well into the aquifer above a depth of 1,150 feet below ground surface. If no other groundwater entered the well above a depth of 1,175 feet below ground surface, the total dissolved solids concentration values should remain the same. However, the total dissolved solids concentrations above a depth of 1,175 feet below ground surface varies between 868 and 1,004 milligrams per liter.

There are two explanations that could explain the variable total dissolved solids concentrations in the well above a depth of 1,175 feet below ground surface. One is that small amounts of groundwater entered the well above a depth of 1,175 feet below ground surface. The deflections in both the vertical profile of the temperature and pressure head under non-pumping conditions indicate that there are two locations where groundwater entered the well above a depth of 1,175 feet. The other explanation could be that because of the low flow velocities, the groundwater is not fully mixed inside the well and sampling equipment did not obtain a representative groundwater sample.

Regardless of the variability in the total dissolved solids concentrations in Figure 5-41, the available information indicates that groundwater with a total dissolved solids concentration of about 900 milligrams per liter is exiting the well across a 30-foot zone at depth of about 1,000 feet below ground surface and entering the aquifer where the total dissolved solids concentration is about 419 milligrams per liter (see Figure 5-40) based upon sampling during pumping conditions. The data in Figure 5-40 and Figure 5-41 illustrate that sufficient vertical flow occurs in the unpumped well to increase the total dissolved solids concentration of groundwater adjacent to the well.

Well #1 in a Harris County Municipal Utility District 1

BESST (2012b) performed a dynamic profile test at Well #1 in a Harris County Municipal Utility District. The well is screened consists of two major intervals. One interval spans a depth from 715 to 729 feet below ground surface and the other interval spans a depth from 740 to 848 below ground surface. The reason for the 11-foot blank section is to block pumping from deposits with high clay content.

The test was performed while the well was pumping a constant rate of 1,247 gallons per minute with an average total dissolved solids concentration of 290 milligrams per liter. Figure 5-42 and Figure 5-43 show the zonal flow rates and zonal concentrations measured during the dynamic profile. The only zone with iron and manganese concentrations about their secondary maximum contaminant levels is from a depth of 715 to 729 feet below ground surface. For this zone, the manganese concentration of 0.142 milligrams per liter is ten times higher than any other zonal manganese concentration. For this zone, the iron concentration is 0.458 milligrams per liter, which is five times higher than any other zonal iron concentration. Besides having the highest iron and manganese, this zone also has the lowest production per foot of thickness than any other zone.

The zone with the highest concentration for uranium and radium-228 concentrations occur from a depth of 740 to 750 feet below ground surface. For this zone, the radium-228 concentration is 18.6 picocuries per liter, which is above its secondary maximum contaminant level of 5 picocuries per liter and is 15 times higher than any other zonal radium-228 concentration. In addition to having the highest radium-228 concentration, this zone also has the highest uranium concentration of 25 micrograms per liter, which is 3.5 times higher than any other zonal uranium concentrations. The zone with the highest radium and uranium concentrations is located in the uppermost 10 feet of a 108-foot screen and below an 11-foot-thick clay-rich deposit that was not screened.

The data from Well #1 illustrates the large differences in zonal concentrations which can occur in Gulf Coast sediments with iron, manganese, uranium, and radium-228. For radium-228, 78 percent of the total mass in the well discharge was produced by only 9 percent (110 gallons per minute) of the total flow rate of 1,247 gallons per minute. For manganese, 50 percent of the total mass total mass in the well discharge was produced by only 3 percent (41 gallons per minute) of the total flow rate.

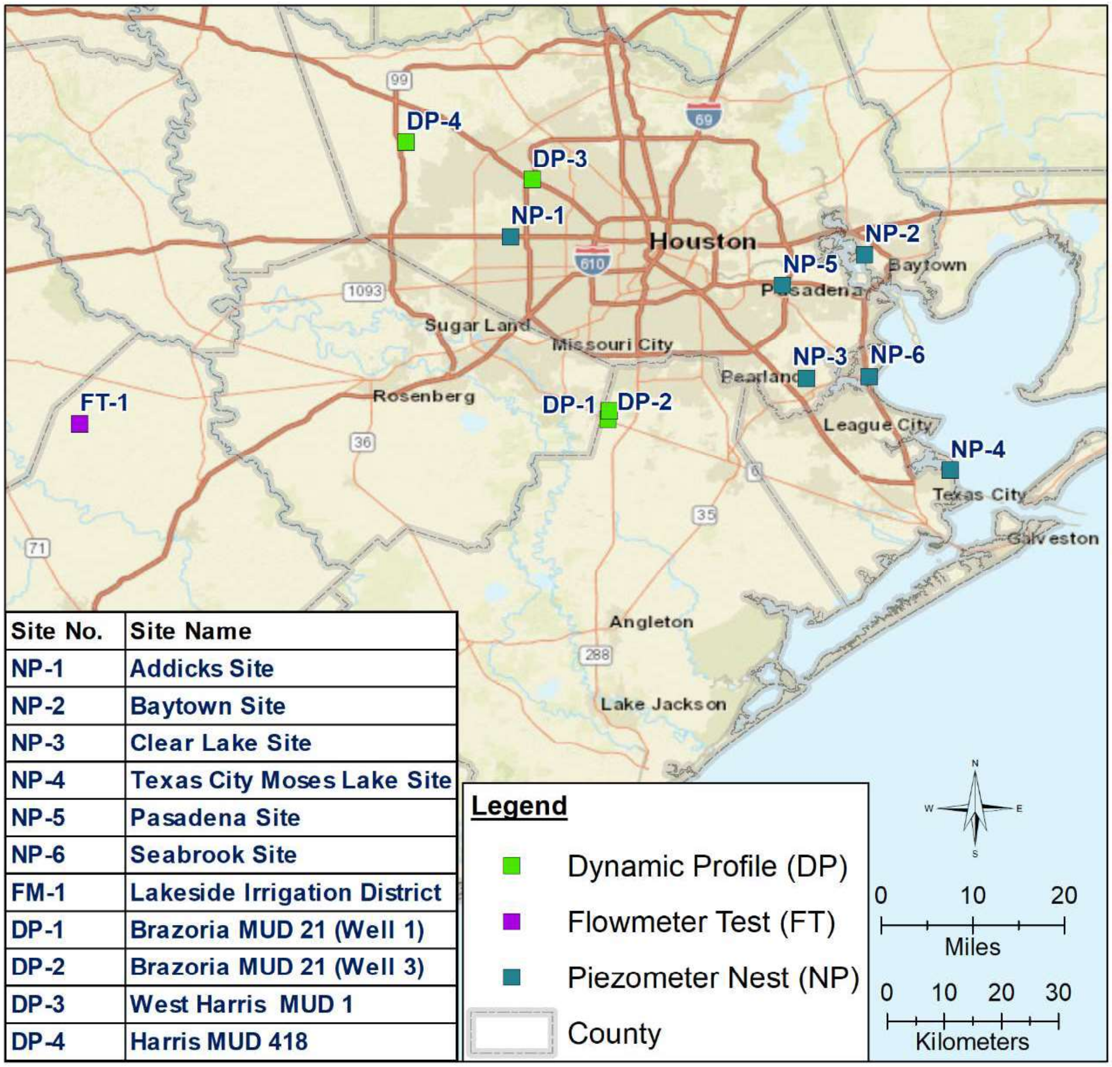
Well #4 in a Harris County Municipal Utility District

BESST (2019) performed a dynamic profile test at Well #4 in a Harris County Municipal Utility District. The well is screened across a 344-foot vertical interval that spans a depth from 810 to 1,154 feet below ground surface. The well screen consists of 10 separate sections of screens with a total length of 192 feet.

The dynamic profile test was performed while the well was pumping a constant rate of 1,336 gallons per minute with an average total dissolved solids concentration of 374 milligrams per liter. Figure 5-44 shows the zonal flow rates and zonal concentrations for arsenic and manganese. Three of the 11 zones have manganese concentrations above the secondary maximum contaminant level of 0.05 milligrams per liter. These three zones have an average manganese concentration of 0.087 milligrams per liter per liter and 25 percent of the total mass of manganese in the pump discharge but only contribute 5 percent (68 gallons per minute) of the total flow. The remaining 8 zones have an average manganese concentration of 0.014 milligrams per liter and contribute 95 percent (1,269 gallons per minute) of the total flow.

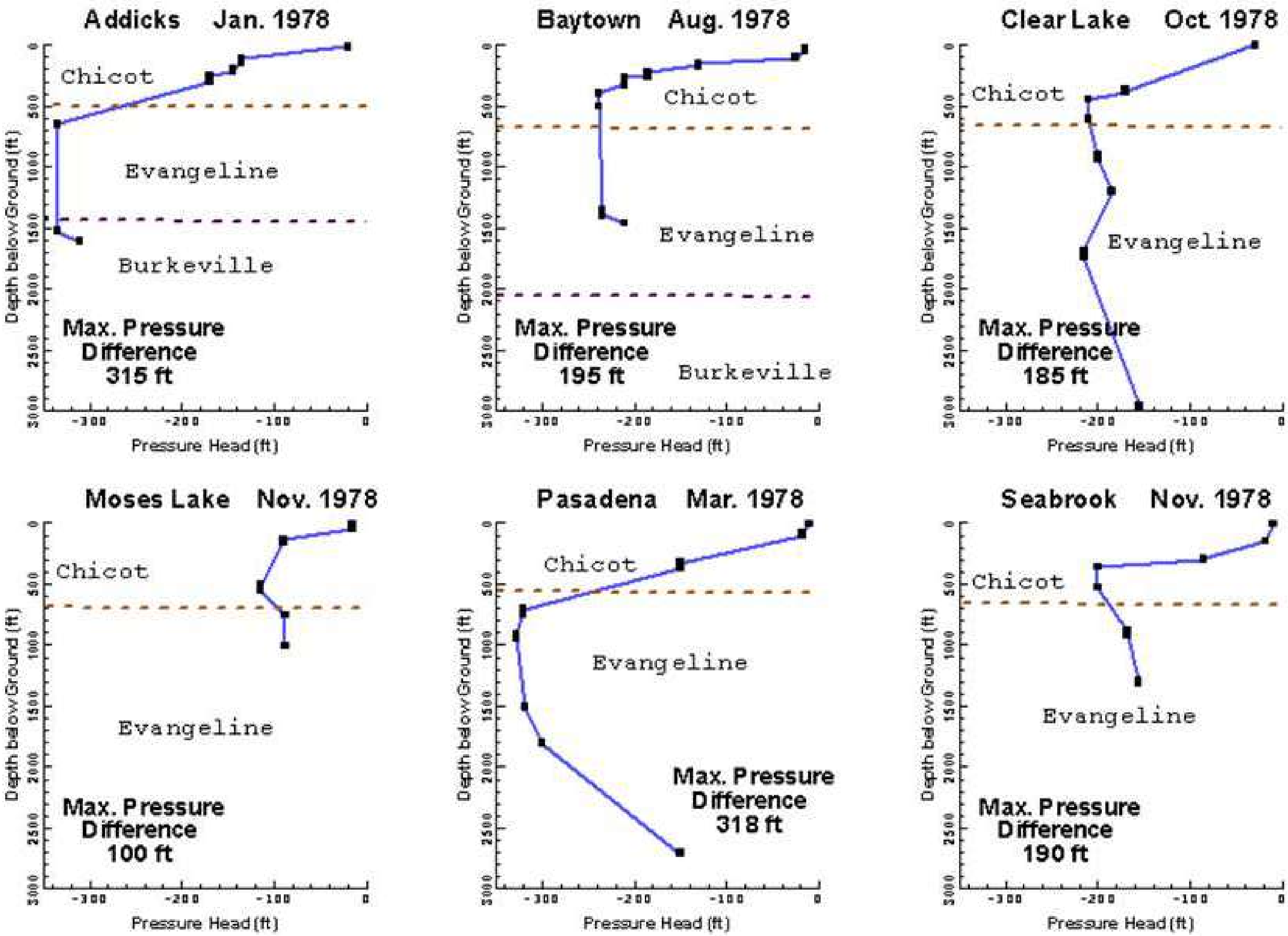
Seven of the 11 zones have arsenic concentrations above the secondary maximum contaminant level of 0.01 milligram per liter. At this well location, the arsenic is well distributed across the deposits that provide most of the production. At the four zones with arsenic concentration below the secondary maximum contaminant level of 0.01 milligram per liter, their total production is 10 percent (134 gallons per minute) of the 1,337 gallons per minute. The 900 to 930 feet depth interval has arsenic concentrations (that are three times greater (0.102 milligram per liter) than any other zonal concentration. Moreover, this 900 to 930 feet depth interval has the lowest amount of production per foot of thickness, which is 0.8 gallon per minute per foot. The average production per foot of screen thickness for the well is 7.0 gallons per minute per foot.

The data from Well #4 illustrates that large differences in zonal concentrations can occur in Gulf Coast sediments with manganese and arsenic. As with the investigation at Municipal Utility District Well #1, there the highest manganese and arsenic concentrations associated with the zones that are among the least productive per foot of screen.



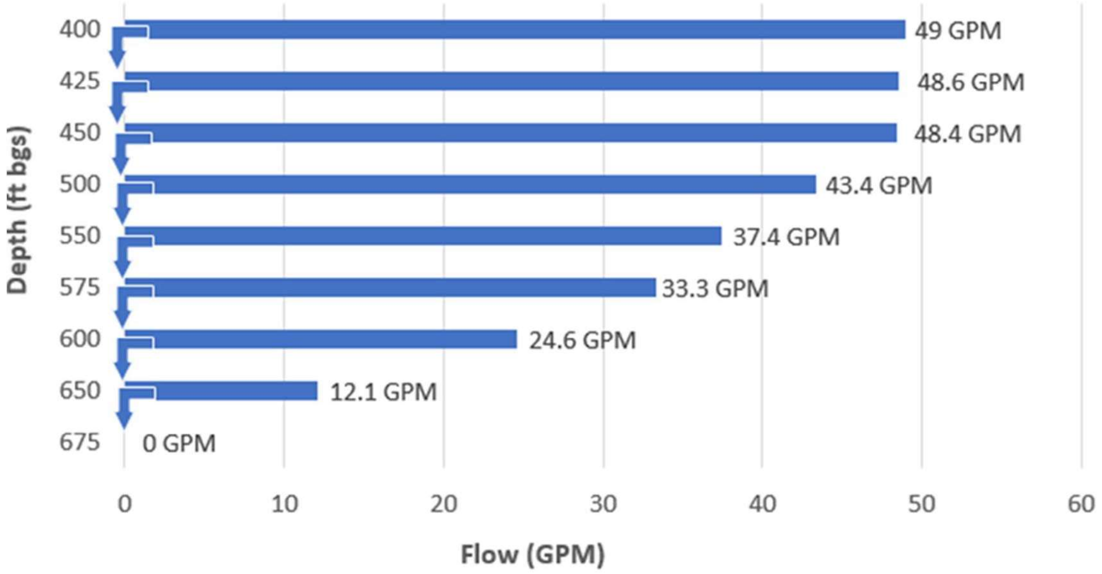
Site No.	Site Name
NP-1	Addicks Site
NP-2	Baytown Site
NP-3	Clear Lake Site
NP-4	Texas City Moses Lake Site
NP-5	Pasadena Site
NP-6	Seabrook Site
FM-1	Lakeside Irrigation District
DP-1	Brazoria MUD 21 (Well 1)
DP-2	Brazoria MUD 21 (Well 3)
DP-3	West Harris MUD 1
DP-4	Harris MUD 418

Figure 5-35. Site Locations for wells associated with the case studies for the Gulf Coast Aquifer.



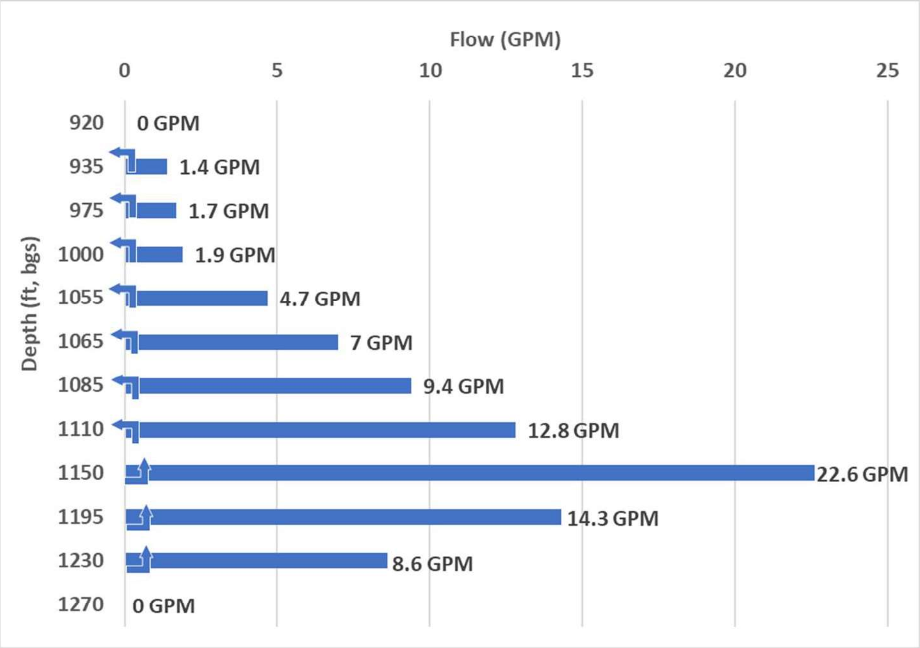
Note: ft = feet

Figure 5-36. **Vertical hydraulic head profiles at six different piezometer nests located in the Houston area in 1978.**



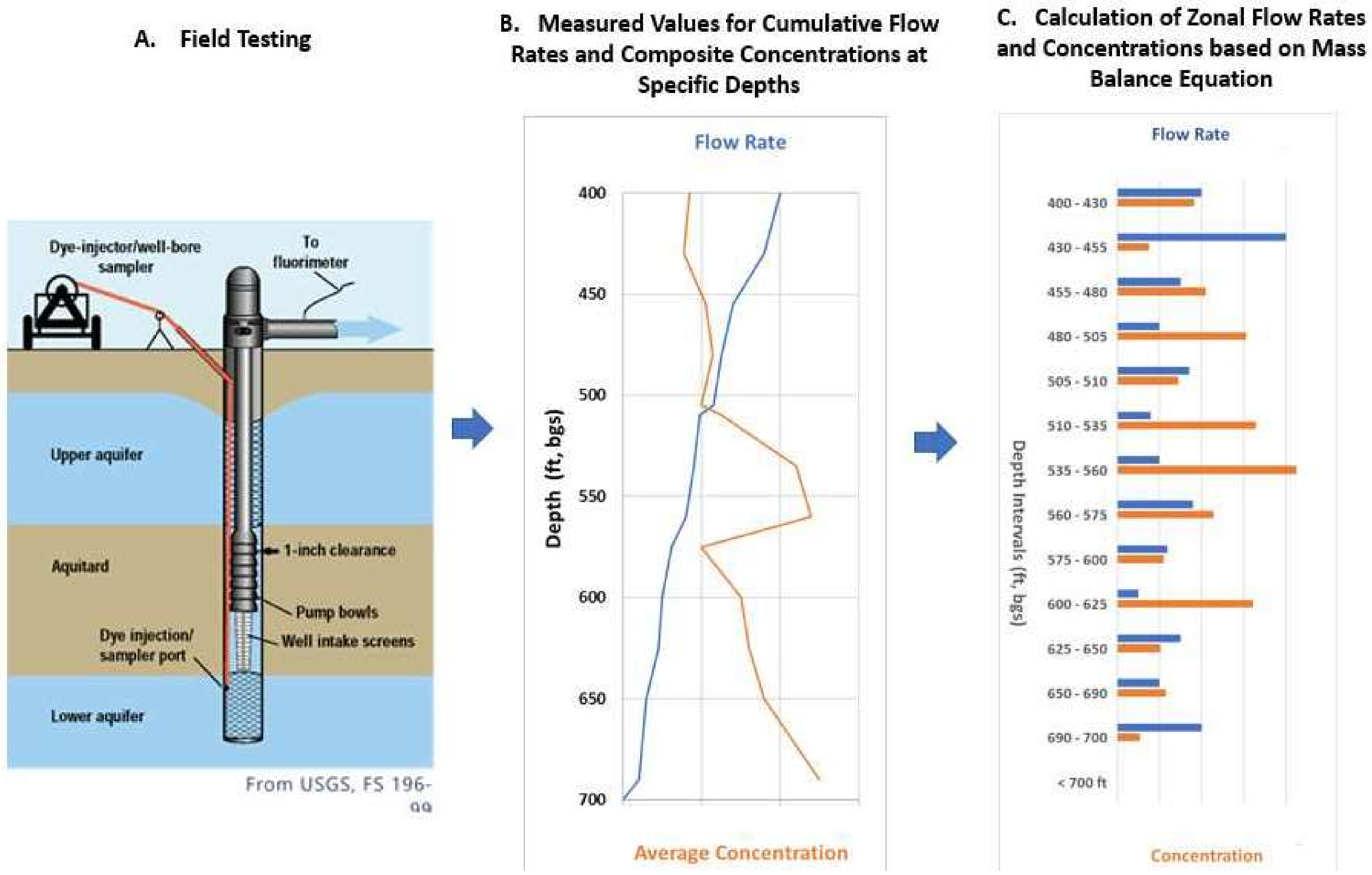
Note: ft bgs = feet below ground surface, GPM = gallons per minute

Figure 5-37. **Downward ambient vertical flow in Lakeside Irrigation District Well #8 .**



Note: ft bgs = feet below ground surface, GPM = gallons per minute

Figure 5-38. **Downward ambient vertical flow in Municipal Utility District Well #1 that results from differences in hydraulic heads along the well screen in the aquifer during non-pumping conditions.**



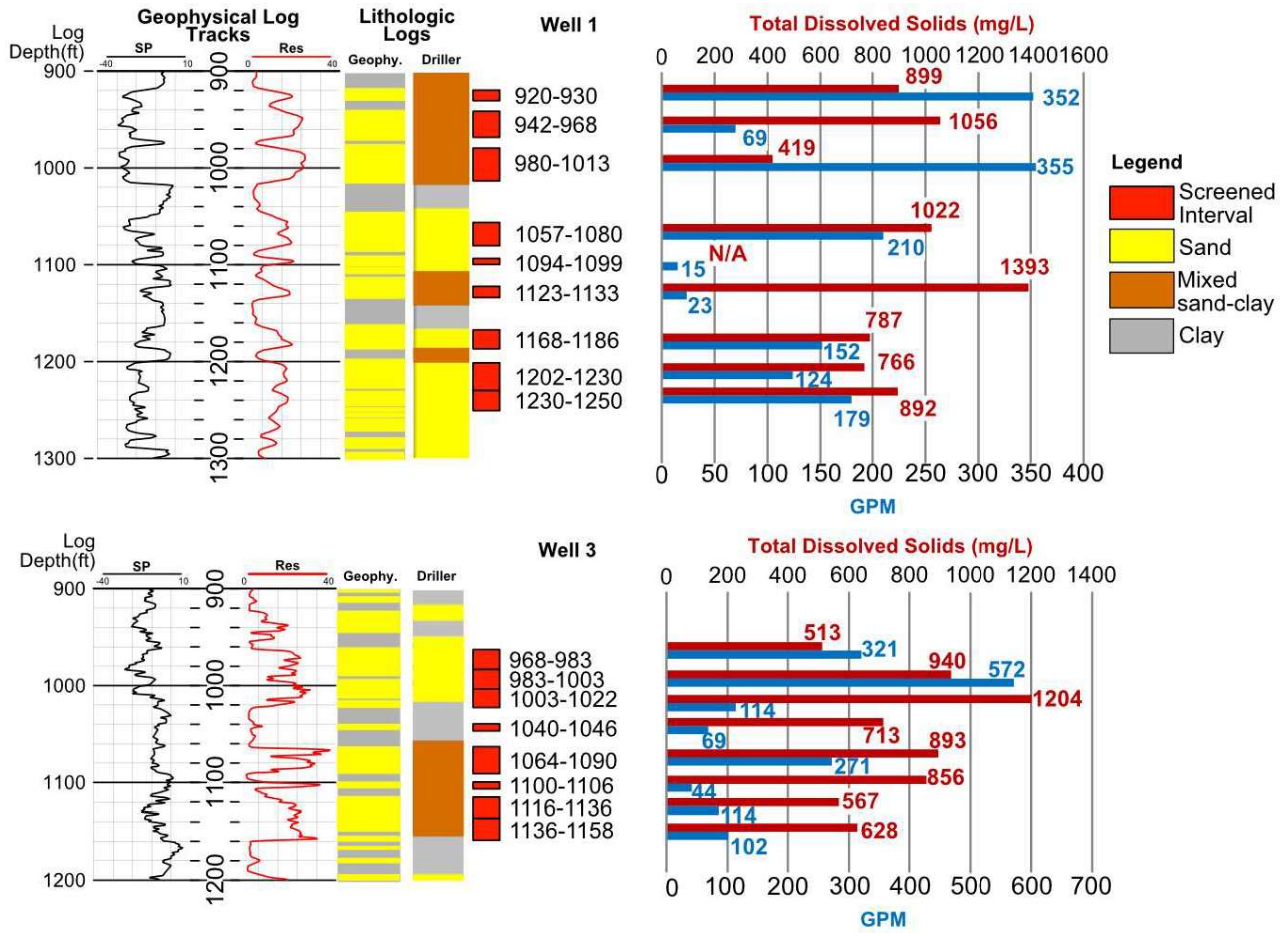
A. Field Testing

B. Measured Values for Cumulative Flow Rates and Composite Concentrations at Specific Depths

C. Calculation of Zonal Flow Rates and Concentrations based on Mass Balance Equation

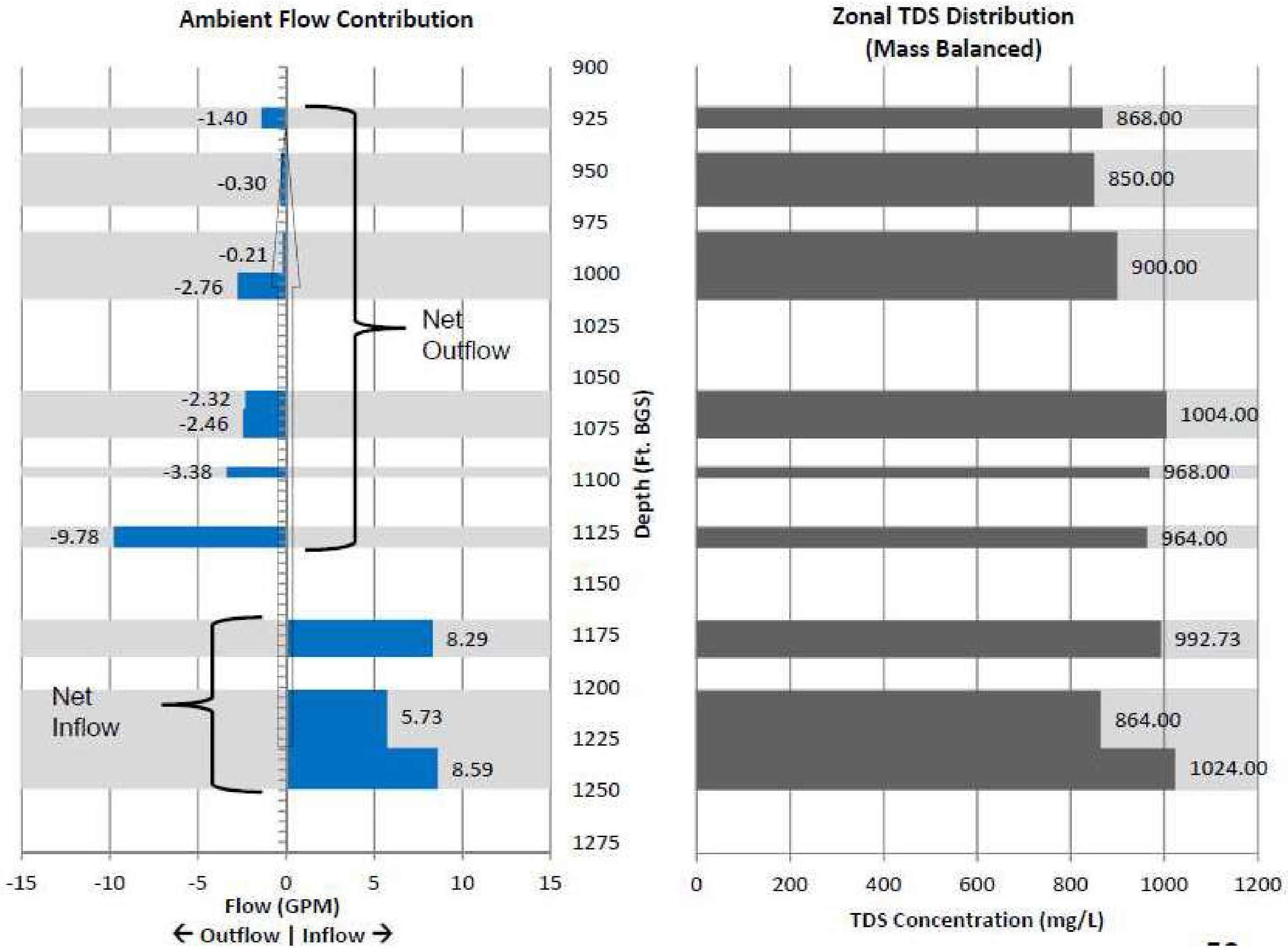
Note: ft bgs = feet below ground surface

Figure 5-39. **Schematic of dynamic well profiling process from tool (a), data collection (b) and interpretation (c).**



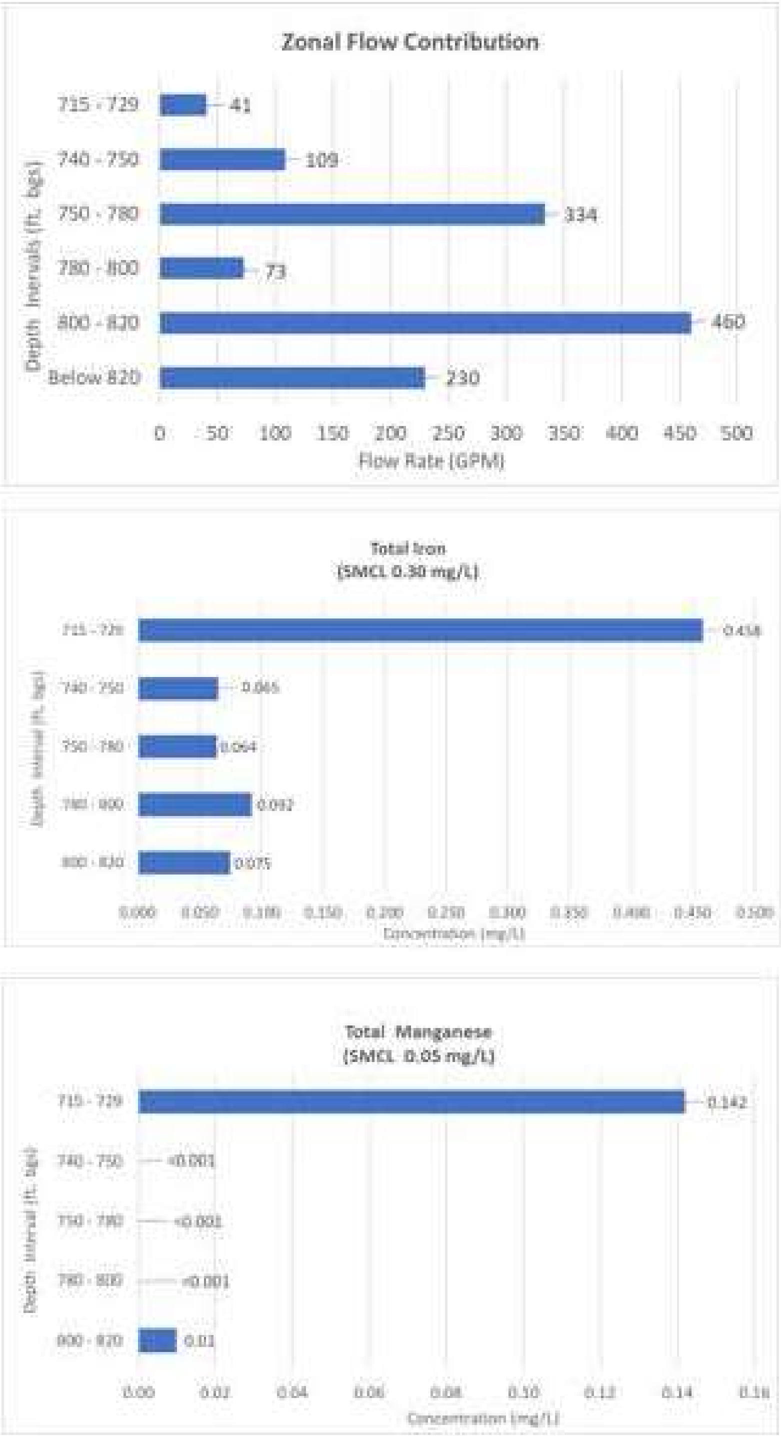
Note: ft = feet, mg/L = milligrams per liter

Figure 5-40. **Results from geophysical logs and dynamic profiles at Wells #1 and #3 at a Municipal Utility District in Brazoria County.**



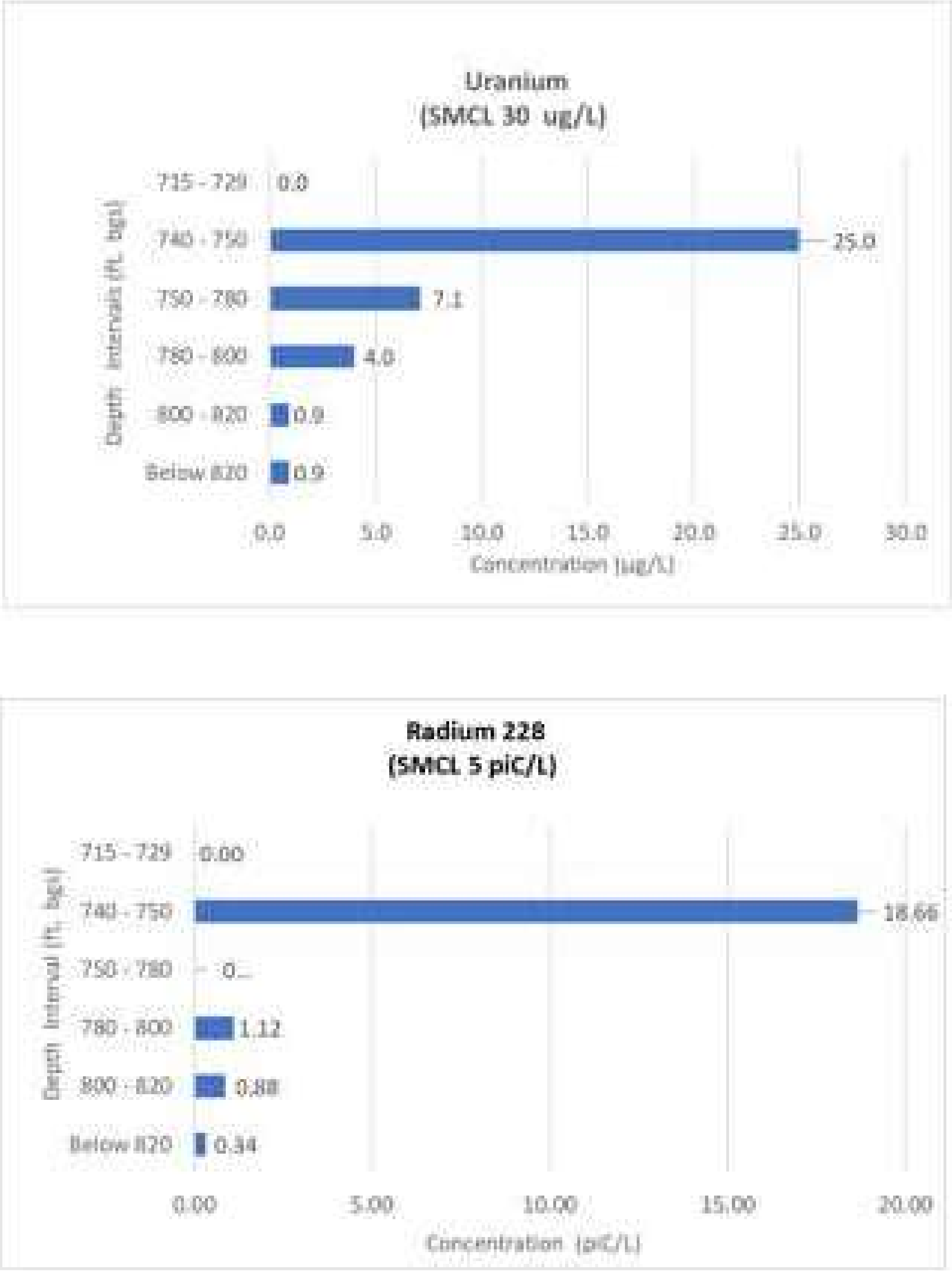
Notes: GPM = gallons per minute, mg/L= milligrams per liter, TDS = total dissolved solids

Figure 5-41. **Downward ambient vertical flow Well #1 that results from differences in hydraulic heads along the well screen in the aquifer during non-pumping conditions. in a Brazoria County Municipal Utility District.**



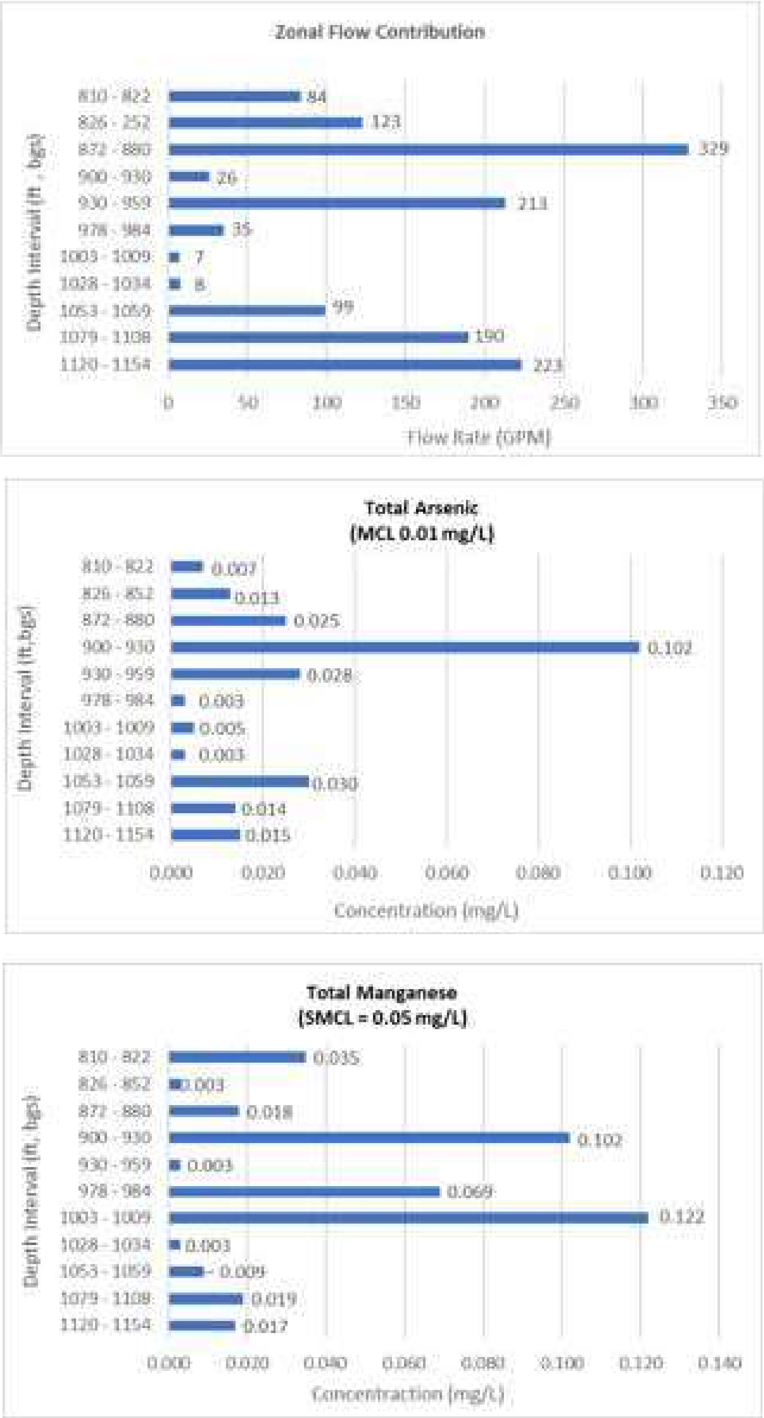
Note: mg/L = milligrams per liter, SMCL = secondary maximum contaminant level

Figure 5-42. **Zonal values for flow rates, iron concentrations, and manganese concentrations determined from dynamic profiling at Well #1 at a Municipal Utility District in Harris County.**



Note: piC/L = picocuries per liter, SMCL = secondary maximum contaminant level

Figure 5-43. **Zonal values for uranium concentrations and Radium-228 concentrations determined from dynamic profiling at Well #1 at a Municipal Utility District in Harris County.**



Note: mg/L = milligrams per liter, MCL = maximum contaminant level, SMCL = secondary maximum contaminant level

Figure 5-44. **Zonal values for flow rates, arsenic concentrations, and manganese concentrations determined from dynamic profiling at Well #1 at a Municipal Utility District in Harris County.**

5.3 Eagle Ford Region

The Eagle Ford Region occurs in a southwest to northeast belt from the Rio Grande in Maverick and Webb counties to Leon, Madison, and Walker counties in Central Texas. This belt generally coincides with the Tertiary aquifers of the Texas Upper Coastal Plain (Figure 5-45). The region is defined by the presence of the Eagle Ford Shale as a hydrocarbon producing formation. While the region is generally considered to extend to the Trinity River in northeast Texas, most oil and gas activity associated with the Eagle Ford Shale play occurs southwest of the Brazos River. As a result, we have set the northern boundary of the Eagle Ford Region to be the Brazos River.

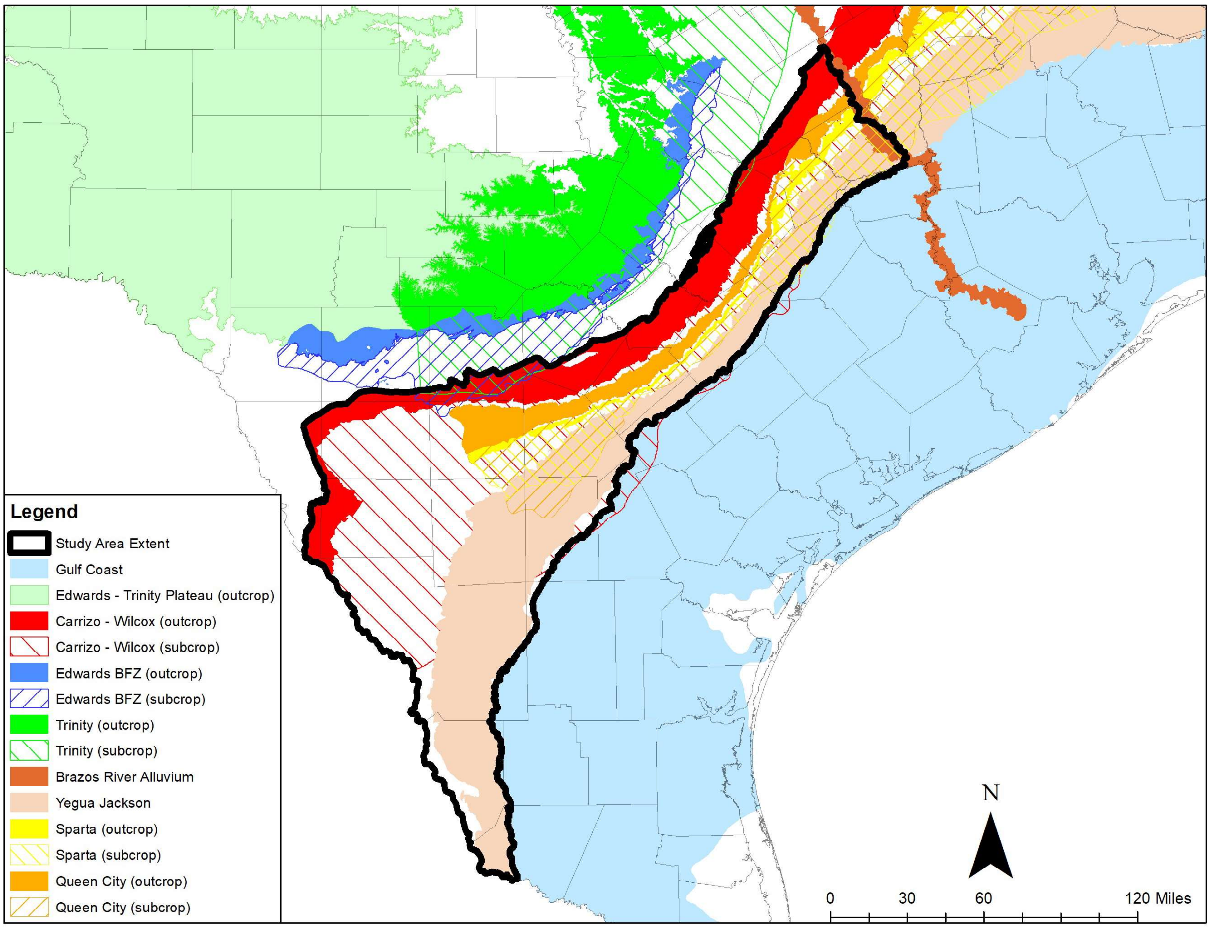


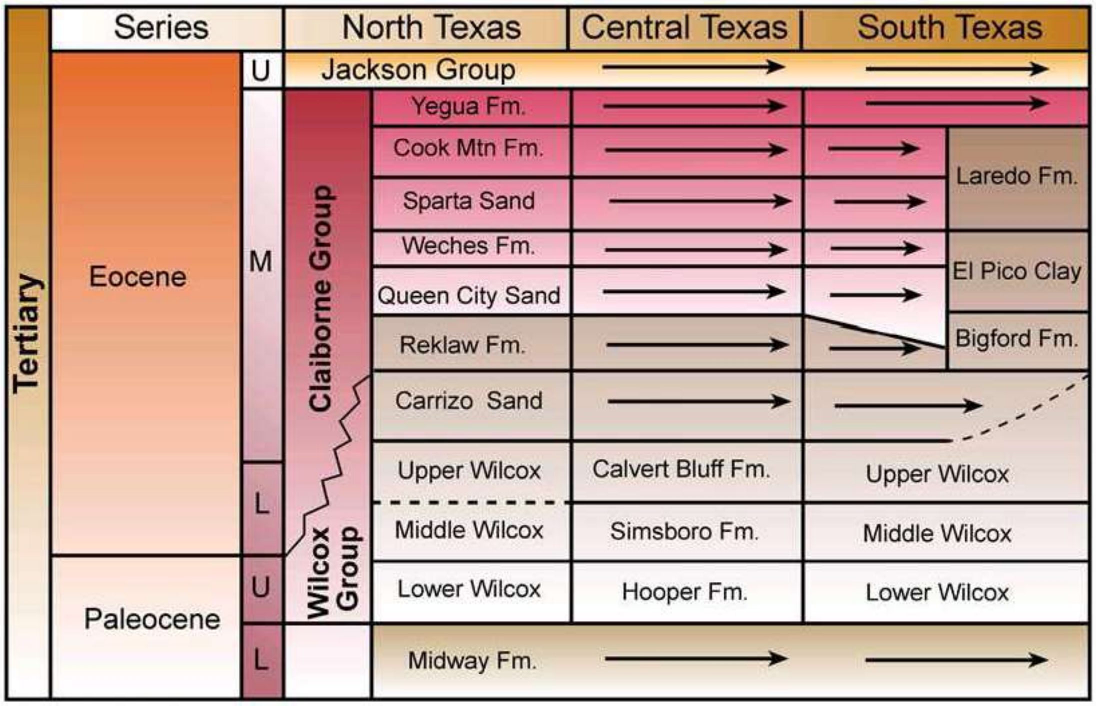
Figure 5-45. **Eagle Ford Region and Associated Aquifers.**

This section provides an assessment of the potential for borehole comingling within the aquifers in the Eagle Ford Region. The section will begin with a description of the aquifers followed by a regional assessment of the potential for comingling of brackish groundwater. Next, the section will look at a specific well where the assessment of the potential for comingling can be based upon direct evidence specific well to that well. Finally, the section will end with a summary of the findings relative to the comingling of groundwater in the region/aquifer.

5.3.1 Description of the Aquifers Within the Eagle Ford Region

The Tertiary formations of the Texas Upper Gulf Coastal Plain form prolific groundwater flow systems (Hutchison and others, 2009) which include both major and minor aquifers. In the Eagle Ford Region, the upper coastal plain aquifers are the primary aquifers and include the Carrizo-Wilcox, Queen City, Sparta, and Yegua-Jackson aquifers (Figure 5-45). As discussed earlier, the assessment of the Brazos River Alluvium was performed in the assessment of the Gulf Coast Aquifers.

Figure 5-46 is a generalized stratigraphic section for the Tertiary Aquifers in the Eagle Ford Region (after Kelley and others, 2009). Each of these aquifers are comprised of formations of sand and shale wedges that dip and thicken toward the coast (Galloway and others, 2000). Major aquifers, such as the Carrizo-Wilcox, are located in the thickest, most laterally extensive, and sand-rich Cenozoic sediment wedges, whereas minor aquifers, such as the Queen City, Sparta, and Yegua-Jackson, are located in sediment wedges that are less sandy and more limited in lateral (especially downdip) extent (George and others, 2011). These units are generally of fluvio-deltaic origin and have significant vertical stratification of lithology.



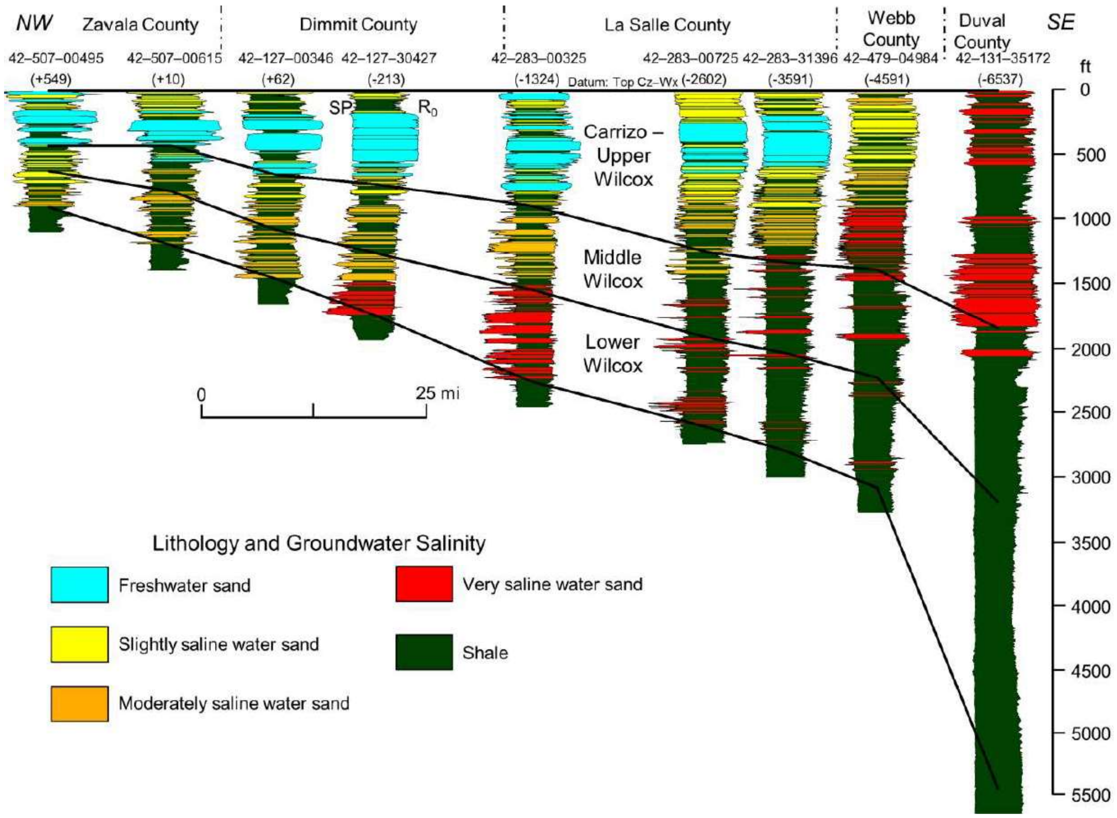
	Series			North Texas	Central Texas	South Texas	
Tertiary	Eocene	U	Jackson Group		→	→	
		M	Claiborne Group	Yegua Fm.	→	→	
				Cook Mtn Fm.	→	→	Laredo Fm.
				Sparta Sand	→	→	
				Weches Fm.	→	→	El Pico Clay
				Queen City Sand	→	→	
				Reklaw Fm.	→	→	Bigford Fm.
				Carrizo Sand	→	→	
		L	Wilcox Group	Upper Wilcox	Calvert Bluff Fm.	Upper Wilcox	
				Middle Wilcox	Simsboro Fm.	Middle Wilcox	
	Paleocene	U		Lower Wilcox	Hooper Fm.	Lower Wilcox	
		L		Midway Fm.	→	→	

Figure 5-46. Generalized Stratigraphic Section for the Tertiary Aquifers in the Eagle Ford Region (after Kelley and others, 2009).

These aquifers are characterized as having recharge enter the aquifer at outcrop where flow partitions between shallow sub-regional flow systems that discharge to creeks and rivers and more regional deeper flow systems that flow down the structural dip of the formation towards the gulf. The aquifers become increasingly saline with depth. In the larger, more sand-rich depositional systems like the Carrizo-Wilcox Aquifer, the fresh water tends to extend further downdip than in the less sand-rich systems such as the Yegua-Jackson Aquifer. Figure 5-47 is a cross-section developed under contract to the TWDB of the Carrizo-Wilcox aquifers from Zavala

County to Duval County showing both the stratification in lithology and the stratification and regional trends in aquifer water quality expressed as total dissolved solids (Hamlin and others, 2019).

The Carrizo-Wilcox Aquifer System is classified as a major aquifer in Texas (George and others, 2011). The Carrizo-Wilcox Aquifer consists of fluvial-deltaic sediments of the upper Paleocene and lower Eocene Wilcox Group and Carrizo Sand. The aquifer is bounded below by marine deposits of the Midway Group and above by the Reklaw and the facies equivalent Bigford formations, which form a semi-confining unit between the Carrizo Sand and the Queen City Formation. In the portion of the aquifer stretching from the Rio Grande to the Colorado River, the Wilcox Group is subdivided into a Lower, Middle, and Upper Wilcox. Between the Colorado and Trinity rivers, the Carrizo-Wilcox Aquifer is composed of four hydrostratigraphic units with distinct hydraulic properties: the Hooper, Simsboro, and Calvert Bluff formations of the Wilcox Group and the Carrizo Sand of the Claiborne Group. In general, the Simsboro and Carrizo formations contain thicker, more laterally continuous and more permeable sands and, therefore, are more important hydrostratigraphic units when determining groundwater availability. The Calvert Bluff and Hooper formations typically are made up of clay, silt, and sand mixtures, as well as lignite deposits. Because of their relatively low vertical permeability, the Hooper and Calvert Bluff formations act as leaky aquitards restricting groundwater flow between the layers.



Note: ft = feet, NW = northwest, SE = southeast

Figure 5-47. **Stratigraphic and Water Quality Cross-Section of the Carrizo-Wilcox Aquifer in the Eagle Ford Region (from Hamlin and others, 2019).**

The Queen City and Sparta aquifers are classified as minor aquifers (George and others, 2011). The Reklaw Formation, composed of marine clays deposited in a major marine transgression, represents the base of the Queen City Aquifer. The Queen City, Weches, and Sparta formations overlie the Reklaw and Carrizo formations and the Wilcox Group. The Queen City Formation is composed of several fluvio-deltaic depositional systems. The Queen City and Sparta aquifers are generally not identified as aquifers west of the Frio River as they transition to less permeable facies equivalents which are used locally for groundwater. The Queen City transitions into the Bigford Formation and the El Pico Clay. The Queen City Formation is overlain by the Weches Formation, a marine unit composed of glauconitic muds. This formation represents a marine transgression between Queen City and Sparta deposition. The Weches is a thin formation, generally less than 100 feet thick. West of the Frio River, the Weches Formation grades into the El Pico Clay. Overlying the Weches Formation is the Sparta Formation. Ricoy and Brown (1977) identified three principal depositional facies within the Sparta: (1) a high-constructive delta facies in East Texas, (2) a stand-plain/barrier bar facies in Central Texas, and (3) a high-destructive wave dominated deltaic facies in South Texas. The Sparta is very identifiable in Texas as a sand-rich unit overlain and underlain by marly marine transgressive units, the Cook Mountain and Weches formations, respectively. The sources of sand to the Sparta delta systems were primarily from East and South Texas, with the stand-plain facies being fed by longshore currents in Central Texas.

The Yegua-Jackson includes the Eocene-aged Yegua Formation of the Claiborne Group and the overlying Eocene-Oligocene-aged Jackson Group (Knox and others, 2007). These units are composed of interbedded sand, silt, and clay, with smaller amounts of lignite, limestone, tuff, shells, and gypsum. The aquifer is composed of alluvial terrace and floodplain deposits along the Brazos River, which flows through east-central Texas into the Gulf of Mexico. The sediments include sand, gravel, silt, and clay that reach up to around 75 feet in thickness in terrace deposits and up to 100 feet in thickness in floodplain deposits.

The groundwater flow system hydrodynamics in the aquifers in the Eagle Ford Study Region are conceptually very similar to the description for the Gulf Coast Aquifer System in Section 5.2.1. The Eagle Ford aquifers are Tertiary coastal plain systems referred to by the TWDB as Upper Coastal Plain aquifers (Hutchison and others, 2009). The Upper Coastal Plain sediments are fluvio-deltaic in origin and tend to have smaller, less extensive sand bodies making the productivity of these aquifers less than the Lower Coastal Plain Gulf Coast Aquifer. Kelley and others (2009) provide a review of the regional flow dynamics, groundwater flow balance and vertical head differences between the Queen City and Sparta aquifers and the Carrizo-Wilcox Aquifer. As in the case of the Gulf Coast Aquifer, the Tertiary aquifers of the Eagle Ford Region, these aquifers have the propensity to have significant vertical head differences within and between aquifers in both predevelopment and post-development times.

Brackish Groundwater in Eagle Ford Aquifers

There are a host of Water Commission and TWDB County Reports and other United States Geological Survey and the Bureau of Economic Geology reports which study water quality of the Eagle Ford aquifers. Pettijohn (1988) performed a study on the regional water quality of the Yegua-Jackson and younger Tertiary deposits in Texas. Payne (1968), Brown (1997), Biri (1997) and Kelley and others (2004) summarized regional water-quality in the Queen City and Sparta aquifers. The southern Carrizo-Wilcox aquifer water quality was summarized in Deeds and others (2003) and more recently in Schorr and others (2021). The central Carrizo-Wilcox Aquifer water quality was summarized in Dutton and others (2003). Brazos River Alluvium Aquifer water quality was reported in Ewing and others (2016).

As part of the TWDB Brackish Resources Aquifers Characterization System program, the brackish groundwater in the southern and southern-central Carrizo-Wilcox and Queen City and Sparta aquifers have been studied in detail with respect to their lithology and water quality as well as occurrence of brackish groundwater (Meyer and others, 2020; Hamlin and others, 2019; Wise, 2014). Meyer and others (2020) is the most complete study in the Eagle Ford Region studying the aquifers of the Upper Coast Plain in Central Texas. They collected, analyzed, and interpreted thousands of well logs and geophysical well logs to map stratigraphy. The study mapped brackish groundwater by salinity class.

5.3.2 Regional Assessment of Comingling

The regional assessment follows the same steps outlined in Section 5.2.2. The key products of the regional assessment are characterization of: (1) well completions with an emphasis on identifying multi-aquifer completions; (2) maximum head differences between aquifers at the location of multi-completed wells; and (3) water quality within the aquifers. Because the Yegua-Jackson groundwater availability model does not include the Queen City and Sparta and Carrizo-Wilcox aquifers as model layers, the regional assessment could not include an assessment of wells multi-completed in the Yegua-Jackson and older aquifers. We performed a regional assessment of the multi-aquifer completions within the Yegua-Jackson Aquifer and the overlying Gulf Coast Aquifer System in Section 5.2.2. The case study for the Eagle Ford Region presented in Section 5.3.3 below involves a well completed in Gulf Coast and Yegua-Jackson aquifers.

Aquifer Completions

The first step is to characterize the well completions within the aquifers and formations represented in the Eagle Ford Region. As explained in Section 5.1, to perform this step, a validated database of groundwater wells and their screen information was developed. Next, the well screens were intersected with aquifer structure to produce tabulations of both single aquifer completed wells and multi-aquifer completed wells.

All Upper Coastal Plain aquifers are included in two groundwater availability models that overlap within the region. These are the Southern and Central Carrizo-Wilcox and Queen City Sparta aquifers groundwater availability models (Kelley and others 2004; Young and others, 2018). Because there is significant overlap in these groundwater availability models in the central portion of the Eagle Ford Region, we used the boundary between Groundwater Management Areas 12 and 13 as our guide. For locations north of the boundary, we used the central groundwater availability model and, for locations south of the boundary we used the southern groundwater availability model.

Table 5-16 lists the well completions for 7,668 wells in the Central Carrizo-Wilcox Groundwater Availability Model area. Multi-completed wells make up 18 percent of the total wells.

Interestingly, the Calvert Bluff has the highest number of single aquifer completions, which is likely because of shallower wells tapping into freshwater sands supporting rural and domestic use. There are 230 wells that are cross completed in both the Sparta and the Queen City aquifers, with 111 of those also completing some portion of the Weches confining unit. Detailed zonal water quality studies as well as interpreted geophysical logs indicate that water quality can degrade in proximity to low permeability or lignite deposits which are more prevalent in the confining units such as the Weches. Cross completing wells between aquifers and confining units increases chances of mixing groundwater of different quality.

There are 532 wells within the Central portion of Carrizo-Wilcox Aquifer that cross complete the Carrizo or the Simsboro, the two primary aquifers, with the Reklaw, Calvert Bluff, or the Hooper. The upper sands of the Calvert Bluff can be fresh, but the Hooper water quality is significantly worse than the Simsboro. There are 230 wells that connect the Queen City and Sparta aquifers in the Central portion of the study area.

Table 5-17 lists the well completions for 5,754 well in the Southern Carrizo-Wilcox Groundwater Availability Model area. Multi-completed wells make up 31 percent of the total wells, which is larger than in the central area. This increase is consistent with the aquifers become less distinguishable as you move to the southwest. When aquifers become less distinguishable, well completions tend to screen as many productive sands as needed irrespective of aquifer. Again, we see a fair number of wells (117) that connect the Queen City and Sparta aquifers in the southern portion of the study area. In the Carrizo-Wilcox the predominant cross-completions are between the Carrizo and Reklaw and Carrizo and Upper Wilcox.

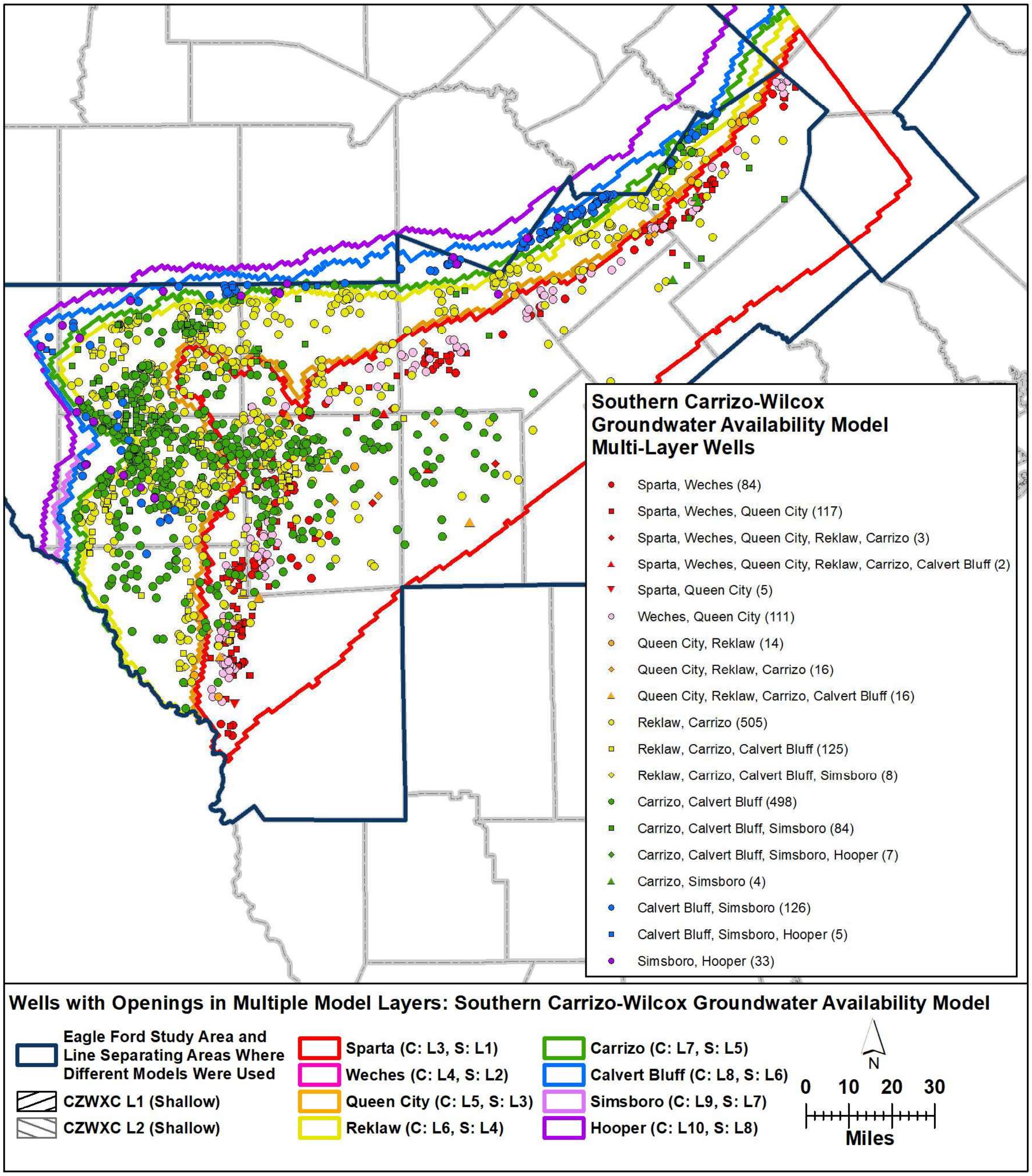
Table 5-16. Aquifer Well Completions in the Central Carrizo-Wilcox, Queen City and Sparta aquifers.

Aquifer(s)	Number of Wells
Alluvium	29
Shallow Outcrop	247
Sparta	1,115
Weches	35
Queen City	1,231
Reklaw	159
Carrizo	503
Calvert Bluff	1,774
Simsboro	575
Hooper	605
Alluvium/Shallow Outcrop	91
Sparta/Weches	134
Sparta/Weches/Queen City	111
Weches/Queen City	119
Queen City/Reklaw	108
Carrizo/Reklaw	127
Carrizo/Calvert Bluff	155
Simsboro/Calvert Bluff	148
Simsboro/Hooper	102
Total single aquifer completions	**6,273**
Total multi aquifer completions	**1,395**
Percent Multi-Completed	**18.2 percent**

Figure 5-48 plots the multi-completed wells by aquifers screened in the Southern Carrizo-Wilcox Aquifer using the Southern Carrizo-Wilcox Aquifer Groundwater Availability Model structure. Figure 5-49 plots the multi-completed wells by intervals screened in the Central Carrizo-Wilcox Aquifer using the Central Carrizo-Wilcox Aquifer Groundwater Availability Model structure.

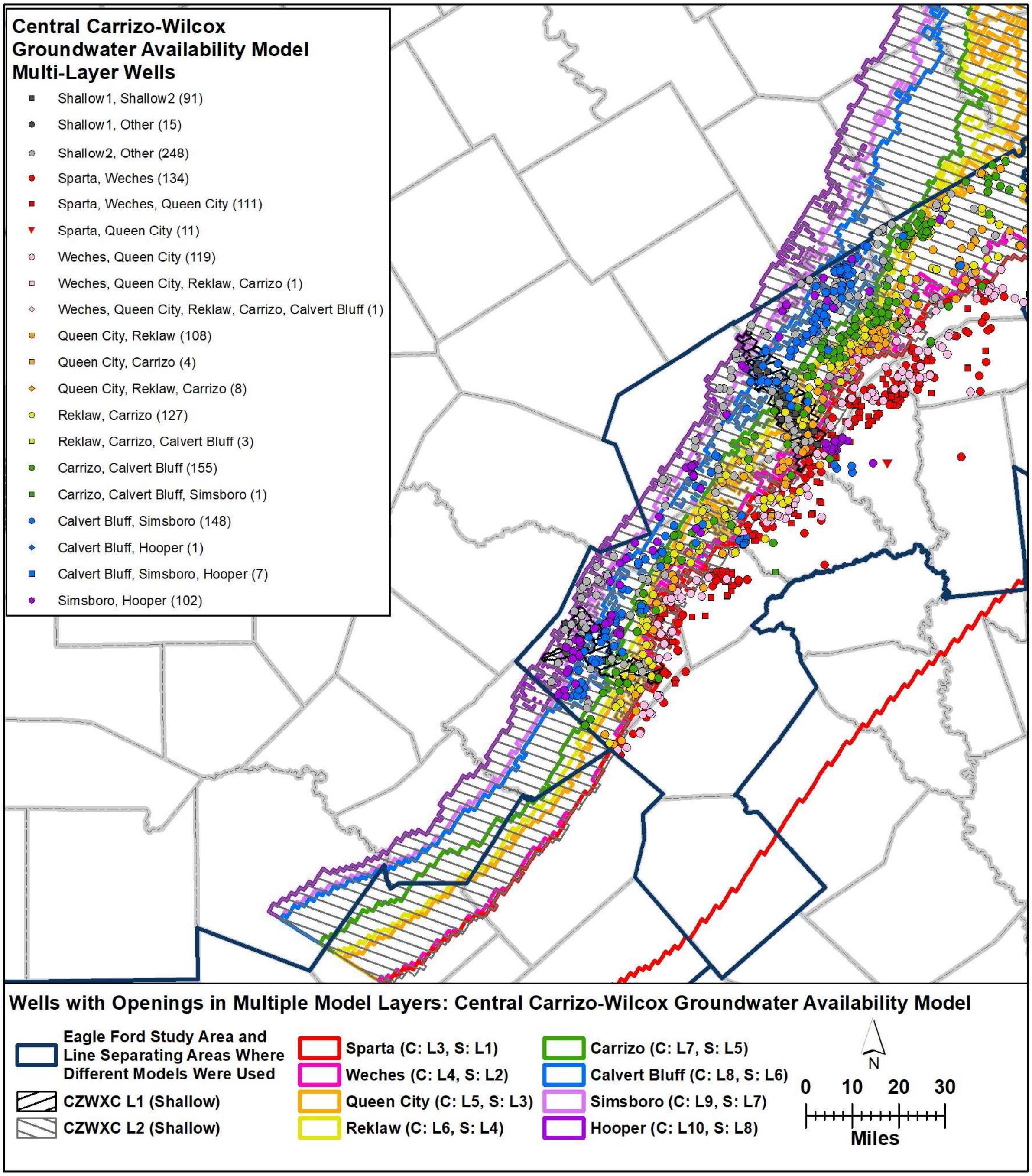
Table 5-17. Aquifer Well Completions in the Southern Carrizo-Wilcox, Queen City and Sparta aquifers.

Aquifer(s)	Number of Wells
Sparta	334
Weches	29
Queen City	860
Reklaw	285
Carrizo	1,790
Upper Wilcox	208
Middle Wilcox	381
Lower Wilcox	102
Sparta / Weches	84
Sparta / Weches /Queen City	117
Weches / Queen City	111
Carrizo / Reklaw	505
Reklaw / Carrizo / Upper Wilcox	125
Carrizo / Upper Wilcox	498
Carrizo / Upper Wilcox / Middle Wilcox	84
Middle Wilcox / Upper Wilcox	128
Middle Wilcox / Lower Wilcox	33
Total single aquifer	**3,989**
Total multi aquifer	**1,765**
Percent Multi-Completed	**30.67 percent**



Note: C = Central Groundwater Availability Model, CZWXC = Central Carrizo-Wilcox Groundwater Availability Model, CZWXS = Southern Carrizo-Wilcox Groundwater Availability Model, L = layer, N = Northern Groundwater Availability Model

Figure 5-48. **Location of wells completed in two or more aquifers in the Southern Carrizo-Wilcox Groundwater Availability Model.**



Note: C = Central Groundwater Availability Model, CZWXC = Central Carrizo-Wilcox Groundwater Availability Model, CZWXS = Southern Carrizo-Wilcox Groundwater Availability Model, L = layer, N = Northern Groundwater Availability Model

Figure 5-49. Location of wells completed in two or more aquifers in the Northern Carrizo-Wilcox Groundwater Availability Model.

Maximum Head Differences

Vertical gradients within the aquifers in the Eagle Ford region have been documented and investigated in terms of regional groundwater flow in Kelley and others (2004, 2009) and Deeds and others (2009). Kelley and others (2009) plotted average composite head in the Queen City and Sparta Aquifer as compared to the composite head in the Carrizo-Wilcox Aquifer across the state for conditions representative of 1980. They showed that predevelopment vertical gradients had largely been reversed in the Wintergarden area with significant downward gradients from the younger to the older aquifers from extensive Carrizo Aquifer development pre-1980. From Atascosa County to Milam County, the gradient is more dominantly upward until you get within a county of the Brazos River. There the gradients become slightly downward because of Simsboro and Carrizo pumping in the Brazos Valley. Downward head differences exceed 200 feet in many areas and upward differences are as high as 100 feet. Ewing and others (2016) evaluated gradients between the Brazos Alluvium and the underlying aquifers including the Carrizo-Wilcox, Queen City and Sparta and the Yegua Jackson aquifers. They found that gradients were prevalent and that, in most cases reviewed, the gradient is upward, which is expected near a large river such as the Brazos. Downward gradients were observed in areas where the underlying aquifers had experienced significant head decline. The literature suggest that vertical head differences are prevalent within the aquifers in the Eagle Ford region.

Table 5-18 is a statistical summary of the highest absolute head difference between aquifers in the Central Carrizo Wilcox and Queen City and Sparta aquifers groundwater availability model. All well completions with a common uppermost layer were considered together, and the head difference for each possible pair of aquifers was calculated. The highest magnitude of these head differences was determined for each well, and Table 5-18 tabulates these values. So, for the column labeled Sparta in Table 5-18, all wells completed in the Sparta and another lower aquifer, and all such permutations, were considered in the calculation. A negative head difference is an upward gradient, and a positive difference is a downward gradient.

Table 5-19 is a statistical summary of the highest absolute head difference between aquifers in the Southern Carrizo Wilcox and Queen City and Sparta aquifers groundwater availability model.

These values are posted by well in Figure 5-50 through Figure 5-55 for the Sparta, Queen City, Reklaw, Carrizo, Upper and Middle Wilcox, respectively. Each figure looks at maximum head differences at each multi-completed well. The Sparta (Figure 5-50) looks at all wells completed in the Sparta as well as any other aquifer or aquitard below the Sparta. The head differences are posted using triangle symbols, the size of which is representative of the magnitude of maximum head difference at that well. If the maximum head difference is down, the triangle points down and if the maximum head difference is up, the triangle points up. Also included in the legend of each figure are the aquifer completions represented in the figure and the number of wells with each completion combination. For example, in the Sparta figure the most common Sparta multi-completed wells are Sparta-Weches and Sparta-Weches-Queen City completions.

Table 5-19 finds that significant vertical head differences exist between most aquifers. The maximum gradients are predominantly downward (positive) which comes from wells near the outcrop or wells in the downdip portions of the aquifers that have seen significant water level declines because of development. Median head differences in the Central groundwater availability model range as high as 26.7 feet for the Calvert Bluff reflecting significant vertical gradients towards the heavily pumped Simsboro.

Table 5-18. **Maximum Head Difference Between Aquifers at Wells in the Central Carrizo-Wilcox and Queen City and Sparta Aquifers.**

Uppermost Aquifer Considered	Alluvium/ Shallow	Sparta	Weches	Queen City	Reklaw	Carrizo	Calvert Bluff	Simsboro
Count	354	256	121	120	130	156	156	102
Min (ft)	-42.8	-79.0	-64.5	-41.7	-16.6	-13.2	-12.8	-178.6
Max (ft)	118.5	70.6	67.6	90.8	50.3	64.0	127.4	16.2
Mean (ft)	17.2	-3.1	2.2	16.1	15.2	19.9	33.9	-35.2
Median (ft)	**5.0**	**-1.4**	**0.1**	**12.6**	**14.5**	**17.4**	**26.7**	**-11.3**
St. Dev. (ft)	28.6	16.2	14.1	22.3	15.6	19.5	34.4	57.3

Note: ft = feet

Table 5-19. **Maximum Head Difference Between Aquifers at Wells in the Southern Carrizo-Wilcox and Queen City and Sparta Aquifers.**

Uppermost Aquifer Considered	Sparta	Weches	Queen City	Reklaw	Carrizo	Upper Wilcox	Middle Wilcox
Count	211	111	46	638	593	131	33
Min (ft)	-59.5	-29.2	-32.7	-107.0	-116.5	-97.8	-141.2
Max (ft)	94.0	161.0	188.4	147.5	222.7	88.5	32.8
Mean (ft)	-0.4	2.9	64.7	-3.7	27.9	-1.5	-9.8
Median (ft)	**-1.3**	**1.8**	**46.0**	**-14.3**	**22.4**	**-3.1**	**-4.2**
St. Dev. (ft)	22.2	20.5	53.6	49.9	38.7	24.8	34.3

Note: ft = feet

Head differences in the Southern Groundwater Availability Model aquifers are also large even when looking at median values with a maximum median of 46 feet for wells completed in the Queen City and also in the underlying Reklaw and Carrizo-Wilcox.

The figures plotting maximum head difference at each well provide insight to the statistics summarized above. Sparta multi-completed wells are mostly comprised of wells co-completed across the Sparta/Weches and Sparta/Weches/Queen City. Maximum head differences tend to be downward in the Wintergarden area and convert to upward heading east into Gonzales County. There are a significant number of wells completed across the Sparta and Queen City with strong potential vertical gradients to cause comingling in a well.

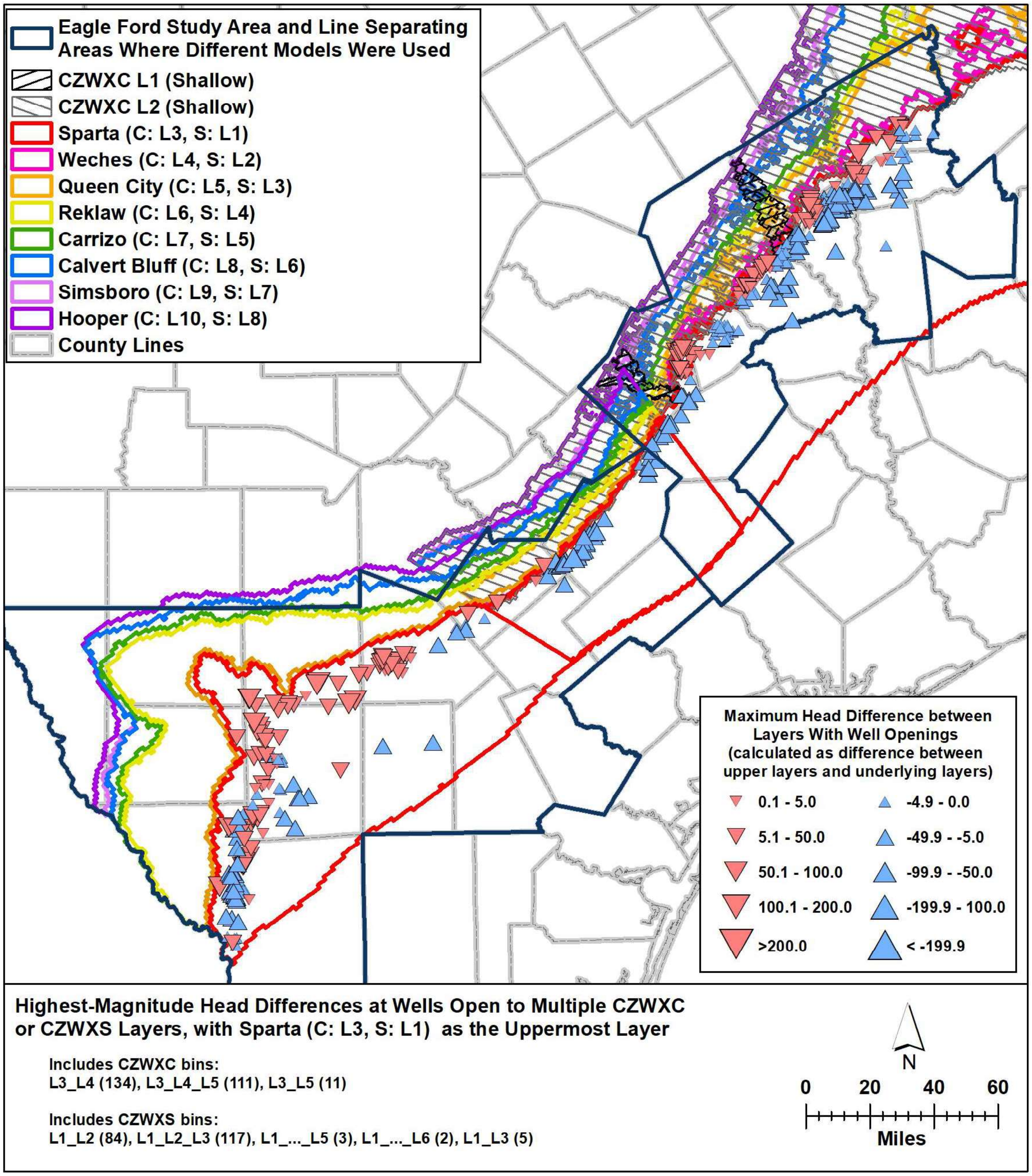
Figure 5-51 posts maximum head differences at each well multi-completed in the Queen City and any other aquifer(s) below the Queen City. Queen City multi-completed wells are mostly comprised of wells co-completed across the Queen City/Reklaw. Maximum head differences tend to be downward although gradients are mixed as you move into central Texas. The median maximum head difference in the southern groundwater availability model region is 46 feet whereas it is 12.6 feet in the central groundwater availability model region.

Figure 5-52 posts maximum head differences at each well multi-completed in the Reklaw and any other aquifer(s) below the Reklaw. Reklaw multi-completed wells are mostly comprised of wells co-completed across the Reklaw/Carrizo. Maximum head differences tend to be mixed in direction. The median maximum head difference in the southern groundwater availability model region is -14.3 feet whereas it is 14.5 feet in the central groundwater availability model region.

Figure 5-53 posts maximum head differences at each well multi-completed in the Carrizo and any other aquifer(s) below the Carrizo. Carrizo multi-completed wells are mostly comprised of wells co-completed across the Carrizo/Calvert Bluff (Upper Wilcox). The median maximum head difference in the southern groundwater availability model region is 22.4 feet and 17.4 feet in the central groundwater availability model region. The strong downward gradient makes sense in the central region because of large head declines in the Simsboro Formation. The downward gradient in the southern region is less intuitive.

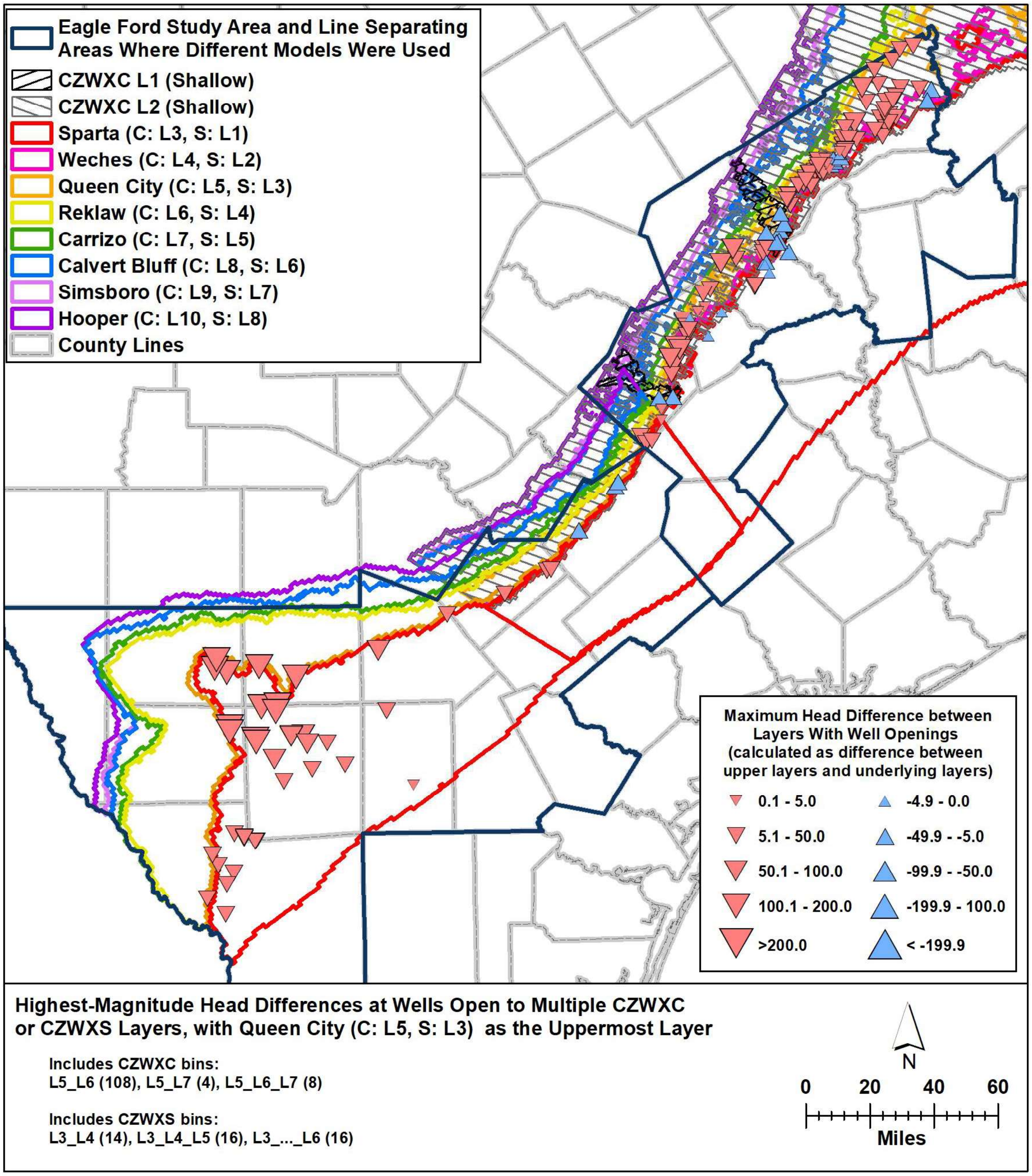
Figure 5-54 posts maximum head differences at each well multi-completed in the Upper Wilcox/Calvert Bluff and any other aquifer(s) below the Upper Wilcox/Calvert Bluff. Maximum head differences tend to be mixed in direction. The median maximum head difference in the central groundwater availability model region is 26.7 feet whereas it is -3.1 feet in the southern groundwater availability model region. This makes sense in that the Simsboro has seen much more development in the central region than the equivalent Middle-Wilcox in the southern region.

Figure 5-55 posts maximum head differences at each well multi-completed in the Middle Wilcox/Simsboro and any other aquifer(s) below the Middle Wilcox/Simsboro. The gradients tend to be upward with a median maximum head difference in the central groundwater availability model region is -11.3 feet whereas it is -4.2 feet in the southern groundwater availability model region.



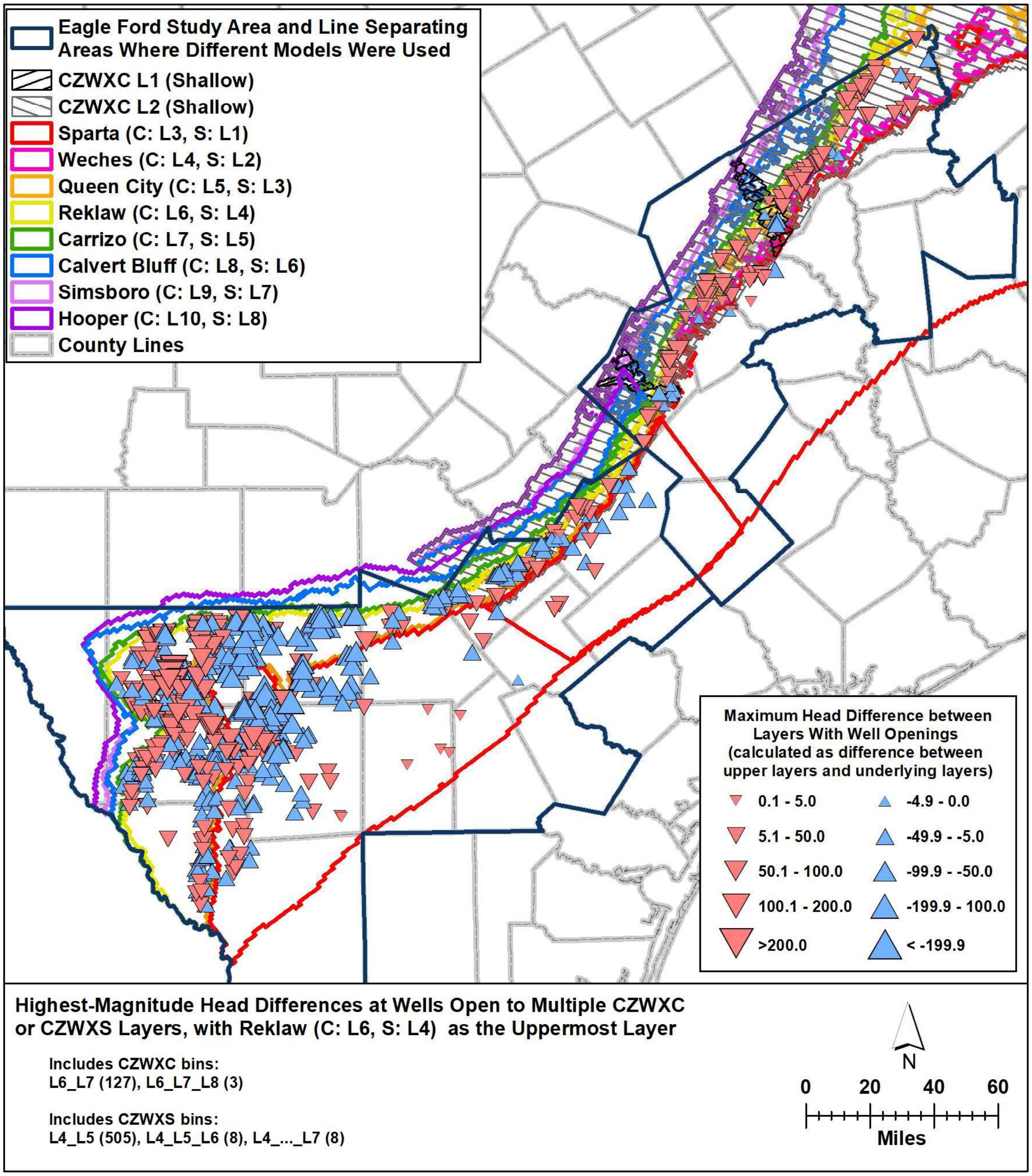
Note: C = Central Groundwater Availability Model, CZWXC = Central Carrizo-Wilcox Groundwater Availability Model, CZWXS = Southern Carrizo-Wilcox Groundwater Availability Model, L = layer, N = Northern Groundwater Availability Model

Figure 5-50. Maximum head difference at each well completed in the Sparta and any underlying aquifer.



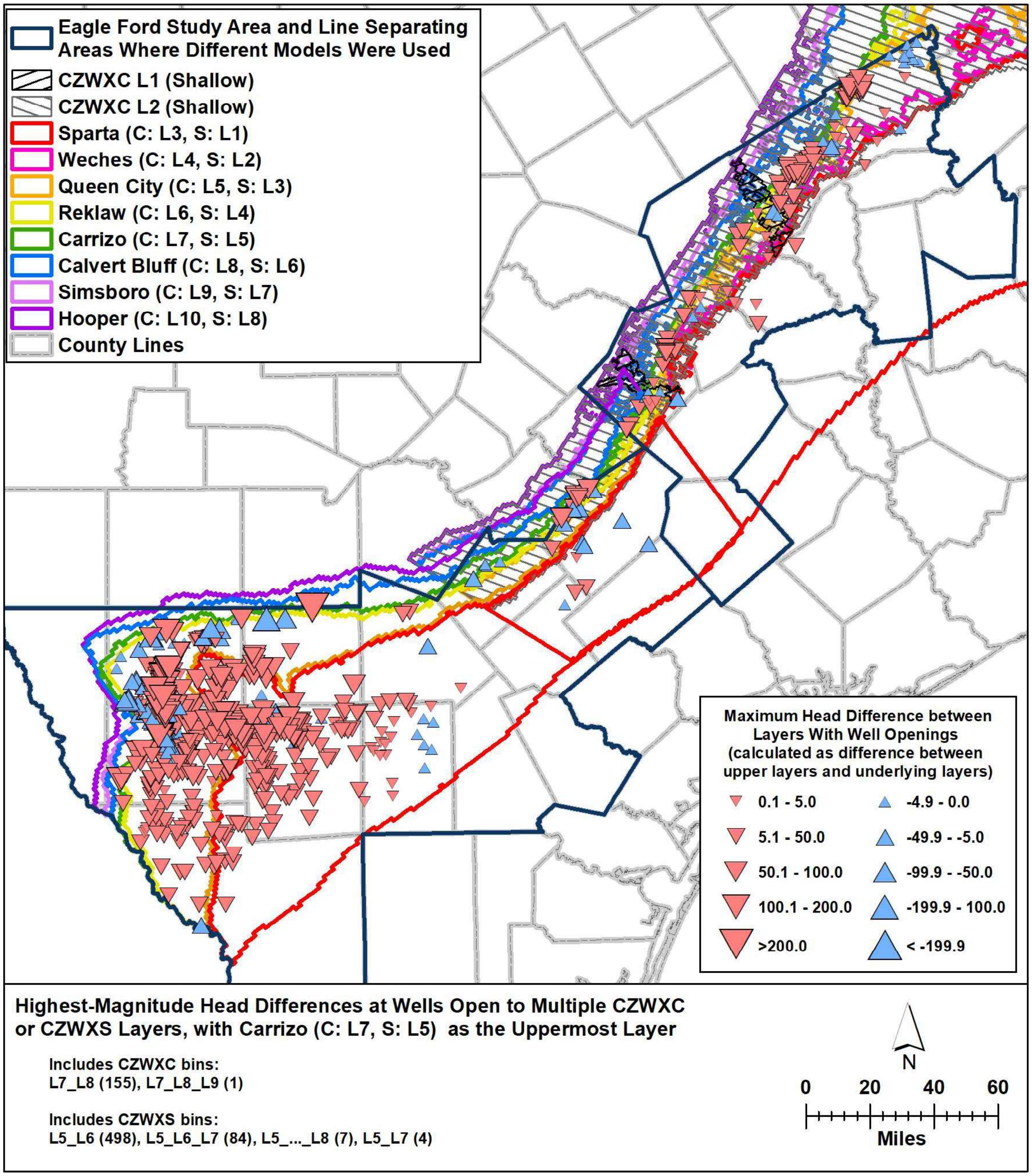
Note: C = Central Groundwater Availability Model, CZWXC = Central Carrizo-Wilcox Groundwater Availability Model, CZWXS = Southern Carrizo-Wilcox Groundwater Availability Model, L = layer, N = Northern Groundwater Availability Model

Figure 5-51. **Maximum head difference at each well completed in the Queen City and any underlying aquifer.**



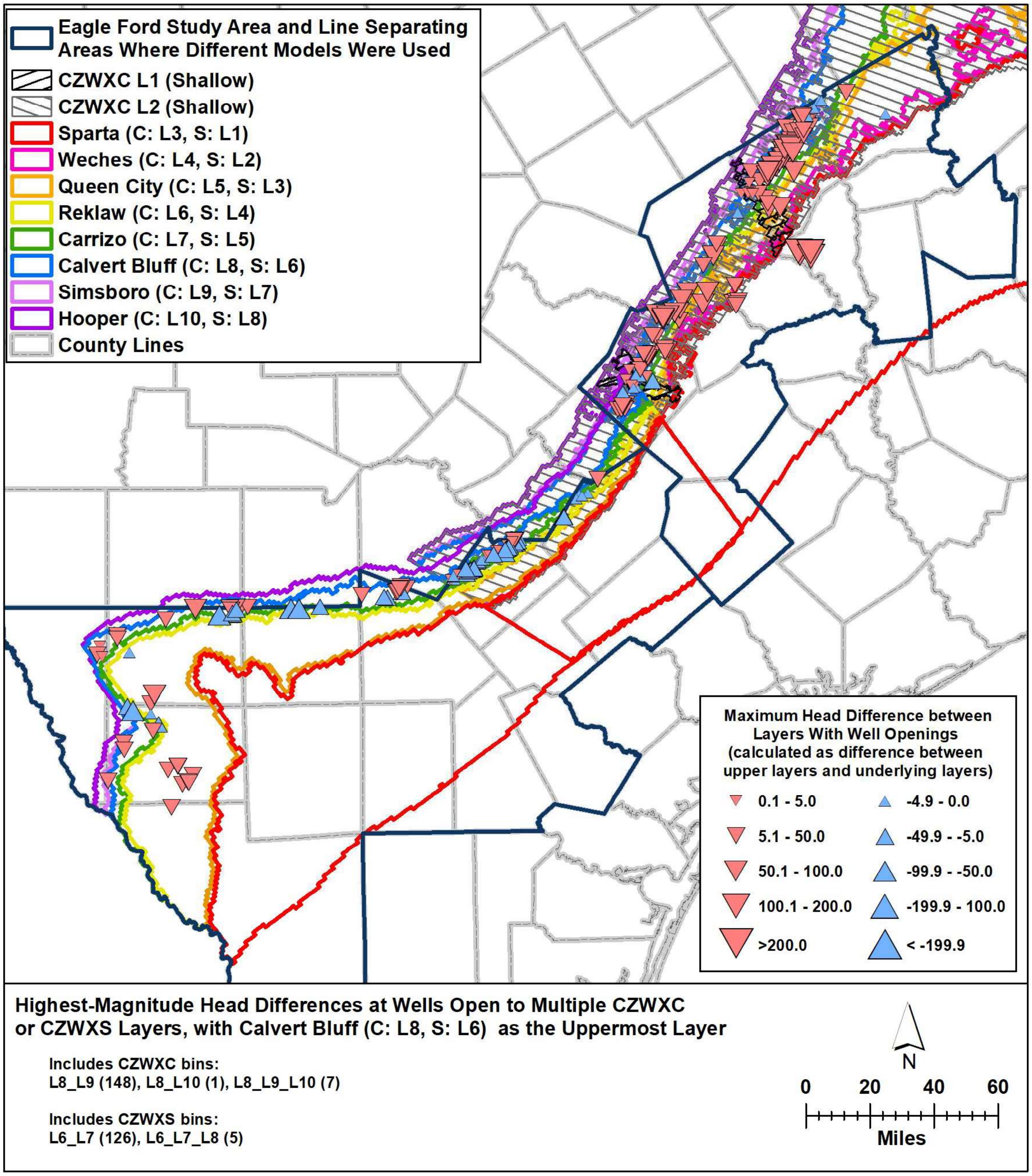
Note: C = Central Groundwater Availability Model, CZWXC = Central Carrizo-Wilcox Groundwater Availability Model, CZWXS = Southern Carrizo-Wilcox Groundwater Availability Model, L = layer, N = Northern Groundwater Availability Model

Figure 5-52. Maximum head difference at each well completed in the Reklaw and any underlying aquifer.



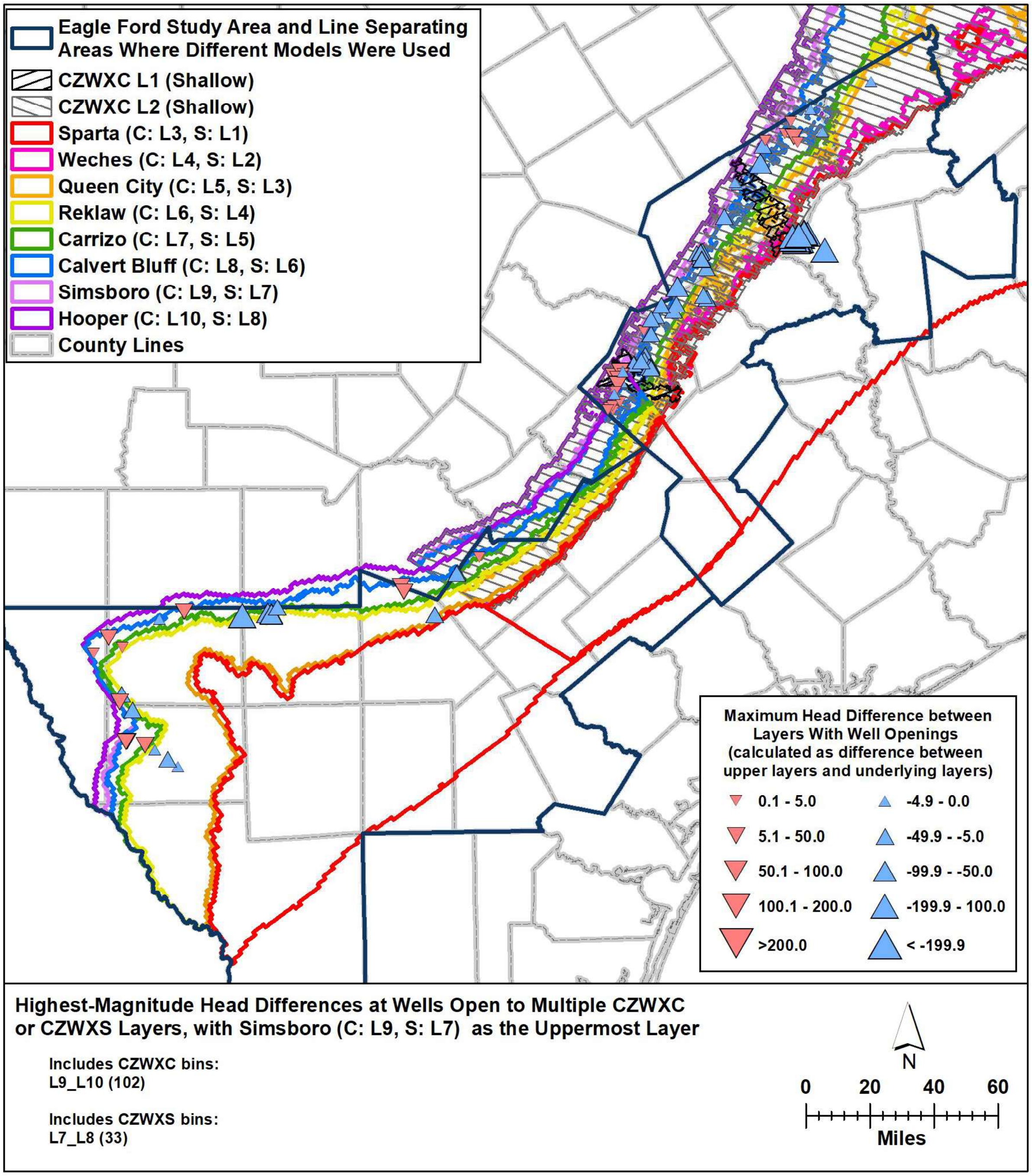
Note: C = Central Groundwater Availability Model, CZWXC = Central Carrizo-Wilcox Groundwater Availability Model, CZWXS = Southern Carrizo-Wilcox Groundwater Availability Model, L = layer, N = Northern Groundwater Availability Model

Figure 5-53. **Maximum head difference at each well completed in the Carrizo and any underlying aquifer.**



Note: C = Central Groundwater Availability Model, CZWXC = Central Carrizo-Wilcox Groundwater Availability Model, CZWXS = Southern Carrizo-Wilcox Groundwater Availability Model, L = layer, N = Northern Groundwater Availability Model

Figure 5-54. Maximum head difference at each well completed in the Upper Wilcox/Calvert Bluff and any underlying aquifer.



Note: C = Central Groundwater Availability Model, CZWXC = Central Carrizo-Wilcox Groundwater Availability Model, CZWXS = Southern Carrizo-Wilcox Groundwater Availability Model, L = layer, N = Northern Groundwater Availability Model

Figure 5-55. **Maximum head difference at each well completed in the Middle Wilcox / Simsboro and any underlying aquifer.**

Water Quality

Water quality has focused on total dissolved solids because brackish salinity classes are defined by total dissolved solids and because total dissolved solids is a proxy of overall water quality. Many studies have demonstrated that as total dissolved solids increase, so do many other ions and constituents that can be problematic for desalination, fracking and other uses (Hamlin and others, 2019; Meyers and others, 2020). As has been discussed earlier in this report, comingling requires mixing of groundwater between aquifers or zones through a well with the requirement that the mixing causes degradation. Because the concept of degradation can be very specific to context, the evaluation of the potential for comingling will be performed using total dissolved solids as a proxy for problem constituents capable of degradation, while recognizing that degradation could occur from specific constituents unrelated to total dissolved solids.

The Texas Commission on Environmental Quality secondary maximum contaminant level for total dissolved solids is 1,000 milligrams per liter. However, there are many other constituents for which the Texas Commission on Environmental Quality have adopted primary and secondary contaminant levels for drinking water. As introduced in Section 5.2.2 above, Reedy and others (2011) looked at the percent of water samples that exceeded either the primary or secondary standard as well as calculated the probability that any given sample would exceed a standard for all minor and major aquifers. Table 5-11 reproduced from Reedy and others (2011) lists the constituents analyzed. We will limit our review to constituents which exceed their standard in 10 percent or more of the samples analyzed. Table 5-20 summarizes the constituents, by aquifer, that exceed their respective maximum contaminant levels. These constituents are nitrate-N, gross alpha, combined radium, aluminum, chloride, iron, manganese, sulfate, total dissolved solids, and pH. It is important to recognize that the samples available for analysis are primarily from the fresher portions of the aquifers. An increase in well completions in brackish portions of aquifers would increase percent exceedance.

Meyer and others (2020) recently performed a study in the Eagle Ford Region studying the aquifers of the Upper Coast Plain in Central Texas. They collected, analyzed, and interpreted thousands of well logs and geophysical well logs to map stratigraphy. The study mapped brackish groundwater by salinity class. Their work determined that the salinity between aquifers was very heterogeneous. However, their study also demonstrated the significant variability of salinity classes within an aquifer. Figure 5-56 is from Meyers and others (2020) showing the salinity class variability in the Carrizo Aquifer which is the most transmissive aquifer in the region. Among other factors, water quality is a result of lithology and residence time which is affected by depositional facies within the aquifers. Consistent with the concept of Walther's Law, that any vertical progression of facies is the result of a succession of depositional environments that are laterally juxtaposed to each, we can infer that significant horizonal variability in water quality would also manifest in significant vertical heterogeneity in water quality. The work of Meyer and others (2020) and Hamlin and others (2019) provide significant evidence that long well screens or multi-aquifer completed wells have the potential to mix groundwater of different salinity class.

Table 5-20. Percent of Groundwater Quality Samples that exceed a Primary or Secondary Maximum Contaminant Level (from Reedy and others, 2011).

Constituent	Carrizo-Wilcox (percent)	Queen City (percent)	Sparta (percent)	Yegua-Jackson (percent)
Nitrate-N				
Gross Alpha				10
Combined Radium	16		40	32
Aluminum		13		
Chloride			19	35
Iron	26	26	25	25
Manganese	19	21	16	35
Sulfate			17	29
Total Dissolved Solids		13	73	43
pH	32	45	23	25

If we assume that the frequency of multi-completed wells increases the potential for mixing of groundwater with the potential for degradation, then we can use multi-completion statistics to look at relative potential for comingling. In the Eagle Ford region coincident with the central groundwater availability model, 18 percent of wells are multi-completed with most cross completing the Carrizo /Calvert Bluff or the Simsboro /Calvert Bluff. In the area coincident with the south groundwater availability model, 31 percent of wells are multi-completed with the majority being either Reklaw / Carrizo or Carrizo /Upper Wilcox wells. The review of well completions did not identify any well that co-completed the Queen City and/or Sparta with the underlying Carrizo or Wilcox. From a review of maximum vertical head differences, the hydraulic driving force to induce mixing of groundwater within wells is prevalent.

Using total dissolved solids as a proxy for water quality characteristics that could degrade groundwater quality, we can review multi-aquifer completions against total dissolved solids to gain insight to the potential for comingling to occur in aquifers in the Eagle Ford. Table 5-21 summarizes the statistics of total dissolved solids for the Carrizo-Wilcox and Queen City and Sparta aquifers. Figure 5-57 provides histograms of total dissolved solids for the Carrizo-Wilcox and Queen City and Sparta aquifers in the Eagle Ford Region. Because these water samples are mostly from drinking water wells, we can see that the mean and median total dissolved solids statistics are all well within the freshwater salinity class. In the Carrizo-Wilcox, the Calvert Bluff is has the poorest water quality and it is known to have lignite beds which locally elevate total dissolved solids and many other constituents. Because of the higher percentage of Calvert Bluff/Upper Wilcox co-completed wells, the potential exists for groundwater mixing that could result in degradation of overall water quality.

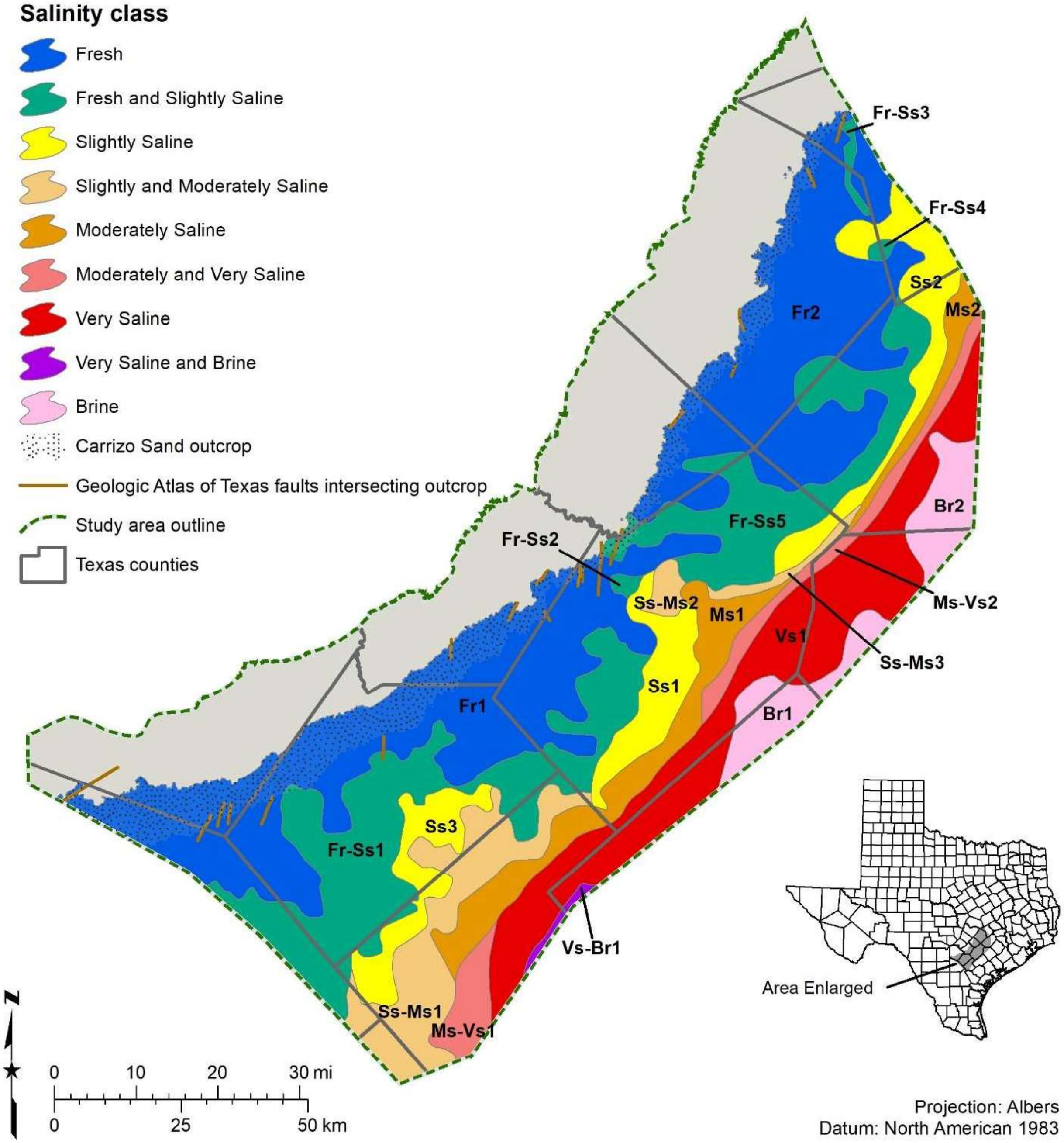


Figure 5-56. Carrizo Aquifer salinity classes (reproduced from Meyer and others, 2020).

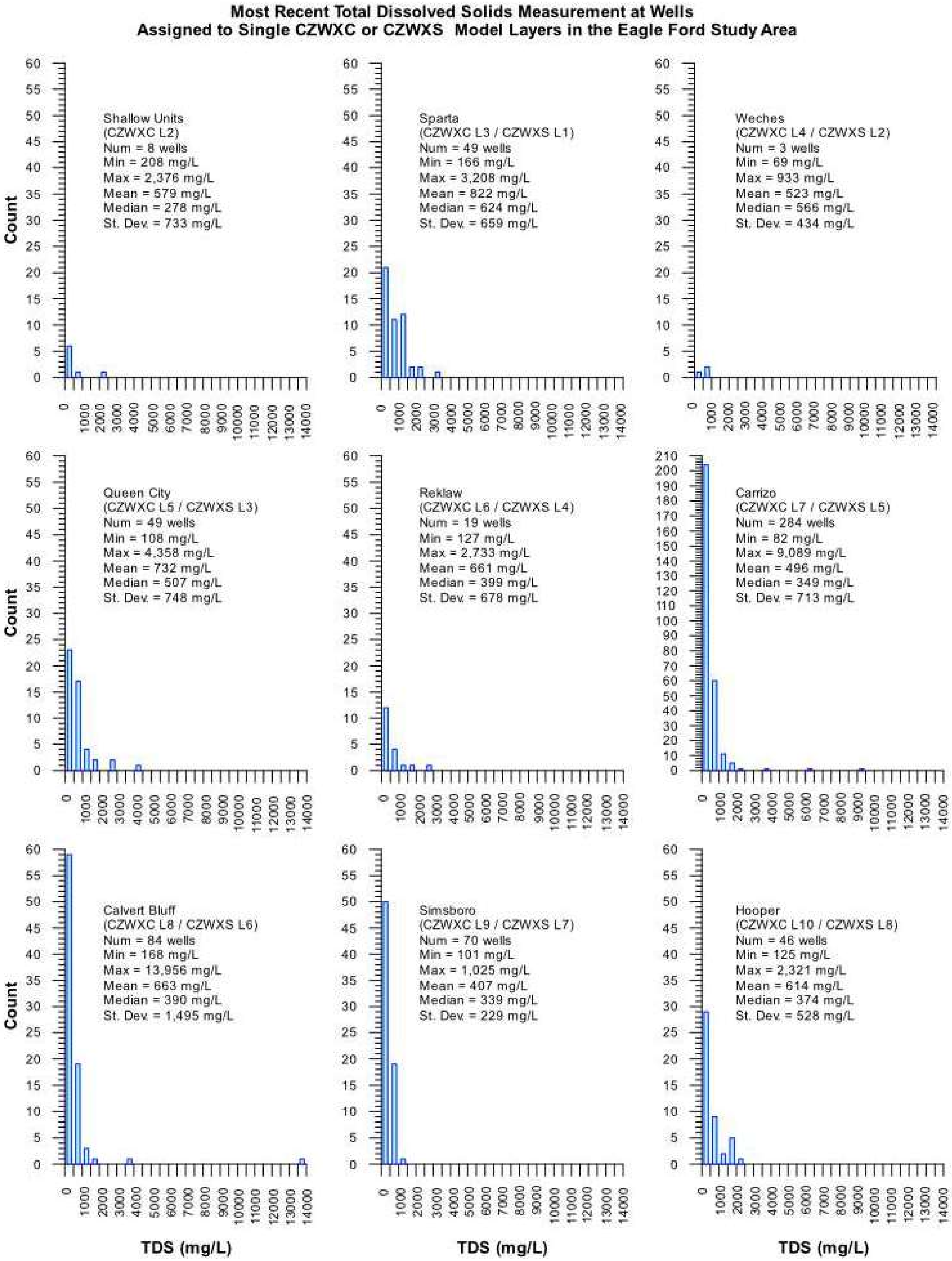
There are a significant number of wells co-completed across both the Queen City and the Sparta. From a review of average total dissolved solids measurements in Table 5-21, one can see that gross water quality is not significantly different between the Queen City and the Sparta aquifers. However, Meyer and others, (2020) in their analysis of brackish groundwater in the Upper Coastal Plain aquifers of Central Texas found significant salinity variability both within aquifers and between aquifers.

The fact that the constituents exceeded maximum contaminant levels provides indirect evidence of comingling because these constituents tend to be very vertically stratified in these aquifers. Kreitler and others (2013) performed a study on the geochemical evolution of water quality as it related to groundwater flow paths in the Eagle Ford aquifers. They documented significant variability in chemical facies and constituent concentrations within and between the aquifers.

There is significant potential for mixing within a borehole to occur in the aquifers in the Eagle Ford Region. Even at the regional aquifer scale of this analysis, 18 percent of wells in the region are co-completed across more than one aquifer. Vertical head differences between the aquifers, especially in the Queen City and Carrizo-Wilcox aquifers, are very high with median values ranging from 11 to 27 feet. While gross averages of total dissolved solids are well within the secondary standard, the local variability of groundwater salinity is very high in these deposits at a scale smaller than the aquifers (Meyer and others, 2020; Hamlin and others, 2019). Trace constituent concentrations also increase as salinity increases. Case studies in similar sediments previously discussed in Section 5.2.3 demonstrate that variability of problematic constituents such as arsenic, manganese, iron and radioactive parameters can render an entire well economically impractical. There is significant potential for comingling when long-screened wells are left inactive. The potential for comingling in the Eagle Ford Region is high.

Table 5-21. **Carrizo-Wilcox, Queen City and Sparta aquifers Total Dissolved Solids (milligrams per liter).**

Model Aquifer	Younger	Sparta	Weches	Queen City	Reklaw	Carrizo	Calvert Bluff	Simsboro	Hooper
Num	8	49	3	49	19	284	84	70	46
Min	208	166	69	108	127	82	168	101	125
Max	2,376	3,208	933	4,358	2,733	9,089	13,596	1,025	2,321
Mean	579	822	523	732	661	496	663	407	614
Median	**278**	**624**	**566**	**507**	**399**	**349**	**390**	**339**	**374**
StDev	733	659	434	748	678	713	1,495	229	528



Note: CZWXC = Central Carrizo-Wilcox Groundwater Availability Model, CZWXS = Southern Carrizo-Wilcox Groundwater Availability Model, mg/L = milligrams per liter, TDS = total dissolved solids

Figure 5-57. **Measured total dissolved solids (milligrams per liter) in each Aquifer/Aquitard.**

5.3.3 Case Study

The case study being considered for the Eagle Ford is the case of a well in the Evergreen Underground Water Conservation District that was co-completed in the Yegua-Jackson and the Gulf Coast Aquifer. The well, termed the Wolverine well, was drilled to supply water for oil and gas. In 2018, the well owner measured the vertical profile of water quality parameters inside the Wolverine well. Figure 5-58 shows the location of the Wolverine well in Karnes County. According to the Texas Well Report Number #465084, the well is screened at four intervals: 210 to 270 feet below ground surface, 310 to 330 feet below ground surface, 350 to 450 feet below ground surface, and 610 to 630 feet below ground surface.

Figure 5-58. Location of the Wolverine Well in Karnes County

The Wolverine well was completed with four screened sections; 210 to 270 feet below ground surface, 310 to 330 feet below ground surface, 350 to 450 feet below ground surface and 610 to 630 feet below ground surface. The well owner desired to understand the in-situ water quality of the multiple screened zones contributing groundwater to the well. They measured the vertical profile of water quality parameters inside the well using two methodologies (Environmental Resources Management, 2018). The two methodologies are summarized below.

In-Situ Groundwater Quality Measurements: A YSI Sonde 6920 water quality meter down the well casing to collect specific conductivity and salinity readings at each of the four screened intervals. The YSI was placed at near the middle of each well screen. Each time the water quality meters were lowered to the targeted screen interval, the water quality meter was allowed to stabilize over a period of three to ten minutes.

Dual Membrane Passive Diffusion Sampling: Immediately following the collection of in-situ groundwater quality measurements, twenty-two Dual Membrane Passive Diffusion bags were placed at eleven sampling intervals on a pre-measured tether (two Dual Membrane Passive Diffusion bags at each location). The Dual Membrane Passive Diffusion bags consisted of a low-density polyethylene bag filled with deionized water, which acts as a semipermeable membrane and is suspended in a well to passively collect groundwater samples (ITRC 2002, Vroblesky, 1997). The Dual Membrane Passive Diffusion bags were allowed to equilibrate for about three weeks. Upon retrieval at the well head, groundwater samples were collected by piercing each Dual Membrane Passive Diffusion bag with a dedicated discharge straw at the bottom of the bag to allow the water to flow into laboratory-provided containers.

Table 5-22 summarizes the measured water quality parameters from the YSI probe as well as from the eleven sampling locations sampled by Dual Membrane Passive Diffusion bags in the well. The Dual Membrane Passive Diffusion samples provided both a total dissolved solids measurement and the concentration of the major ions. The summation of the ion concentrations is also shown in Table 5-22. Both the YSI and the Dual Membrane Passive Diffusion data show an increase in concentrations with depth. Near the top of the screen, the total dissolved solids concentrations are about 1,000 milligrams per liter; near the bottom of the screen the total dissolved solids concentrations are near 3,000 milligrams per liter. Figure 5-59 plots the total dissolved solids concentrations measured in the eleven Dual Membrane Passive Diffusion bags as a function of depth. Figure 5-59 also shows the location of the well screen intervals and information from the geophysical and driller logs.

Based on the TWDB studies of the Yegua-Jackson aquifer (Deeds and others, 2010), the boundary between the Catahoula and Upper Jackson formations occurs at a depth near 460 feet below ground surface. This boundary places the upper three well screen intervals into the Catahoula Formation of the Gulf Coast Aquifer and the lowest screen into the Jackson Formation of the Yegua-Jackson Aquifer. As shown in the lithologic logs, there is a noticeable difference in the frequency of sand units between the two formations. Over the well screen interval, the Catahoula has significantly thicker sands and a greater percentage of sand than the Jackson Aquifer. This difference is reflected in the amount of well screen in the two formations. For the 260-foot interval that occurs between the top of the well screen to the bottom of the Catahoula, 70 percent (180 feet) is covered by well screens. For the 170-foot interval that occurs between the top of the Jackson Formation and the bottom of the well screen, 12 percent (20 feet) is covered by well screens.

For each of the four well screen intervals, there are at least two Dual Membrane Passive Diffusion stations (bags) with measured total dissolved solids concentrations. For three of the well screens, the measured total dissolved solids concentrations for the bags in the well screen are within about 10 percent of the averaged total dissolved solids concentration for the bags. For the two uppermost screened intervals (210 to 270 feet bgs; 310 to 330 feet bgs), both in the Catahoula Formation, the total dissolved solids concentrations range between 1,120 and 1,170 milligrams per liter. These concentration values are in good agreement with measured total dissolved solids concentrations from the TWDB database for wells in the Catahoula Formation within a 5-mile radius of the Wolverine well. For the lower well screen interval (610 to 630 feet below ground surface), the total dissolved solids concentration ranges between 2,540 and 2,800 milligrams per liter. These concentrations are in good agreement with measured total dissolved solids concentrations from in the TWDB database for wells in the upper portion of the Jackson Aquifer and within a 5-mile radius of the Wolverine well.

The well screen interval from a depth of 350 feet to 450 feet below ground surface has total dissolved solids concentrations that range from 1,200 and 2,440 milligrams per liter and an increase in total dissolved solids concentration of 850 milligrams per liter between the depths of 400 and 440 feet below ground surface. Such large differences in the total dissolved solids concentrations indicate that mixing of groundwater with different qualities is occurring in the well and well annulus. Despite these large differences in total dissolved solids concentration, one cannot determine with confidence the risk of comingling without measurements of either vertical flow in the well or hydraulic head along the vertical extent of the well screen. Both data sets lacking for this well. Although Environmental Resources Management (2018) states that an In-Situ Troll was used to measured hydraulic heads in the well at each well screen location, Environmental Resources Management (2018) does not provide the data.

We propose the following explanation for the measured total dissolved solids concentrations in the Wolverine Well. Groundwater from the Catahoula Formation with a total dissolved solids concentration of about 1,150 milligrams per liter is entering the upper two well screens and flowing downward until a depth of about 400 feet below ground surface. Groundwater from the Jackson Formation and with a total dissolved solids concentration of about 2,500 milligrams per liter is entering the lowest well screen and flowing upward until a depth of about 440 feet below ground surface. In the 100-foot well screen and near a depth of 400 to 440 feet below ground surface groundwater is flowing outward into the Catahoula Aquifer with a total dissolved solids concentration that ranges between 2,500 and 1,500 milligrams per liter. This is a possible interpretation of the concentration and as such is not certain but is based upon years of experience interpreting in borehole tracing data.

The data from the Wolverine well demonstrates that mixing of groundwater with significant different chemistries is occurring and that two different methodologies were successful in measuring the vertical profile for total dissolved solids concentrations. One methodology used a downhole probe to measure specific conductance. The other methodology used Dual Membrane Passive Diffusion bags. The data provides evidence of mixing of different water qualities within the borehole and shows potential for mixing between aquifers and zones. The question of degradation, and therefore comingling, associated with this mixing is a subject of interpretation.

Table 5-22. Measured Concentrations in the Wolverine Well using a YSI Sonde and Dual Membrane Passive Diffusion bags (data from ERM, 2018).

Depth (feet bgs) of Well Screened Interval[1]	YSI Measured Specific Conductivity (µs/cm) and estimated TDS concentration (mg/l) in Well Screen Interval[2,3]	YSI Measured Salinity (Practical Salinity Units [ppt][4] in Well Screen Interval	Depth (feet bgs) of Dual Membrane Passive Diffusion	Dissolved Concentrations (mg/l)[5] Measured in the Dual Membrane Passive Diffusion Bags							
				TDS	Ca	Mg	K	Na	Cl	S0$_4$	Ca + Mg + K + Na + Cl + SO$_4$
210 to 270	1868 µs/cm (1,083 mg/l)	0.94 ppt	220	1160 J	92.2	8.8	28	352	380	136	997
			240	1140 J	46.9	3.5	20.2	402	318	40	830.6
			260	1120 J	40.3	2.6	18.6	406	297	277	1041.5
310 to 330	1896 µs/cm (1,100 mg/l)	0.96 ppt	315	1160 J	39.9	2.7	17.9	435	299	265	1059.5
			325	1170 J	39.6	2.7	18.4	429	301	265	1055.7
350 to 450	4860 µs/cm (2,819 mg/l)	2.59 ppt	360	1200 J	43.1	3.2	18.5	430	304	267	1065.8
			400	1590 J	41.2	2.9	22.6	666	437	445	1614.7
			420	2020	39.4	2.6	25.5	886	532	620	2105.5
			440	2440	38	2.3	27.6	1080	642	818	2607.9
610 to 630	6288 µs/cm (3,647 mg/l)	3.40 ppt	615	2540	41.5	3	26.3	936	639	804	2449.8
			625	2800	40.6	2.9	28.1	1090	815	925	2901.6

Notes: [1] Screened interval from State of Texas Well Report #465084

[2] µs/cm = microSiemens per centimeter; mg/L = milligram/liter

[3] TDS concentration calculated using a conversion of 0.58 (µs/cm)/(mg/l) for a Na-Cl rich solution (Young and others 2016)

[4] ppt = parts per thousand

[5] TDS = Total Dissolved Solid; Ca = calcium; Mg = magnesium; mg/L = milligrams per liter, K=potassium; Na=sodium; Cl=chloride; S0$_4$=sulfate

Qualifiers: J = Qualified during the data usability assessment as an estimated concentration

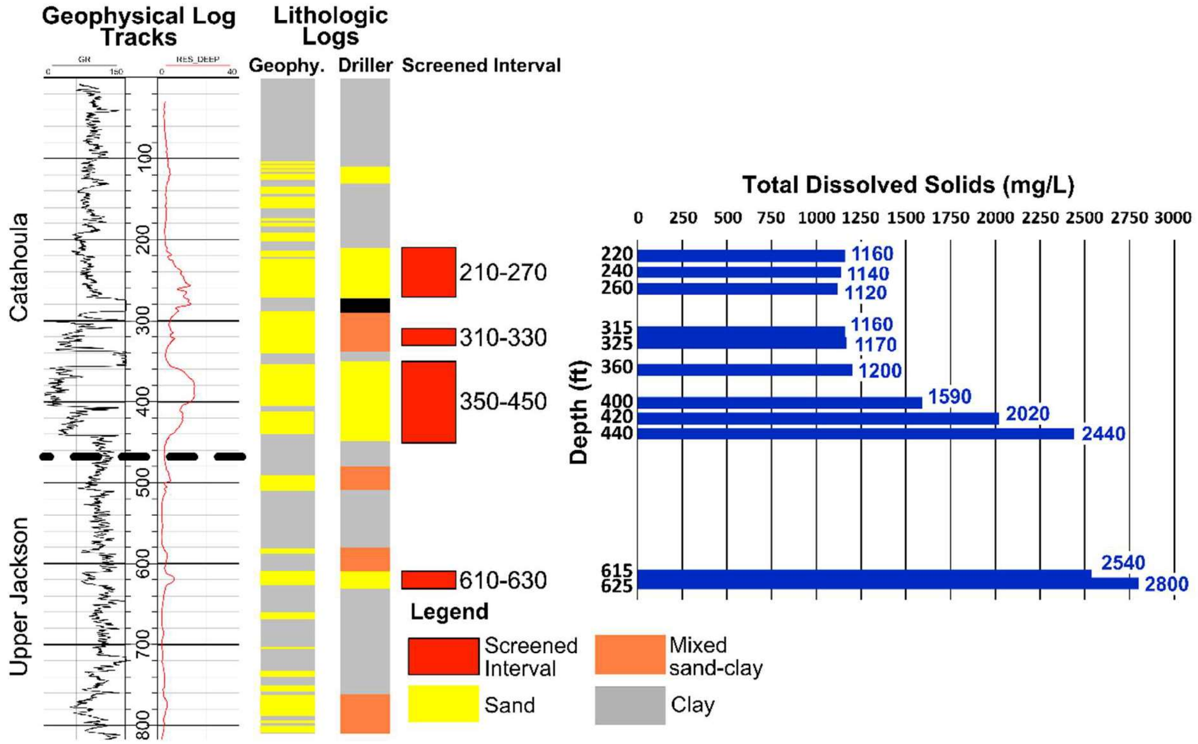


Figure 5-59. **Wolverine Well Data Including Geophysical Log Tracks, Lithologic Profiles based on geophysical logs and driller logs, well screen intervals, and total dissolved solids concentration profiles measured in the Dual Membrane Passive Diffusion Bags.**

5.4 Trans-Pecos Region

The Trans-Pecos Region area is bordered on the north and east by the Pecos River and is transitional eastward to the Edwards Plateau. The region is bordered by the south and west boundaries by the Rio Grande. The region is structurally and geologically complex (Urbanczyk and others, 2001) and as a result the aquifers are diverse in character from the bolson aquifer systems to the igneous aquifer systems. The Edwards-Trinity (Plateau) Aquifer extends westward over the Central Basin Platform into the eastern portion of the Trans-Pecos region and the Ogallala and Dockum aquifers extend into the region from the north. Regional groundwater flow systems are an important aspect of the groundwater aquifers in the Trans-Pecos (Sharp, 2001; Uliana and Sharp, 2001; Uliana, 2000). Many of the aquifers are in direct contact and are prone to being co-completed. Many other aquifers in the region are distinct with little potential for being cross completed to another aquifer.

Surface water is not a reliable source over much of the Trans-Pecos Region making aquifers of heightened importance as a water supply to the region. Most of the area is very sparsely populated. Water use from energy user groups is significant in the region because the Permian Basin extends across most of the central and eastern portions of the Trans-Pecos Region. Historically groundwater has been used for secondary recovery and pressure drive in oil and gas fields (Brackbill and Gaines, 1964; Hiss 1975). With the development of unconventional drilling and completion techniques, groundwater has become a significant resource in the region for fracking reservoir rocks and increasing productivity (Scanlon and others, 2017).

This section provides an assessment of the potential for borehole comingling within the aquifers in the Trans-Pecos Region. As in the prior two regional assessments, this section will begin with a description of the aquifers followed by a regional assessment of the potential for comingling of brackish groundwater. A case study of a situation which could be considered comingling will be discussed and the section will end with a summary of the findings relative to the potential for comingling of groundwater in the region/aquifer.

5.4.1 Description of the Aquifers Within the Trans-Pecos Region

The aquifers underlying the Trans-Pecos Region of West Texas are as diverse as the overlying geography. The aquifers comprising the Trans-Pecos Region of West Texas are presented in Figure 5-60 and include (in alphabetical order): Bone Springs – Victoria Peak, Capitan Reef Complex, Dockum, Edwards-Trinity (Plateau), Hueco – Mesilla Bolson, Igneous, Marathon, Pecos Valley, Rustler and West Texas Bolsons aquifers. Each of these aquifers have literature detailing their geology and hydrogeology and all except the Marathon have a TWDB Groundwater Availability Model that is used to represent the hydraulics inherent to the aquifer. A groundwater availability model for the Marathon Aquifer is currently under development by the TWDB.

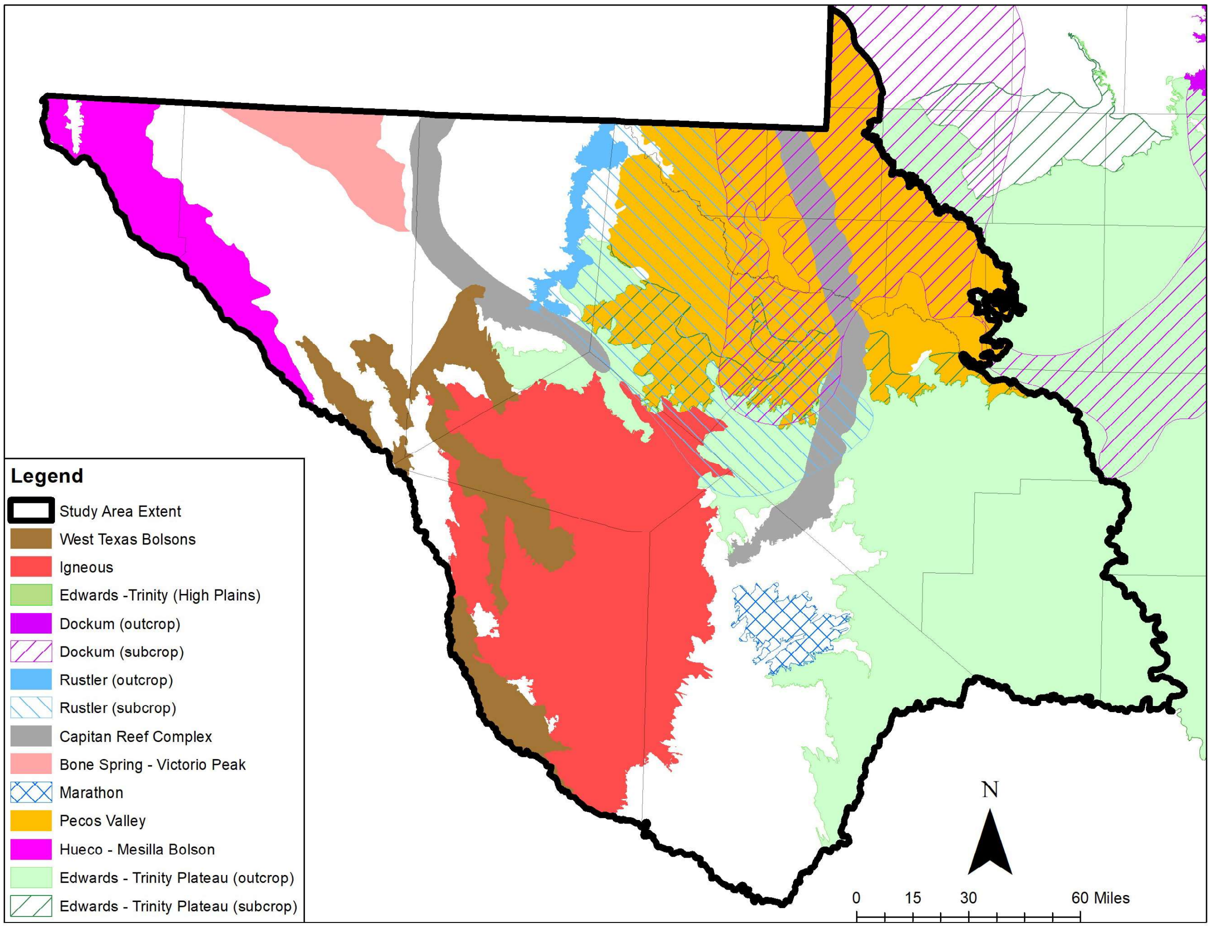


Figure 5-60. **Trans-Pecos Region and Associated Aquifers**

Although we show the aquifers as separate entities, many are hydraulically connected to each other. For example, some of the West Texas Bolsons are connected to the Igneous and Capitan Reef aquifers (Angle, 2001). The Pecos Valley Alluvium, Edwards-Trinity (Plateau), Dockum, Rustler, and Capitan Reef aquifers also hydraulically intermingle with each other in different areas. Sharp (2001) presented an interpretation of regional flow paths in the Trans-Pecos Region aquifers that are regional, and which may connect aquifers across areas without recognized aquifers. Trans-Pecos Region aquifer flow systems are generally complex reflecting orographic recharge, complex geology and structure and complicated discharge mechanisms. The following is a summary of each of the aquifers in the Trans-Pecos Region.

5.4.2 Bone Springs – Victorio Peak

The Bone-Spring Victorio Peak Aquifer is a minor aquifer located in Hudspeth County extending north into the Crow Flats area of New Mexico (Mace, 2001). The primary water bearing rocks within the aquifer are composed of limestones and dolomites from the Bone Spring and Victorio Peak formations. The aquifer is overlain by upwards of 150 feet of Quaternary and recent alluvial sediments. The transmissivity of the aquifer is attributed to secondary porosity in the form of fractures and solution cavities. Water use in the aquifer is primarily for irrigation.

Water levels have historically declined in the aquifer but have remained relatively steady since the late 1970s. The Bone Spring-Victoria Peak Aquifer is somewhat isolated from other aquifers although connected to the Diablo Plateau limestones to the south and west. There is little opportunity for multi-aquifer completions in the aquifer footprint, though salinity contrasts within the aquifer can be extreme, providing potential for wells within the aquifer to encounter a range of salinity classes (Kelley and others, 2020).

5.4.3 Capitan Reef Complex

In Texas, the Capitan Reef Complex Aquifer is a minor aquifer located in Culberson, Hudspeth, Jeff Davis, Pecos, Reeves, Ward, and Winkler counties connected across its northern extent in Southern New Mexico. The Capitan Reef Complex Aquifer is an ancient reef that formed around the margins of the Delaware Basin in the Permian. The reef complex is composed of the reef which is traditionally considered the aquifer, and forereef and back reef deposits of which many are targets of oil and gas development. The reef is composed of up to 2,360 feet of dolomite and limestone, and, in Texas, generally has poor water quality except in the exposed areas of the aquifer. In Texas, most water pumped from the aquifer has historically been in Ward and Winkler counties in support of oil and gas waterflood operations (Brackbill and Gaines, 1964; Hiss, 1975). The aquifer contains significant quantities of brackish groundwater and test drilling in New Mexico has documented vertical stratification of water quality in the aquifer with higher salinities with depth. The productivity of the aquifer is controlled by secondary porosity.

5.4.4 Dockum

The Dockum Aquifer is a minor aquifer, which is primarily located in the High Plains underneath the Ogallala Aquifer and the Edwards-Trinity (Plateau) Aquifer to the north into New Mexico. In the Trans-Pecos Region, the Dockum Aquifer occurs underlying the Edwards-Trinity (Plateau) Aquifer and the Pecos Valley Alluvium Aquifer. The dominant water bearing portion of the Dockum in the Trans-Pecos Region is the Santa Rosa Formation in the Lower Dockum. The Dockum Aquifer consists of up to 700 feet of sand and conglomerate, with layers of silt and shale of the Dockum Group (Mace, 2001). Water quality is variable in the Trans-Pecos Region and ranges from fresh in unconfined or semi-confined areas to moderately saline in confined portions of the aquifer typically used for water production. It is not uncommon to find wells in the Dockum in the Trans-Pecos Region also completed into other aquifers to increase productivity and water quality.

5.4.5 Edwards-Trinity (Plateau)

The Edwards-Trinity (Plateau) Aquifer is a minor aquifer in the Trans-Pecos Region. The Edwards-Trinity (Plateau) Aquifer consists of rocks of the Comanche Peak, Edwards, and Georgetown Formations and the Trinity Group. The Trinity Group consists primarily of sands (Antlers and Maxim sands) and limestones. The Comanche Peak, Edwards, and Georgetown formations consist primarily of limestones and dolomites. The aquifer is a good water source in the region and is most prolific in the Belding Farm Area in Pecos County where historically it has been used as a source of irrigation water. Water quality is reasonably good for the region varying from fresh to slightly saline (George and others, 2011).

5.4.6 Hueco – Mesilla Bolson

The Hueco-Mesilla Bolson Aquifer consists of two bolsons: the Hueco and the Mesilla Bolsons. The Hueco Bolson is in El Paso and Hudspeth, Texas and extends into Mexico to the south and New Mexico to the North. The Hueco-Mesilla Bolsons are composed silt, sand, gravel and clay. The thickness of these deposits reached 9,000 feet in the Hueco Bolson and 2,000 feet in the Mesilla Bolson (George and others, 2011). Water quality in both aquifers ranges from fresh to moderately saline in the portions of the aquifers typically encountered by water supply wells. The Hueco Bolson is a primary water source for the City of El Paso and the aquifer is the location of the world's largest inland desalination plant producing brackish groundwater for El Paso.

5.4.7 Igneous

The Igneous Aquifer is a minor aquifer primarily located in Presidio, Jeff Davis, and Brewster counties. The aquifer consists of a complex system of welded, pyroclastic, lava and volcanoclastic sediments (George and others, 2011). Groundwater is fresh given the inert nature of the aquifer matrix, but fluoride and silica can be elevated in some locations (George and others, 2011). The productivity of the aquifer is inconsistent and relies on volcanic rocks with either high primary porosity, significant fracturing or the combination of both. Alpine, Fort Davis, and Marfa rely on the aquifer as a source of municipal water.

5.4.8 Marathon

The Marathon Aquifer is a minor aquifer isolated to Brewster County. The aquifer is composed of structurally complex rocks folded and faulted and comprised of a range of lithologies including chert and limestone. Wells are typically shallow in depth (less than 250 feet) and produce their groundwater from secondary porosity features such as faults and solution cavities. The groundwater is fresh and generally hard (George and others, 2011). The aquifer serves as a water source for Marathon with the remainder of use being domestic and livestock.

5.4.9 Pecos Valley

The Pecos Alluvium Aquifer is a major aquifer that overlies several minor aquifers in the northeastern portion of the Trans-Pecos Region (Figure 5-60). The aquifer is composed of alluvial and windblown sediments which vary in thickness from less than 100 feet to over 1,500 feet. The aquifer thickness is significantly affected by two structural troughs; the Pecos Trough in the west and the Monument Draw in the east. The aquifer deposits are composed of sands, gravels, and clays. The natural groundwater quality is highly variable and total dissolved solids increases with depth in the aquifer. Meyer and others (2011) studied both the structure and the occurrence of brackish groundwater in the aquifer. They found that total dissolved solids concentrations in the Pecos Valley Alluvium Aquifer range from less than 200 to more than 10,000 milligrams per liter (fresh to saline). The aquifer is in contact with the Dockum and Edwards-Trinity (Plateau) aquifers in portions of the Trans-Pecos Region where these aquifers underlie the Pecos Valley Aquifer (Mace, 2001). As a result, it is common to find wells completed in multiple aquifers in areas where the Pecos Valley Alluvium Aquifer is thin.

5.4.10 Rustler

The Rustler Aquifer is a minor aquifer outcropping in Culberson County and extending into the subsurface towards the east. The Rustler Aquifer extends into New Mexico where it is largely a saline aquifer and extends across the Central Basin Plateau to the east. The aquifer delineation is defined by the TWDB as the approximate limit of less than 5,000 milligrams per liter total dissolved solids groundwater. The aquifer is comprised of dolomite, anhydrite, polyhalite and mudstones (Ewing and others, 2012). Lupton and others (2016) evaluated potential brackish groundwater production zones under funding of the TWDB. Their study mapped aquifer structure, which is very complex and mapped the brackish resources within the aquifer. Water quality in the aquifer varies from fresh in the southwestern portion of the outcrop to moderately saline in the confined portions of the aquifer. As one moves east of the Monument Trough the groundwater quality becomes very saline to brine. Given the poor-quality of the aquifer, the groundwater is primarily used for irrigation, livestock, and for waterflood operations.

5.4.11 West Texas Bolson

The West Texas Bolson Aquifers are minor aquifers located in Culberson, Hudspeth, Jeff Davis, and Presidio counties and are part of the Red Light Draw, Eagle Flat, Green River Valley, and Presidio-Redford bolsons, as well as the Salt Basin. The Salt Basin is divided into the Wild Horse, Michigan, Lobo, and Ryan flats. The aquifers are bolson deposits comprised of sediments and rocks eroded from the surrounding highlands. These can range from volcanic rocks and limestones to silt and clay lake deposits. Groundwater from the Bolson aquifers ranges in quality from fresh to moderately saline and is used for irrigation and municipal supply (George and others, 2011).

5.4.12 Brackish Groundwater in the Trans-Pecos Region Aquifers

Most groundwater in storage in the Trans-Pecos Region is brackish groundwater and the region has historically used slightly saline groundwater for domestic, irrigation, and livestock. The occurrence of brackish groundwater has been studied in the county reports and aquifer reports developed by the Water Commission, TWDB, and United States Geological Survey.

The Capitan Reef Complex Aquifer was studied in detail by Hiss (1975) and his study remains a seminal work on the aquifer. The water quality of the Capitan Reef Complex Aquifer is also documented in Jones (2016). Ashworth (1990) reviewed the occurrence and quality of groundwater in all the aquifers in Loving, Pecos, Reeves, Ward, and Winkler counties. Deeds and others (2015) summarized water quality as part of development of the High Plains Aquifer System conceptual framework and this included the Ogallala, Dockum, Edwards-Trinity (Plateau) and the Pecos Valley Alluvium aquifers. Kreitler and others (2013b) studied the hydrochemistry of the aquifers in Groundwater Management Areas 3 and 7, which included the western Trans-Pecos Region portions of the Edwards-Trinity (Plateau) and the Dockum aquifers. Nance (2010) documented a detailed analysis of the variability and evolution of water quality in the Edwards-Trinity (Plateau) Aquifer. Rustler Aquifer water quality was summarized in Ewing and others (2012) and has been updated in a brackish groundwater report discussed below. Water quality in the Presidio-Redford Bolsons was summarized in Wade and others (2011).

The Igneous aquifers and the Bolson aquifers have been summarized in several reports associated with the development of Groundwater Availability Model studies. These include Beach and others (2004) for the Igneous, Wild Horse Flat, Michigan Flat, Ryan Flat and Lobo Flat aquifers and Beach and others (2008) for West Texas Bolsons including Red Light Draw, Green River Valley and Eagle Flat. The United States Geological Survey documented the water quality and geochemistry of groundwater within the Hueco Bolson Aquifer in Texas and New Mexico (Ging and others, 2020).

The TWDB has completed two brackish groundwater studies in the Trans-Pecos Region for the Pecos Valley Alluvium and Rustler aquifers. The TWDB currently has a brackish groundwater resource study in progress for the Edwards-Trinity (Plateau) Aquifer.

Meyer and others (2011) performed a detailed analysis of the structure of the Pecos Valley Alluvium Aquifer in Texas and delineated the brackish groundwater resources in the aquifer. They interpreted geology, lithology, structure, and water quality from thousands of water wells and geophysical well logs and established stratigraphic relationships throughout the aquifer. They also mapped areas where the Pecos Valley Alluvium is in direct contact with Dockum sands. Meyer and others (2011) estimate that the Pecos Valley Alluvium Aquifer contains approximately 85 million acre-feet of brackish groundwater and 15 million acre-feet of fresh groundwater.

Lupton and others (2016) delineated the brackish groundwater resources in the Rustler Aquifer to support TWDB designation of brackish production zones. The study made structural, lithologic, and stratigraphic picks from 589 geophysical logs within the aquifer. Because of the minerology of the Rustler Aquifer, they used state-of-the art petrophysical analysis techniques to analyze geophysical logs for both porosity and water quality to augment quality analyses from water wells. It was estimated that the aquifer contains approximately 18.5 million acre-feet of groundwater, of which 0.4 million acre-feet is fresh and 18.1 million acre-feet is brackish.

5.4.13 Regional Assessment of Comingling

The regional assessment follows the same steps outlined in Section 5.2.2 above. The regional assessment characterizes the potential for comingling in the Trans-Pecos Region aquifers through a regional assessment of: (1) well completions with an emphasis on identifying multi-aquifer completions; (2) maximum head differences between aquifers at the location of multi-completed wells; and (3) water quality within the aquifers. As in the previous two regions discussed in this section, we use the TWDB Groundwater Availability Model structure to define well aquifer completions.

The multi-aquifer Groundwater Availability Models available for use in the Trans-Pecos Region includes; the High Plains Aquifer System Groundwater Availability Model (Deeds and Jigmund, 2015), the Capitan Reef Complex Aquifer Groundwater Availability Model (Jones, 2016), the Igneous-Bolson Aquifers Groundwater Availability Model (Beach and others, 2004), the West Texas Bolson Aquifers Groundwater Availability Model (Beach and others, 2008) and the Presidio and Redford Bolson Aquifers Groundwater Availability Model (Wade and others, 2011).

Aquifer Completions

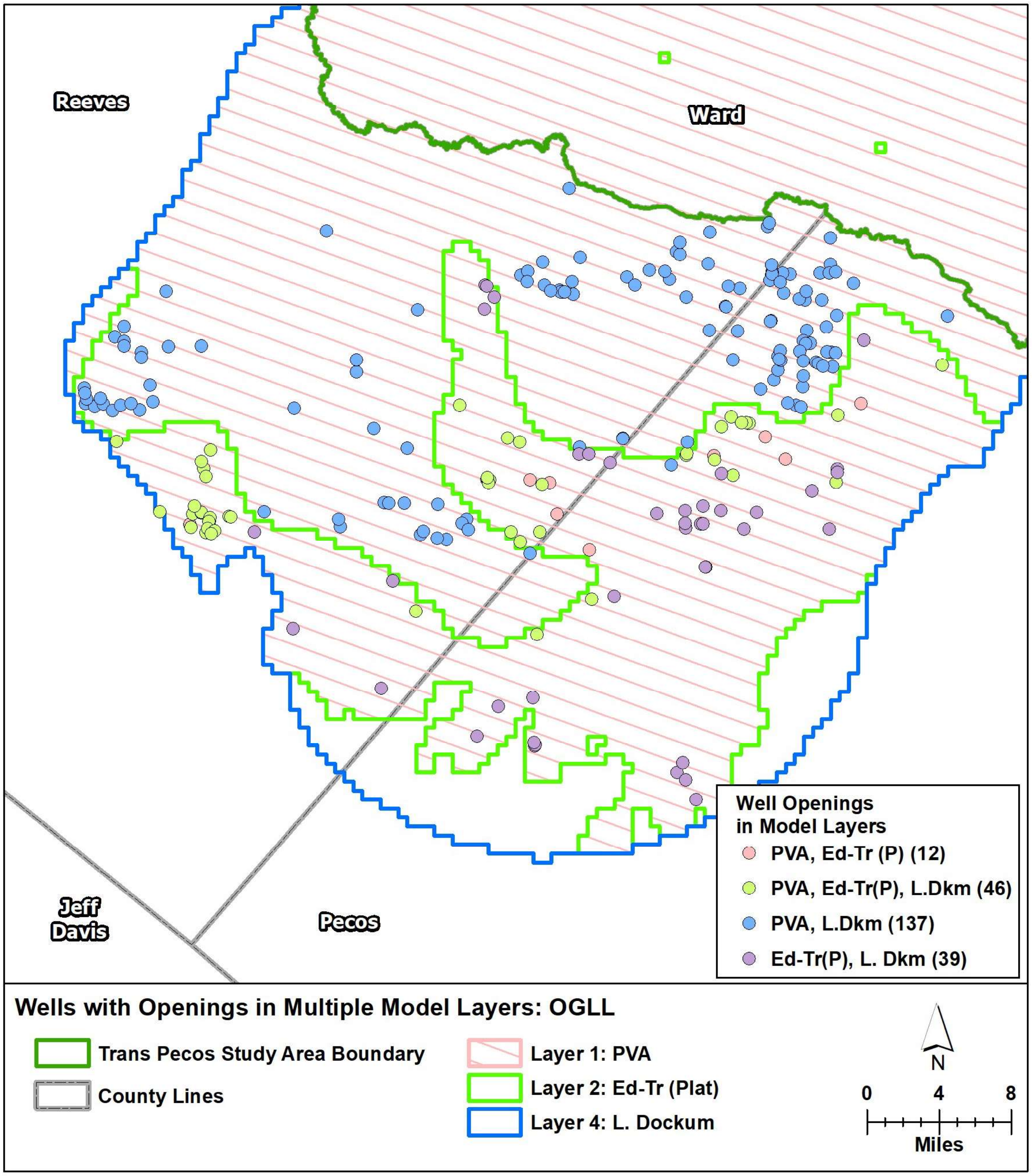
The first step is to characterize the well completions within the aquifers and formations represented in the Trans-Pecos Region. As explained in Section 5.1 above, to perform this step a validated database of groundwater wells and their screen information was developed. Next, the well screens were intersected with aquifer structure to produce tabulations of both single-aquifer completed wells and multi-aquifer completed wells.

Table 5-23 lists the well completions for 848 wells in the High Plains Aquifer System Groundwater Availability Model in the Trans-Pecos Region. Multi-completed wells make up 28 percent of the total wells intersected with model structure with most (137) being in the Pecos Valley Alluvium and Lower Dockum aquifers. There were 39 wells completed in the Edwards-Trinity (Plateau) and the Dockum aquifers and 46 that co-completed in these two aquifers and the Edwards-Trinity (Plateau) Aquifer.

Figure 5-61 plots the multi-completed wells by aquifer completions in the High-Plains Aquifer System Groundwater Availability Model. Figure 5-61 shows and even distribution of wells across the overlap areas for the aquifers in the Trans-Pecos Region, suggesting that cross-completed wells are common.

Table 5-23. Well Completions for the High Plains Aquifer System

Aquifer(s)	Number of Wells
Pecos Valley Alluvium	416
Edwards-Trinity (Plateau)	35
Lower Dockum	163
Pecos Valley Alluvium / Edwards-Trinity (Plateau)	12
Pecos Valley Alluvium /Edwards-Trinity (Plateau)/ Lower Dockum	46
Pecos Valley Alluvium / Lower Dockum	137
Edwards-Trinity (Plateau) / Lower Dockum	39
Total single aquifer	**614**
Total multi-aquifer	**234**
Percent Multi-Completed	**27.6 percent**



Note: OGLL = High Plains Aquifer System Groundwater Availability Model, PVA = Pecos Valley Alluvium, Ed-Tr (Plat) = Edwards-Trinity (Plateau), L = layer

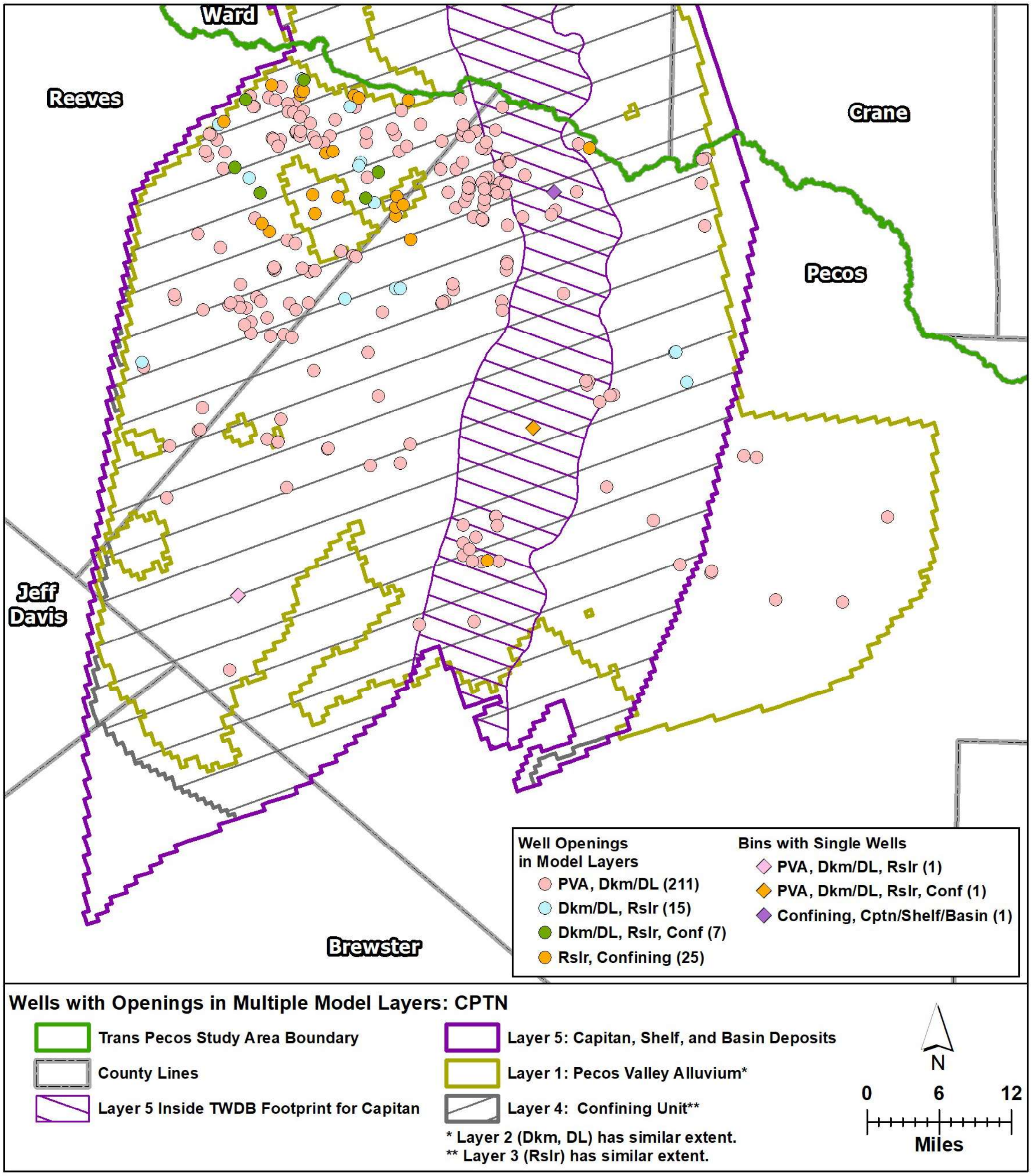
Figure 5-61. **Location of wells completed in two or more aquifers in the High Plains Groundwater Availability Model in the Trans-Pecos Region.**

Table 5-24 lists the well completions for 748 wells in the Capitan Reef Complex Aquifer Groundwater Availability Model in the eastern Trans-Pecos Region. Multi-completed wells make up 35 percent of the total wells intersected with model structure with most (211) being co-completed within the Edwards-Trinity (Plateau) and the Dockum aquifers. The Capitan Reef Complex Aquifer Groundwater Availability Model combines some formations across the model domain. Some layers represent multiple formations based upon location in the model. This makes interpretation of completion counts difficult. The important conclusion from the counts is that the most co-completed wells occur between the Edwards-Trinity (Plateau) and the Dockum aquifers for a total of 211 wells. This is consistent with what we saw in the analysis of the High Plains Aquifer System.

Table 5-24. Well Completions for the Capitan Reef Complex Aquifer.

Aquifer(s)	Number of Wells
Edwards-Trinity (Plateau) or Pecos Valley Alluvium	314
Dockum or Dewey Lake	149
Rustler	16
Artesia or Salado or Castile	1
Capitan or Delaware Mountain Group	7
Edwards Trinity (Plateau) & Dockum	211
Edwards Trinity (Plateau)/Dockum/Rustler	1
Edwards Trinity (Plateau)/Dockum/Rustler/Artesia	1
Dockum/Rustler	15
Dockum/Rustler/Artesia	7
Artesia/Capitan	26
Total single aquifer	**487**
Total multi-aquifer	**261**
Percent Multi-Completed	**34.9 percent**

Figure 5-62 plots the multi-completed wells by aquifer completions in the Capitan Reef Complex Aquifer Groundwater Availability Model. The figure again shows an even distribution of co-completed wells between the Edwards-Trinity (Plateau) and the Dockum aquifers. Few wells would be expected to co-complete the Capitan Reef Complex Aquifer with another aquifer because of the lack of a good aquifer directly overlying the Capitan Reef Complex Aquifer in this area of the Trans-Pecos Region.



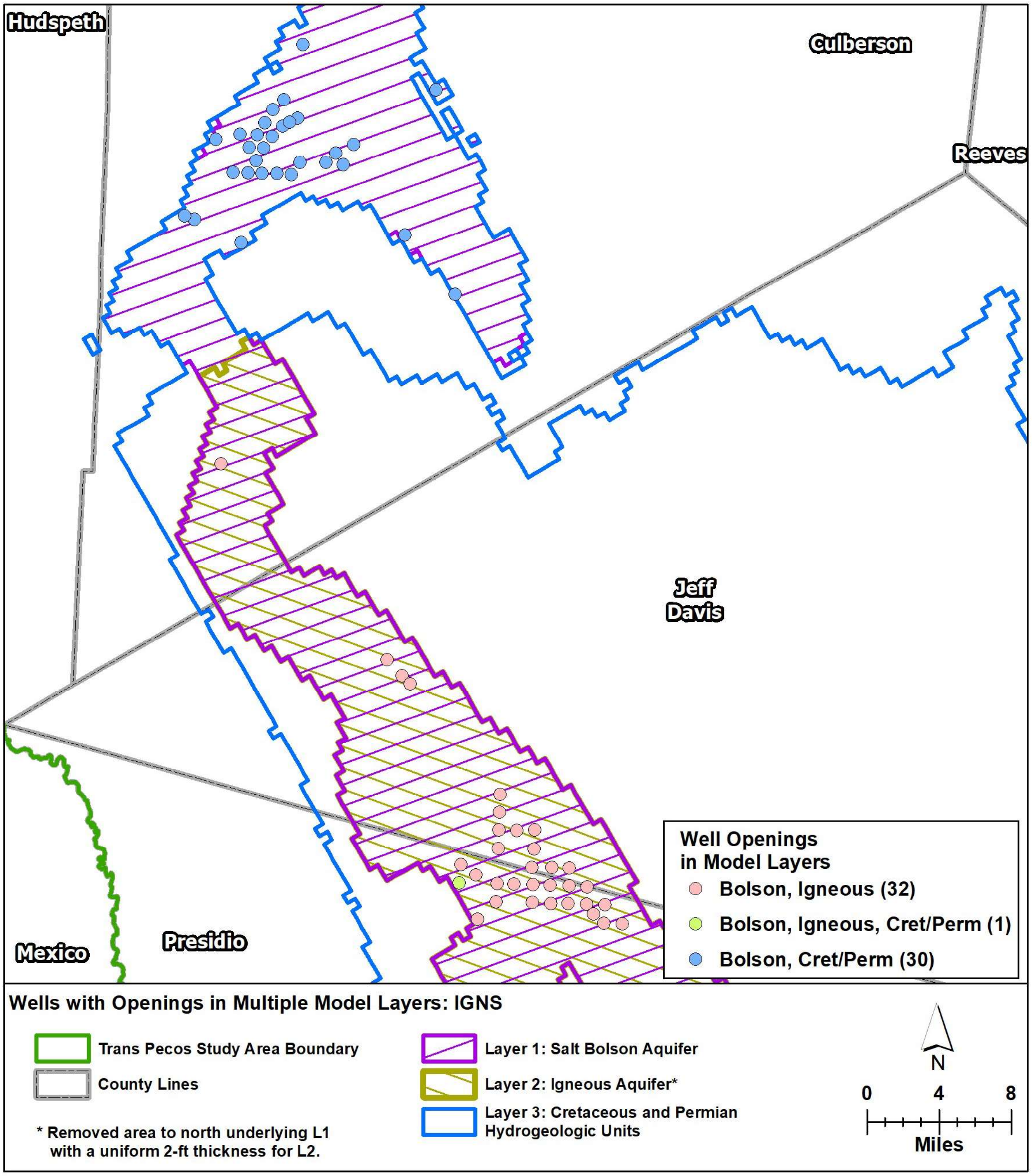
Note: CPTN = Capitan Groundwater Availability Model, Dkm = Dockum, DL = Dewey Lake, Rslr = Rustler, L = layer

Figure 5-62. **Location of wells completed in two or more aquifers in the Capitan Reef Complex Aquifer Groundwater Availability Model in the Trans-Pecos Region.**

Table 5-25 lists the well completions for 226 wells in the Igneous and Bolson aquifers Groundwater Availability Model. Multi-completed wells make up 28 percent of the 226 wells intersected with model structure. The wells are evenly split between the Bolson / Igneous aquifers and the Bolson /underlying Cretaceous bedrock. Figure 5-63 plots the multi-completed wells. The two sets of multi-completed wells are geographically separated to the north and south because of the location of the aquifer contacts.

Table 5-25. Well Completions for the Igneous and Bolson aquifers.

Aquifer(s)	Number of Wells
Bolson	149
Igneous	1
Cretaceous/Permian	13
Bolson/Igneous	32
Bolson/Igneous/Cretaceous	1
Bolson/Cretaceous	30
Total single aquifer	**163**
Total multi-aquifer	**63**
Percent Multi-Completed	**27.9 percent**



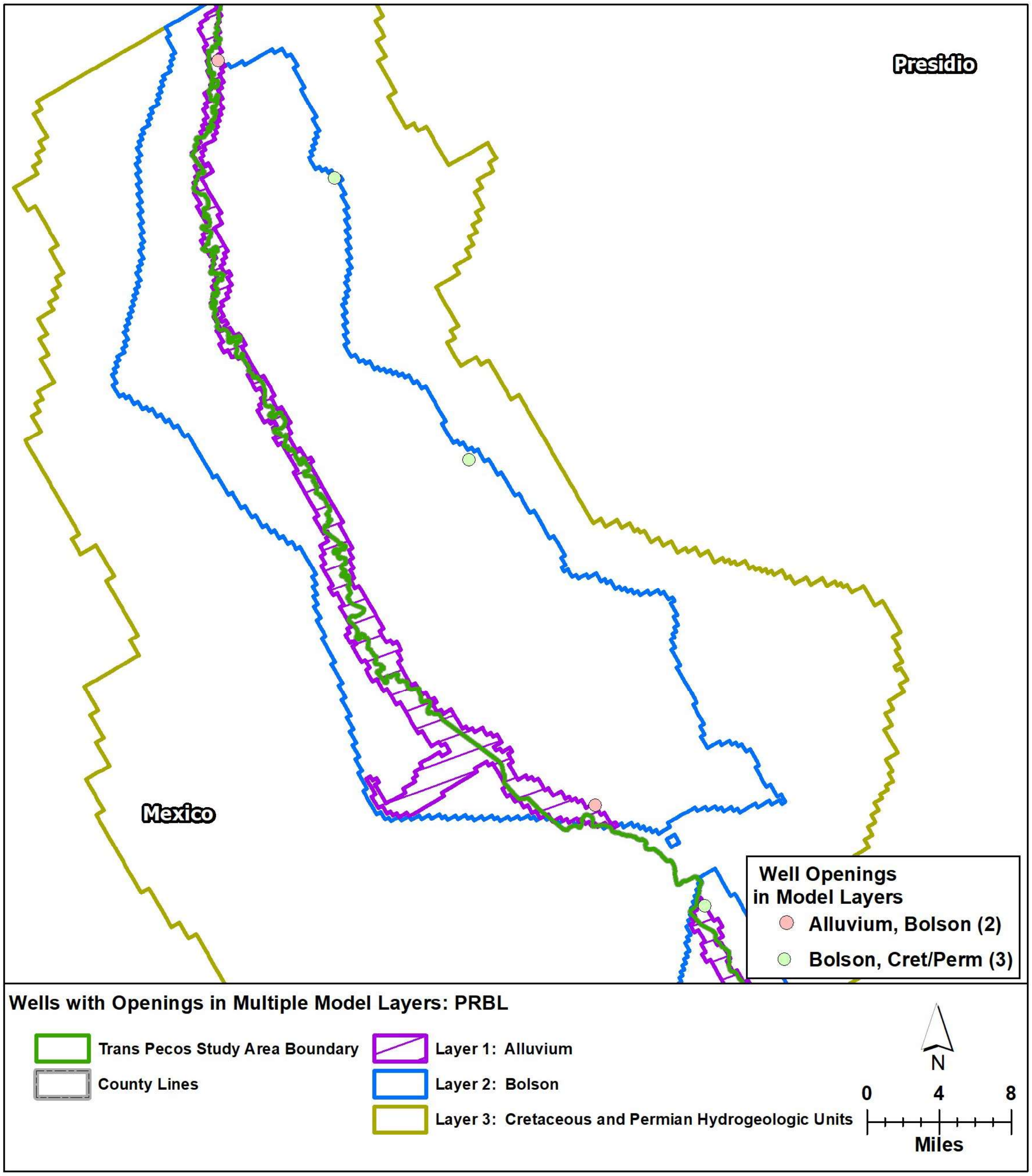
Note: IGNS = Igneous-Bolson Aquifer Groundwater Availability Model, Cret/Perm = Cretaceous / Permian, L = layer

Figure 5-63. **Location of wells completed in two or more aquifers in the Igneous-Bolson Aquifer Groundwater Availability Model in the Trans-Pecos Region.**

Table 5-26 lists the well completions for 88 wells in the Presidio-Redford Bolson Aquifers. Multi-completed wells only make up 5.7 percent (five wells) of the total wells intersected with model structure. Figure 5-64 plots the multi-completed wells. The data suggests that multi-completed wells are not prevalent between this set of aquifers.

Table 5-26. Well Completions for the Presidio and Redford Bolsons Aquifers.

Aquifer(s)	Number of Wells
Alluvium	17
Bolson	45
Igneous/K/Pm	21
Alluvium / Bolson	2
Bolson/ Bedrock	3
Total single aquifer	**83**
Total multi-aquifer	**5**
Percent Multi-Completed	**5.7 percent**



Note: PRBL = Presidio-Redford Bolson Aquifer Groundwater Availability Model, Cret/Perm = Cretaceous / Permian, L = layer

Figure 5-64. **Location of wells completed in two or more aquifers in the Presidio-Redford Bolsons Aquifers Groundwater Availability Model in the Trans-Pecos Region.**

Table 5-27 lists the well completions for six wells in the West Texas Bolson aquifers. Of the six wells intersected with structure, only one shows as multi-completed. The lack of cross-completed wells is consistent with the work of Beach and others (2008) who did not report a prevalence of multi-completed wells.

Table 5-27. Well Completions for the West Texas Bolson Aquifers.

Aquifer(s)	Number of Wells
Bolson	5
Bolson / Bedrock	1
Total single aquifer	**5**
Total multi-aquifer	**1**
Percent Multi-Completed	**16.67 percent**

Maximum Head Differences

Vertical gradients have not been studied in the Trans-Pecos aquifers as extensively as in the coastal plain aquifers of Texas. However, given the orographic controls on recharge in much of the region one would anticipate significant vertical hydraulic gradients in most of the aquifers and between aquifers. To provide insight into vertical gradients or head differences between aquifers in the Trans-Pecos Region we will use the available groundwater availability models to estimate head differences along well screens identified within the aquifers. We will use the last year of the model historical calibration period to calculate the head differences.

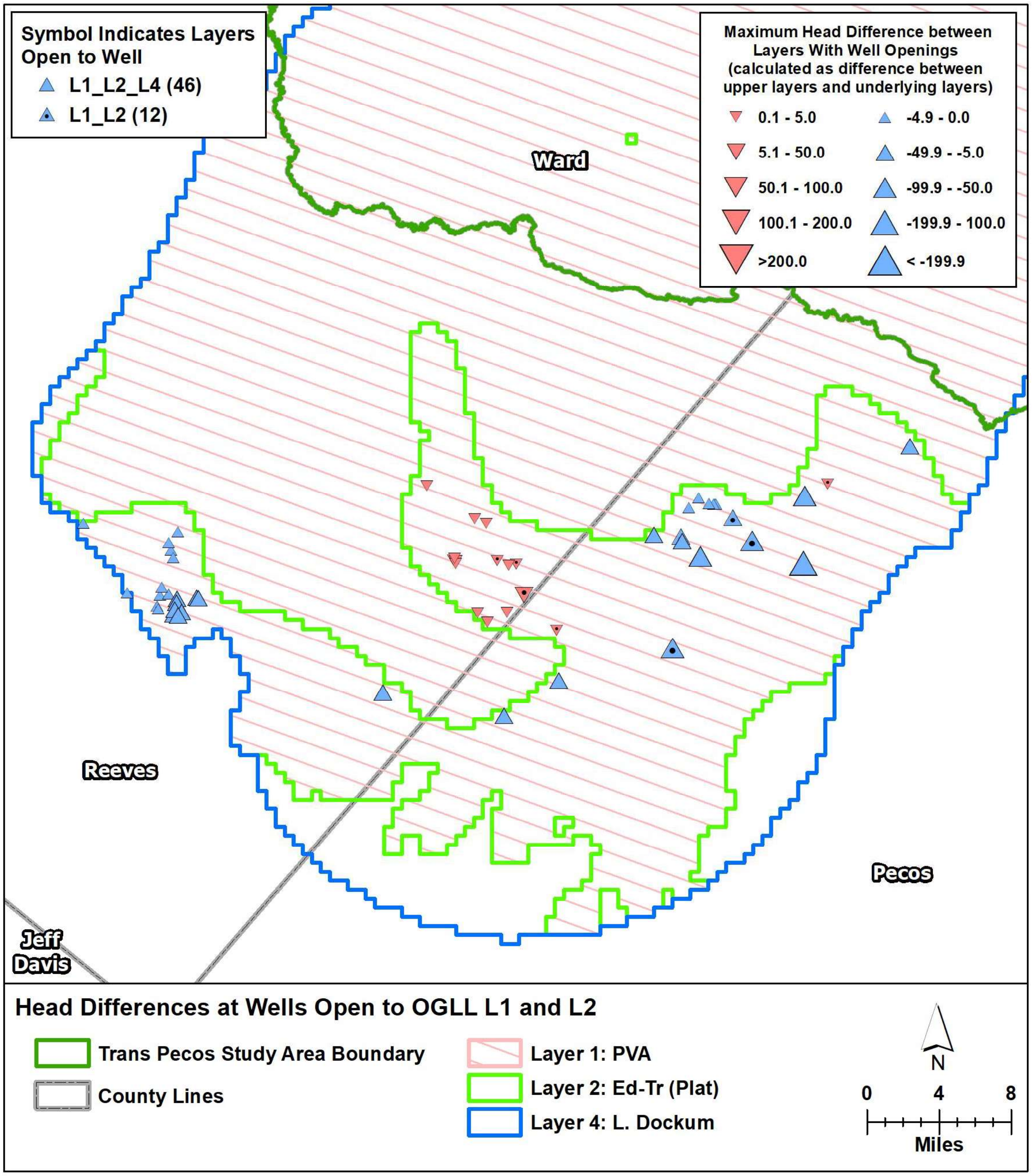
Table 5-28 is a statistical summary of the highest absolute head difference between aquifers in the High Plains Aquifer System Groundwater Availability Model. The highest magnitude of these head differences was determined for each well, and Table 5-28 tabulates these values. So, for the column labeled Pecos Valley Alluvium in Table 5-28 below, all wells completed in the Pecos Valley Alluvium Aquifer and another lower aquifer, and all such permutations, were considered in the calculation. The Upper Dockum is not present in the area, so the model treats layer 3 as a pass-through layer of nominal thickness. Layer 4 of the model is the Lower Dockum. As a result, Table 5-28 has two columns of data representing the maximum head differences for wells completed in the Pecos Valley Alluvium Aquifer and the Edwards-Trinity (Plateau) and or the Lower Dockum and maximum head differences between the Edwards-Trinity (Plateau) Aquifer and the Lower Dockum. Negative head difference is an upward gradient, and a positive difference is a downward gradient. The median vertical-head gradient from the Pecos Valley Alluvium Aquifer to underlying aquifers is upward and the gradient from the Edwards-Trinity (Plateau) Aquifer to the Lower Dockum is downward. The median maximum head differences are significant and adequate to initiate inter-borehole flow.

Figure 5-65 plots the maximum head differences calculated at wells completed in the Pecos Valley Alluvium and Edwards-Trinity (Plateau) aquifers. The figure includes wells with screens co-completed between the Edwards-Trinity (Plateau) and the Dockum. Figure 5-66 plots the maximum head differences calculated at wells completed in the Pecos Valley Alluvium Aquifer and underlying aquifer which would include the Edwards-Trinity (Plateau) Aquifer and the Lower Dockum. These figures clearly show geographic trends in the magnitude and direction of head differences between the aquifers which are likely related to areas where either the Edwards-Trinity (Plateau) or the Dockum aquifers have had significant drawdown. In these areas we should see downward gradients. There do appear to be upward gradients near the Pecos River (Figure 5-66). Figure 5-67 plots maximum head differences calculated at wells completed in the Edwards-Trinity (Plateau) Aquifer and the Lower Dockum.

Table 5-28. Maximum Head Difference Between Aquifers at Wells in the High Plains Aquifer System.

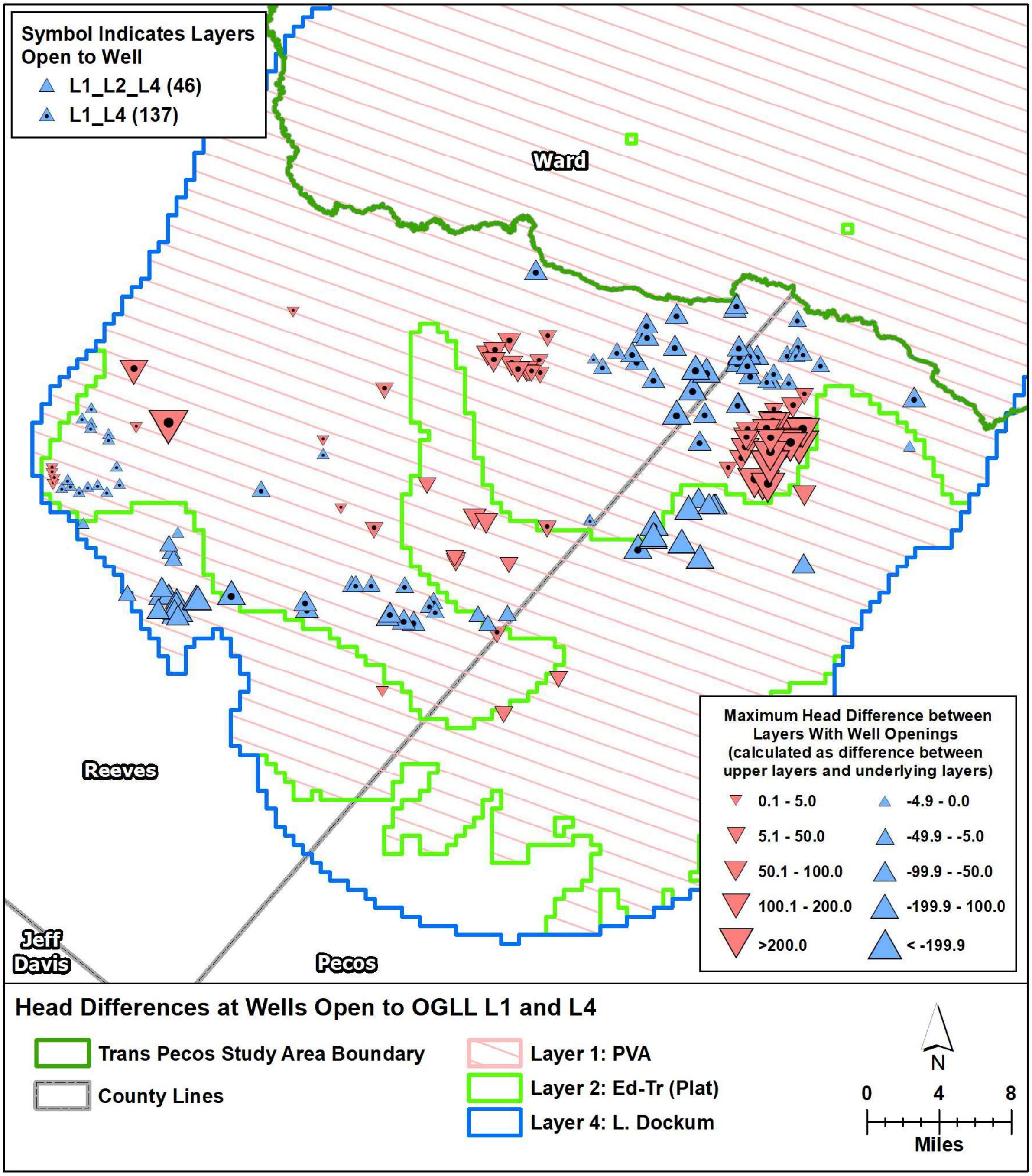
Uppermost Aquifer Considered	Pecos Valley Alluvium	Edwards/Trinity
Count	195	9
Min (ft)	-75.1	-44.3
Max (ft)	1267.4	50.9
Mean (ft)	5.7	11.9
Median (ft)	**-7.7**	**11.1**
St. Dev. (ft)	104.6	22.2

Note: ft = feet



Note: OGLL = High Plains Aquifer System, PVA = Pecos Valley Alluvium, Ed-Tr (Plat) = Edwards-Trinity (Plateau), L = layer

Figure 5-65. Maximum head difference at each well completed the Edwards-Trinity (Plateau) Aquifer and a lower aquifer.



Note: OGLL = High Plains Aquifer System, PVA = Pecos Valley Alluvium, Ed-Tr (Plat) = Edwards-Trinity (Plateau), L = layer

Figure 5-66. Maximum head difference at each well completed in the Pecos Valley Alluvium and the Edwards-Trinity (Plateau) or the Lower Dockum aquifers

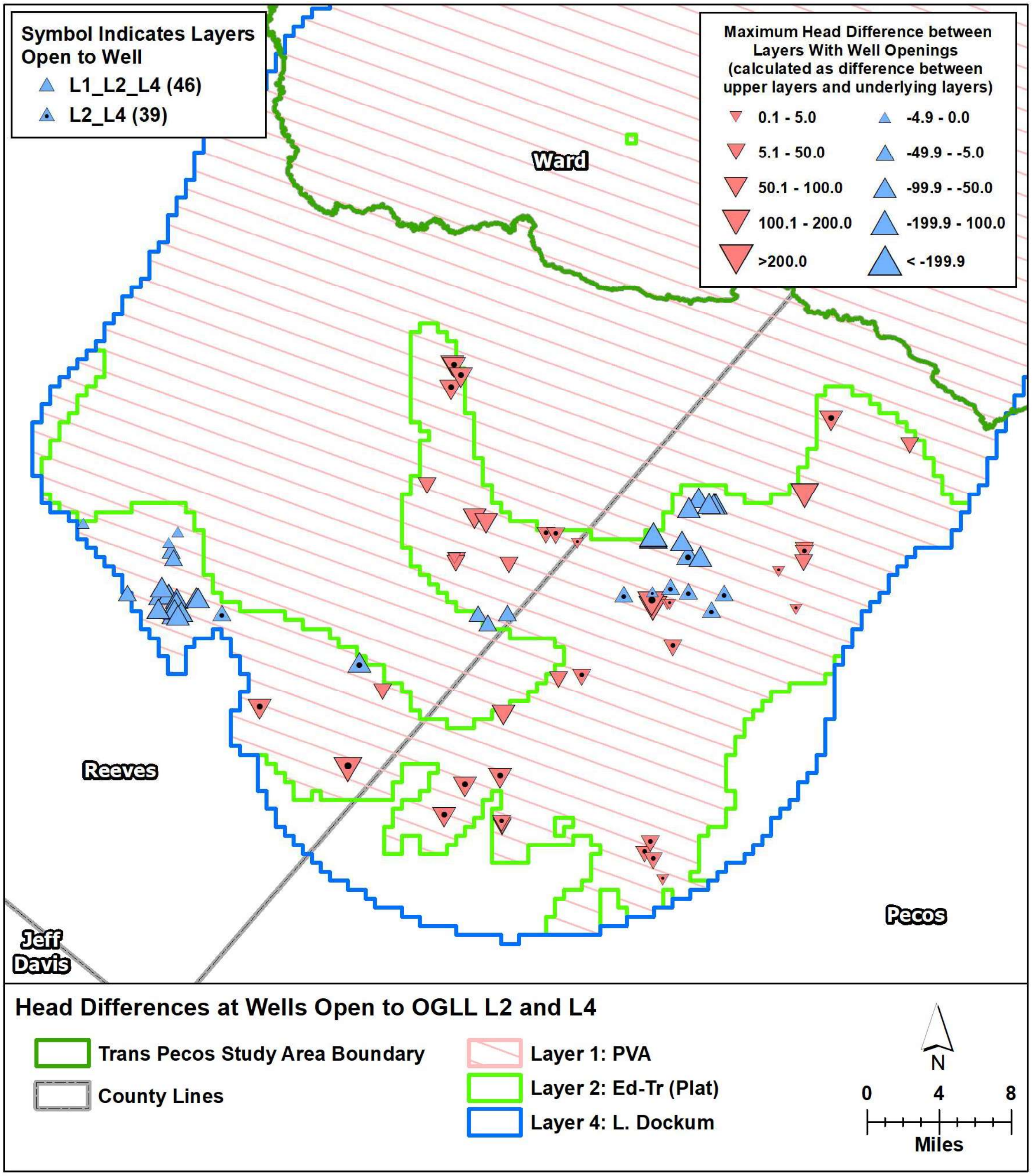
Table 5-29 is a statistical summary of the highest absolute head difference between aquifers in the Capitan Reef Complex Aquifer Groundwater Availability Model. Because the Capitan Reef Complex Aquifer is the lower layer of the model there are no head difference values calculated between it and underlying aquifers. The Artesia Group (model layer 4) is not an aquifer so statistics for it are also not included. While the minimum values of maximum head difference are very large and consistently upward, these values are likely outliers given the median values very close to zero. It appears that the Edwards-Trinity and Pecos Valley Alluvium aquifers (layer 1) and the Dockum and Dewey Lake (layer 2) aquifer heads are near hydrostatic in the model. This is inconsistent with the High Plains Aquifer System Groundwater Availability Model and seems unlikely. The Rustler median maximum head difference indicates a slight upward gradient.

Table 5-29. **Maximum Head Difference Between Aquifers at Wells in the Capitan Reef Complex Aquifer.**

Uppermost Aquifer Considered	Edwards-Trinity/Pecos Valley	Dockum/Dewey Lake	Rustler
Count	213	22	25
Min (ft)	-90.2	-363.7	-339.8
Max (ft)	0.6	0.1	-2.7
Mean (ft)	-0.5	-27.6	-52.2
Median (ft)	**0.0**	**-0.1**	**-8.4**
St. Dev. (ft)	6.2	80.2	88.4

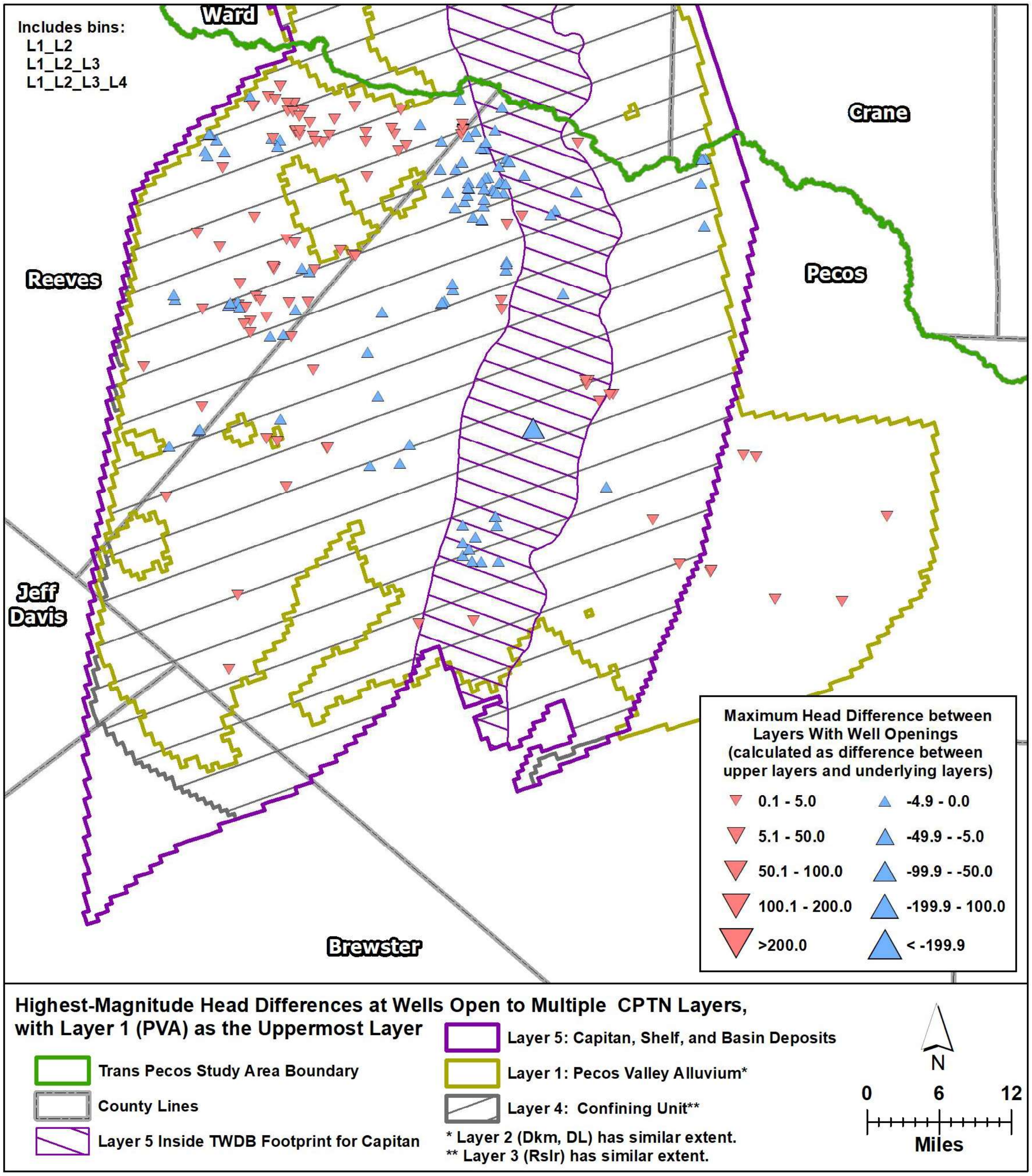
Note: ft = feet

Figure 5-68 plots the maximum head differences calculated at wells completed in the Pecos Valley Alluvium or the Edwards-Trinity (Plateau) aquifers (model layer 1) and any underlying aquifer. Figure 5-69 plots the maximum head differences calculated at wells completed in the Dockum/Dewey Lake (model layer 2) and any underlying aquifer and Figure 5-70 plots the maximum head difference for any well completed in the Rustler Aquifer (model layer 3) and an underlying aquifer.



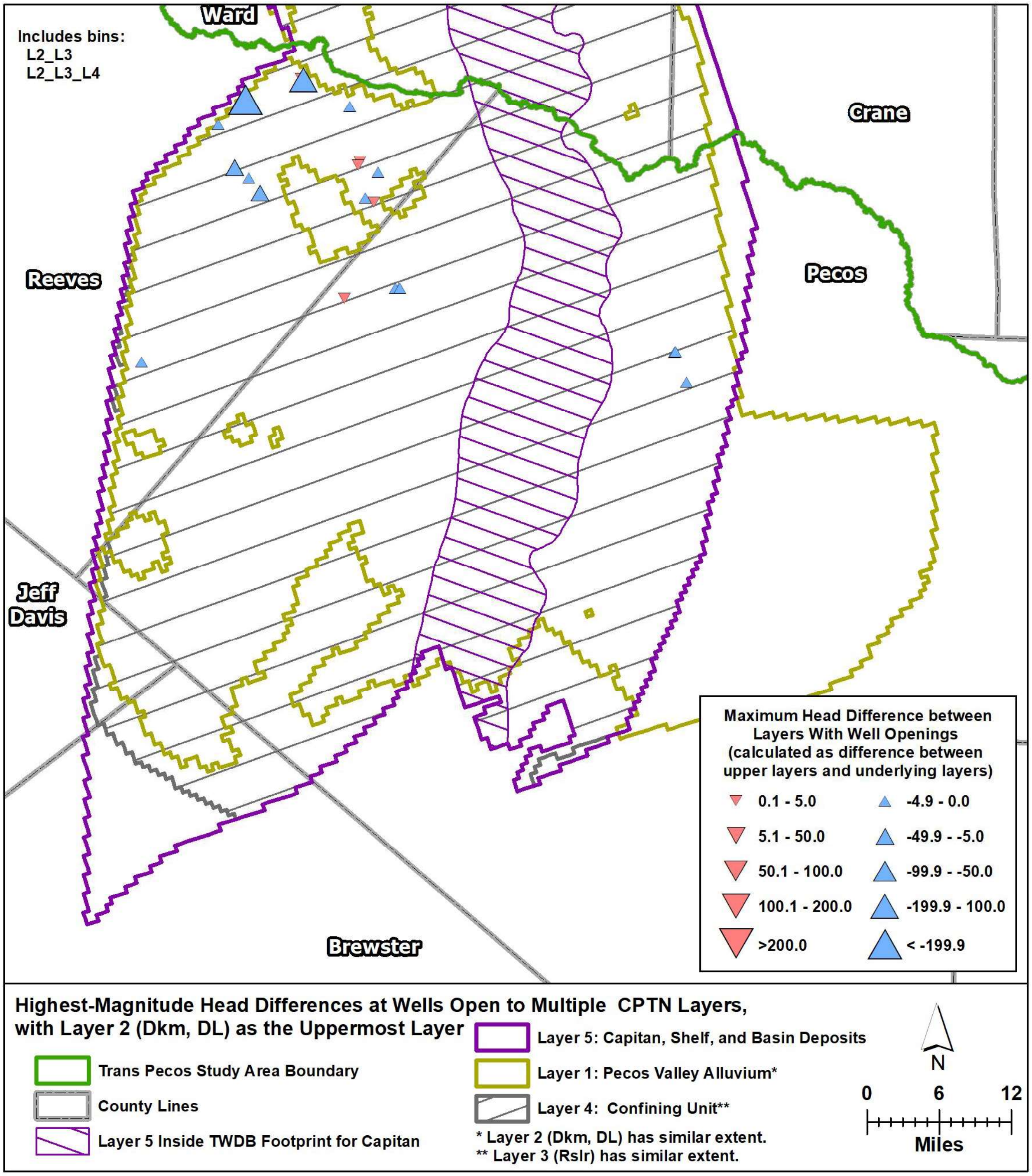
Note: OGLL = High Plains Aquifer System, PVA = Pecos Valley Alluvium, Ed-Tr (Plat) = Edwards-Trinity (Plateau), L = layer

Figure 5-67. **Maximum head difference at each well completed in the Edwards-Trinity and the Lower Dockum (Santa Rosa).**



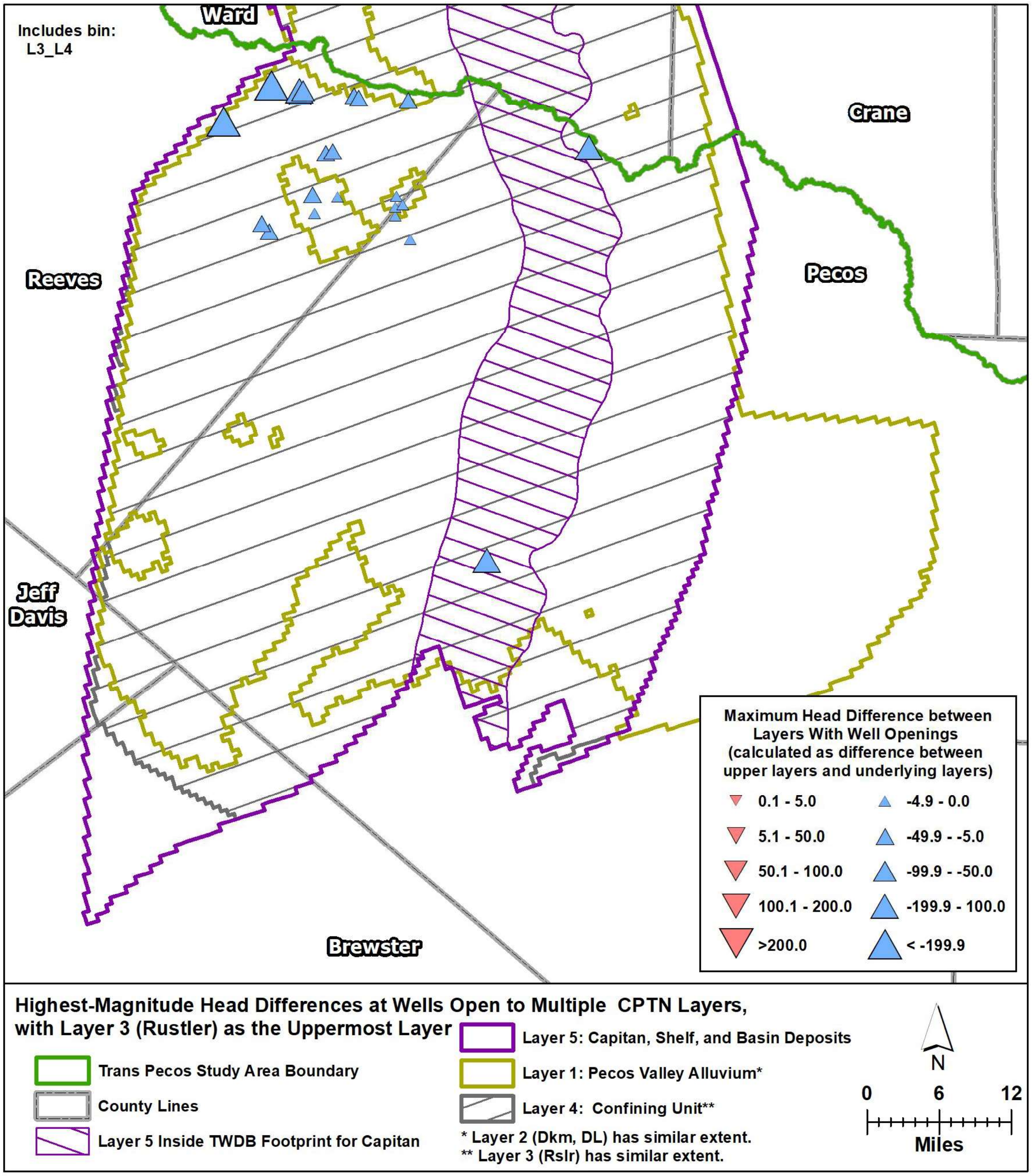
Note: CPTN = Capitan Groundwater Availability Model, Dkm = Dockum, DL = Dewey Lake, Rslr = Rustler, L = layer

Figure 5-68. **Maximum head difference at each well completed in the Pecos Valley Alluvium or Edwards-Trinity (Plateau) and all underlying aquifers.**



Note: CPTN = Capitan Groundwater Availability Model, Dkm = Dockum, DL = Dewey Lake, Rslr = Rustler, L = layer

Figure 5-69. **Maximum head difference at each well completed in the Dockum/Dewey Lake and all underlying aquifers.**



Note: CPTN = Capitan Groundwater Availability Model, Dkm = Dockum, DL = Dewey Lake, Rslr = Rustler, L = layer

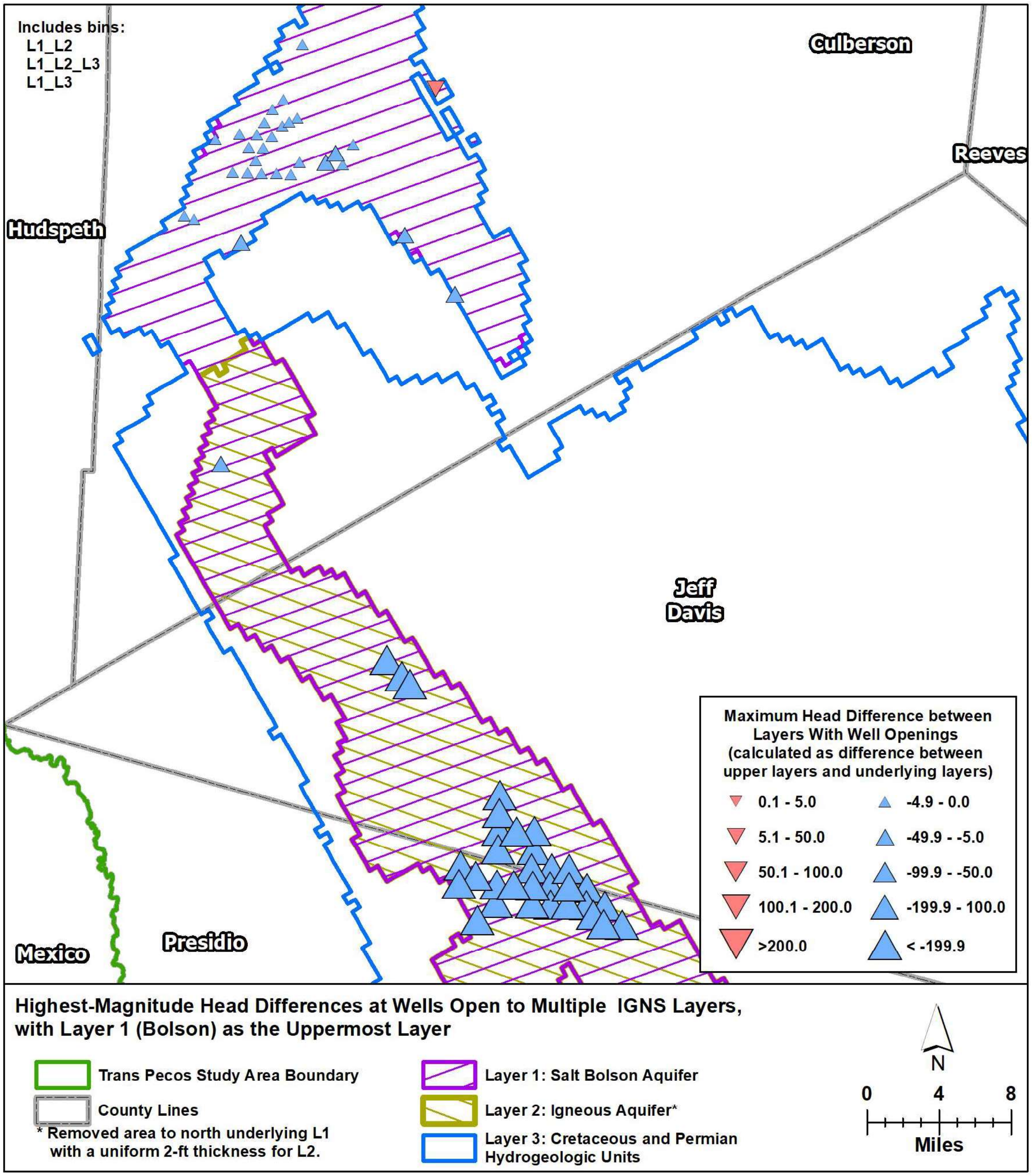
Figure 5-70. Maximum head difference at each well completed in the Rustler and all underlying aquifers.

Table 5-30 is a statistical summary of the highest absolute head difference between the Bolson aquifers and the underlying bedrock units calculated using the Igneous-Bolsons aquifers Groundwater Availability Model. The gradients are strongly upward reflecting that the Bolson aquifers are regional discharge areas. The median head difference is -247.4 feet. Figure 5-71 plots the maximum head differences calculated at wells completed in the Bolson aquifers and either the igneous or Cretaceous bedrock. The gradients in Jeff Davis County in the Bolson are greatest.

Table 5-30. Maximum Head Difference Between Aquifers at Wells in the Igneous Bolson aquifers.

Uppermost Aquifer Considered	Bolsons
Count	63
Min (ft)	-347.6
Max (ft)	12.5
Mean (ft)	-156.2
Median (ft)	**-247.4**
St. Dev. (ft)	154.2

Note: ft = feet



Note: IGNS = Igneous-Bolson Groundwater Availability Model, L = layer

Figure 5-71. **Maximum head difference at each well completed in the Bolson-Uppermost Igneous Aquifers and all underlying aquifers.**

Table 5-31 is a statistical summary of the highest absolute head difference for five wells with screen information completed in the upper two layers and all underlying layers of the of the Presidio-Redford Bolsons aquifers Groundwater Availability Model. As expected, gradients are strongly upward to the alluvium of the Rio Grande. There are only three wells with screen information completed in the Bolson aquifers and the underlying Cretaceous and Permian units. The low number of wells available make these numbers suspect. It also means that aquifer cross-completed wells are not a big issue for this aquifer system.

Table 5-31. Maximum Head Difference Between Aquifers at Wells in the Presidio and Redford Bolsons.

Uppermost Aquifer Considered	Alluvium	Bolson
Count	2	3
Min (ft)	-57.6	-52.8
Max (ft)	-44.3	23.9
Mean (ft)	-50.9	-5.8
Median (ft)	**-50.9**	**11.4**
St. Dev. (ft)	--	41.1

Note: ft = feet

Water Quality

As has been discussed earlier in this report, comingling involves mixing of groundwater between aquifers or zones through a well with the requirement that the mixing causes degradation. Because the concept of degradation is very specific to the details and context, the evaluation of the potential for comingling will be performed using total dissolved solids as a proxy for problem constituents capable of degradation. However, this does not imply that degradation from comingling could not be because of many different constituents, both anthropogenic and natural.

The Texas Commission on Environmental Quality secondary maximum contaminant level for total dissolved solids is 1,000 milligrams per liter. However, there are many other constituents for which the Texas Commission on Environmental Quality have adopted primary and secondary contaminant levels for drinking water. Reedy and others (2011) looked at the percent of water samples that exceeded either the primary or secondary standard as well as calculated the probability that any given sample would exceed a standard for all minor and major aquifers. The constituents analyzed and reviewed by Reedy and others (2011) for all Texas aquifers are shown in Table 5-11 which was reproduced earlier in this report for the Gulf Coast Aquifer. We will limit our review to constituents which exceed their standard in 10 percent or more of the samples analyzed. Table 5-32 summarizes the constituents, by aquifer, that exceed their respective maximum contaminant levels. These constituents are nitrate-N, gross alpha, combined radium, aluminum, chloride, iron, manganese, sulfate, total dissolved solids, and pH. Fluoride is of particular concern when it comes to desalination (Meyer and others, 2011). The Igneous and the Marathon aquifers have the best groundwater quality in the region, neither exceeding the total dissolved solids standard of 1,000 milligrams per liter.

Table 5-32. **Percent of Groundwater Quality Samples that exceed a Primary or Secondary Maximum Contaminant Level (from Reedy and others, 2011).**

Constituent	Edwards-Trinity (Plateau)	Pecos Valley Alluvium	Dockum	Igneous	West Texas Bolsons	Bone Spring-Victoria Peak	Capitan	Marathon	Rustler
Arsenic				17%	18%				
Nitrate-N		14%	11%			15%		25%	
Gross Alpha	20%	17%	28%			40%	33%		76%
Gross Beta								12%	50%
Combined Radium	21%		18%				50%		100%
Uranium	10%	40%				50%			
Chloride	17%	58%	29%			88%	35%		36%
Fluoride (1)	18%	29%	28%	37%	44%	24%	22%		44%
Iron		15%	28%				26%		29%
Manganese		15%	15%				18%		
Sulfate	28%	70%	36%		16%	100%	68%		100%
Total Dissolved Solids	28%	71%	40%		17%	100%	61%		93%
pH					10%				

(1) Comparison to the Secondary Fluoride standard of 2 milligrams per liter

Note: % = percent

In terms of the occurrence of brackish groundwater in the region, there have been two recent studies completed by the TWDB. Meyer and others (2011) completed a study of the Pecos Valley Alluvium Aquifer and Lupton and others (2016) completed a study on the Rustler Aquifer. The TWDB also has an ongoing study of the Edwards-Trinity (Plateau) Aquifer.

The study of Meyer and others (2011) mapped the occurrence of brackish groundwater in the Pecos Valley Alluvium Aquifer. The study mapped total dissolved solids in two dimensions but provided significant evidence of total dissolved solids stratification in geophysical logs interpreted. Higher salinity can overlie lower salinity and vice versa. These conditions can result in wells completing across salinity boundaries.

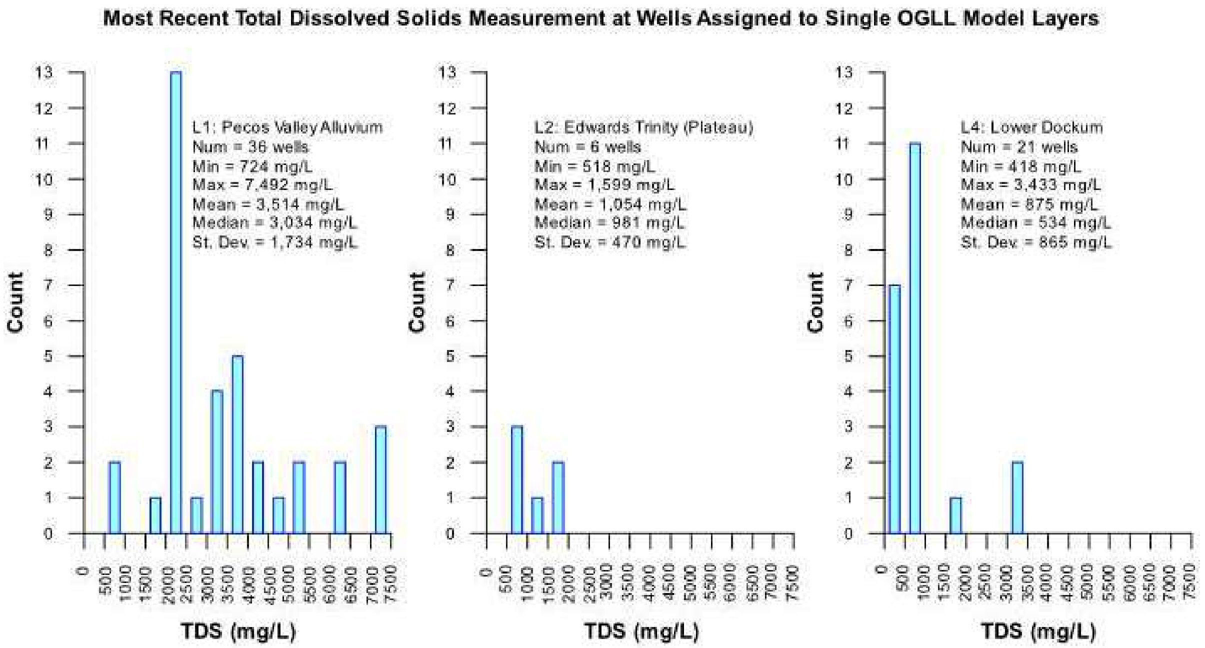
Lupton and others (2016) mapped salinity within the Rustler Aquifer. The aquifer, while relatively thin, is a complex layered assemblage of lithologies. Wells are typically completed across the entire thickness of the Rustler Aquifer therefore no attempt was made in the study to investigate stratification of salinity in the aquifer. Within the aquifer boundaries, the groundwater is mostly slightly and moderately saline with smaller amounts of fresh groundwater. However, the Rustler continues east and becomes saline and brine.

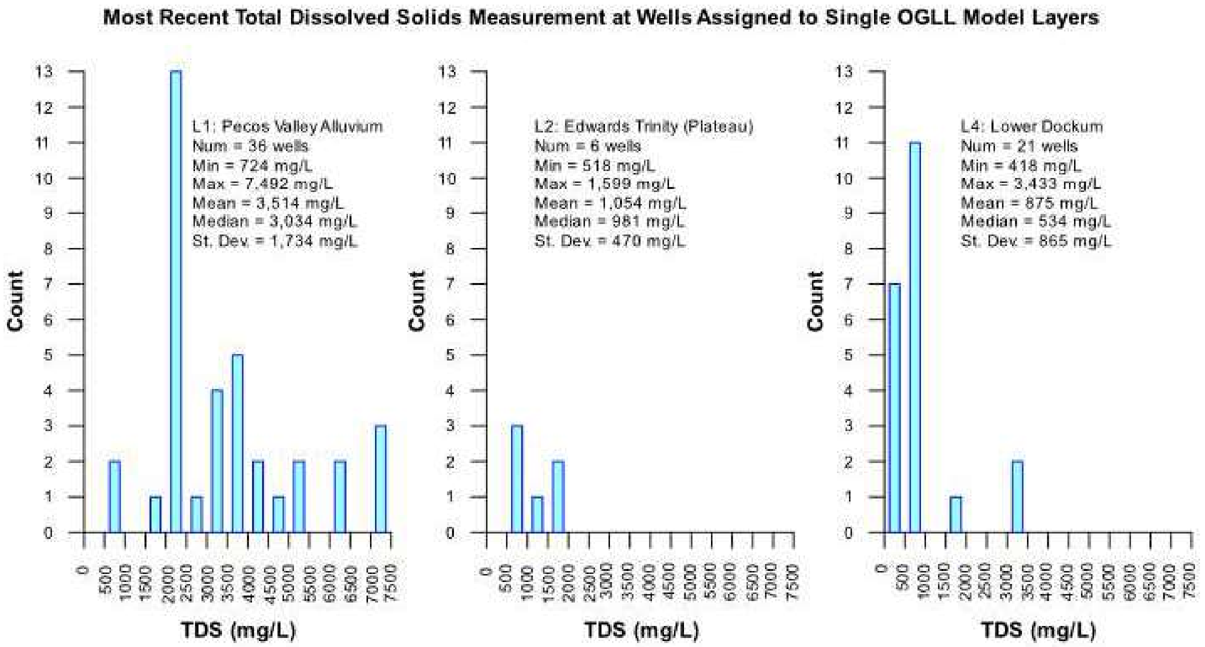
The next step in the regional assessment is to organize water quality, expressed as total dissolved solids, by aquifer in each of the groundwater availability model domains used to investigate well completions and maximum head differences between aquifers. Combined with the well-completion data and the vertical head differences we can gain insight into the potential for comingling in the aquifers adequate data exists.

Table 5-33 summarizes the statistics of total dissolved solids for the aquifers in the High Plains Aquifer System Groundwater Availability Model in the Trans-Pecos Region. Figure 5-72 provides histograms of total dissolved solids for the aquifers in the High Plains Aquifer System Groundwater Availability Model in the Trans-Pecos Region. We found that the predominance of multi-completed wells in this area were between the Pecos Valley Alluvium and the Lower Dockum aquifers followed by the Edwards-Trinity (Plateau) wells completed in the Pecos Valley Alluvium and the Lower Dockum or just between the Edwards-Trinity (Plateau) and the Lower Dockum aquifers (refer back to Table 5-2).We can also see that there are significant vertical head differences between these aquifers.(refer back to Table 5-28). Table 5-33 documents significant differences in total dissolved solids between these aquifers. The potential for mixing of groundwater of different water quality is relatively high in these aquifers.

Table 5-33. Total Dissolved Solids Measurements in Wells within the domain of the High Plains Aquifer System Groundwater Availability Model.

Model Aquifer	Pecos-Valley Alluvium	Edwards-Trinity	Lower Dockum
Num	36	6	21
Min	724	518	418
Max	7,492	1,599	3,433
Mean	3,514	1,054	875
Median	**3,034**	**981**	**534**
StDev	1,734	470	865





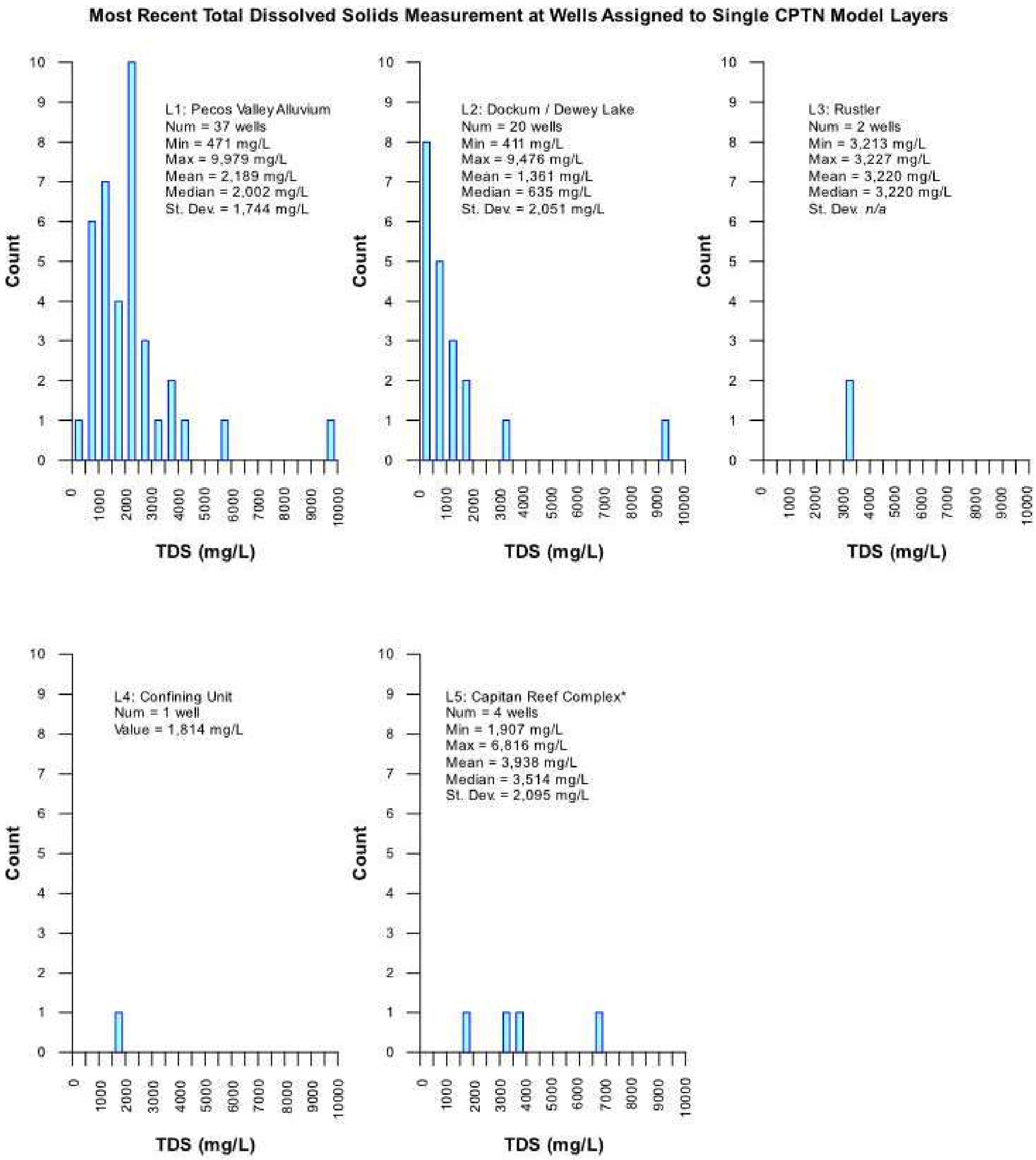
Note: mg/L = milligrams per liter, OGLL = High Plains Aquifer System Groundwater Availability Model, TDS = total dissolved solids

Figure 5-72. **Measured total dissolved solids (milligrams per liter) in from wells within the domain of the High Plains Aquifer System Groundwater Availability Model.**

Table 5-34 summarizes the statistics of total dissolved solids for the aquifers in the Capitan Reef Complex Aquifer Groundwater Availability Model in the Trans-Pecos Region. Figure 5-73 provides histograms of total dissolved solids for the Capitan Reef Complex Aquifer Groundwater Availability Model. Similar to the High Plains Aquifer System, the multi-completed wells are dominated by Edwards-Trinity and or Pecos Valley Alluvium and Lower Dockum completions. The median vertical head differences between these aquifers is close to zero but one can conclude that the vertical head differences between these wells at individual wells can be significant (tens of feet). Table 5-34 documents significant differences in total dissolved solids between these aquifers with the combined Edward-Trinity Plateau and Pecos Valley Alluvium Aquifer water quality significantly worse than the Lower Dockum. Based upon Table 5-33, it would seem the poor water quality is driven by the Pecos Valley Alluvium Aquifer. If we assume that the few wells are completed in the Dewey Lake, there is a regional potential for higher total dissolved solids groundwater from Edwards-Trinity (Plateau) or Pecos Valley Alluvium Aquifer to mix with Lower Dockum groundwater which locally may be of better quality. Again, the potential for mixing of groundwater of different water quality is relatively high in these aquifers. These aquifers have a number of constituents that can be above standards. Comingling potential within the Capitan Reef Complex Aquifers is considered moderate because of the low degree of cross-completed wells with the Capitan Aquifer. However, there are significant salinity contrasts within the Capitan Aquifer where mixing of water quality could occur and be considered comingling.

Table 5-34. Total Dissolved Solids Measurements in Wells within the domain of the Capitan Reef Complex Aquifer Groundwater Availability Model.

Model Aquifer	Edwards-Trinity / Pecos Valley Alluvium	Dockum/Dewey Lake	Rustler	Artesia / Salado	Capitan / Delaware Mountain Group
Num	37	20	2	1	4
Min	471	411	3,213	1,814	1,907
Max	9,979	9,476	3,227	1,814	6,816
Mean	2,189	1,361	3,220	1,814	3,938
Median	**2,002**	**635**	**3,220**	**1,814**	**3,514**
StDev	1,744	2,051	--	--	



* Layer 5 also includes shelf deposits and basin deposits outside the Capitan Aquifer. Verified that all wells classified as being fully or partially in L5 are also within the official TWDB aquifer boundary.

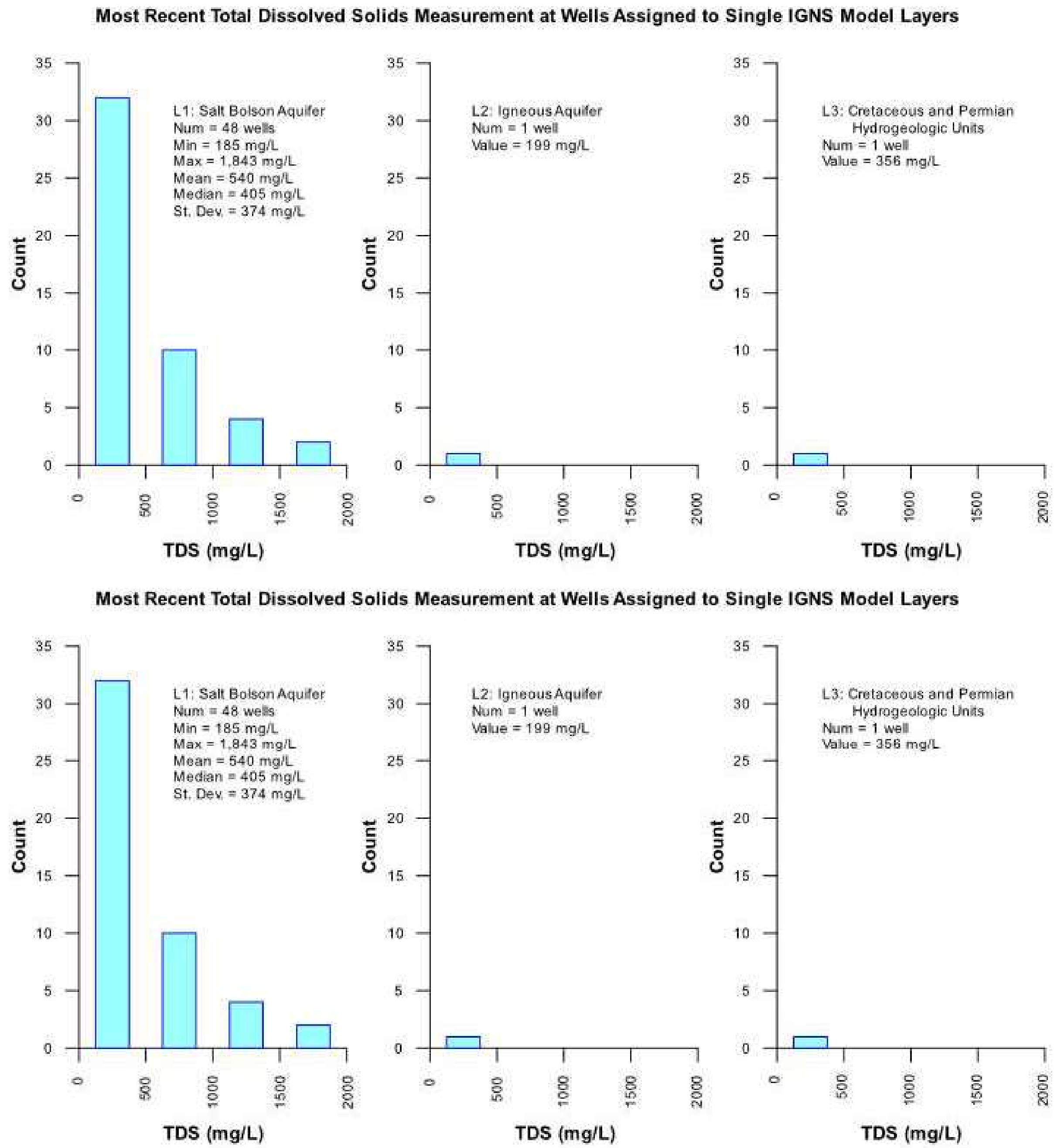
Note: CPTN = Capitan Groundwater Availability Model, mg/L = milligrams per liter, TDS = total dissolved solids

Figure 5-73. **Measured total dissolved solids (milligrams per liter) in from wells within the domain of the Capitan Reef Complex Aquifer Complex Groundwater Availability Model.**

Table 5-35 summarizes the statistics of total dissolved solids for the aquifers in the Igneous-Bolson aquifers Groundwater Availability Model in the Trans-Pecos Region. Figure 5-74 provides histograms of total dissolved solids for the Igneous-Bolson aquifers Groundwater Availability Model. The predominance of multi-completed wells in this area were between the Bolson aquifers and the underlying bedrock. There are significant vertical head differences with a strong vertical gradient upward to the Bolson aquifers so there is strong potential for mixing of groundwater from co-completed aquifers. However, as we can see in Table 5-35, that mixing could only likely cause degradation from trace constituents, not total dissolved solids. The potential for mixing of groundwater of different water quality is relatively high but the potential for degradation appears low except for arsenic and fluoride.

Table 5-35. Total Dissolved Solids Measurements in Wells within the domain of the Igneous and Bolson Aquifers Groundwater Availability Model

Model Aquifer	Bolson	Igneous	Cretaceous / Permian
Num	48	1	1
Min	185	199	356
Max	1,843	199	356
Mean	540	199	356
Median	**405**	**199**	**356**



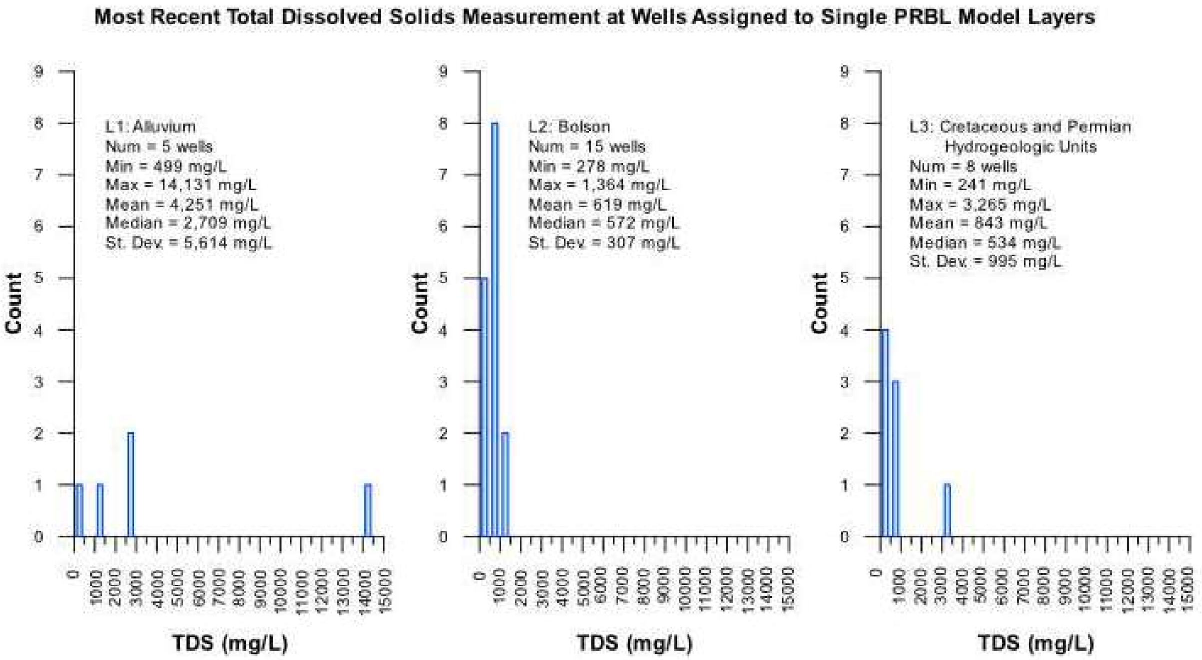
Note: IGNS = Igneous-Bolson Aquifer Groundwater Availability Model, mg/L = milligrams per liter, TDS = total dissolved solids

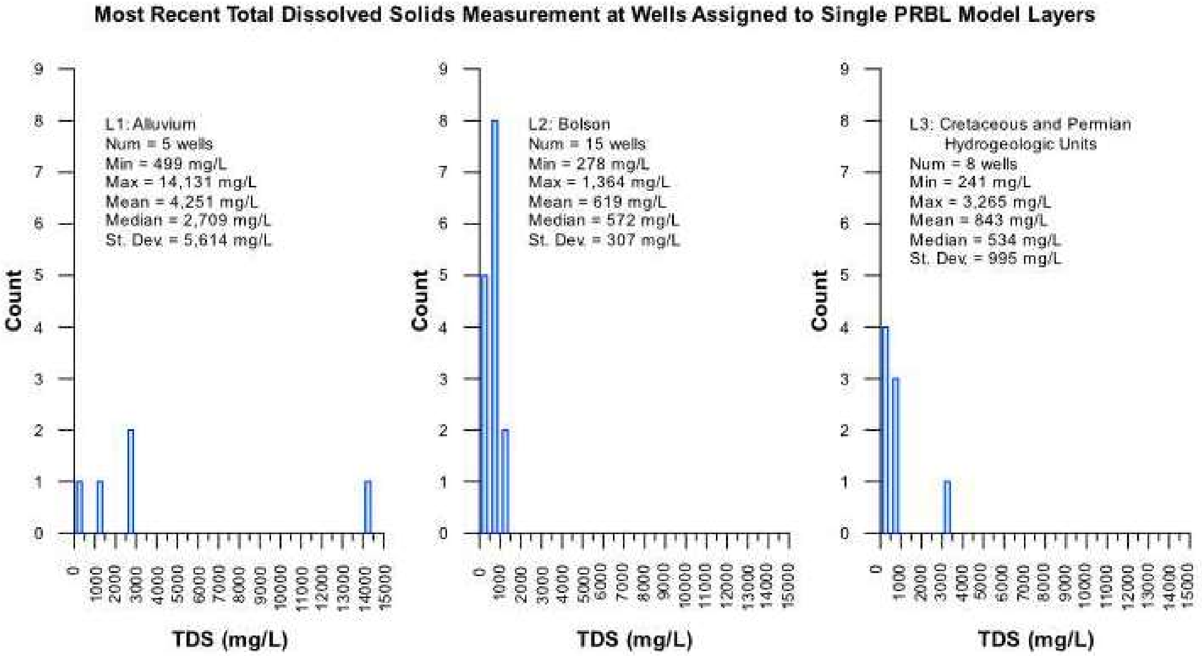
Figure 5-74. Measured total dissolved solids (milligrams per liter) in from wells within the domain of the Igneous-Bolson Aquifer Complex Groundwater Availability Model.

Table 5-36 summarizes the statistics of total dissolved solids for the aquifers in the Presidio-Redford Bolson Aquifers Groundwater Availability Model in the Trans-Pecos Region. Figure 5-75 provides histograms of total dissolved solids for the Presidio-Redford Bolson Aquifers Groundwater Availability Model. The majority of wells (94 percent) in this aquifer are completed in a single aquifer. Head differences between the Bolson aquifers and the bedrock units are high with a strong vertical gradient from the bedrock to the Bolson. Based upon total dissolved solids in the Bolson aquifers and the bedrock, any mixing from the bedrock to the bolsons would likely not degrade water quality. The exception could be trace constituents in the bedrock aquifers. However, the flux contributed from the bedrock units relative to the Bolson aquifers is likely small making the potential for comingling in this aquifer to be low.

Table 5-36. Total Dissolved Solids Measurements in Wells within the domain of the Presidio and Redford Bolson Aquifers.

Model Aquifer	Alluvium	Bolson	Igneous/Cretaceous/Permian
Num	5	15	8
Min	499	278	241
Max	14,131	1,364	3,265
Mean	4,251	619	843
Median	**2,709**	**572**	**534**





Note: mg/L = milligrams per liter, PRBL = Presidio-Redford Bolson Aquifer Groundwater Availability Mode, TDS = total dissolved solids

Figure 5-75. Measured total dissolved solids (milligrams per liter) from wells within the domain of the Presidio-Redford Bolson Aquifer Groundwater Availability Model footprint.

Table 5-37 summarizes the statistics of total dissolved solids for the aquifers in the West Texas Bolson Aquifers Groundwater Availability Model in the Trans-Pecos Region. We found very few wells with screen information in these aquifers to calculate reasonable completion data. These systems likely have local situations where wells are co-completed between the Bolson Aquifers and the bedrock. However, like the Presidio-Redford case, the potential for comingling appears to be low based upon inference and a lack of data.

Table 5-37. Total Dissolved Solids Measurements in Wells within the domain of the West Texas Bolsons.

Model Layer	Bolson
Num	3
Min	323
Max	2,398
Mean	1,103
Median	**587**

5.4.14 Case Study

In this section, we will take a more local look at a specific well completion case to provide insight into the potential for comingling on an actual case study. As previously discussed, direct data providing evidence for comingling in wells is rare because wells with interval discrete water quality and head data is rare in the public domain. The case study presented here brings together various types of data to develop a conceptual framework for potential comingling at wells in Winkler County.

Public Water Supply Case Study

The Public Water Supply is located to the southeast of Kermit, Texas and is completed in the Pecos Alluvium and Dockum (Lower Dockum, Santa Rosa) aquifers (Figure 5-76). In this part of Texas, the Santa Rosa Sandstone is the main water bearing unit within the Dockum Aquifer. The Santa Rosa varies in thickness between 200 and 400 feet regionally and averages around 200 feet thick locally. The Pecos Valley Aquifer is composed of Tertiary- and Quaternary-age alluvium (mostly unconsolidated or poorly cemented clay, sand, gravel and caliche) ranging in thickness from less than 100 feet on the basin edge to over 1,500 feet in the Pecos-Loving and Monument Draw Troughs; two syndepositional solution collapse structural features. The wellfield is situated on the eastern side of the Monument Draw Trough.

Locations for the water supply wells were sampled to raster surfaces representing the base of the Pecos Valley Aquifer (Meyer and others, 2011) and the base of the Dockum Aquifer (Ewing and others, 2008) which is also the base of the Santa Rosa Sandstone. The structural elevations for the two surfaces were combined with well construction data extracted from the submitted driller's reports and are summarized in Table 5-38. Borehole depths for wells in the field average 536 feet belowground surface with an average screen length of 442. The average depth to the base of the Pecos Valley Alluvium Aquifer within the well field is 142 feet below ground surface and the average depth to the base of the Dockum aquifer is 624 feet below ground surface.

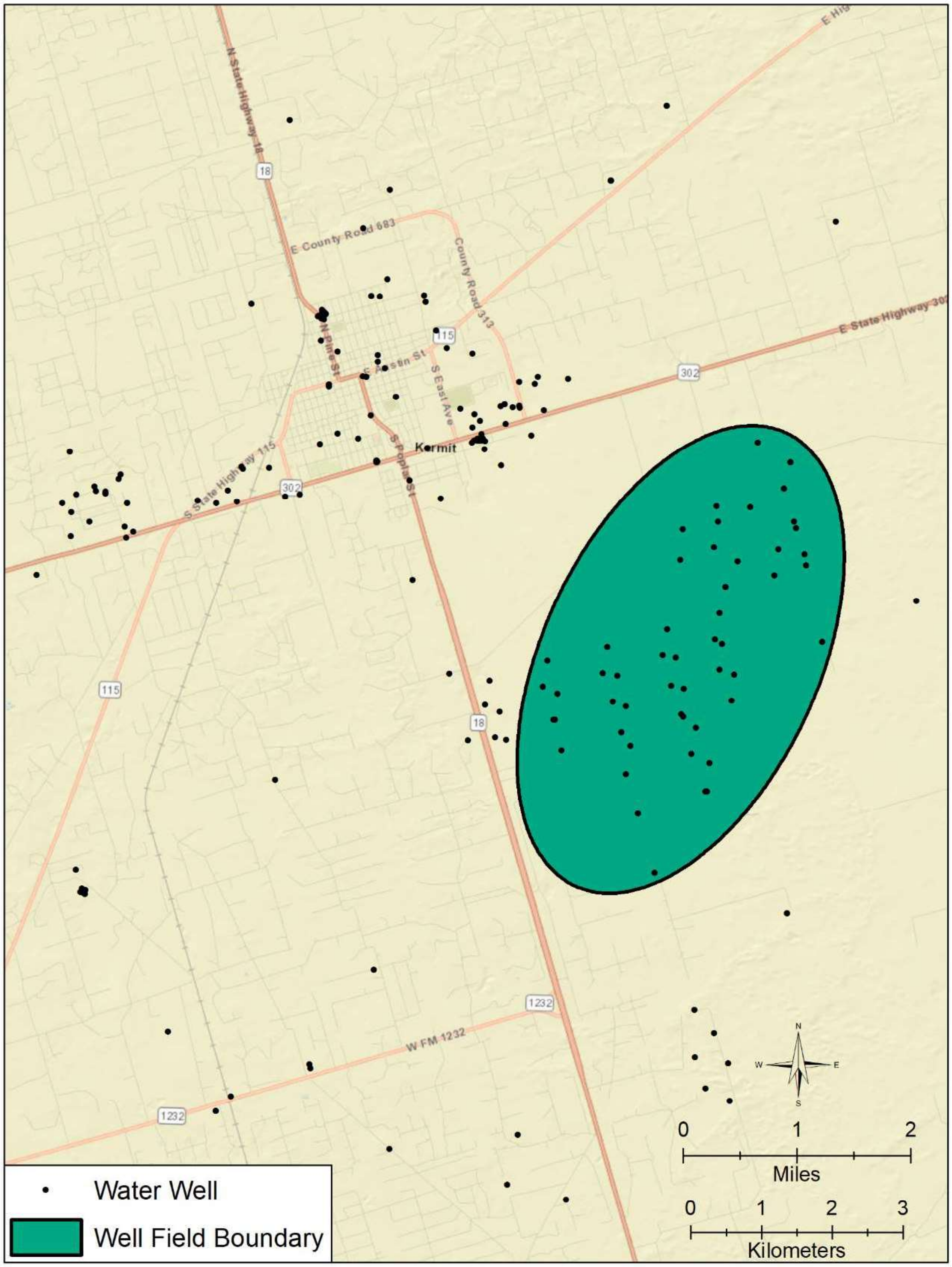


Figure 5-76. **Base map of the location of the well field.**

A review of Brackish Resources Aquifer Characterization System Well Identification 6136 (Figure 5-77; Log Id 5708 / API 42-495-32887) on the south end of the wellfield shows very clear picks for:

- base of Pecos Valley at 153 feet below ground surface (log datum is 17 feet above ground surface),
- base of Dockum at 513 feet below ground surface and
- base of Dewey Lake at 850 feet below ground surface.

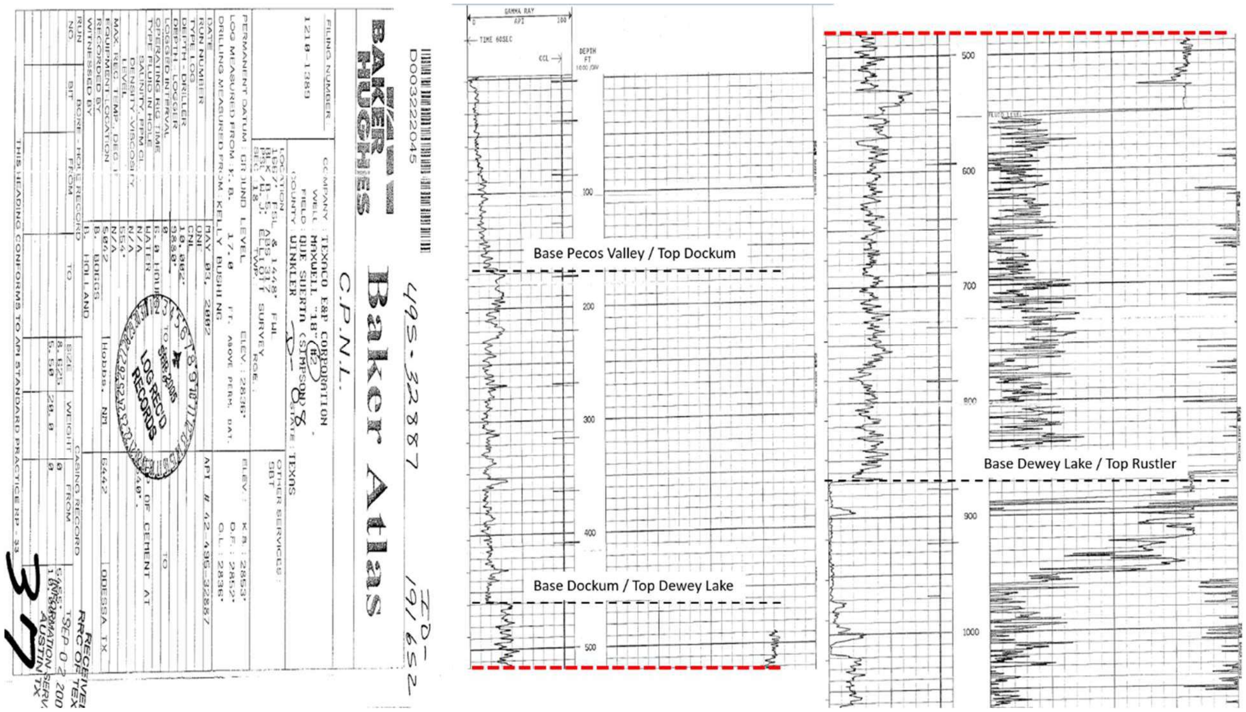
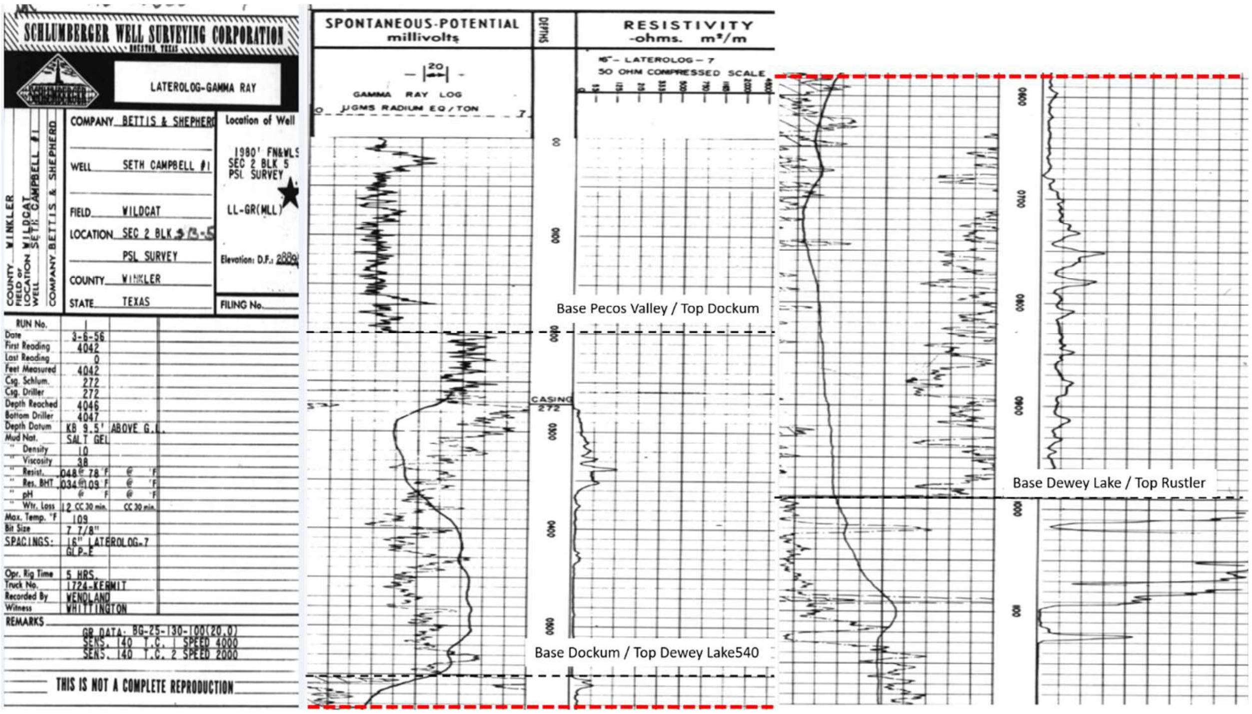


Figure 5-77. **Gamma log for Brackish Resources Aquifer Characterization System Well Identification 6136, Log Identification 5708 / API 42-495-328887.**

A review of Brackish Resources Aquifer Characterization System Well Identification 18621 (Figure 5-78; Log identification 17954 / API 42-495-00300) on the north end of the wellfield shows very clear picks for:

- base of Pecos Valley at 190 feet below ground surface (log datum is 10 feet above ground surface),
- base of Dockum at 540 feet below ground surface and
- base of Dewey Lake at 980 feet below ground surface.



SCHLUMBERGER WELL SURVEYING CORPORATION

HOUSTON, TEXAS

LATEROLOG-GAMMA RAY

COUNTY WINKLER
FIELD or LOCATION WILDCAT
WELL SETH CAMPBELL #1
COMPANY BETTIS & SHEPHERD

COMPANY BETTIS & SHEPHERD
WELL SETH CAMPBELL #1
FIELD WILDCAT
LOCATION SEC 2 BLK $ 13-5
PSL SURVEY
COUNTY WINKLER
STATE TEXAS

Location of Well
1980' FN&WLS
SEC 2 BLK 5
PSL SURVEY
LL-GR(MLL)
Elevation: D.F.: 2889
FILING No.

RUN No.	1
Date	3-6-56
First Reading	4042
Last Reading	0
Feet Measured	4042
Csg. Schlum.	272
Csg. Driller	272
Depth Reached	4046
Bottom Driller	4047
Depth Datum	KB 9.5' ABOVE G.L.
Mud Nat.	SALT GEL
" Density	10
" Viscosity	38
" Resist.	.048 @ 78 °F
" Res. BHT	.034 @ 109 °F
" pH	
" Wtr. Loss	12 CC 30 min.
Max. Temp. °F	109
Bit Size	7 7/8"
SPACINGS:	16" LATEROLOG-7 GLP-E
Opr. Rig Time	5 HRS.
Truck No.	1724-KERMIT
Recorded By	WENDLAND
Witness	WHITTINGTON

REMARKS
GR DATA: BG-25-130-100(20.0)
SENS. 140 T.C. 1 SPEED 4000
SENS. 140 T.C. 2 SPEED 2000

THIS IS NOT A COMPLETE REPRODUCTION

Figure 5-78. Gamma log for Brackish Resources Aquifer Characterization System Well Identification 18621, Log Identification 17954 / API 42-495-00300.

Based on the two geophysical logs situated to the south and north of the wellfield, the base of the Pecos Valley Aquifer is approximately 172 feet below ground surface on average and the base of the Dockum is approximately 527 feet below ground surface on average. This puts the average base of the Pecos Valley Aquifer from geophysical logs approximately 30 feet deeper than the base from the Meyer and others (2011) surface and the base of Dockum Aquifer from geophysical logs approximately 97 feet deeper than the base from the Ewing and others (2008) surface. Therefore, for our analysis an additional 30 feet of Pecos Valley depth was added to the interpolated surface values sampled to the individual wells summarized in Table 5-38. No changes were made to values sampled from the base Dockum surface because the well completions were more reflective of the Dockum depth from the geophysical logs. That is, most of the total depths of the wells were coincident with the base of the Dockum Aquifer from the geophysical logs.

Based on the structural surfaces and reported well completions summarized in Table 5-38, wells in this field are, on average, 20 percent completed within the Pecos Valley aquifer and 80 percent completed within the Dockum Aquifer. It is known that water quality and heads in these two aquifers can be expected to be different in this county. However, there are not publicly available data from these specific wells to review. As a result, we will use available data from local wells in the vicinity to evaluate the potential for mixing of groundwater of differing qualities within the wells in this local.

Water Quality

The closest Dockum well to the wellfield with a publicly available water quality measurement is located approximately 10 miles to the east of the perimeter of wellfield (State Well Number

4510201 in Figure 5-79). The well has a total depth of 1,113 feet below ground surface and has a sampled total dissolved solids value of 1,118 milligrams per liter from 1/28/1957. The closest geophysical well log is Brackish Resources Aquifer Characterization System well id 68169 (Q-log number Q145_495), is located approximately 1 mile to the west of State Well Number 4510201 (Figure 5-79) and has a base of Dockum/top of Dewey Lake ranging between 950 and 1000 feet below ground surface (Figure 5-80; datum is 0 feet above ground surface). While well completion information is not available for this well, the depth of the well, depth to the base of the Dockum Aquifer and the fact that the Pecos Valley Aquifer is extremely thin to unsaturated in this area confirm that water quality is a good reflection of Dockum water quality. While water quality measurements for the Dockum Aquifer in this area are sparse, a value in excess of 1,000 milligrams per liter is consistent with expectations. The water bearing portion of the Dockum Aquifer, primarily the Santa Rosa Sandstone in this area is a deep confined system and recharge to the unit, whether through outcrop to the east or through vertical leakage from the Pecos Valley Aquifer is minimal.

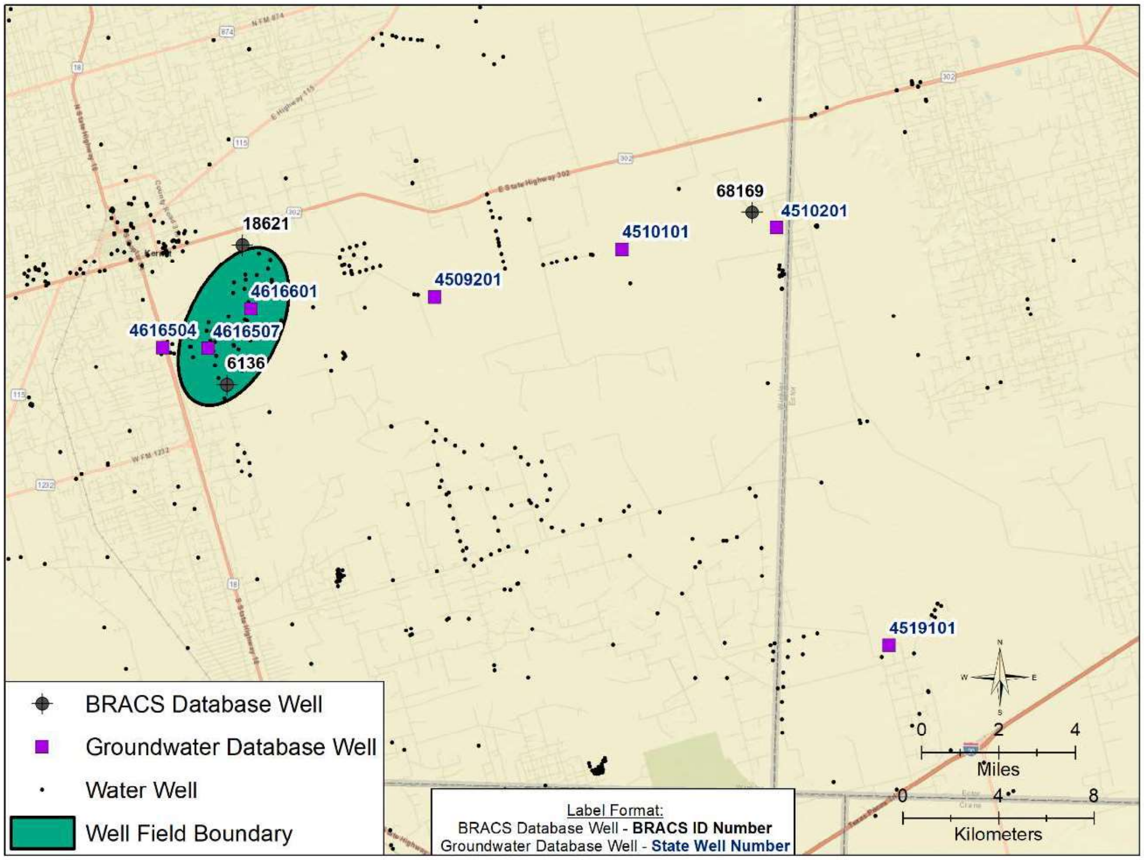


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Figure 5-79. **Base map of well-field region with select wells highlighted.**

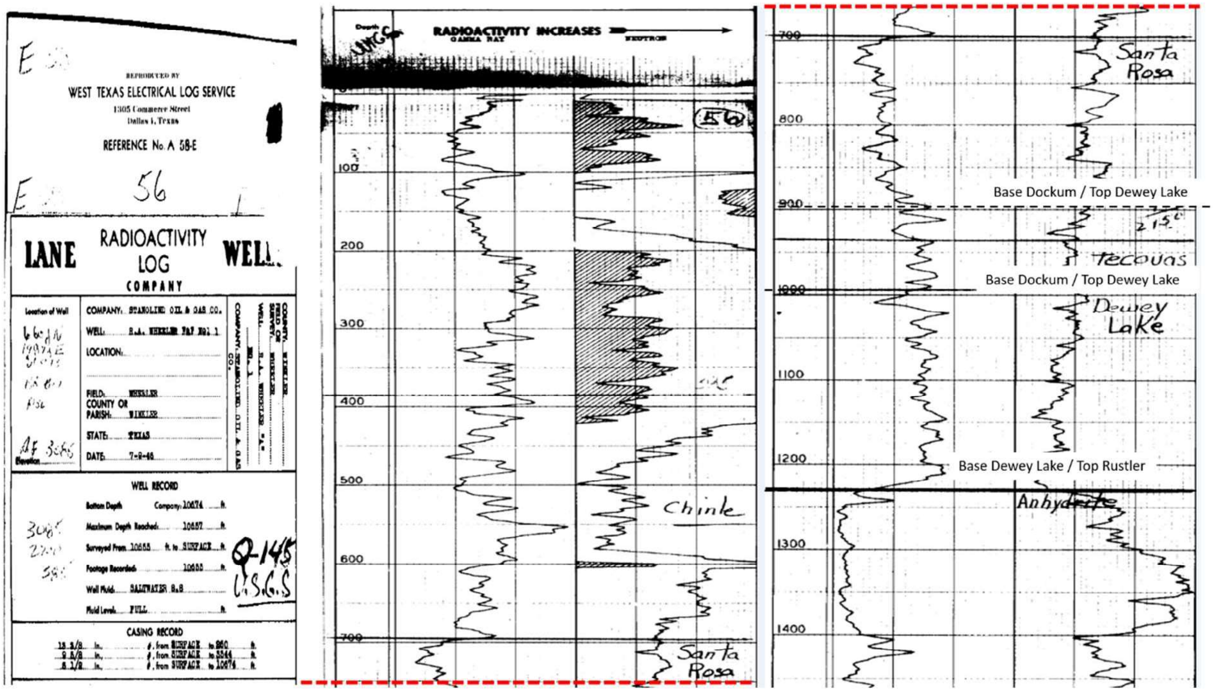

Figure 5-80. Gamma log for Brackish Resources Aquifer Characterization System well 68169, Q145_495.

Water quality measurements for wells completed within the Pecos Valley Aquifer are abundant in the area. Two wells (State Well Numbers 4510101 and 4509201) located between the Santa Rosa well to the east (State Well Number 4510201) and the wellfield to the west have total dissolved solids values of 198 and 360 milligrams per liter, respectively, both of which were sampled in the year 1957. The total depth of the wells reflects the thinning nature of the Pecos Valley Aquifer to the east and are 75 feet below ground surface for state well 4510101 and 140 feet below ground surface for state well 4509201. Directly in the wellfield, State Well 4616507 has a total depth of 153 feet below ground surface and a sampled total dissolved solids value of 220 milligrams per liter from 10/24/1956. The well depth is consistent with the base of the Pecos Valley Aquifer. State well 4616601, also within the wellfield has a total depth of 179 feet below ground surface (consistent with base of Pecos Valley Aquifer) and a total dissolved solids value of 272 milligrams per liter. These low total dissolved solids values are consistent with the conceptual model for the Pecos Valley Aquifer in this area. It is a shallow (less than 150 feet thick) unconfined system that is primarily comprised on wind blow silica sands with lesser amounts of alluvial sands and gravels. Recharge is directly from rain events and rock/water interactions are minimal due to the inert nature of the sediments comprising the formation. It is likely that any minor (approximately 100 milligram per liter) increase in total dissolved solids above 250 milligrams per liter is reflective of areas with higher clay/silt content.

Table 5-38. **Well completion and aquifer structure details at wells in the vicinity of the well field.**

Well Report	Water Level (ft-bgs)	Water Level Date	Borehole Depth (ft-bgs)	Ground Surface Elevation (ft)	PVA +30 base [1] (ft-bgs)	Dockum base (ft-bgs)	Top of screen (ft-bgs)	Base of Screen (ft-bgs)	PVA screen length (ft)	Percent PVA screen	Dockum Screen Length (ft)	Percent Dockum Screen
320870	60	5/20/2013	585	2863	178	682	70	580	108	21%	402	79%
365884	71	5/20/2014	590	2885	187	684	85	580	102	21%	393	79%
365886	71	5/20/2014	590	2885	187	684	85	580	102	21%	393	79%
365982	71	5/9/2014	570	2871	206	648	85	560	121	25%	354	75%
365983	71	5/7/2014	570	2873	199	670	85	560	114	24%	361	76%
365986	70	5/17/2014	550	2876	177	683	85	540	92	20%	363	80%
365990	68	5/4/2014	570	2871	191	669	85	560	106	22%	369	78%
365994	71	5/12/2014	590	2875	176	685	85	580	91	18%	404	82%
366002	71	5/15/2014	570	2876	164	694	85	560	79	17%	396	83%
366011	61	3/24/2014	470	2844	169	535	85	460	84	22%	291	78%
366021	65	4/6/2014	530	2852	172	566	85	520	87	20%	348	80%
366171	69	4/4/2014	530	2854	175	592	85	520	90	21%	345	79%
366173	66	4/11/2014	550	2861	181	636	85	540	96	21%	359	79%
366177	71	5/1/2014	570	2861	179	665	85	560	94	20%	381	80%
366187	58	3/16/2014	470	2844	163	529	75	460	88	23%	297	77%
366189	58	3/19/2014	510	2849	164	562	85	500	79	19%	336	81%
366204	61	4/2/2014	510	2853	167	589	85	500	82	20%	333	80%
366209	71	4/9/2014	530	2857	173	628	85	520	88	20%	347	80%
366212	69	4/29/2014	570	2859	169	659	85	560	84	18%	391	82%
366407	59	3/26/2014	450	2842	154	525	85	440	69	19%	286	81%
366412	64	3/28/2014	470	2846	158	578	90	460	68	18%	302	82%

Brackish Groundwater Comingling

Well Report	Water Level (ft-bgs)	Water Level Date	Borehole Depth (ft-bgs)	Ground Surface Elevation (ft)	PVA +30 base [1] (ft-bgs)	Dockum base (ft-bgs)	Top of screen (ft-bgs)	Base of Screen (ft-bgs)	PVA screen length (ft)	Percent PVA screen	Dockum Screen Length (ft)	Percent Dockum Screen
366418	65	4/22/2014	530	2856	161	621	90	520	71	17%	359	83%
366428	67	4/26/2014	550	2860	164	647	90	540	74	16%	376	84%
366435	61	3/31/2014	490	2845	149	579	85	480	64	16%	331	84%
366646	65	4/15/2014	510	2849	155	622	85	500	70	17%	345	83%
366649	78	4/13/2014	510	2841	160	591	85	500	75	18%	340	82%
Average	67		536	2860	172	624	85	526	88	20%	354	80%

[1] Meyer and other (2012) depth plus 30 feet

Note: % = percent, ft = feet, ft-bgs = feet below ground surface

Unfortunately, no water quality measurements are publicly available for wells completed as part of the wellfield which screens both the Pecos Valley Alluvium and Lower Dockum aquifers. However, State Well 4616504, located on the western edge of the field, has a sampled water quality of 287 milligrams per liter total dissolved solids and a similar co-completion of these two aquifers. The total depth of the well is 442 feet below ground surface. The average depth of all 26 wells within the wellfield is 536 feet below ground surface or 94 feet deeper.

Water Levels

Each of the wells in the wellfield has a reported static water level measurement on the submitted driller's report (see Table 5-38). Average reported static water level was 67 feet below ground surface. The closest Dockum well with a water level measurement is state well number 4519101 in southeastern Winkler County and has a series of water level measurements starting with 189.13 feet below ground surface on 12/5/1963 and ending with 266.87 feet below ground surface on 1/13/1988; Figure 5-79). Assuming the first water level measurement is representative of the pre-developed water level in the system, the hydraulic head in the Dockum Aquifer is around 190 feet below ground surface. This is consistent with the potentiometric surface map of the lower Dockum in Deeds and others (2015). It is also consistent with INTERA's findings drilling both Santa Rosa and Pecos Valley alluvial wells for a private client immediately to the east of the wellfield.

Therefore, based upon available data, the hydraulic head in the Pecos Valley Alluvium in this area is above the hydraulic head in the Dockum. The Pecos Valley Alluvium Aquifer also generally has a higher hydraulic conductivity than the Dockum Aquifer. As a result, it would be expected that the measured water levels under non-pumping conditions in the wellfield would be most representative of the Pecos Valley Alluvium Aquifer. If that were the case, during non-pumping conditions, groundwater would flow from the Pecos Valley Alluvium Aquifer (approximate hydraulic head of 2793 feet above mean sea level calculated as the average ground surface elevation for all wells in the field minus average depth to water) to the Dockum (estimated predevelopment head approximately 2670 feet above mean sea level). It is also possible that portions of the Dockum Aquifer may not produce groundwater to the well even during pumping conditions and in fact vertical downward flow could occur in portions of a well under certain field conditions. Clearly, multi-completed wells connecting two aquifers with significantly different hydraulic properties and hydraulic heads are very complicated as we discussed in Section 4 of this report.

This case study is interesting because the evidence suggests that two aquifers of differing heads and water qualities are co-completed by production wells. In this case, the evidence suggests that the well has very good water quality (less than 300 milligrams per liter total dissolved solids) from the Pecos Valley Alluvium Aquifer with poorer water (approximately 1,000 milligrams per liter total dissolved solids) of the Dockum Aquifer. There is not adequate data to determine if this could be comingling. The question of degradation could be complicated in this example. The reality is that the cross-completion of the two aquifers in this case likely results in a better water quality for consumption. When these wells are not pumping it is expected that any inter-aquifer flow through the borehole would be down to the Santa Rosa. If that were true, the water quality of the Pecos Valley Alluvium would be preserved and the water quality of the Santa Rosa local to the wells could be improved.

5.5 Regional Assessment Summary

In this section a regional assessment of potential for comingling was performed for three regions of Texas: Gulf Coast Region, the Eagle Ford Region and the Trans-Pecos Region. The Gulf Coast and the Eagle Ford regions are composed of Tertiary aged fluvio-deltaic sediments that are very stratified in both lithology and water quality and have large potential for comingling. The Trans-Pecos Region has a wide variety of aquifers of different lithology and depositional environment. There are aquifers within the Trans-Pecos where which have relatively low or moderate potential for comingling and aquifers that have high potential for comingling. All three regions support oil and gas development, and Class II injection wells are common.

The approach for performing the regional assessment used a combination of data types. To assess regional potential, we developed a database of wells completion data using the TWDB groundwater database (TWDB, 2020a) and the Texas Well Report Submittal and Retrieval System Database managed by the TWDB and the Texas Department of Licensing and Regulation (TWDB, 2020b). The database used in this study only included wells where a screen depth was reported and included 102,699 wells within the Gulf Coast Aquifer System, 35,580 wells in the Eagle Ford Region and 5,815 wells in the Trans-Pecos Region. The other data required included aquifer extent and structure and heads within the aquifers of interest. Because of the size of the regions, we used the TWDB Groundwater Availability Models for aquifer structure and aquifer heads.

For water quality we used total dissolved solids as a proxy for water quality in general recognizing that comingling may occur from mixing of a wide variety of water constituents. Water quality data was compiled from two sources: the Brackish Resources Aquifer Characterization System and the Groundwater databases (TWDB, 2020a).

The regional assessments defined aquifer well completions with an emphasis on identifying multi-aquifer completions. This data was then combined with the most recent calibrated historical groundwater availability model head to calculate maximum head differences between aquifers co-completed by a well. Finally, water quality of the aquifers in each region was summarized and discussed in context of the potential for comingling based upon actual well completion data in the region.

For each region analyzed at least one case study was developed using actual field conditions at a well to evaluate the potential for comingling. To assess the potential for comingling at a well requires detailed characterization data including interval water quality data and interval data or measured borehole interval flow rates. This data is rare. If this data is collected as part of an exploration borehole, it rarely finds its way into the Public Water Supply Well files housed by the Texas Commission on Environmental Quality. For the Gulf Coast Region and the Eagle Ford Region cases studies are developed that have detailed characterization data. For the Trans-Pecos Region, the case study is based upon local evidence but not from detailed borehole interval characterization data.

The potential for comingling is significant throughout most of the Gulf Coast Aquifer System. The hydrogeologic conditions that promote comingling in the Gulf Coast Aquifer System are a result of the systems stratigraphy and lithology, mineralogy and geochemistry and groundwater flow dynamics. A prerequisite for comingling to occur is for a well screen to intersect zones of different groundwater quality and different hydraulic pressure. The system is unique because the ubiquitous clay layering within the aquifer makes it possible to have water quality variability that could be injurious in long screen water supply wells. In addition to total dissolved solids, there are a host of trace constituents that are problematic for impacting long-screen wells in this formation. In fact, even short screen wells can be impacted based upon the screen placement relative to fine grained zones bounding the transmissive zones.

Numerous case studies were presented for intra-borehole flow and water quality variability within the Gulf Coast Aquifer System. Two examples were presented demonstrating the degree of vertical flow which can occur in a borehole under non-pumping conditions. One example was from an irrigation well in the Lakeside Irrigation District and in two municipal water supply wells in Harris County. Non-pumping flow rates of as high as 49 gallons per minute have been documented. This is significant because if a well has flow within it under non-pumping conditions, that means groundwater is flowing into a well in a zone(s) and flowing out in another zone(s). This clearly sets the stage for mixing of groundwater quality within the borehole and potentially recharging injurious groundwater from one zone to another.

In the Gulf Coast Region, detailed data on zonal water quality within wells was available and presented for three wells. All three of these field investigations were performed at by dynamic profiling in municipal water supply wells. The detailed characterization data was collected to identify the zonal source within each well contributing to degraded water quality. The zonal flow rates combined with concentration data can be used by the well owners to determine if the well screen could be modified to reduce or eliminate the water quality problem. These case studies provide direct evidence of borehole mixing of constituents exceeding their primary and secondary drinking water standards with groundwater meeting those standards. The case studies also demonstrated that many times the zones with poorer water quality are the less productive zones.

The Gulf Coast case studies confirm that vertical variations in total dissolved solids concentrations along a well screen can be a legitimate comingling concern. However, the case study data also demonstrate that a more significant drinking water concern are constituents such as radionuclides, arsenic, iron, and manganese that can have significantly greater vertical variation in concentration than total dissolved solids. These compounds are a concern because their concentrations can be dependent on presence of specific minerals and/or geochemistry associated with a particular deposit rather than the bulk mineralogy of the deposits. In the Gulf Coast, several specific deposits such as volcanic ash can create situations where there are thin zones of poor water quality surrounded by good water quality.

The aquifers in the Eagle Ford Region are similar to the aquifers of the Gulf Coast Aquifer in that they are Tertiary fluvio-deltaic sediments and are typical hydrodynamic flow systems. Except for the Carrizo and the Simsboro Formations of the Carrizo-Wilcox Aquifer, the Eagle

Ford aquifers are comprised of lower energy, finer grained sediments. Like the Gulf Coast Aquifer System, the maximum head differences between co-completed aquifers can be in the tens of feet on average. These head differences are the combined result of the natural hydrodynamics in the aquifers and production from selective zones and aquifers. An example of the latter is the regional drawdown in the Carrizo in the southern portion of the Eagle Ford and the Simsboro in the northern Eagle Ford Region in Central Texas. The percent of multi-aquifer completed wells in the southern portion of the Eagle Ford Region is 31 percent of the wells analyzed as compared to 18 percent in the central portion of the Eagle Ford Region.

The case study documented in the Eagle Ford Region involved a well in the Evergreen Underground Water Conservation District that was co-completed in the Yegua-Jackson and the Gulf Coast Aquifer. The well was constructed to supply water to oil and gas activities. The well is screened across four intervals from a depth of 210 to 630 feet below ground surface. The well owner measured zonal water quality in the well using a YSI Sonde lowered into the well at various depths and a series of Dual Membrane Passive Diffusion bags positioned across the screens at several depths. Total dissolved solids ranged from approximately 1,000 to 3,000 milligrams per liter in the wellbore. Zonal flow measurements were not measured on the well. However, a possible interpretation of the water quality data indicates a convergent flow cell in the well where groundwater from the Jackson Formation with a total dissolved solids of about 2,500 milligrams per liter is mixing with Lower Catahoula aquifer groundwater of approximately 1,100 milligrams per liter and flowing into the Upper Catahoula zone.

The Trans-Pecos Region has a range of aquifer types from volcanic rocks to mudstones, anhydrites and polyhalites. Unlike the other two regions, groundwater flow in many of the aquifers in the Trans-Pecos Region are controlled by secondary porosity. While many of the aquifers in the region are in direct contact and are prone to being co-completed, several others are isolated in extent and offer little potential for comingling from cross-aquifer completions.

The aquifers comprising the Trans-Pecos Region of West Texas are presented include Bone Springs – Victoria Peak, Capitan Reef Complex, Dockum, Edwards-Trinity (Plateau), Hueco – Mesilla Bolson, Igneous, Marathon, Pecos Valley, Rustler and West Texas Bolsons aquifers. Cross-aquifer completions were most prevalent between the Pecos-Valley Alluvium, Edwards-Trinity (Plateau) and Dockum aquifers with the combination ranging from 28 to 35 percent of all wells depending which groundwater availability model is used. Maximum hydraulic head differences between these aquifers average near 10 feet. The Igneous Bolson aquifers also have a high percent (29 percent of wells) of cross-completed wells and model predicted vertical gradients are large (greater than 100 feet). Bolson aquifers are regional discharge features and gradients from bedrock to these aquifers should be significant. The available water quality data for the igneous and bedrock formations to the bolson aquifers is too sparse to draw conclusions. There is unexamined potential for comingling to occur between zones in a single aquifer. Aquifers that likely fit this category are the bolson aquifers and the Bone Spring-Victoria Peak aquifers which have increased salinity with depth.

The regional assessment provides a good understanding of the physical conditions that may be conductive to comingling. The regional studies documented herein provide significant evidence of conditions where comingling may be occurring. This assessment did not make determinations of degradation in the case studies presented and therefore did not make determinations of comingling.

The key conclusions from this section are:

- Physical aquifer conditions that are conducive to comingling exist in all three regions.
- The Gulf Coast Aquifer Region is the region with the highest potential for comingling.
- The Trans-Pecos Region has the lowest potential of the three regions. However, the aquifer combination of the Pecos Valley Alluvium, Edwards-Trinity (Plateau) and the Dockum aquifers show the greatest likelihood of comingling occurring.
- Case studies presented show that vertical flow rates within aquifers and zones cross-completed in wells can be significant (tens of gallons per minute).
- Aquifer and zonal water quality variability can be significant in cross-completed wells and small zones of poor water quality can significantly degrade wellhead water quality.
- When considering comingling in a particular well, trace metals and radioactive constituents can be the source of degradation.
- Most of the aquifers analyzed have water quality constituents that exceed their primary or secondary standards in ten percent or greater of the available water quality analyses. It is expected that trace constituent concentrations will increase in groundwater encountered in brackish production wells and these percentages would increase.
- Assessment of comingling potential at a well requires detailed zonal characterization of both non-pumping zonal flow rates and zonal water quality data. This data is rarely collected.

A limitation of the regional assessment is that the aquifer layering used in the analysis is based upon the groundwater availability models which typically represent each aquifer as a single model layer. As such, the regional assessment does not investigate comingling on a sub-aquifer, or zonal scale except in the case studies discussed. This implies that comingling potential could be even greater that indicated by the regional assessment.

A second limitation is that for the regional analysis total dissolved solids is used as a proxy for water quality. The case studies have demonstrated that individual constituents, such as arsenic or radioactive constituents, can be above standards and can degrade wellhead water quality when zonal total dissolved solids concentration is below secondary standards.

6 Statewide Assessment of Potential for Comingling of Brackish Groundwater

The objective of the statewide assessment is to evaluate the relative potential for brackish groundwater comingling for both the major and minor aquifers. The assessment is based upon development of a relative ranking process that is informed by metrics that attempt to quantify natural aquifer conditions required to cause comingling in Texas major and minor aquifers. The aquifer conditions conducive to causing comingling are derived from the more detailed select aquifer/region review documented in Section 5. If an aquifer system has a high potential to comingle as determined by aquifer conditions, a poorly constructed well may result in comingling. Consistent with the previous methodology of this report, this analysis considers natural groundwater quality with a focus of brackish groundwater.

6.1 Approach

This assessment is best thought of as a statewide survey of the relative potential for brackish comingling within the major and minor aquifers. Comingling as per its definition requires a borehole or filter pack to be the conduit for mixing and requires degradation to occur. There are several attributes of brackish aquifers that make the potential for comingling higher than within freshwater system. This assessment focuses on the aquifer characteristics that make comingling possible within an aquifer. The treatment of the borehole completion and its impact are indirectly considered in this assessment. Although the definition of comingling requires degradation, it is not included within this overview.

The general approach to estimating the hydrogeologic potential for comingling of brackish groundwater is as follows:

1. Consider hydrogeological aquifer conditions effect the potential for brackish groundwater comingling.
2. Estimate these hydrogeological conditions for each of the major and minor aquifers in Texas.
3. Develop a strategy for scoring the hydrogeologic conditions on their relative potential for contributing to comingling of brackish groundwater.
4. Combine the scores to create a final score representing the potential for comingling of brackish groundwater per aquifer.
5. Use the magnitude of the brackish comingling score to rank (high, medium, and low) each aquifer for their potential for comingling of brackish groundwater.

6.2 Screening Methodology

To assess the potential for comingling of brackish groundwater, a series of metrics are estimated for each aquifer. These metrics are based upon aquifer conditions important to the potential mixing of brackish groundwater. The assessment is at the aquifer scale and is therefore regional, for example, many of the coastal plain aquifers span most of the state. In practice, the local potential for comingling is a very site-specific, and borehole- specific condition. However, this assessment does provide a hierarchical ranking of aquifer conditions that could be conducive to comingling through a well within a given aquifer. The following is a description of the hydrogeological suitability parameters chosen for this analysis.

6.2.1 Screening Metric Selection

Several factors identified in Section 5 as contributing to the potential for comingling will be used in this section to assess the potential for comingling in Texas aquifers identified by the TWDB. Each of these factors will be termed a metric in recognition that they sum to make a relative score. The metrics are described in Table 6-1.

Table 6-1. Comingling potential metrics.

Metric Name	Notes
Brackish Groundwater Availability	Relative metric defining the availability of brackish groundwater in the aquifer (after LBG-Guyton, 2003).
Brackish Groundwater Productivity	Relative metric defining the productivity of brackish groundwater in the aquifer. (after LBG-Guyton, 2003).
Range of Salinity Classes Present	Relative measure of range of salinity classes within the aquifer
Historical Hydraulic Head Differences Within the Aquifer	Relative metric of the presence of significant hydraulic head differences within the aquifer. These head differences are the driving force for mixing within a borehole in no-pumping and to a lesser degree during pumping conditions.
Aquifer Layering	Relative metric describing whether the aquifer is composed of multiple formations.
Cross-Aquifer Completions	Relative metric describing whether the aquifer has documented cross-aquifer completions

Brackish Groundwater Availability – A metric that provides an estimate of the relative amount of brackish groundwater available in a specific aquifer. The metric provides a relative measure of the volume of brackish groundwater available for recovery. With the emphasis of this study on brackish groundwater, this is the only metric which accounts for the relative presence of brackish resources in the aquifer.

Brackish Groundwater Productivity - A metric that provides an estimate of the relative productivity within an aquifer with brackish groundwater. The underlying assumption behind this metric is that if an aquifer has low brackish groundwater productivity, there may lower interest in developing the resource and causing comingling.

Range of Salinity Classes Present – A metric that provides a relative measure of the number of salinity classes distributed within an aquifer. The assumption is that the greater the range in salinity within the aquifer, the higher the potential to mix groundwaters of different quality.

Historical Hydraulic Head Differences Within the Aquifer – A metric that provides a relative measure of the magnitude of head differences observed within an aquifer. The vertical head differences within an aquifer are the driving force for causing comingling to occur in open boreholes. Vertical head differences, along with the vertical distribution of transmissivity within the screen, control mixing within a borehole during pumping. This metric is subject to data availability as some aquifers have good documentation of vertical head differences while others do not. Because of the relative importance of head differences as the driving force for comingling, this metric was included even though the degree of information available to inform across all aquifers may significantly vary.

Aquifer Layering – A metric that provides a relative measure of the vertical hydrogeologic variability of the aquifer. Specifically, this metric characterizes the degree to which the aquifer is composed of multiple formations. The assumption is that multiple formations increase the probability of vertical water quality variability and increases the probability that wells screen multiple formations. In consideration of this metric, we also considered if the specific formations were targets for production within the aquifer versus the formations being considered a single hydrogeologic unit for development purposes. This metric does not include an evaluation of depositional processes within the boundaries of a typical geologic formation. Those types of layering and bedding are ubiquitous to geologic materials.

Cross-Aquifer Completions - A metric that provides a relative measure of the degree of cross-aquifer completions occurring in an aquifer. Aquifers typically have different chemistry and the underlying assumption with this metric is that the higher the occurrence of cross-aquifer completions, the higher the potential for comingling.

6.2.2 Scoring Methodology

In this section, the method of scoring is described for the regional metrics considered most relevant for the relative assessment and ranking of the potential for brackish comingling within an aquifer. Because the product of this assessment is a relative ranking of aquifer potential, each of the metrics will be assessed using a normalized scale.

One way of putting all the metrics on the same relative scale is to normalize the range captured by each metric to a scale from zero to one. This technique is well suited for combining both qualitative and quantitative parameters into a decision process. For this analysis, the metrics being used are primarily qualitative measures; however, the brackish groundwater availability metric is based upon a quantitative assessment (LBG-Guyton, 2003). Many of the metrics will be estimated on a low, moderate, and high scale. These categorical scores are converted to a normalized score (NS) from zero to one. By normalizing all scores from zero to one, the ability to combine scores to get a total score is facilitated for quantitative and qualitative metrics.

Some metrics may be considered of a higher importance for determining the potential for comingling in an aquifer. As a result, some scores can and may be weighted higher than others in the summation of the total score. The summation of the normalized scores into a Total Normalized Score considers an assigned weight for each normalized score. The Total Normalized Score varies from a minimum of zero to a maximum of one and is comparable across aquifers The equation for Total Normalized Score is as follows:

$$Total\ Normalized\ Score\ (TNS) = \frac{\sum_{i=1}^{n} weight_{NS,i}\, NS_i}{\sum_{i=1}^{n} weigh\ _{NS,i}} \qquad \text{(Equation 2)}$$

In Equation 2, normalized score is a single metric normalized score, $weight_{NS}$ is the weight assigned to a single metric in the calculation of Total Normalized Score. The weights must sum to one. The scoring methodology allows high-level categorization of hydrogeological potential for comingling of brackish groundwater. However, because the normalized score and the Total Normalized Score are normalized to range from zero to one, the fractional score may over represent the precision of this assessment. As a result, once the Total Normalized Score is calculated for all aquifers, the final ranking will be presented in a categorical framework of low, medium, and high potential. These ranking techniques have been applied to a range of disciplines and uses including the aquifer storage and recovery and managed aquifer recharge suitability study (Shaw and others, 2020).

6.2.3 Metric Scores

Each of the six metrics (Table 6-1) used to estimate normalized scores has a scoring system assigned to them. Most of these metrics are semiquantitative or qualitative and are prone to subjectivity. As a result, they will be categorized, and each category will be assigned a normalized score from one to zero, with one having the highest potential for contributing to comingling brackish groundwater, and zero having the lowest potential. The scoring scheme for each metric is defined below.

Table 6-2 provides the categorical value and the associated score for two metrics: Brackish Groundwater Availability and Brackish Groundwater Productivity. For these two metrics the categories used are consistent with those in Table 9 of the Brackish Groundwater Manual for Texas Regional Water Planning Groups (LBG-Guyton, 2003). The benefit of the Brackish Groundwater Manual for Texas Regional Water Planning Groups Report is that it provides a consistent assessment of brackish availability and productivity for all but one of the current designated Texas aquifers. The Cross-Timbers Aquifer was not designated as an aquifer in 2003 and therefore was not included in the LBG-Guyton and Associates (2003) report. Based upon the work of Nicot and others (2013) on the Cross-Timber Aquifer formations, we assigned the categorical score for brackish groundwater availability and productivity as moderate to high and moderate, respectively. If LBG-Guyton and Associates (2003) classified an aquifer availability or productivity as unknown, then we assigned the aquifer a score of 0.2 based upon the prevalence of brackish resources in Texas aquifers (LBG-Guyton and Associates, 2003). LBG-Guyton and Associates (2003) estimated brackish groundwater availability and productivity by regional water planning group. If an aquifer spanned more than one and planning group, the aquifer metric categorical score (Table 6-2) was calculated as the arithmetic average. As a result, the aquifer metric score could be the average of the metric categorical scores in Table 6-2.

Table 6-3 provides the categorical value and the associated score for three metrics: Range of Salinity Classes, Historical Vertical Head Differences and Aquifer Layering. These three metrics use a scoring range that varies from 0.25 to one. This metric sets a low value at 0.25 recognizing that most Texas aquifers possess some level of the characteristic being assessed by that metric.

The scoring scheme used for the Cross-Aquifer Completions metric is identical to that in Table 6-3 except that a normalized score of zero is assigned to lowest category (see Table 6-4). A low category represents the situation where an aquifer does not have evidence that cross-aquifer completions are typical.

The metric used for Range of Salinity Classes present in the aquifer is quantitative like Brackish Groundwater Availability and Brackish Groundwater Productivity. The TWDB classifies groundwater as having five salinity classes ranging from fresh groundwater to brine groundwater. The metric was calculated based upon the number of groundwater salinity classes identified in the aquifer based determined from a literature review divided by five. So, if the aquifer has five salinity classes, the score would be one and if it had two salinity classes the score would be 0.4.

From a review of data sources each metric was assigned a metric range and from that a metric categorical score was assigned so that a total score could be calculated. For Brackish Groundwater Availability and Brackish Groundwater Productivity metrics the metric ranges were taken from LBG-Guyton (2003). These were then converted to relative scores ranging from zero to one. If availability and productivity were provided for multiple Table 6-5 lists the scores assigned to each of the six metrics used to develop a total score.

Table 6-2. **Categorical Scoring Scheme for Brackish Groundwater Availability and Productivity.**

Metric Range from LBG-Guyton (2003)	Metric Categorical Score
None	0
Unknown	0.2
Low	0.2
Low to Moderate	0.35
Moderate	0.5
Low to High	0.6
Moderate to High	0.75
High	1

Table 6-3. **Categorical Scoring Scheme for Vertical Head Difference and Aquifer Layering.**

Metric Range	Metric Categorical Score
Low	0.25
Medium	0.5
High	1

Table 6-4. **Categorical Scoring Scheme Cross-Aquifer Completions.**

Metric Range	Metric Categorical Score
Low	0
Medium	0.5
High	1

6.2.4 Data Sources

The metrics provided in Table 6-1 above were defined to describe the regional potential for comingling of brackish groundwater to occur in an aquifer. The metrics are more qualitative than quantitative and as a result require review of the literature to develop estimates. Texas is unique in the breadth of hydrogeologic reports available for nearly all state aquifers. This is largely the result of the TWDB Groundwater Availability and Innovative Water Programs. These two programs have developed a standardized set of scientific investigations for the aquifers of the state. In most cases we have used the conceptual model reports associated with the groundwater availability models developed for each aquifer. These reports provide a consistent and detailed analysis of the available data to describe each aquifer's character.

In addition to these reports, we use the water quality conceptual model reports developed by the Groundwater Availability Model Group for select aquifers and relevant Brackish Resource Aquifer Characterization System reports. Table 6-6 provides a summary of the primary data sources used to assign scores to each metric. The rationale for all metrics not derived from the Texas Brackish Groundwater Manual (LBG-Guyton and Associates, 2003) can be found in Appendix B of this report and a detailed reference list of sources used is included in that Appendix.

Table 6-5. Normalized Scores by Screening Metric.

Aquifer	Brackish Availability	Brackish Productivity	Range of Salinity Classes	Aquifer Layering	Cross-Aquifer Completions	Vertical Head Difference
Blaine	0.73	0.35	0.8	0.5	0.5	0.25
Blossum	0.20	0.20	0.8	0.25	0	0.25
Bone Spring/Victoria Peak	1.00	1.00	0.6	0.25	0	0.5
Brazos River Alluvium	1.00	1.00	0.6	0.25	0	0.25
Capitan	1.00	1.00	1	0.25	0	0.5
Carrizo-Wilcox	0.59	0.53	1	1	0.5	1
Cross Timbers	0.5	0.35	0.8	1	1	0.25
Dockum	0.30	0.20	1	1	1	1
Edwards (BFZ)	0.55	0.35	0.8	1	0.5	1
Edwards-Trinity (Plateau)	0.20	0.20	0.6	1	1	1
Edwards-Trinity (High Plains)	0.50	0.20	0.6	1	1	0.5
Ellenburger-San Saba	0.32	0.50	0.6	0.5	0	0.25
Gulf Coast	0.64	0.89	1	1	1	1
Hickory	0.35	0.50	0.6	0.25	0	0.25
Hueco Bolson	1.00	0.50	0.8	0.5	0	0.5

Aquifer	Brackish Availability	Brackish Productivity	Range of Salinity Classes	Aquifer Layering	Cross-Aquifer Completions	Vertical Head Difference
Igneous	0.00	0.00	0.2	0.5	0.5	0.25
Lipan	1.00	0.50	0.6	1	0.5	0.25
Marathon	0.00	0.00	0.2	1	0.5	0.25
Marble Falls	0.20	0.00	0.4	0.25	0	0.25
Nacatoch	0.28	0.20	0.8	0.5	0	0.25
Northern Trinity	0.34	0.25	0.8	1	0.5	1
Ogallala	0.57	1.00	0.6	0.5	0.5	0.25
Pecos Valley Alluvium	1.00	1.00	0.8	0.5	1	0.25
Queen City & Sparta	0.55	0.24	0.8	1	0.5	1
Rita Blanca	0.20	0.35	0.4	1	0.5	0.25
Rustler	0.68	0.40	1	1	0.5	0.25
Seymour	0.40	0.50	0.4	0.5	0.5	0.5
West Texas Bolsons	0.50	0.50	0.6	0.25	0	0.25
Woodbine	0.57	0.35	0.6	0.25	0	0.25
Yegua Jackson	0.73	0.20	0.6	1	1	0.5

For the Brackish Groundwater Availability and Productivity Metrics, the values were based upon the work of LBG-Guyton (2003) using their qualifiers and converting them to normalized categorical scores (see Table 6-2). The values assigned for the other four metrics were determined using professional judgment after a review of the literature. Appendix B provides tables describing the literature sources and a brief rationale for the categorical scores.

Table 6-6. Data Sources for the Decision Metrics.

Metric Name	Notes
Brackish Groundwater Availability	Texas Water Development Board Brackish Groundwater Manual – LBG-Guyton (2003); Table 9.
Brackish Groundwater Productivity	Texas Water Development Board Brackish Groundwater Manual – LBG-Guyton (2003); Table 9.
Range of Salinity Classes Vertical Head Differences Aquifer Layering Cross-Aquifer Completions	Brackish Resources Aquifer Characterization System Studies: • Brackish Groundwater Resources for Specific Aquifers (numerous) • Potential Brackish Groundwater Production Zone Reports (numerous) • Texas Water Development Board Brackish Groundwater Manual – LBG-Guyton (2003) Texas Water Development Board Groundwater Availability Group (Groundwater Availability Model): • Groundwater Availability Model Conceptual Models (numerous) • Hydrochemical and Isotopic Data Interpretation Reports for Groundwater Management Area 3,7,11,12 and 13. (2 reports)

6.3 Statewide Assessment Results

In this section the scores in Table 6-5 are combined using Equation 2 to calculate a total score which reflects the potential for a specific aquifer to have characteristics conducive to comingling of brackish groundwater. Equation 2 considers weights for each metric score, which sum to one. The concept of using weights is based upon the idea that some metrics would be more important when considering the potential for comingling.

Table 6-7 provides the weights used in this assessment. Weights were determined using a qualitative and qualitative/quantitative hybrid assessment of the parameters and the scoring results. Qualitative assessments are based on experience and information determined from the literature, and one parameter is generally considered more important than another. Parameters that are broad discriminators for comingling, like vertical head differences within an aquifer or the frequency of inter-aquifer completions, were weighted relatively high. An assessment was performed in which the team reviewed the final scores and compared the scores to results determined in the select region/aquifer analysis presented in Section 5.

Table 6-7. Metric Weights Used in this Assessment (see Equation 2).

Metric Category	Metric Weight
Brackish Groundwater Availability	0.1
Brackish Groundwater Productivity	0.1
Range of Salinity Classes	0.1
Aquifer Layering	0.1
Historical Vertical Head Differences	0.3
Cross-Aquifer Completions	0.3

Once these metrics are determined, one can use the information in Table 6-4 through Table 6-6 and Equation 2 to calculate a total score which is normalized to range from zero to one. Because the precision of this analysis is inconsistent with a percentile ranking, the total normalized scores are finally converted to a categorical score shown in Table 6-78.

Table 6-8. Relationship for Relating Total Score to a Brackish Groundwater Comingling Category Score.

Total Normalized Score	Category
0 to 0.35	Low
0.35 to 0.65	Medium
0.65 to 1.0	High

Table 6-9 provides the total normalized scores and the categorical scores organized by final potential ranging; high, medium, and low. We performed a sensitivity analysis to determine if the weighting scheme (Table 6-7) made a significant difference in the final category scores (high, medium, low). Four aquifers changed category if we assumed equal weighting.

The highest-ranking aquifer is the Gulf Coast Aquifer which is consistent with findings presented in Section 5. The highest-ranking aquifers tend to be aquifers with distinct multi-aquifer architecture or aquifers that have a high occurrence of cross-aquifer completions. By cross-aquifer completions we mean completions within an aquifer that also co-complete across adjacent (above/below) aquifers.

Table 6-9. Total Normalized Score and Categorical Score by Aquifer.

Aquifer	Score	Category
Gulf Coast	0.95	High
Dockum	0.85	High
Edwards-Trinity (Plateau)	0.80	High
Carrizo-Wilcox	0.76	High
Edwards (BFZ)	0.72	High
Queen City & Sparta	0.71	High
Pecos Valley Alluvium	0.71	High
Northern Trinity	0.69	High
Yegua Jackson	0.69	High
Edwards-Trinity (High Plains)	0.68	High
Cross-Timbers	0.64	Medium
Lipan	0.54	Medium
Rustler	0.53	Medium
Ogallala	0.49	Medium
Seymour	0.48	Medium
Capitan	0.48	Medium
Blaine	0.46	Medium
Bone Spring/Victoria Peak	0.44	Medium
Hueco-Mesilla Bolson	0.43	Medium
Rita Blanca	0.42	Medium
Brazos River Alluvium	0.36	Medium
Marathon	0.35	Low
Igneous	0.30	Low
Ellenburger-San Saba	0.27	Low
West Texas Bolsons	0.26	Low
Nacatoch	0.25	Low
Woodbine	0.25	Low
Hickory	0.25	Low
Blossum	0.22	Low

6.4 Findings and Limitations of Assessment

The highest-ranking aquifers tend to be aquifers with distinct multi-aquifer architecture or aquifers that have a high occurrence of cross-aquifer completions. By cross-aquifer completions we mean completions within an aquifer that also co-complete across adjacent (above/below) aquifers.

This assessment has several limitations given the statewide scope of the assessment and the fact that comingling is very well/aquifer specific condition. That said, the analysis attempts to use available information to rank the relative potential for comingling of brackish groundwater within that aquifer. There is no doubt that aquifers that are ranked low in this assessment will have wells where comingling may occur. The assessment is meant to be a broad assessment of potential.

This assessment does provide a framework for understanding the potential for comingling to occur in an aquifer, even between water qualities that are not brackish. The assessment provides an indication that many of Texas's aquifers have the potential to commingle brackish groundwater. This points to the importance of good characterization of aquifer water quality and compliance with state well completion requirements as codified in 16 TAC 76.

7 Conclusions and Limitations

This report documents a desktop study of comingling from the context of its definition in the Texas Water Well Drillers and Pump Installers Rules in the TAC. The report reviews comingling relative to its definition in statute, interpretation of that definition and assessment of the potential for comingling of brackish groundwater in Texas aquifers. The study makes several conclusions and recommendations which are summarized below along with the study's limitations.

7.1 Conclusions

A review of the statutes related to the comingling of brackish water shows that there are some definitions or concepts not clearly defined in code. Comingling is defined in the Texas Water Well Drillers and Pump Installers Rules TAC §76.10.10(16) as the "mixing, mingling, blending or combining through the borehole casing annulus or the filter pack of waters that differ in chemical quality, which causes quality degradation of any aquifer or zone." In this definition, two conditions must be met for comingling to occur: the mixing occurs between waters of different chemical quality and the subsequent mixing causes degradation to an aquifer or a zone, thus, comingling does not occur when only one of the two conditions is met. Three examples when comingling does not occur include: (1) the mixing of waters of the same chemical quality within a well or borehole, (2) the mixing of two differing quality waters within a borehole occurs, but that mixing does not cause degradation, and (3) the mixing of two differing quality waters within a borehole occurs, but the hydraulic heads are effectively hydrostatic and degradation of a zone is unlikely.

There are two concepts in this definition that are not clearly defined and are open to interpretation:

- "differ in chemical quality"
- "degradation"

One interpretation is that 16 TAC§76 intends to prevent contamination of useable water quality with water that is either a human health or environmental health risk. The statement "differ in chemical quality" then refers to water which contains enough salinity or contaminants to reduce the overall usefulness of a source of water. If we assume that the rules regarding comingling apply equally to all groundwater, including brackish groundwaters, then based upon our review of the body of relevant administrative code and statutes, mixing of poor water qualities which have no expected beneficial use for human consumption and could not reasonably be expected to discharge into the environment would not be considered "degradation" and therefore would not be considered comingling.

It is not stated in 16 TAC§76 whether preserving the current or future use of the groundwater encountered is a standard to be considered in evaluating degradation or impairment. The consideration of groundwater use, or its ultimate usefulness, is explicitly considered in the definition of pollution which is found in 16 TAC§76.10(42).

A report that considers end use to determine the level of groundwater protection is the Groundwater Protection Committee's Groundwater Classification System documented in the

2019 Joint Groundwater Monitoring and Contamination Report (2020). The report states that protection, or restoration, can be varied based upon the groundwater salinity level and if the following conditions are met; current groundwater uses are not impaired, potential groundwater uses are not impaired, a public health hazard is not created; and the quality of groundwater is restored if feasible.

This study presents a detailed conceptual model of the well and aquifer conditions that may result in comingling. Mixing of groundwater resulting in degradation can occur under several conditions. First, it could occur during drilling and prior to well completion. Second, it could occur during a period when a well has been drilled but is left open prior to completion or plugging and abandonment as might occur in a test borehole. Finally, comingling can occur in wells that have been drilled and completed but allow for mixing of groundwater from one aquifer/zone to another during non-pumping periods. Intra-borehole groundwater flow can occur under non-pumping conditions if the hydraulic head within aquifers or zones co-completed by the well have different hydraulic heads. In this situation, one zone(s) will be of higher head than the other zone(s) creating a flow cell within the borehole from the high hydraulic head zone to the lower hydraulic head zones. For that intra-borehole flow to be comingling the zones or aquifers connected by the borehole must have differences between their water quality which would result in degradation of the zone or aquifer receiving intra-borehole flow.

Using these physical aquifer conditions as indicators of the potential for comingling within an aquifer, the study assessed the potential for comingling in three regions of the state, the Gulf Coast Region, the Eagle Ford Region, and the Trans-Pecos Region. A review of these three regions found that the potential for comingling exists in all three regions based upon the available data with the Gulf Coast Aquifer Region and the Eagle Ford Regions having the highest potential of the three. For each region at least one case study was presented where detailed well-specific examples were evaluated to understand the intra-borehole flow potential and zonal water quality. The case studies provide evidence of how comingling could occur, and they also provide insight into the types of detailed characterization data that must be collected to evaluate comingling.

While standard geophysical logs may offer detailed zonal information on total dissolved solids, this study has demonstrated that the presence of trace constituents and intra-borehole flow rates under non-pumping conditions may control the potential for comingling. Standard characterization techniques generally do not collect adequate information to make such an assessment. Zonal water quality data is rare. Zonal hydraulic head data is even more rare. In most cases zonal heads are inferred from measured intra-borehole flow rates.

To assess the potential for comingling of brackish groundwater across the state a ranking methodology was developed based upon metrics describing aquifer conditions important to the potential mixing of brackish groundwater. The assessment is super-regional and at the aquifer scale. For example, many of the coastal plain aquifers span the breadth of the state. In practice, the potential for comingling is a very site-specific, and a borehole-specific condition. However, this assessment does provide a hierarchical ranking of aquifer conditions that could be conducive to comingling through a well within a given aquifer. The assessment ranked all major and minor aquifers for their potential for comingling of brackish groundwater. Ten aquifers were ranked as having high potential for brackish groundwater comingling. The highest-ranking aquifers tend to be aquifers with distinct multi-aquifer architecture or aquifers that have a high occurrence of cross-aquifer completions.

The statewide assessment provides a framework for understanding the factors that impact the potential for comingling to occur in an aquifer, even between water qualities that are not brackish. The assessment provides an indication that many of Texas's aquifers have the potential to commingle brackish groundwater.

There is currently a shifting paradigm about what constitutes economically viable aquifers and what may be a useable water supply. As we increase the development of brackish water resources, our understanding of comingling and how the statutes are to be interpreted and applied may need to be revaluated. An interpretation of the statutes would suggest that some degree of groundwater mixing can occur and may not be considered comingling consistent with the State's groundwater protection strategies. In addition, the characterization of aquifers should include efforts to improve data collection to identify the potential for comingling both prior to and during development. One example that can improve aquifer characterization is the collection of zonal hydraulic head data and water quality data. A regulatory question outside the scope of this report is when the collection of this data would be required.

The case studies documented herein demonstrate that stratification of water quality commonly occurs in aquifers. It is expected that water quality stratification and occurrence of problematic concentration of constituents such as metals, silica, and radioactive constituents will increase as development moves to deeper and more brackish portions of aquifers. Characterization of these resources will need to improve to take full advantage of brackish groundwater. Characterization techniques will be required to demonstrate isolation from fresh-water portions of the aquifer, optimize produced water quality and to demonstrate that any aquifer mixing that may occur in the well is protective of the beneficial use of the groundwater and the aquifer.

In 2019, the 86th Texas Legislature passed House Bill 722 and created a framework for groundwater conservation districts to establish rules for producing brackish groundwater from TWDB designated brackish groundwater production zones for a municipal drinking water project or an electric generation project. The TWDB recently adopted rules related to brackish groundwater production zone by amending Title 31 TAC§356 and adding a new Subchapter G to (1) clarify how the agency identifies and designates local or regional brackish groundwater production zones, (2) outline how the agency will conduct an assessment and technical review of a brackish groundwater production zone operating permit applications, and (3) outline how the agency will investigate and conduct a technical review of annual reports, upon request by a groundwater conservation district. These rules also describe the information required to conduct the technical reviews and the information contained in the reports that the agency will submit to the groundwater conservation districts.

Texas Water Code Section 16.060 stipulates that brackish groundwater production zones are separated by hydrogeologic barriers sufficient to prevent significant impacts to water availability or water quality in any area of the same or other aquifers, subdivisions of aquifers, or geologic strata that have an average total dissolved solids level of 1,000 milligrams per liter or less at the time of designation of the zones. Future compliance with this statute will require a minimum level of characterization data to evaluate the potential for comingling. We would recommend that TWDB, groundwater conservation districts, and other stakeholders work together on defining minimum data standards regarding the assessment of potential comingling that can create statewide standards that help inform the planning, regulation, and development of brackish groundwater projects.

7.2 Limitations

A literature review of the definition of comingling in statute documented in Section 2 of this report was completed without legal consultation. The purpose of the review was to further the understanding of comingling, document statute that affects comingling, and help inform regulatory agency and entities.

As the case studies demonstrate, the potential for comingling to occur in a well is affected by multiple factors including the regional characteristics of the aquifer, the well design, the well construction, the well operation, and by the groundwater pumping. Consequently, the statewide assessments of potential for comingling in brackish groundwater are limited by their regional scope. The aquifer-wide assessments use available information to rank the relative potential for comingling of brackish groundwater within that aquifer. Because of the general lack of information available regarding measured vertical profiles of hydraulic heads and water quality parameters in wells, the aquifer-wide assessments are limited by their reliance on hydraulic head predicted by groundwater models and salinity zones delineated by TWDB studies of brackish groundwater. As a result, the aquifer-wide assessment is meant to be a broad assessment of potential for commingling to occur and should not be used as a substitute for well-specific evaluations.

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10 Appendix A: Geographic Information System Datasets

The geographic information system (GIS) datasets used in the current study are located in the GIS_Final" folder included in the final electronics deliverables. Acronyms not specific to data format extensions are provided in Section 10.3. The structure of this folder is asfollows:

10.1 "*GIS_Final*"(main folder)

1.All *.mxd* files corresponding to map figures in the report

- the main folder contains all .mxds used in the report

2."*png"* (folder)

- contains .png files of all the .mxd files included in the main GIS_Final folder.

3."*shp*" (folder)

a. All shapefiles (.shp) used in the current study are included in the main "*shp*" folder

b. "*aois*" (folder)

- Contains the area of interest boundary data for the Gulf Coast, Trans Pecos, and Eagle Ford regions

c. "*models_cells_of_interest*" (folder)

- Contains .shps for model layer footprints for layers in various models: ABZR, CZWXC, CZWXS, GLFCC, GLFCN, GLFCS, YGJK, CPTN, IGNS, OGLL, and PRBL

d. "wells_for_GC_WQ_rasters" (folder)

- Contains the .shp for wells with openings above the 1,000 mg/L surface

e. "wells_in_multiple_lyrs" (folder)

- Contains .shp files for wells with openings in the various model layers: ABZR, CZWXC, CZWXS, GLFCC, GLFCN, GLFCS, YGJK, CPTN, IGNS, OGLL, and PRBL
-

10.2 GIS file name codes

The following section includes explanations of naming conventions and acronyms used in the GIS data delivery. Most of this information can also be found in the metadata associated with the individual rasters and shapefiles.

1..*mxd* files and *.png* files

- For clarity, the .mxds are labelled with the corresponding report figure number and a short description of the figure. As an example, "Fig_4_35_Gulf_Coast_wells.mxd" is the .mxd corresponding to "Figure 4-35 Site Locations for wells associated with the case studies for the Gulf Coast Aquifer" in the report. All .png files are assigned the same name as the corresponding .mxd file.

2."*shp*" (folder)

- There is no consistent naming convention used for these shapefiles, but titles were made as descriptive as possible.

Shapefile name	**Shapefile description**
Shp directory	
all_transects	Stratigraphic cross-sections (Figures 4-1 and 4-3)
ClearwaterRanch_Bracs	Wells from the BRACS Database that are located near Clearwater Ranch whose logs have been analyzed for stratigraphy contacts
Comingling_Report_ClearwaterRanch	Wells from the TWDB Groundwater Database that are located near Clearwater Ranch with water quality data
GC_Well_Locs	Site locations for wells associated with case studies for the Gulf Coast Aquifer (Figure 4-35)
Major_Aquifers	Major Aquifers of Texas as defined by the TWDB
Minor_Aquifers	Minor Aquifers of Texas as defined by the TWDB
Regions	Boundaries for the Trans Pecos, Gulf Coast, and Eagle Ford Regions
TWDB_GMAs_Detailed_05212021	Boundaries of the Groundwater Management Areas of Texas as defined by the TWDB
tx_counties	Texas Counties
Wellfield_Boundary	Clearwater Ranch Well Field Boundary
Wells_near_Kermit_Monahans	Locations from the Submitted Driller Reports database located near Kermit and Monahans Texas.
YGJK_line_4mi_from_L2_updip_052121	Line used to divide L1 between shallow outcrop (updip) and Catahoula (downdip). (Figure 4-22)
Aois directory	
AOI_eagleford_counties_dissolved_00_012521	Eagle Ford Study Area

AOI_GulfCoastAquifer_020516	Gulf Coast Study Area
AOI_transpecos_counties_dissolved_00_012521	Trans Pecos Study Area
div_line_CZWX_S_and_C_032921	Line separating CZWXS model from CZWXC model
Models_cells_of_interest directory	
EF_GC_ABZR_L2_pos_thk_dissolved_022321	Boundary for Layers 1 and 2 of the ABZR Model: Brazos River Alluvial Aquifer
EF_GC_ABZR_L3_boundary_030921	Boundary for Layer 3 of the ABZR Model: Underlying Aquifers
EF_GC_CZWXC_L1_pos_thk_dissolved_022321	Boundary for Layer 1 of the CZWXC Model: Shallow Aquifer
EF_GC_CZWXC_L2_pos_thk_dissolved_022321	Boundary for Layer 2 of the CZWXC Model: Shallow Aquifer
EF_GC_CZWXC_L3_pos_thk_dissolved_022321	Boundary for Layer 3 of the CZWXC Model: Sparta
EF_GC_CZWXC_L4_pos_thk_dissolved_022321	Boundary for Layer 4 of the CZWXC Model: Weches
EF_GC_CZWXC_L5_pos_thk_dissolved_022321	Boundary for Layer 5 of the CZWXC Model: Queen City
EF_GC_CZWXC_L6_pos_thk_dissolved_022321	Boundary for Layer 6 of the CZWXC Model: Reklaw
EF_GC_CZWXC_L7_pos_thk_dissolved_022321	Boundary for Layer 7 of the CZWXC Model: Carrizo
EF_GC_CZWXC_L8_pos_thk_dissolved_022321	Boundary for Layer 8 of the CZWXC Model: Calvert Bluff
EF_GC_CZWXC_L9_pos_thk_dissolved_022321	Boundary for Layer 9 of the CZWXC Model: Simsboro
EF_GC_CZWXC_L10_pos_thk_dissolved_022321	Boundary for Layer 10 of the CZWXC Model: Hooper
EF_GC_CZWXS_L1_pos_thk_dissolved_022321	Boundary for Layer 1 of the CZWXS Model: Sparta
EF_GC_CZWXS_L2_pos_thk_dissolved_022321	Boundary for Layer 2 of the CZWXS Model: Weches
EF_GC_CZWXS_L3_pos_thk_dissolved_022321	Boundary for Layer 3 of the CZWXS Model: Queen City
EF_GC_CZWXS_L4_pos_thk_dissolved_022321	Boundary for Layer 4 of the CZWXS Model: Reklaw
EF_GC_CZWXS_L5_pos_thk_dissolved_022321	Boundary for Layer 5 of the CZWXS Model: Carrizo
EF_GC_CZWXS_L6_pos_thk_dissolved_022321	Boundary for Layer 6 of the CZWXS Model: Calvert Bluff
EF_GC_CZWXS_L7_pos_thk_dissolved_022321	Boundary for Layer 7 of the CZWXS Model: Simsboro
EF_GC_CZWXS_L8_pos_thk_dissolved_022321	Boundary for Layer 8 of the CZWXS Model: Hooper
EF_GC_GLFCC_L1_pos_thk_dissolved_022321	Boundary for Layer 1 of the GLFCC Model: Chicot
EF_GC_GLFCC_L2_pos_thk_dissolved_022321	Boundary for Layer 2 of the GLFCC Model: Evangeline
EF_GC_GLFCC_L3_pos_thk_dissolved_022321	Boundary for Layer 3 of the GLFCC Model: Burkeville

EF_GC_GLFCC_L4_pos_thk_dissolved_022321	Boundary for Layer 4 of the GLFCC Model: Jasper
EF_GC_GLFCN_L1_pos_thk_dissolved_022321	Boundary for Layer 1 of the GLFCN Model: Chicot
EF_GC_GLFCN_L1_pos_thk_dissolved_031121	Boundary for Layer 1 of the GLFCN Model: Chicot
EF_GC_GLFCN_L2_pos_thk_dissolved_022321	Boundary for Layer 2 of the GLFCN Model: Evangeline
EF_GC_GLFCN_L2_pos_thk_dissolved_031121	Boundary for Layer 2 of the GLFCN Model: Evangeline
EF_GC_GLFCN_L3_pos_thk_dissolved_022321	Boundary for Layer 3 of the GLFCN Model: Burkeville
EF_GC_GLFCN_L3_pos_thk_dissolved_031121	Boundary for Layer 3 of the GLFCN Model: Burkeville
EF_GC_GLFCN_L4_pos_thk_dissolved_022321	Boundary for Layer 4 of the GLFCN Model: Jasper
EF_GC_GLFCN_L4_pos_thk_dissolved_031121	Boundary for Layer 4 of the GLFCN Model: Jasper
EF_GC_YGJK_L2_pos_thk_dissolved_022321	Boundary for Layer 2 of the YGJK Model: Upper Jackson
EF_GC_YGJK_L3_pos_thk_dissolved_022321	Boundary for Layer 3 of the YGJK Model: Lower Jackson
EF_GC_YGJK_L4_pos_thk_dissolved_022321	Boundary for Layer 4 of the YGJK Model: Upper Yegua
EF_GC_YGJK_L5_pos_thk_dissolved_022321	Boundary for Layer 5 of the YGJK Model: Lower Yegua
GC_GLFCS_L2_pos_thk_dissolved_022221	Boundary for Layer 2 of the GLFCS Model: Evangeline
GC_GLFCS_L3_pos_thk_dissolved_022221	Boundary for Layer 3 of the GLFCS Model: Burkeville
GC_GLFCS_L4_pos_thk_dissolved_030821	Boundary for Layer 4 of the GLFCS Model: Jasper
TP_CPTN_L1_pos_thk_dissolved_022221	Boundary for Layer 1 of the CPTN Model: Pecos Valley Alluvium
TP_CPTN_L4_pos_thk_dissolved_022221	Boundary for Layer 4 of the CPTN Model: Confining Unit
TP_CPTN_L5_pos_thk_dissolved_022221	Boundary for Layer 5 of the CPTN Model: Capitan, Shelf, and Basin Deposits
TP_CPTN_L5_pos_thk_dissolved_intersect_022221	Boundary for Layer 5 of the CPTN Model inside the TWDB footprint for the Capitan
TP_IGNS_L1_pos_thk_dissolved_022221	Boundary for Layer 1 of the IGNS Model: Salt Bolson Aquifer
TP_IGNS_L2_pos_thk_dissolved_030321	Boundary for Layer 2 of the IGNS Model: Igneous Aquifer
TP_IGNS_L3_pos_thk_dissolved_022221	Boundary for Layer 3 of the IGNS Model: Cretaceous and Permian Hydrogeologic Units
TP_OGLL_L1_pos_thk_dissolved_022221	Boundary for Layer 1 of the OGLL Model: Pecos Valley Alluvium
TP_OGLL_L2_pos_thk_dissolved_022221	Boundary for Layer 2 of the OGLL Model: Edwards-Trinity (Plateau)
TP_OGLL_L4_pos_thk_dissolved_022221	Boundary for Layer 4 of the OGLL Model: Lower Dockum
TP_PRBL_L1_pos_thk_dissolved_022221	Boundary for Layer 1 of the PRBL Model: Alluvium

TP_PRBL_L2_pos_thk_dissolved_022221	Boundary for Layer 2 of the PRBL Model: Bolson
TP_PRBL_L3_pos_thk_dissolved_022221	Boundary for Layer 3 of the PRBL Model: Cretaceous and Permian Hydrogeologic Units
wells_for_GC_WQ_rasters	
wells_GC_paired_to_WQdepth_rasters_00_031021	Wells in the Gulf Coast Region with openings above the 1,000 mg/L surface (Figure 4-28)
wells_in_multiple_lyrs	
EF_wells_multilyr_CZWXC_033021	Wells open to multiple CZWXC layers
EF_wells_multilyr_CZWXS_033021	Wells open to multiple CZWXS layers
GC_wells_multilyr_ABZR_030521	Wells open to multiple ABZR layers
GC_wells_multilyr_GLFCC_030521	Wells open to multiple GLFCC layers
GC_wells_multilyr_GLFCN_030821	Wells open to multiple GLFCN layers
GC_wells_multilyr_GLFCN_031121	Wells open to multiple GLFCN layers
GC_wells_multilyr_GLFCS_030821	Wells open to multiple GLFCS layers
GC_wells_multilyr_YGJK_030821	Wells open to multiple YGJK layers
TP_wells_multilyr_CPTN_030321	Wells open to multiple CPTN layers
TP_wells_multilyr_IGNS_030321	Wells open to multiple IGNS layers
TP_wells_multilyr_OGLL_030321	Wells open to multiple OGLL layers
TP_wells_multilyr_PRBL_030321	Wells open to multiple PRBL layers

10.3 Acronyms

ABZR = Brazos River Alluvium Aquifer Groundwater Availability Model

CPTN = Capitan Aquifer Complex Groundwater Availability Model

CZWXC = Central Carrizo-Wilcox Aquifers Groundwater Availability Model

CZWXS = Southern Carrizo-Wilcox Aquifers Groundwater Availability Model

CZWXN = Northern Carrizo-Wilcox Aquifers Groundwater Availability Model

GC = Gulf Coast Study Region

EF = Eagle Ford Study Region

GLFCC = Central Gulf Coast Aquifer Groundwater Availability Model

GLFCN = Northern Gulf Coast Aquifer Groundwater Availability Model
GLFCS = Southern Gulf Coast Aquifer Groundwater Availability Model
IGNS = Igneous Bolson Aquifer Groundwater Availability Model
L# = Groundwater Availability Model Layer Number
OGLL = High Plains Aquifer System Groundwater Availability Model
PRBL = Presidio and Redford Bolson Aquifers Groundwater Availability Model
TP = Trans-Pecos Study Region
WQ = Water Quality
YGJK = Yegua-Jackson Aquifers Groundwater Availability Model

11 Appendix B: Statewide Aquifer Metric Basis and References

Table B-1. Basis and Reference for Salinity Class Range Metric.

Aquifer	Citation(s)	Notes
Blaine	Finch and others (2016)	Figure 6.1 and Table 12-1. The Blaine water volume greater than 10,000 parts per million is less than a tenth of a percent of the total volume. Because there is very saline and brine in the Blaine, but at very low volumes. We assigned 4 salinity classes to the Blaine.
Blossum	Beach and Laughlin (2017)	Table 1-1 of Beach and Laughlin (2017) provides groundwater volumes in storage for 4 salinity classes. Also refer to Figure 6-1.
Bone Spring/Victoria Peak	Eberle and Cadol (2020) in Kelley and others (2020)	Figure 2 of Eberle and Cadol (2020) plots total dissolved solids concentrations in the aquifer system and the maximum reported value is 4,600 parts per million. We assigned 3 salinity classes.
Capitan	Jones (2016)	Figure 4.7.1 of Jones (2016) shows total dissolved solids measurements up to 190,000 parts per million resulting in five salinity classes.
Carrizo-Wilcox	Meyer and others (2020)	Water quality is the most saline in the Southern Carrizo-Wilcox. Based upon the brackish groundwater volumes tables and mapping reported in Meyer and others (2020) there are five salinity classes. See Figure 7.2.5-2.
Cross-Timbers	Ballew and French (2019)	Ballew and French (2019) report that most groundwater samples measure a concentration less than 3,000 parts per million but reports that water quality is highly variable. Figure 6.1 of the same report reports 4 salinity classes.
Pecos Valley Alluvium	Meyers and Wise (2012)	Figure 6-28 and Table 6-4 of Meyers and Wise (2012) report four salinity classes for the aquifer. They group classes greater than 10,000 parts per million.
Dockum	Deeds and others (2015)	Figure 4-8-3 of the High Plains Aquifer Groundwater Availability Model (Deeds and others, 2015) plots total dissolved solids concentrations greater than 10,000 parts per million. However, the text notes that concentrations as one approached the center of the basin can reach 50,000 parts per million. We assumed 5 salinity classes.
Edwards (BFZ)	Jones (2020)	The Conceptual Model for the Northern Segment of the Edwards (Balcones Fault Zone) Aquifer shows four salinity classes based upon total dissolved solids measurements (Figure 4.7.1).
Edwards-Trinity (Plateau)	Kreitler and others (2013) and LBG-Guyton Associates (2003)	The Edwards Group measured total dissolved solids is generally less than 2,000 parts per million (Figure 8-9 of Kreitler and others, 2013) and the Antlers has total dissolved solids concentrations reported between 2,001 and 27,325 parts per million (Figure 8-13 of Kreitler and others, 2013) but no information is provided to see if the high value is an outlier. LBG-Guyton Associates

Aquifer	Citation(s)	Notes
		(2003) report that concentrations tend to be less than 10,000 parts per million so we will assume 3 salinity classes is representative.
Edwards-Trinity (High Plains)	Deeds and others (2015)	Figure 3-8-4 of the High Plains Aquifer System Conceptual Model shows that total dissolved solids measurements are generally less than 10,000 parts per million with only one measurement above. We have assumed 3 salinity classes.
Ellenburger-San Saba	Shi and others (2016)	Based on the work of Shi and others (2016) they report three salinity classes shown in Figure 4.7.10 of that report. The figure groups all total dissolved solids concentrations greater than 3,000 parts per million.
Gulf Coast	Young and others (2016)	See Table 12.3 of this report which reports groundwater volumes for five salinity classes.
Hickory	Shi and others (2016)	Based on the work of Shi and others (2016) they report three salinity classes shown in Figure 4.7.19 of that report. The figure groups all total dissolved solids concentrations greater than 3,000 parts per million but it is limited to one well.
Hueco-Mesilla Bolson	LBG Guyton Associates (2003)	LBG Guyton Associates (2003) report in Figure 3 that there are wells exceeding 10,000 parts per million total dissolved solids indicating four salinity classes.
Igneous	LBG Guyton Associates (2003) and Beach and others (2004)	LBG Guyton Associates (2003) report that the Igneous Aquifer is comprised of fresh groundwater. Beach and others (2004) report only fresh water in Figure 4.1.26 of that report.
Lipan	Robinson and others (2018)	Robinson and others (2018) report that there are three salinity classes in the Lipan Aquifer.
Marathon	LBG Guyton Associates (2003)	LBG Guyton Associates (2003) report that groundwater in the Marathon Aquifer is fresh (Figure 37).
Marble Falls	Preston and others (1996)	Preston and others, 1996 report that total dissolved solids ranges from 324 to 1,106 parts per million so we have assumed 2 salinity classes is representative.
Nacatoch	Laughlin and others (2017)	Laughlin and others (2017) report that total dissolved solids ranges over 4 salinity classes (Figure 6-2)
Ogallala	Deeds and others (2015)	Figure 4-8-2 of the High Plains Aquifer System Conceptual Model shows that total dissolved solids measurements are generally less than 10,000 parts per million with only a few measurements above. We have assumed 3 salinity classes.
Queen City & Sparta	Schorr and others (2021) and Meyer and others (2020)	Schorr and others (2021) report four salinity classes in the Queen City and Sparta Aquifers (Figures 2-75 and 2-76) and this is consistent with Meyer and others (2020).
Rita Blanca	LBG Guyton Associates (2003)	LBG Guyton Associates (2003) report that groundwater in the Rita Blanca Aquifer ranges over two salinity classes with limited amounts of slightly saline groundwater.

Aquifer	**Citation(s)**	**Notes**
Brazos River Alluvium	Ewing and others (2016)	Figure 4.7.1 shows that total dissolved solids ranges over three salinity classes.
Rustler	Lupton and others (2016)	Figure 10.3 shows measured and interpreted total dissolved solids concentrations and shows that in the “fresh” aquifer footprint total dissolved solids is generally less than 10,300 parts per million. However, east of the Capitan Reef concentrations can exceed 35,000 parts per million. The Rustler also has halite and polyhalite interbedded in it. We have assumed the Rustler has 5 salinity classes.
Seymour	Ewing and others (2004)	Based upon water quality results presented in Figure 4-8.6 we have assumed 2 salinity classes is representative of the aquifer.
Northern Trinity	Robinson and others (2019)	Robinson and others (2019), report four salinity classes in the Northern Trinity Aquifer (Figure 7-2).
West Texas Bolsons	Beach and others (2004) and LBG Guyton Associates (2003)	Beach and others, 2008 in Figure 4.8.1 shows that most groundwater is fresh or slightly saline with one sample that exceeds 10,000 parts per million so we have assumed 3 salinity classes consistent with Guyton and others (2003).
Woodbine	Kelley and others (2014)	Figure 4.4.9 of Kelley and others (2014) shows that total dissolved solids measurements range over 3 salinity classes.
Yegua Jackson	Deeds and others (2010)	Figure 4.8.2 of Deeds and others (2010) shows that total dissolved solids measurements range over 3 salinity classes.

Table B-2. Basis and Reference for Aquifer Layering Metric.

Aquifer	Citation(s)	Notes
Blaine	Ewing and others (2004), Finch and others (2016)	The Blaine Formation is composed of limestones, gypsum and evaporites. There are some cross-completions in the Dog Creek Shale in one county (Ewing and others, 2004). The aquifer was scored medium.
Blossum	Beach and Laughlin (2017)	Beach and Laughlin (2017) depict the Blossum as a single aquifer, so we assign a low score.
Bone Spring/Victoria Peak	Fichera (2020) in Kelley and others (2020) and Hutchison (2008)	While the aquifer is composed of the Bone Springs and Victoria Peak limestones, Fichera (2020) reports that where the two are stacked, the limestones collectively constitute a major water-bearing unit. This is consistent with how Hutchison (2008) modeled the aquifer. We assigned the aquifer a low score.
Capitan	Jones (2016)	The Capitan has been modeled as a single aquifer although it is recognized to be composed of multiple formations. We have assumed a low score based upon conceptualizations of the aquifer in models.
Carrizo-Wilcox	Meyer and others (2020)	The Carrizo-Wilcox is composed of multiple formations which are aquifers and multi-completed wells are common. We assign a high score recognizing the layered nature of the aquifer with distinct high productivity formations. Models consistently model this aquifer with multiple layers.
Cross-Timbers	Ballew and French (2019)	The Cross Timbers Aquifer is composed of multiple formations within four geologic groups. The productivity and water quality within formations can vary significantly and multi-completed wells are common. We assign a high score recognizing the layered nature of the aquifer.
Pecos Valley Alluvium	Meyers and Wise (2012)	The Pecos Valley Alluvium is composed of interbedded layers of sand silt and clay but is typically modeled as a single aquifer. We assign a medium score recognizing the heterogeneity of lithology in the aquifer.
Dockum	Deeds and others (2015)	The Dockum is a very thick sequence of interbedded siltstones, mudstones and sandstone conglomerates. We assign a high score recognizing the layered nature of the aquifer.
Edwards (BFZ)	Jones (2020)	The Edwards (Balcones Fault Zone) Aquifer is layered aquifer system with regional variability from changing depositional facies (Figure 6 of Jones, 2020). We assigned this aquifer a high score.
Edwards-Trinity (Plateau)	Kreitler and others (2013) and LBG-Guyton Associates (2003)	The Edwards-Trinity Plateau is comprised of the Edwards Group overlying the Trinity Group. These groups are comprised of multiple formations and the carbonates in the Edwards Group are comprised of multiple layers with distinct properties. We assigned this aquifer a high score.
Edwards-Trinity (High Plains)	Deeds and others (2015)	Deeds and others (2015) model the aquifer as a single layer but George, Mace and Petrosian (2011) and Blanford and others (2008) report that the aquifer is composed of multiple layers of clay/shale, limestone and sandstone. We assigned this aquifer a high score

Aquifer	Citation(s)	Notes
Ellenburger-San Saba	Preston and others (1996) and Shi and others (2016)	Preston and others, 1996 report that the Ellenburger Group is composed of several formations. However, combined with the San Saba they are considered one aquifer and that is how Shi and others (2016) modeled the aquifer. We assign a medium score recognizing that the aquifer is layered but also considered one hydrogeologic unit.
Gulf Coast	Young and others (2016)	Young and others (2016) provide significant evidence of the heterogeneity and layering of the formations comprising the Gulf Coast Aquifer. We assign a high score to this aquifer.
Hickory	Preston and others (1996)	According to Preston and others (1996) the Hickory is a single sandstone member, so we have assigned a low score.
Hueco-Mesilla Bolson	Heywood and Yager (2003)	The Hueco-Mesilla Bolson aquifer is composed of multiple hydrogeologic facies according to Heywood and Yager (2003, Pg. 5). We assigned the aquifer a medium score recognizing the depositional heterogeneity.
Igneous	LBG Guyton Associates (2003) and Beach and others (2004)	Beach and others (2004) report that the aquifer is composed of multiple formations and is structurally complex. We assign a medium value to this aquifer.
Lipan	Robinson and others (2018) and George and others (2011)	The Lipan is comprised of Quaternary alluvial deposits its including alluvium, the Leona Formation and Cretaceous and Permian unconformably underlying and dipping formations. We assigned the aquifer a high score.
Marathon	George and others (2011)	The Marathon is composed of multiple formations with the Marathon Limestone as the most productive formation within the aquifer. Because of the presence of multiple formations and structural complexity we assign a high score.
Marble Falls	Preston and others (1996)	Preston characterizes the aquifer as a single limestone formation, so we assign a low score.
Nacatoch	Laughlin and others (2017)	Aquifer is effectively one aquifer, but it is comprised of multiple sands. In the Nacatoch Brackish Resources Aquifer Characterization System report (Laughlin and others, 2017) they mapped Lower Navarro sands as part of the Nacatoch and they document total dissolved solids variability across salinity classes in a cross section (Figure 6.5) providing evidence that the aquifer is composed of multiple formations. Most Nacatoch wells are completed in the primary Nacatoch sand. We have this aquifer a medium score.
Ogallala	Deeds and others (2015)	While the Ogallala is generally modeled as a single aquifer, there is significant lateral and vertical heterogeneity and there are multiple formations recognized in the aquifer. Most groundwater availability models simulate the Ogallala with a single model layer. We assign a medium score.

Aquifer	**Citation(s)**	**Notes**
Queen City & Sparta	Schorr and others (2021) and Kelley and others (2007)	The Queen City and Sparta Aquifers are similar in architecture as the Carrizo-Wilcox Aquifer with distinct aquifers and aquitards. We assigned this aquifer a high score similar to all the Tertiary Coastal Plain clastic systems.
Rita Blanca	George and others (2007)	The Rita Blanca is composed of the Lytle and Dakota formations as well as in the Exeter Sandstone and the Morrison Formation. We assigned this aquifer a high score.
Brazos River Alluvium	Ewing and others (2016)	The Brazos River Alluvium Aquifer consists of Quaternary-age water-bearing sediments in the floodplain and terrace deposits of the Brazos River. While being fluvial in nature the aquifer is generally considered to be a single aquifer unit well hydraulically connected. We assigned this aquifer a low score.
Rustler	Lupton and others (2016)	The Rustler Formation is a complex multi-lithologic aquifer comprised of anhydrites, mudstones, dolomites and limestone. The lithology is affected by dissolution in some areas. We assigned a score of high based upon the complex lithology for a relatively thin aquifer.
Seymour	Ewing and others (2004)	The Seymour aquifer, as defined by the Texas Water Development Board, is composed of remnants of the Seymour Formation, the Lingos Formation, and younger alluvial deposits all of Quaternary age (see Figure 2.23 of Ewing and others, 2004). Assigned a medium score.
Northern Trinity	Kelley and others (2014)	The Northern Trinity Aquifer is composed of many formations and facies equivalents. We assigned this aquifer a high score.
West Texas Bolsons	Beach and others (2004) and LBG Guyton Associates (2003)	Aquifer are composed of alluvial deposits of various parent materials but are generally treated as a single aquifer layer in models and cross-sections. We assigned a score of low.
Woodbine	Kelley and others (2014)	The Woodbine Aquifer is generally conceptualized as one formation with variable sand fraction. We assigned this aquifer low score.
Yegua Jackson	Deeds and others (2010) and Knox and others (2007).	The Yegua-Jackson Aquifer is composed of several formations and we assigned a high score for this aquifer.

Table B-3. Basis and Reference for Cross-Aquifer Completion Metric.

Aquifer	Citation(s)	Notes
Blaine	Ewing and others (2004)	There are some cross-completions in the Dog Creek Shale in one county within the aquifer (Ewing and others, 2004). We assign a medium score for the Blaine.
Blossum	Wade, Boghici and Wade (2021)	Cross-aquifer completions are not reported in the Blossum Aquifer in Wade, Boghici and Wade (2021).
Bone Spring/Victoria Peak	Fichera (2020) in Kelley and others (2020) and Hutchison (2008)	While the aquifer is composed of multiple formations, Fichera (2020) reports that the limestones collectively constitute a major water-bearing unit. This is consistent with how Hutchison (2008) modeled the aquifer. We assigned the aquifer a low score.
Capitan	Jones (2016)	Cross-completions in the Capitan are rare because the aquifer is very productive and is generally overlain by the productive Pecos Valley Alluvial Aquifer. This study only found one cross-completed Capitan well. We assigned the aquifer a low score.
Carrizo-Wilcox	Meyer and others (2020), Kelley and others (2004) and this study	The Carrizo-Wilcox Aquifer System generally comprised of aquifers and aquitards and wells typically target the high sand content aquifers (Carrizo, Simsboro). Because of the aquifer's productivity, it is rare that wells are cross-completed outside of the aquifer system. However, it does occur close to outcrops. Inter-aquifer cross completions are common. We assigned this aquifer a medium score because of the multi-aquifer nature of the aquifer system.
Cross-Timbers	Ballew and French (2019)	Cross-completions within the aquifer are very common and in many cases the rule as people try to grab as much productivity as they can. Water quality is quite variable in the formations, so the Cross-aquifer completions have potential to mix multiple water quality. Inter-aquifer completions occur between the Northern Trinity Hosston in the shallow updip limits of the Hosston. We give this aquifer a high score.
Pecos Valley Alluvium	Meyers and Wise (2012) and this study	Meyers and Wise (2012) and this study provide significant evidence of inter-aquifer completions between the Pecos Valley Alluvium and other aquifers (mostly the Lower Dockum and the Edwards-Trinity). We give this aquifer a high score.
Dockum	Deeds and others (2015) and this study	Deeds and others (2015) map a significant number of inter-aquifer completions. This study finds that cross-aquifer completions are very common in the Trans-Pecos Region. We give this aquifer a high score.
Edwards (BFZ)	Jones (2020)	Jones does not provide evidence of cross-aquifer completions. Wells generally either target the Edwards or the underlying Trinity Hosston. There are significant gradients within the layered limestones within the Edwards and vertical flow within boreholes have been documented by the Edwards Aquifer Authority. We assign this aquifer a medium score because of the multi-aquifer nature of the aquifer system.

Aquifer	Citation(s)	Notes
Edwards-Trinity (Plateau)	Kreitler and others (2013)	Kreitler and others (2013) report that wells completed in both the Edwards and Trinity and common in the central portions of the aquifer. In the western portions of the aquifer system wells are completed both in the Trinity and the Dockum and in the Ogallala and Trinity. We gave this aquifer a high score because of the multiple aquifers available for completion within the aquifer and the documented inter-aquifer completions.
Edwards-Trinity (High Plains)	Deeds and others (2015)	Deeds and others (2015) map multi-completed wells within the Edwards-Trinity Plateau aquifer (Figure 4.3.2). Because multi-completed wells are common, we assigned a high score.
Ellenburger-San Saba	Shi and others (2016)	No good evidence of cross-aquifer completions provided by Shi ad others (2016). Guyton and Associates (2003) state that in some areas of the aquifer system the intervening confining beds between the Ellenburger-San Saba and the overlying Marble Falls aquifer may be in contact.
Gulf Coast	This Study	The Gulf Coast Aquifer System is comprised of several formations and multiple recognized aquifers. There are many wells within the System that cross-complete both aquifers within the Gulf Coast Aquifer System and to overlying aquifers such as the Yegua-Jackson. Cross-completions are most common in the shallower, updip regions where individual aquifer thicknesses thin. Because the Gulf Coast Aquifer is recognized as a system of aquifers and aquicludes and cross-completions within the system are common, we assign a high score.
Hickory	Shi and others (2016)	Shi and others (2016) provide no evidence for multi-completed wells so we assigned a low score.
Hueco-Mesilla Bolson	Heywood and Yager (2003)	No evidence provided in Heywood and Yager (2003) of multi-aquifer completed wells. This is reasonable given that the bolson deposits are generally very thick decreasing the need to complete below the aquifer. We gave the aquifer a low score.
Igneous	This study and Beach and others (2004)	No supporting data in was found in Beach and others (2004). However, this study found that approximately 28 percent of the wells analyzed were cross completed to Bolson or Cretaceous sediments. We assigned a score of medium.
Lipan	Robinson and others (2018)	Completions between the alluvium and Leona Formation and the underlying formations is common for depths up to a couple hundred feet. However, these underlying units are typically considered part of the Lipan Aquifer. We assigned a score of medium recognizing that the lower boundary of the Lipan is poorly constrained.
Marathon	Smith (2001)	There is little to no evidence of cross-aquifer completed wells in the Marathon with the exception of some wells completed in both overlying alluvium and the Marathon. We assigned a low score to the Marathon.
Marble Falls	Shi and others (1996), Smith (2004)	A review of the literature provided no evidence of cross-aquifer completions. We assigned a low score.

Aquifer	Citation(s)	Notes
Nacatoch	Laughlin and others (2017)	Aquifer is effectively one aquifer, but it is comprised of multiple sands. The Nacatoch Potential Brackish Production Zone report (Laughlin and others, 2017) mapped Lower Navarro sands as part of the Nacatoch and they document total dissolved solids variability across salinity classes in a cross section (Figure 6.5) providing evidence that the aquifer is composed of multiple formations. However, they report that most Nacatoch wells are completed in the primary Nacatoch sand. We assign this aquifer a low score.
Ogallala	Deeds and others (2015)	Deeds and others (2015) plot a significant number of multi-completed wells (Figure 4.3.1) into the underlying red beds. Most of these wells are being extended into the Dockum to increase saturated thickness without increasing productivity significantly. However, there are Rita Blanca and Edwards-Trinity multi-completed wells also. We assigned this aquifer a medium score.
Queen City & Sparta	Schorr and others (2021), Kelley and others (2004) and this study.	The occurrence of cross-completed wells in the Queen City and Sparta aquifers is rare according to the literature. There are wells completed in both Queen City and Sparta. Kelley and others (2004) did find cross-completed wells in the southern portion of the aquifer as one gets near the outcrops. We assigned this aquifer a medium score.
Rita Blanca	Deeds and others (2015)	Deeds and others (2015) report that there are a significant number of cross-aquifer completed wells connecting the Rita Blanca to overlying as well as underlying aquifers. We assigned a medium score to the Rita Blanca.
Brazos River Alluvium	Ewing and others (2016) and this study.	Does not appear to be many cross-aquifer completions in the aquifer. Our analysis in the Gulf Coast Groundwater Availability Model footprint indicated that less than 1 percent of the wells are completed below base BRAA. This is consistent with the findings in this study. We assigned the Brazos River Alluvium a low score.
Rustler	Lupton and others (2016)	Rustler wells are typically only completed in the Rustler though multi-completed wells do exist. We assigned a medium score because this study documents a multi-completed Rustler well.
Seymour	Ewing and others (2004)	Aquifer cross-completions are not that common in the Seymour but in select counties Ewing and others (2004) found that some wells were cross-completed with alluvial deposits based upon drillers logs. We assigned this aquifer a medium score.
Northern Trinity	Kelley and others (2014)	Cross-aquifer completions are Because the Northern Trinity Aquifer is recognized as a system of aquifers and aquicludes and cross-completions within the system are common, we assign this aquifer a medium score.
West Texas Bolsons	Beach and others (2004) and this study	There is no evidence in Beach and others (2004) or this study for significant cross-aquifer well completions. We assign this aquifer a low value.

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Aquifer	**Citation(s)**	**Notes**
Woodbine	Kelley and others (2014)	Kelley and others, 2014 suggests very little to no cross-aquifer completions as the Woodbine is underlain by the approximately 500 feet thick Washita-Fredericksberg Formation. The Washita-Fredericksburg Formation is composed almost entirely of shale and limestone.
Yegua Jackson	Deeds and others (2010)	The occurrence of cross-completed wells within the Yegua-Jackson aquifers is common according to Deeds and others (2010). The occurrence of cross-aquifer completed wells (primarily the Catahoula) has also been found to be common in this study. We assigned this aquifer a medium score.

Table B-4. **Basis and Reference for Aquifer Vertical Head Difference Metric.**

Aquifer	Citation(s)	Notes
Blaine	Ewing and others (2004)	Ewing and others (2004) reported no measured head differences at a given location within the aquifer. They did document head differences between the Blaine and other aquifers. We have assumed a low score based upon conceptualizations of the aquifer in the Groundwater Availability Model.
Blossum	Beach and Laughlin (2017)	Beach and Laughlin (2017) depict the Blossum as a single aquifer and did not document vertical head differences within the aquifer. We assigned this aquifer a low score.
Bone Spring/Victoria Peak	Fichera (2020) in Kelley and others (2020) and Hutchison (2008)	Fichera (2020) and Hutchison (2008) did not report vertical head differences within the aquifer and both characterize the limestones making up the aquifer as collectively making a major water-bearing unit. This is consistent with how Hutchison (2008) modeled the aquifer. Carbonate aquifer sequences typically have inter-borehole flow over large sequences. We assigned the aquifer a medium score.
Capitan	Jones (2016)	The Capitan has been modeled as a single aquifer although it is recognized to be composed of multiple formations. There is little evidence to suggest strong vertical gradients within the aquifer. That said, it is a carbonate aquifer with thicknesses many hundreds of feet. These aquifers generally have vertical gradients. We have assumed a medium score based upon conceptualizations of the aquifer in models.
Carrizo-Wilcox	Kelley and others (2004); Kelley and others (2009); Fogg and others (1983)	The Carrizo-Wilcox is composed of multiple formations which are aquifers and multi-completed wells are common. Kelley and others (2004; 2009) and Fogg and others (1983) documented significant vertical head gradients within the aquifer driving regional and subregional flow systems. We assign this aquifer a high score.
Cross-Timbers	Ballew and French (2019)	The Cross Timbers Aquifer is composed of multiple formations within four geologic groups. The formations dip to the east and the productive portions of the aquifer are shallow. 95 percent of the wells are domestic or livestock with an average depth of 174 feet. Vertical head differences within the first several hundred feet of the aquifer are assumed to be low. We assign a low score.
Pecos Valley Alluvium	Anaya and Jones (2009)	The Pecos Valley Alluvium is composed of interbedded layers of sand silt and clay but is typically modeled as a single aquifer as in the Groundwater Availability Model (Anaya and Jones, 2009). The Groundwater Availability Model report provides no evidence of significant vertical head differences within the aquifer, and we assign a low score to this aquifer.
Dockum	Deeds and others (2015)	The Dockum has been hydrostratigraphically conceptualized as an Upper and Lower Dockum. Deeds and others (2015) provide head maps showing hundreds of feet of vertical head difference between upper and lower units. We assign a high score.

Aquifer	Citation(s)	Notes
Edwards (BFZ)	Jones (2020)	Jones does not provide evidence of cross-aquifer completions in the Groundwater Availability Model report. Wells generally either target the Edwards or the underlying Trinity Hosston. There are significant gradients within the layered limestones within the Edwards and significant vertical flow within boreholes have been documented by the Edwards Aquifer Authority. We assign this aquifer a high score.
Edwards-Trinity (Plateau)	Kreitler and others (2013) and Nance (2009)	The Edwards-Trinity Plateau is comprised of the Edwards Group overlying the Trinity Group. These groups are comprised of multiple formations and the carbonates in the Edwards Group are comprised of multiple layers with distinct properties. Anaya and Jones modeled the Edwards and Trinity aquifers as two different model layers but did not report spatial head maps for each to calculate head differences. The research of Kreitler (2013) and Nance document both local and regional shallow and deep flow systems in the aquifers using hydrochemical analysis techniques. The water quality evidence suggest significant vertical gradients within the aquifer and we assigned this aquifer a high score.
Edwards-Trinity (High Plains)	Deeds and others (2015), George and others (2011) and Blanford and others (2008)	Deeds and others (2015) model the aquifer as a single layer but George and others (2011) and Blanford and others (2008) report that the aquifer is composed of multiple layers of clay/shale, limestone and sandstone. We assumed a medium score for this aquifer.
Ellenburger-San Saba	Preston and others (1996) and Shi and others (2016)	Preston and others, 1996 report that the Ellenberger Group is composed of several formations. However, combined with the San Saba they are considered one aquifer and that is how Shi and others (2016) modeled the aquifer. We assign a low score based upon a lack of evidence of significant vertical gradients within the aquifer system.
Gulf Coast	Kasmarek and Robinson (2004), Young and Kelley (2006) and Young and others (2009)	Kasmarek and Robinson (2004), Young and Kelley (2006) and Young and others (2009) provide significant evidence of strong vertical head differences within the Gulf Coast Aquifer System. We assign a high score to this aquifer.
Hickory	Preston and others (1996)	According to Preston and others (1996) the Hickory is a single sandstone member and there was no evidence reported of significant vertical head differences within the aquifer. We assigned a low score to this aquifer.
Hueco-Mesilla Bolson	Heywood and Yager (2003)	The Hueco-Mesilla Bolson aquifer was modeled by Heywood and Yager (2003) with multiple aquifer layers in part to account for topographic drive and discharge to the Rio Grande. This would imply vertical head differences within the aquifer. However, the simulated comparison of heads in the shallow layers (1,2) and the deeper layer 5 are very close. We assigned the aquifer a medium score.

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Aquifer	**Citation(s)**	**Notes**
Igneous	LBG Guyton Associates (2003) and Beach and others (2004)	Beach and others (2004) report that the groundwater flow mimics topography which implies some vertical gradients within the aquifer. However, they successfully simulated the aquifer as one model layer. We assign a low value to this aquifer based upon a lack of evidence.
Lipan	Robinson and others (2018) and George, Mace and Petrosian (2011)	The Lipan is comprised of Quaternary alluvial deposits including alluvium, the Leona Formation and Cretaceous and Permian unconformably underlying and dipping formations. Many wells complete in both the alluvial deposits and the very shallow bedrock formations. There is no evidence of significant head differences within the aquifer, and we assigned the aquifer a low score.
Marathon	George and others (2011)	The Marathon is composed of multiple formations with the Marathon Limestone as the most productive formation within the aquifer. This aquifer is an unconfined to semi-confined system and vertical head differences within the aquifer are expected to be low. We assumed a low score.
Marble Falls	Preston and others (1996)	Preston characterizes the aquifer as a single limestone formation, so we have assumed a low score based upon a lack of data to provide evidence of significant vertical head differences.
Nacatoch	Beach and others (2009)	Aquifer is effectively one aquifer, but it is comprised of multiple sands. The aquifer is essentially 2 to 3 sands which can be completed together. Most Nacatoch wells are completed in the primary Nacatoch sand. Vertical gradients are not documented in Beach and others (2009). We assign this aquifer a low score.
Ogallala	Deeds and others (2015)	The Ogallala is generally modeled as a single aquifer and Deeds and others (2015) provide no evidence of vertical head differences within the aquifer. We assign a low score.
Queen City & Sparta	Kelley and others (2004); Kelley, Deeds and Fryar (2009)	The Queen City and Sparta Aquifers are similar in architecture as the Carrizo-Wilcox Aquifer with distinct aquifers and aquitard sand documented vertical head differences between sand formations driving regional flow. We assigned this aquifer a high score as with all the Tertiary Coastal Plain clastic systems.
Rita Blanca	Deeds and others (2015)	Deeds and others (2015) modeled the Rita Blanca as a single model layer separate from the Ogallala even though many wells cross-complete these aquifers. A review of head maps presented in the Groundwater Availability Model report show non-discernable head difference between the two aquifers on a regional scale. We assigned this aquifer a low score.
Brazos River Alluvium	Ewing and others (2016)	The Brazos River Alluvium Aquifer is generally considered to be a single aquifer unit hydraulically well connected. We assigned this aquifer a low score.
Rustler	Lupton and others (2016)	The Rustler Formation is a complex multi-lithologic aquifer but was modeled as a single hydrogeologic unit in Ewing and others (2012). We assigned this aquifer a low score.

Brackish Groundwater Comingling

Aquifer	Citation(s)	Notes
Seymour	Ewing and others (2004)	Ewing and others, 2004 did not evaluate vertical gradients within the Seymour because of the thin nature of the aquifer and the fact that it is under water table conditions. There would be some topographic drive expected but it would be subdued. We assigned this aquifer a low score.
Northern Trinity	Kelley and others (2014)	The Northern Trinity Aquifer is composed of many aquifers and aquitards and strong vertical head differences between formations are documented in Kelley and others (2014). We assigned this aquifer a high score.
West Texas Bolsons	Beach and others (2004) and LBG Guyton Associates (2003)	Beach and others modeled the West Texas Bolsons as a single hydrogeologic unit and provided no evidence of significant vertical head differences within the aquifer. We assigned a score of low.
Woodbine	Kelley and others (2014)	The Woodbine Aquifer is generally conceptualized as one hydrogeologic unit with variable sand fraction. Kelley and others (2014) did not document vertical head differences within the aquifer, and we assigned this aquifer low score.
Yegua Jackson	Deeds and others (2010)	Deeds and others (2010) reviewed the potential for vertical cross-formation flow within the Yegua-Jackson Aquifer and found evidence for it. However, they noted that lack of water levels measurements at a given location in multiple formations and uncertainty in well completions made their analysis uncertain. Like the other Tertiary clastic coastal aquifer, conceptually one would expect significant vertical head differences. However, given the magnitudes documented in Deeds and others (2010) we assigned a medium score for this aquifer.

12 Appendix C: Comment Responses

Attachment 1

Contract 2000012442
TWDB Draft Final Report Comments
Report Title: Brackish Groundwater Comingling
Comments on Draft Final Report

General comments

1. TWDB has provided tracked changes in an attached MS Word document copy of the draft final report for ease of use. Please address comments and edits in the attached Word document and the comments included in this letter below. – ***Complete.***
2. Professional Geoscientists must affix seal and sign in the final report. – ***Complete.***
3. Add the TWDB Contract Number to the front cover of the final report. – ***Complete.***
4. Limit use of acronyms in the final report. If needed, add a list of acronyms in the front of final report. – ***We limited the use and added a list***.
5. Capitalize aquifer, formations, and counties when used as part of the official name. Plural designations are not capitalized: Gulf Coast and Edwards aquifers vs. Gulf Coast Aquifer. – ***Complete.***
6. Spell out Texas Water Development Board once and then use the TWDB acronym for the remainder of the report. Limit use of other acronyms but if necessary add a list of acronyms in front of report. – ***Complete.***
7. Do not use hyphens in the following prefixes/suffixes: statewide – ***Complete.***
8. Parenthetical citations should go at the end of the sentence, unless absolutely necessary. ***This has been limited and corrected.***

Specific comments

Section 1

1. Questions by the Water Well Drillers Advisory Council were assigned by only part of the workgroup as explained by TDLR – ***Text modified to reflect this.***

Section 2

2. Include that all GIS files are available as appendices after section 7. – ***Complete.***

Section 3.1

3. Page 7. Section 3.1: Remove the orphaned header and the following paragraphs will be the introduction. – ***Complete.***

4. Page 7. Section 3.1, first paragraph, last sentence: Delete the latter part of the sentence and change to "However, the review is meant to help inform regulatory entities." – ***Complete.***

Section 3.1.1

5. Page 8. Section 3.1.1, last paragraph: Add reference for Merriam Webster online. – ***Complete.***
6. Page 9. Section 3.1.1, last paragraph: State the words that need to be defined. ***Complete.***

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Section 3.5

7. Page 24 and 25. Section 3.5, fourth paragraph: Moved the content related to the Groundwater Protection Committee to its own Section 3.4. ***Complete.***
8. Page 24. Section 3.5, third paragraph: Add a sentence or two to close the section. ***Complete.***

Section 4.1

9. Pargagraph 1, Line 3. "an aquifer" should be "a well" – ***Fixed.***
10. Figure 4-1. Figure is low resolution – ***Agreed. This is the best we can do on this figure.***

Section 4.3.2

11. Consider defining "concentration"! since the study considers brackish groundwater, "concentration" could be defined as that of TDS, and a note, similar to the discussion on the page 128 that water quality is about other constituents as well, could be added. - ***This equation is generic consistent with this general conceptual section. Would prefer to keep it as is.***

Section 5.1

12. Replace "Structure" with "Surface" when discussing GIS surfaces. ***Complete***.
13. Page 42 and throughout the "Aquifer Storage and Recoverability Survey should be referred to as the "Statewide Aquifer Storage and Recovery Survey. – ***The phrase referenced is not found in the document. We looked at the report and will replace "Aquifer Storage and Recovery Suitability Study" with "Statewide Aquifer Storage and Recovery Survey" as suggested.***

Section 5.2.1

14. Add GMAs to Figure 5-1 on page 44 – ***Complete in Final Report.***
15. Page 46, Paragraph 2: Simplify sentence about thickness variation as "There is considerable variation in the relative thickness between the two aquifers" - ***Complete***

16. Page 49, paragraph 2, "In the vicinity of San Patricio, Nueces, Bee, Aransas and Calhoun counties" refers to counties not labeled on any figure, so additional description of the area is needed – ***Complete.***

17. Page 49, paragraph 3, Brackish groundwater should be defined as "a total dissolved solids concentration of between 1,000 and 10,000 milligrams per liter" instead of "less than 10,000…" – ***Complete.***

18. Page 52. Paragraph 2. The Chicot Aquifer covers all of the Gulf Coast, not most in this area. – ***Change made.***

Section 5.3

19. Figure 5-45. Add Add study area extent to legend.- ***Complete.***

Section 5.3.2

20. Figure 5-48. Define aquifers' acronyms. Possibly add them to the foot legend. Figure is crowded, consider making two separate figures, one per model, flowing table 5-16 and 5-17, with highlighted overlap in both. – ***Completed and made 2 figures.***

21. Figures 5-49-54 are too crowded. Consider using different colors for triangles, e.g., blue for upwards and red for downwards. Also, if document size allows, consider making two different figures, one per difference direction. – ***Good suggestion. Changed all figures of this type.***

22. Figure 5-55. Legend is unclear, projection details is cropped. Consider using 400 dpi image. – ***Received higher resolution figure from TWDB and will be replaced in final report.***

Section 5.2.2

23. Page 63, paragraph 1, The report notes that vertical gradients within the aquifers in the Gulf Coast Aquifer region have been documented by numerous investigators since the early 1970s and then references the USGS initiative. The only citations are from the USGS initiative. There should be some examples of other included studies cited. – ***Modified to say USGS rather than numerous investigators.***

24. Page 66, paragraph 1. In several places the report refers to "groups of aquifers" but these "groups" are subdivisions of the larger aquifers. I suggest the use of "Hydrologic units" – ***After reviewing all of Section 5 we decided to use the term aquifers to be consistent with the general GAM nomenclature and it seems to work best as a single word in the context of Section 5.***

25. Page 66, paragraph 2, same comment on "hydrologeologic units" above. Just needs to ensure consistency. ***Agreed. Moved to "aquifers".***

Section 5.4

26. Page 137. Section 5.4: Call out figures in order and place figure after calling out. See Figure 5-59, 5-62, 5-64, 5-65, 5-70, 5-73, 5-74, 5-76, 5-77, 5-78, and 5-79 and Table 5-58 and 5-31. Others may also apply. – ***Fixed.***
27. Page 137. Section 5.4: Use consistent naming convention for the following words:
    a. Trans Pecos vs. Trans-Pecos
    b. Edwards-Trinity (Plateau) vs. Edwards-Trinity
    c. Water-flooding vs. waterflooding
    d. Igneous Bolson vs. Igneous-Bolson

    Complete

28. Page 141. Section 5.4.9, first paragraph, fifth sentence: Change "increase" to "increases". **– *Complete*.**
29. Page 142. Brackish Groundwater in the Trans Pecos Region Aquifers: Make this a subheading and it becomes 5.4.12. – ***Complete.***
30. Page 142. Brackish Groundwater in the Trans Pecos Regions Aquifers, first paragraph, second sentence: Change sentence to "The occurrence of brackish groundwater has been studied in the county reports and aquifer reports developed by the Water Commission, TWDB, and United States Geological Survey." – ***Complete.***
31. Page 143. Fifth paragraph, last sentence: Remove hyphen from "85 million-acre feet" and change to "85 million acre-feet of brackish groundwater and 15 million acre-feet of fresh groundwater." – ***Complete.***
32. Page 143. Sixth paragraph, last sentence: Change remove hyphens and change to "18.5 million acre-feet of groundwater, of which 0.4 million acre-feet is fresh and 18.1 million acre-feet is brackish." – ***Complete.***

Section 6

33. No major edits

Section 7.2

34. This section was modified by the reviewer in the attached document. The primary reason was to get more directly at the core matter of "what defines degradation" as discussed in Section 3. This section has been edited to read" A literature review of the statutes related to the comingling of brackish water shows that there are definitions or concepts not clearly defined in code. Comingling is defined in the Texas Water Well Drillers and Pump Installers Rules TAC §76.10.10(16) as the "mixing, mingling, blending or combining through the borehole casing annulus or the filter pack of waters that differ in chemical quality, which causes quality degradation of any aquifer or zone." In this definition, two conditions must be met for comingling to occur: the mixing occurs between waters of different chemical quality and the subsequent mixing causes degradation to an aquifer or a zone, thus, comingling does not occur when only one of the two conditions is met. Three examples when comingling does not occur include: (1) the

mixing of waters of the same chemical quality within a well or borehole, (2) the mixing of two differing quality waters within a borehole occurs, but that mixing does not cause degradation, and (3) the mixing of two differing quality waters within a borehole occurs, but the hydraulic heads are effectively hydrostatic and degradation of a zone is unlikely." ***– Reviewer's commented were accepted.***

35. Additional edits are included in the attached document ***– Reviewed and Dispositioned.***

Section 9

36. David Gunn and Adam Foster at TDLR have now reviewed the entire report. ***– Edited to reflect that.***

Section 10.1

37. Aquifer acronyms need defined in appendix ***– Complete.***

GIS Files

1. Major_Aquifers.shp: Needs Description and Summary to match Minor_aquifers.shp. ***The Major_Aquifers.shp has had their metacritic updated to match that of the Minor_aquifers.shp file***
2. One shapefile is missing in GLFCN_grid file folder: GLFCN_wells_single_lyr_Rev01_031121.shp.AUS-CHROMIUM.15776.9320.sr.lock is a lock file, not shapefile. The folder "GLFCN_grid is not included in the appendix. ***The GLFCN_wells_single_lyr_Rev01_031121.shp was supposed to be omitted from the previous deliverable as it does not appear in any of the maps. The folder and lock file have been deleted from this iteration of the deliverable.***
3. All PNGs are in section 5. Although figure number is correct, the file names need to be changed to Fig_5_XX_Text.png. ***The PNGs have had their text and figure numbers changed to be consistent with the report.***
4. All MXDs are referenced in section 5. Although figure number is correct, the file names need to be changed to Fig_5_XX_Text.mxd. ***The MXDs have had their text and figure numbers changed to be consistent with the report.***
5. Fig_4_08-28, 48-54, and 60-70. In layout view there are legend data that are outside the final figure that do not have to do with the figure. Those should be removed where possible. ***All figures have been reviewed and have had data elements outside of the figure page removed. Now only data inside the figure page of the layout view remains as requested.***
6. Fig_4_75_Clearwater_Ranch.mxd and Fig_4_78_Clearwater_Ranch_Selected_Wells.mxd data frames are in NAD83 and need to be converted to GAM projection. ***The data frames for the aforementioned figures have been converted to GAM projection.***