TWDB Contract No. 2000012453
Final Report
Received: February 4, 2022

Final Report: Develop Procedures and Tools to Delineate Areas Designated or Used for Class II Well Wastewater Injectate

Texas Water Development Board Contract # 2000012453

Prepared for:
Texas Water Development Board

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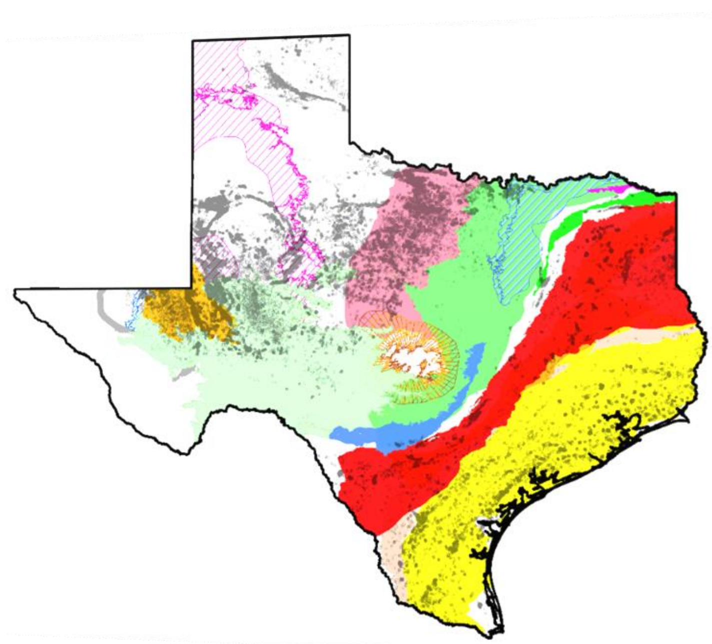

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Geoscientist and Engineering Seal

The Texas Water Development Board (TWDB) contracted with WSP USA, a licensed professional engineering firm (Texas License No. 2263).

This report documents the work of the following Licensed Texas Geoscientists and Licensed Texas Professional Engineer:

Rohit R. Goswami, Ph.D., PE

Dr. Goswami was the technical Project Manager for this study. He was the lead author of Chapters 1 and 2 and contributed to Chapter 3. He also contributed to the development of the injectate mapping process. He provided overall technical guidance during the development of all the online tools discussed in this report and delivered as part of the contract.

02/04/2022

John (Jack) M. Sharp, Ph.D., PG

Dr. Sharp was the lead technical reviewer for the project team during the study. He was also the lead author of Appendix A and provided general technical guidance throughout the project.

1/20/2022

Other Contributors:

Maurice (Jay) Fagan

Mr. Fagan was the task lead for developing the manual workflows for processing the Texas Railroad Commission (RRC) databases and the Class II injection well intersection analysis and contributed to Chapter 2. He provided oversight and quality assurance during the development of the Feature Manipulation Engine (FME) tools. He was also the lead author of Appendices B and C.

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Tingting Chen, PhD

Dr. Chen was the task lead on developing the methodology to process the Texas Railroad Commission (RRC) databases and obtain injection well parameters for the injectate mapping tasks.

1/20/2022

Uvashree J. Mohandass, EIT

Ms. Janani was responsible for assessing the aquifer parameters described in the default aquifer parameters table in Chapter 2. She was also instrumental in GIS assessment activities throughout the project and in generating report figures and geodatabase deliverables.

1/20/2022

Christopher Bente, GISP

Mr. Bente was the task lead for the Feature Manipulation Engine (FME) tools. The FME tools were developed to automate the manual workflows for processing the Texas Railroad Commission (RRC) databases and Class II injection well intersection analysis. He was also the lead author of Appendix D.

Christopher Bente

1/20/2022

Vivek Bedekar, PhD

Dr. Bedekar was the task lead for the injectate mapping process. He conducted the groundwater modeling tasks and was the lead author of Chapter 3 and Appendix E. He also led the development of the online injectate mapping tool and provided technical suggestions during the development of the FME tools.

Vivek Bedekar 1/20/2022

Christopher J. Neville, M.Sc.

Mr. Neville conducted extensive research on the available modeling and mapping techniques relevant to this study and guided the comparative analysis to evaluate them. He also contributed to and was the lead reviewer for Chapter 3 and Appendix E.

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Acknowledgments:

Mr. Juan Acevedo (TWDB), Contract Manager and lead technical reviewer for TWDB

Ms. Erika Mancha (TWDB), Ms. Andrea Croskrey, PG (TWDB), Ms. Alysa Suydam, PG (TWDB), Mr. Evan Strickland, PG (TWDB), and Mr. Mark Robinson, PG (TWDB) – for technical review and input on the project from TWDB

Mr. Larry French, PG (TWDB), Ms. Natalie Ballew, PG (TWDB), Ms. Cindy Ridgeway, PG (TWDB), Mr. John Dupnik, PG (TWDB), Ms. Alysa Suydam, PG (TWDB), Mr. Mark Robinson, PG (TWDB), Mr. Evan Strickland, PG (TWDB), Ms. Sydney Weitkunat, PG (TWDB), Ms. Kristie Laughlin, PG (TWDB), Ms. Olga Bauer (TWDB), Mr. James Harcourt, PG (RRC), Mr. Sean Avitt, PG (RRC), Ms. Leslie Savage, PG (RRC), Mr. Jim Moore, PG (RRC), Ms. Lorrie Council, PG (TCEQ), Mr. Dan Hannah, PG (TCEQ), Mr. Terance Virtue, PG (TCEQ), Ms. CJ Tredway (TxOGA), Ms. Tulsi Oberbeck (TxOGA) , Mr. Dustin Kinder (EOG resources), Mr. Gregory Stanton, PG (USGS), Dr. Bridget Scanlon, Ph.D., PG (UT-BEG), Dr. Michael Young, Ph.D., PG (UT-BEG), Ms. Mary Musick (GWPC), Mr. David Gunn (TDLR), Mr. Adam Foster (TDLR), Ms. Leah Martinsson (TAGD), Ms. Hope Wells (SAWS), Mr. Kevin Morrison, PE (SAWS), Mr. Dean Metcalf (Xcel Energy), Mr. John Lomas (Xcel Energy), Mr. Scott Hutchinson (AECT), Ms. Kerry Harpole (Marathon Oil), Mr. Brian Bohm, PG (Apache Corp.), Mr. Brian Kuh (WXP Energy), and Dr. Alex Mayer, Ph.D., PE (UT El Paso)- for workgroup participation, technical suggestions, and feedback on the project.

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1. Introduction and Background

This study was conducted to develop methods and tools for delineating areas designated or used for Class II well wastewater injectate in the State of Texas. The work was done to meet the requirements set by House Bill 30 (HB 30). HB 30 was enacted by the legislature of the State of Texas and was related to the development of seawater and brackish groundwater resources. The language of the bill as provided in [Section 16.060 (b) (5) (A)] sets requirements regarding the impact of brackish water development on water availability and water quality in other water-bearing formations with an average total dissolved solids level below 1,000 milligrams per liter.

HB 30 requires that the Texas Water Development Board (TWDB) submit a report to the Governor, Lieutenant Governor, and the Speaker of the House of Representatives by December 1 of each even-numbered year. Among other information, the report includes the requirement of designating brackish groundwater production zones under certain circumstances. While designating these zones, TWDB is required to address the following two issues:

1. Determine the amount of brackish groundwater that the zone is capable of producing over a 30-year period and a 50-year period without causing a significant impact to water availability or water quality as described by Subsection (b) (5) (A) of HB 30.
2. Make recommendations regarding monitoring methods to observe the effects of brackish groundwater production in these zones.

It is important to note that, as per HB 30, the brackish groundwater productions zones cannot be identified "in an area of a geologic stratum that is designated or used for wastewater injection through the use of injection wells of disposal wells permitted under Chapter 27". There are thousands of Class II injectate wells in Texas, making it not feasible to analyze the extent of wastewater injectate migration due to each individual well. To meet the requirements of HB 30, TWDB staff had previously applied a conservative buffer of 15 miles around each of the Class II injection wells identified within the mapped brackish aquifer zones. However, a more detailed and scientifically defensible approach is required to estimate the extent of migration of the wastewater injectate from these Class II injection wells.

The project's objective is to develop methods and tools that may be applied to map the extent of injectate migration around existing and future Class II injection wells that inject wastewater within the identified brackish formations in the State. A key component of this project is that the procedures and tools developed during this project should be scientifically defensible and applicable to potential future changes in Class II injection well data and locations. Therefore, the first step is to understand the state of the science in estimating injectate migration patterns. The currently accepted methodology used to assess injectate migration is the application of mathematical models that simulate the migration patterns of groundwater constituents. Several numerical and analytical modeling techniques and tools are available to perform such analyses (Konikow, 2011; Anderson and others, 2015; USGS webpage, 2017).

Our main goal, in the preliminary research reported in this Chapter, has been to synthesize the various modeling approaches used for estimating the migration patters of groundwater constituents. Our research is based on the principle of Occam's razor that advocates model complexity should be minimized to address the modeling objectives and data availability (Simmons and Hunt, 2012; Clement, 2011). In the case of HB 30, the objectives are:

1. Analyzing the significant impacts on water availability while producing brackish groundwater over periods of 30 and 50 years; and
2. Analyzing the significant impacts on water quality while producing brackish groundwater over periods of 30 and 50 years

To analyze the first modeling objective, significant impact on water availability, we considered the groundwater availability models (GAMs). A major purpose of the groundwater availability modeling (GAM) program is to assess groundwater availability in the officially designated aquifers of Texas. The GAMs are used to estimate modeled available groundwater based on desired future conditions of aquifers determined by the groundwater management areas. The constraints of desired future conditions limit the estimated modeled available groundwater projected by the GAMs. The groundwater conservation districts and regional water planning groups then consider the estimated modeled available groundwater in developing their management and regional water plans.

The GAMs are conceptualized and constructed to help estimate water availability in the official aquifers. Therefore, TWDB staff can use the same approach used in applying GAMs to analyze impacts on water availability while producing brackish groundwater. Time horizons used for calculating estimated modeled available groundwater (50 to 60 years) are similar to the time horizons for analyzing the significant impact on water availability (30 and 50 years). However, in some cases, the spatial (horizontal and vertical) extent of the GAMs may not be sufficient to include potential brackish water production zones while estimating the impact on water availability. Thus, the GAMs can be assumed to have lower parameterization than that required in their current forms. Therefore, we must assess if such a level of parameterization is sufficient for our purposes. Appropriate parameterization is a cause for continuing debate among researchers (Simmons and Hunt, 2012) and has been analyzed further in the current and later chapters in this report in relation to our modeling objectives.

The second modeling objective is to analyze for significant impact on water quality while producing brackish groundwater. Water quality modeling involves simulating subsurface solute transport. Konikow (2011) noted that simulating solute transport in groundwater is difficult and suggested that a relatively simple or moderately complex model should be developed to simulate transport rather than a highly complex one. Such a model should then be used to further the conceptual understanding of the physical system and that the expectations from the predictive capabilities of the transport model should be kept reasonably low (Konikow, 2011).

Deeds and Jones (2011) assessed numerical codes that might be applicable for brackish water applications and summarized the hydrogeologic features of the brackish water aquifers in Texas. They also analyzed how the characteristics of the various codes could affect the suitability of a code for modeling each type of hydrogeologic feature. The widely accepted method to model solute transport involves simulation of both advective and dispersive transport processes occurring in the domain. However, Molz (2015) suggested that solute transport is advection-dominated and many of the processes controlling dispersion are not well understood. Furthermore, Berkowitz et al. (2009) reported that the advection-dispersion equation, most commonly used for simulating transport in groundwater, failed to match breakthrough curve for a non-reactive tracer in a laboratory experiment. However, both Berkowitz et al. (2009) and Konikow (2011) indicated that the dispersive part of solute transport tends to be significantly less critical than the advective part and can be ignored under certain conditions. One such condition is simulating solute transport at a large spatial scale under pumping or injection conditions, which is the case in our study. Therefore, it appears that a groundwater model simulating just the advective component of solute transport should be sufficient for our analysis.

It is essential to acknowledge analytical solutions available for modeling groundwater movement. Some analytical models deal with aquifer and well-pumping analyses, including Thiem (1906), Theis (1935), Cooper and Jacob (1946), Hantush (1961), Papadopulos and Cooper (1967), Javandel (1982), Dougherty and Babu (1984), and Faybishenko and others (1995). However, these models do not provide techniques to simulate the migration of groundwater constituents. Several Environmental Protection Agency (EPA) documents are also available that provide guidance and propose the use of specific analytical solutions (Warner and others, 1979; EPA, 2021). The use of these solutions is limited to evaluating the radius of pressure influence of injection wells or for what the EPA calls "the zone of endangering influence of an injection well". However, these EPA techniques are also restricted to simulating near-well dynamics only and are not applicable for long-term and extensive spatial-scale (regional scale) migration of injectate. Another analytical methodology, by Bear and Jacobs (1965), is available that includes advective transport of wastewater injectate. Bear and Jacobs presented a method that deals with the movement of water bodies injected into confined aquifers. They investigated two cases dealing with injection through a single well under steady flow conditions into a confined aquifer with uniform ambient flow and the time-dependent movement of injected water bodies under non-steady flow conditions. These conditions are similar to what we encounter in the case of Class II well wastewater injectate.

Particle-tracking is another technique used to simulate the advective transport of groundwater constituents. Prickett (1979) and Tompson et al. (1988) describe the development and use of particle-tracking codes for solute transport modeling. Konikow (2011) suggested that an advective transport tool such as the particle-tracking code MODPATH (Pollock, 1994) is often a cost-effective alternative to highly complex advective-dispersive solute transport models for estimating solute transport direction and time. However, MODPATH or any other particle-tracking code requires an underlying groundwater model (such as the GAMs) that provides the flow simulation necessary to conduct particle-tracking. This reliance upon the availability of an underlying tool makes the particle-tracking method an unfeasible option for our analysis.

Revisiting the concept of parameterization with respect to particle-tracking, we also considered the study conducted by Doherty and Christensen (2011). They reported a synthetic modeling study comparing results from two models - a relatively more parameterized (complex) model and a lesser parameterized (simple) model. The study involved simulation of flow using MODFLOW-2000 (Harbaugh and others, 2000) and transport using MODPATH. Results showed that predictive accuracy due to reduced parameterization in the simple model did not significantly impact the hydraulic head calculations obtained from MODFLOW-2000. We can infer from their result that reduced parameterization of a simpler model is not expected to reduce the hydraulic head prediction accuracy. However, as reported in their study, the predictive accuracy of the advective transport code MODPATH (particle-tracking only) decreased considerably. The authors state that such a result was expected from the transport simulation since the simple model assumed uniform porosity while porosity differed significantly in the complex model.

Overall, in our assessment, building a complex numerical groundwater model requires a significant investment of time and resources, including staff training and a considerably higher budget similar to the TWDB GAM program. Therefore, we focused further investigations on using simpler approaches applicable on regional scales and over extended periods. These investigations and their results are discussed further in Chapter 3. During our research, various other publications were reviewed for background information. A complete list of these reviewed publications and corresponding notes is available in Appendix A.

Chapter 2 provides a description of the methods developed to analyze the selected aquifers and the available Class II injection well databases. These aquifers were selected based on the likelihood of occurrence of Class II injection wells within their spatial extent. The methodologies used to obtain the aquifer and Class II injection well parameters, as input for the injecate mapping method, and the automated tools developed to facilitate these proceses are discussed in detail in Chapter 2.

Chapter 3 provides a description of the selection and development of the final injectate mapping techniques. Results from a case study conducted on the Northern section of the Trinity Aquifer and from a test study conducted on the Nacatoch Aquifer are also presented in Chapter 3. Finally, some recommendations on the use of the injectate mapping tools are also provided for the user's benefit.

1.1 Workgroup Formation and Project Meetings

At the beginning of the study, TWDB staff assembled a workgroup to provide technical and other feedback during project progress. The workgroup consisted of experts from academia, industry, research institutions, and governmental and regulatory authorities. TWDB staff hosted five regular workgroup meetings with input from the project team to provide updates on the project's progress and to discuss proposed future direction(s). The workgroup meetings were in addition to the regular project meetings between the project team and TWDB staff. More details on these meetings can be obtained from the project website or by contacting TWDB staff.

2. Aquifer Assessment

This chapter provides a detailed explanation regarding the workflow involved in identifying the aquifers for our study, evaluating these aquifers for the likelihood of occurrence of Class II well injections, and estimating aquifer parameters. As part of this task, we evaluated the major and minor aquifers in Texas that share or are likely to share a geologic stratum with the Class II injection or disposal wells as defined under Chapter 27 of the Texas Water Code (Texas Water Code §16.060(b)(5)(B)(iv)). TWDB staff determined that of the 31 major and minor aquifers, 18 Texas Aquifers are the most likely to meet the criteria for recommending brackish groundwater productions zones. These 18 aquifers are further assessed in this chapter. The identified 18 major and minor aquifers are listed below and mapped in Figure 2-1.

- Blossom
- Capitan Reef Complex
- Carrizo-Wilcox
- Cross Timbers
- Dockum
- Edwards-Trinity (Plateau)
- Edwards (Balcones Fault Zone)
- Ellenburger-San Saba
- Gulf Coast system
- Hickory
- Nacatoch
- Pecos Valley
- Queen City
- Rustler
- Sparta
- Trinity
- Woodbine and Yegua-Jackson

The following sections briefly describe the assessment methodology for the above-listed aquifers evaluated in the project. Based on the available data and the aquifer extent mapping, the tools and methods are developed to delineate geological areas for the list of Class II injection wells obtained from The Railroad Commission of Texas (RRC) database. The assessment methodologies include the workflow process developed to perform the mapping exercise to determine the Class II wells' horizontal and vertical location within the evaluated aquifers. Figure 2-2 shows the Class II injection wells identified as per the RRC database. There were 123,247 class II injection well screens within Texas, as analyzed from the database downloaded in October 2020. This count included duplicate API entries for wells with multiple screens and is explored further and filtered during the study.

This chapter describes the methodology developed and applied to determine the intersection of the identified Class II injection wells with some aquifer formations. A general method used to estimate aquifer parameters based on available data and the subsequent results is also presented. We have identified some guidelines to estimate the values where data is not available.

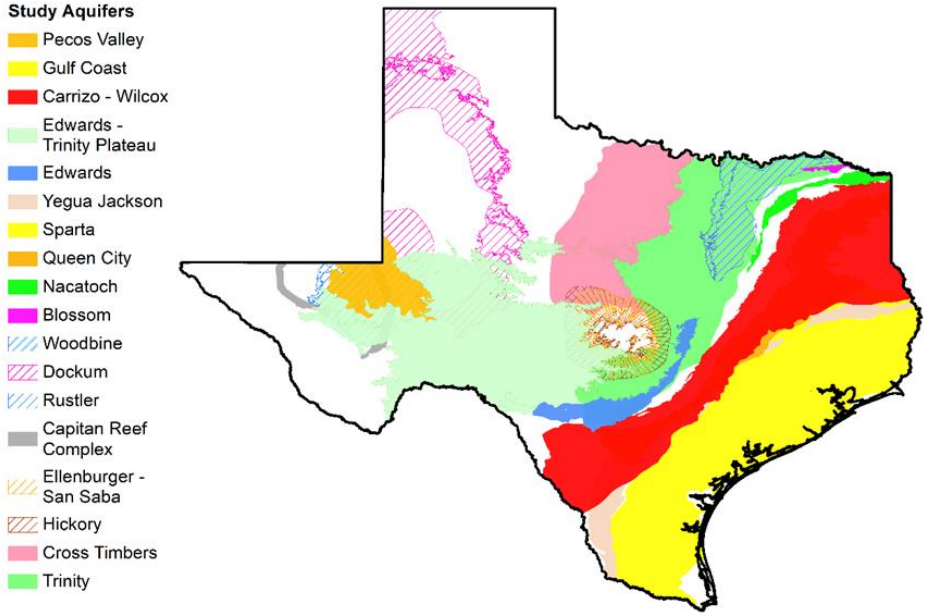

Figure 2-1: List of identified 18 Minor and Major Study Aquifers

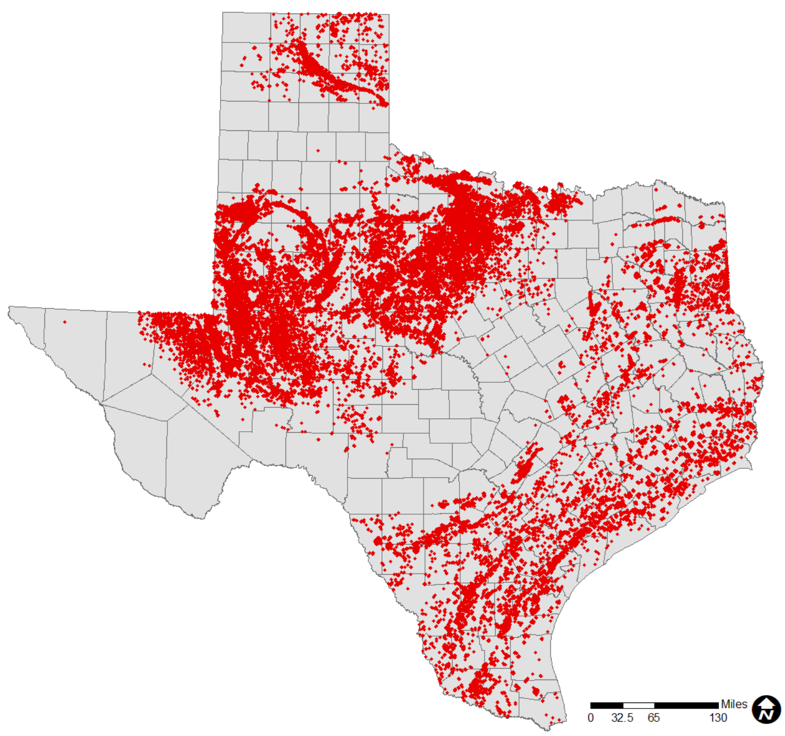

Figure 2-2: Class II injection wells within Texas. Total of 123,247 injection wells pictured above. This count includes duplicate API entries for wells with multiple screens.

2.1 Aquifer Assessment Priority

TWDB staff provided WSP with a list of aquifers to prioritize for the project (Table 2-1). For the first phase of the assessment, aquifers in Category 1 were prioritized and assessed. Later, most of the aquifers in Categories 2 and 3 were also assessed. Assessment methodologies described here can be used to complete the assessment for the remaining aquifers where sufficient data is not currently available. Later in this report, there is also a case study section (3.7) where the final methods developed during the study were applied to the Northern-Trinity Aquifer and tested on the Nacatoch Aquifer (Section 3.8).

Table 2-1: TWDB Aquifer Assessment Prioritization Categories. LGRV = Lower Rio Grande Valley.

	Aquifer
Category 1 (these have designated BGPZs)	Nacatoch
	Trinity (northern section)
	Blossom
	Carrizo-Wilcox (southern section)
	Gulf Coast (north of the LRGV)
	Rustler
Category 2 (these have BRACS tops and bottoms but no BGPZs)	Carrizo-Wilcox (central section)
	Gulf Coast (LRGV)
	Pecos Valley
	Queen City (central and southern sections)
	Sparta (central and southern sections)
	Yegua-Jackson (central and southern sections)
Category 3 (active BRACS mapping)	Trinity (Hill Country)
	Sparta (east section)
	Edwards-Trinity Plateau
Category 4 (no BRACS tops and bottoms and no active study)	Carrizo-Wilcox (eastern section)
	Queen City (eastern section)
	Yegua-Jackson (eastern section)
	Edwards (Balcones Fault Zone, has top of Trinity but not top of Edwards)
	Capitan Reef complex
	Cross-Timbers
	Ellenburger-San Saba
	Hickory
	Dockum
	Woodbine

2.2 Aquifer Assessment (Injection Well Intersection and Presence)

The main goals of this task are: 1) evaluating the probability of the aquifer stratum to be used by Class II injection wells, 2) classifying aquifers as being likely or unlikely to have Class II injection wells in the same stratum, 3) explaining why an aquifer is likely or unlikely to have Class II injection wells, 4) discuss data availability for each of the 18 aquifers for injectate mapping, and 5) provide estimates for the identified aquifer parameters to assist in the injectate mapping process.

2.2.1 Data Sources

The project team obtained data for Class II Injection wells from two primary sources: (1) RRC Underground Injection Control (UIC) Database, and (2) Texas RRC Oil and Gas Well Data Full Wellbore Database.

The data downloaded from the RRC website includes the ASCII format text file (uif700a.txt, dated October 29, 2020) of the UIC database and the ASCII format text file (dbf900.txt, dated October 27, 2020) of the Full Wellbore database at the beginning of this project. The project team conducted the analysis described within this report using these versions of the databases. A table describing all the data sources is available as part of the deliverables.

2.2.2 Data Processing Workflow

A custom online tool, developed using the Feature Maniption Engine (FME) platform, is available to assist in the data processing task. A summary of the general data processing workflow implemented in the online tool is described in this section, and a summary flowchart is provided in Figure 2-3. The main steps of the automated workflow are:

1. Download RRC datasets from the RRC website
2. Upload the RRC datasets to the Feature Manipulation Engine (FME) platform "Well Injection Workflow" interface:
    a. https://fme.wspis.com/fmeserver/apps/TWDB
    b. Automated data processing workflows implemented within the FME tools are based on previous manual workflows originally developed by TWDB and improved by WSP. Documentation of the previous manual workflows is provided in Appendices B and C.
3. Receive email from FME platform containing processed data, including:
    a. All processed RRC tables, per the RRC user guides.
    b. gClass2injWell table for input into the FME "Well Intersection Workflow" interface.
    c. Summary injection statistics table for input into the FME "Well Intersection Workflow" interface.
4. Upload items 3b and 3c to the FME "Well Intersection Workflow" interface.
5. Receive email from FME platform containing processed data, including:
    a. Class II well intersection determination table.
    b. Injectate mapping input table.
6. Upload processed data to Injectate Mapping Tool platform.
7. Select options and run the Injectate Mapping Tool.
8. Display and Export results.
9. User(s) can export injectate mapping results shapefiles.

Details on the automated data processing workflow are available in Appendices B and C. Instructions on using the automated workflows are provided in Appendices D and E.

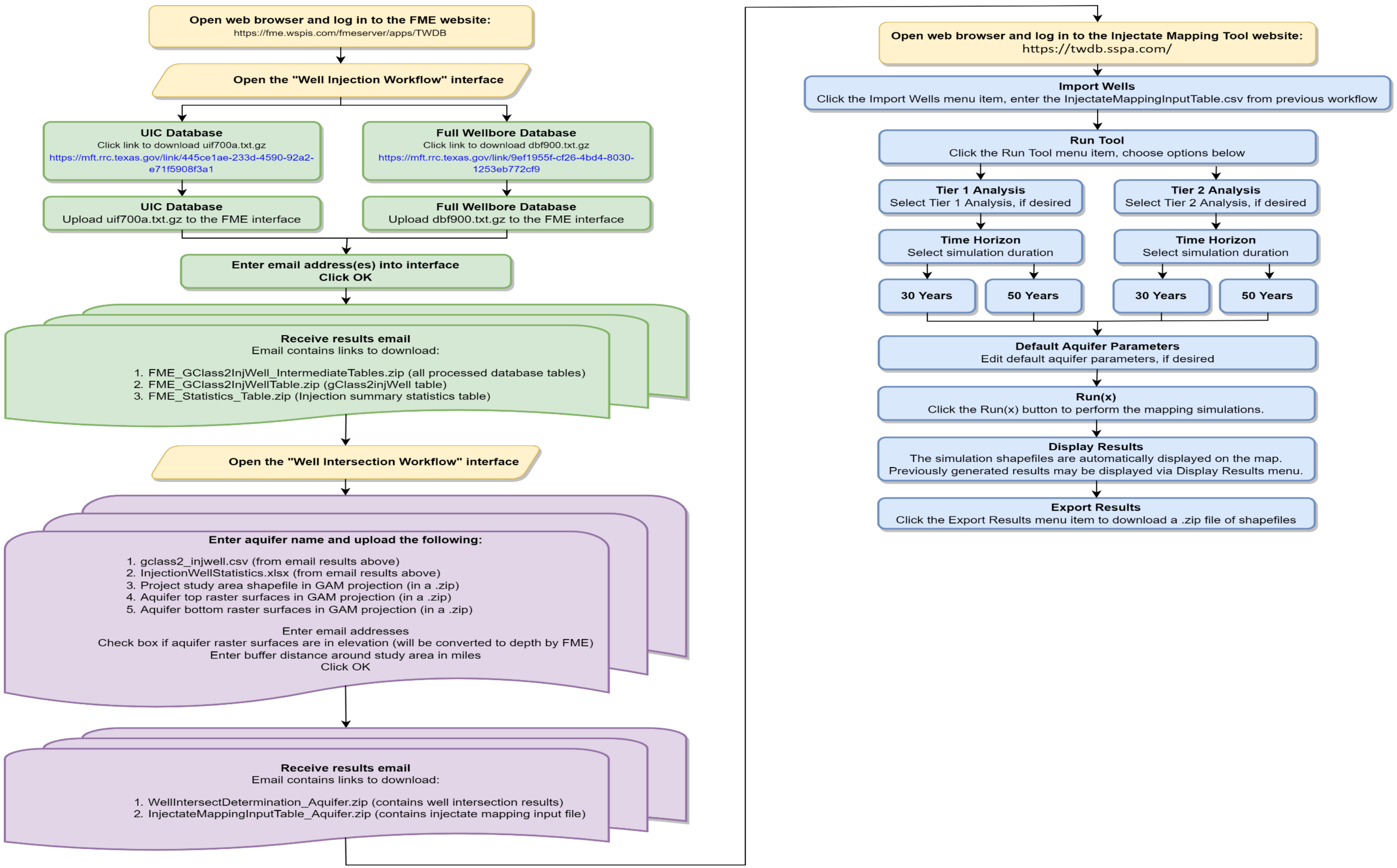

Figure 2-3: TWDB Data Processing Workflow

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2.2.3 Determining Well Injection Depth Relative to Aquifer of Interest: General Methodology

While determining whether an aquifer is likely to share geologic stratum with Class II wells, the following two critical steps are used:

a) determine which Class II injection wells are present within the horizontal boundaries of the respective aquifer study areas, and

b) determine which injection wells identified in subsection a) above contain screen intervals vertically intersecting the aquifer formation(s) and therefore are potentially injecting into the aquifer of interest.

This section describes the general workflow for determining which Class II Injection wells are potentially injecting into the aquifer of interest.

The master Class II injection well table described in Section 2.2.2 was imported into ArcMap and clipped to each aquifer study area, resulting in Class II injection well sub-lists for each identified aquifer.

Raster and/or shapefiles of the aquifer top surface and bottom surface depths (or elevations) were obtained from the BRACS studies, if available, and from GAM studies as a secondary source. The aquifer top and bottom depths (or elevations) were extracted at each well location within a given aquifer study area. If raster surfaces were provided in elevations, the elevations were converted to depths by utilizing a 10m/30m Digital Elevation Model (DEM) of Texas.

Figure 2-4 presents the horizontal location of the Class II injection wells mapped over the identified 18 aquifers. Further analysis was conducted to determine the Class II injection wells where the injection (screening) intervals intersect the aquifer formation. Table 2-2 below shows the total Class II injection well counts based on intersection with aquifers and well counts outside the aquifer boundaries. Please note that these well counts are applicable for the specific database versions identified earlier, and downloaded from the RRC.

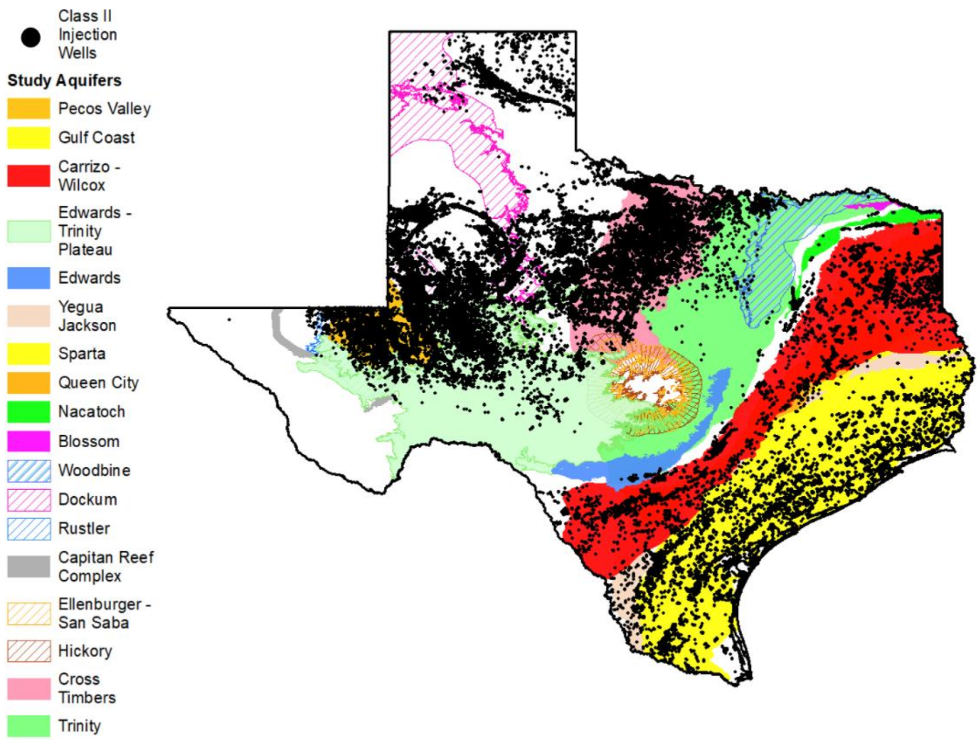

Figure 2-4: Class II injection wells within Texas Boundary

Table 2-2: RRC Class II injection well counts based on different criteria

Criteria	Well Counts
Total number of Class II injection wells identified as per RRC database within Texas. This count includes duplicate API entries for wells with multiple screens	123,247
Total number of Class II wells intersecting a single identified aquifer (within the aquifer XY footprints, doesn't consider Z component)	80,065
Total number of Class II wells intersecting multiple identified aquifers (within the aquifer XY footprints, doesn't consider Z component)	6,641
Total number of Class II wells identified outside the identified aquifer boundaries	36,541

The location of identified Class II injection wells is mapped to the identified aquifers in the study area. As discussed above, both BRACS and GAM study boundaries may be used to fill the identified data gaps and determine the geological formation that the Class II injection wells may be intersecting. It is important to note that BRACS is the preferred method for this study; that is, for an aquifer with a completed BRACS study, the resulting boundaries are used for assessment of the injection wells. For aquifers without a completed BRACS study, available data from the GAM studies, such as the appropriate layer top and bottom data may be used to assess the intersection of the Class II injection wells, if applicable. The primary objective of this process is to determine if the injection well screen interval is intersecting within an aquifer's top and bottom.

The following workflow describes the method used to determine which wells were potentially injecting into the aquifer of interest. TWDB staff provided the project team with an initial version of this workflow at the beginning of the project. Figure 2-5 illustrates the various possible scenarios for the depth of an injection well screen relative to the aquifer of interest (aquifer of interest shown in blue). Scenarios and the corresponding QA/QC flags described in items a, b, and d below were provided by TWDB staff. The project team added scenarios described in item c and QA/QC flags described in item d(iv). The determination of these scenarios for each Class II Injection well within the horizontal boundaries of a given study area has been implemented with various logic statements.

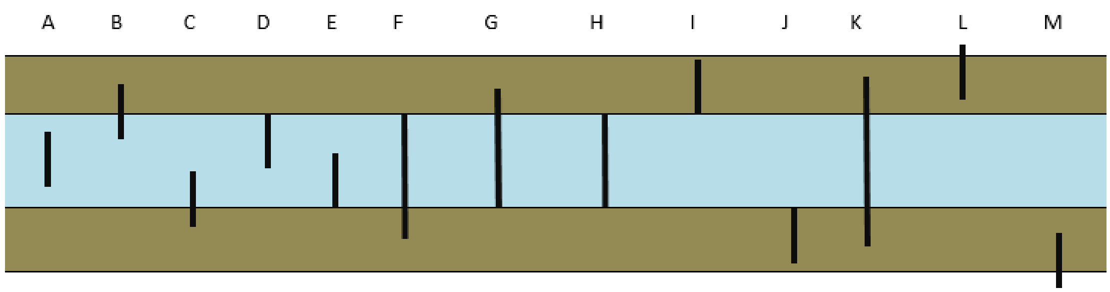

Figure 2-5: Injection Scenarios, aquifer of interest shown in blue.

These Class II injection well intersection scenarios are discussed below:

a. Scenario A through K intersect the formation (scenarios I and J intersect the formation because there is no separation between injection and a coincident formation surface).

b. Scenario L and M do not intersect the formation.

c. Additional scenarios added to the workflow by project team

    i. Scenario N - if bottom injection and perforation interval are 0, but top injection interval depth is available and is below the aquifer top, injection well can be excluded.

    ii. Scenario O – if no injection depth or perforation depth intervals are available, injection well could potentially be screened within the aquifer of interest, so it is included as intersecting the formation, but will also be flagged for manual review.

    iii. Scenario P – most aquifer top and bottom depth surfaces are available as raster datasets. The top and bottom aquifer depth is extracted from the rasters at the well locations, but in some cases, the top and/or bottom rasters do not cover the entire study areas or official aquifer boundaries. Wells located in those areas outside of the raster coverage would have the top and/or bottom depth populated with a default value of -9999 due to lack of raster coverage. Scenario P flags these wells (as QA/QC scenario "d") and requires manual review. This condition also prevents the injection well from being erroneously flagged by other scenarios.

d. Queries are developed to flag wells with data quality issues. This information is not provided directly in this assessment but is included in the results of the workflow for QA/QC purposes. Injection wells meeting these criteria are included as "intersecting the formation" in the initial workflow well count as a conservative measure; however, these wells are flagged for further review and then re-assigned to the appropriate scenario based on any additional information obtained. The QA/QC queries identify injection wells where:

    i. The top and bottom depths of the screened interval are zero.

    ii. The bottom screen depth is zero (top is valid).

    iii. The top of the screen is deeper than the bottom (and the bottom is valid).

    iv. They are located in areas outside of the aquifer surface raster coverage having the top and/or bottom depth populated with a default value of -9999 due to lack of raster coverage.

TWDB staff provided feedback to improve the workflow and streamline the manual review process. The project team also implemented additional scenarios and QA/QC flags described towards the end of Appendix C. The project team understands that TWDB staff intends for the tools developed during this study to be live. Therefore, additional scenarios and QA/QC flags can be added later, as required.

2.2.4 Assessed Aquifers

This section summarizes the workflow results described in Section 2.2.3 for a selected set of aquifers. Detailed workflow results for all currently assessed aquifers are available in data tables submitted as part of the deliverables. A data table summarizing the data sources for files utilized in the workflow has also been provided as part of the deliverables. Official aquifer boundaries referred to within this study and displayed on associated figures have been clipped to relevant study areas. A 10m/30m digital elevation model (DEM) of Texas is used to convert aquifer surface elevations to depths for assessments where aquifer surfaces are provided in elevation (DEM source: USGS. National Elevation Dataset, 2013-01-01. Web. 2021-01-29). Within these figures (Figure 2-6 to Figure 2-15) and Table 2-3, "Wells Potentially Injecting Into [aquifer of interest]" refers to scenarios "A" through "K", "O" and "P", described in Section 2.2.3. "Wells Injecting Above [aquifer of interest]" refers to scenario "L". "Wells Injecting Below [aquifer of interest]" refers to scenario "M". "Wells With Anomalous Data" refers to scenario "N" (which can probably be assigned to scenario "M" during future improvements to the workflow), and other scenarios not fitting those already described. Wells in the "Wells With Anomalous Data" scenario are flagged for internal QA/QC for manual review and to check available data to fill the identified data gaps. During manual review, injection wells with sufficient data can be manually assigned to an appropriate scenario. Assessed aquifers include: Nacatoch, Trinity (Northern Section), Blossom, Carrizo-Wilcox (Upper Coastal Plain (UCP)), Gulf Coast (North of the Lower Rio Grande Valley (LRGV)), Rustler, Gulf Coast (LRGV), Pecos Valley, Trinity (Hill Country), and Sparta (East Section).

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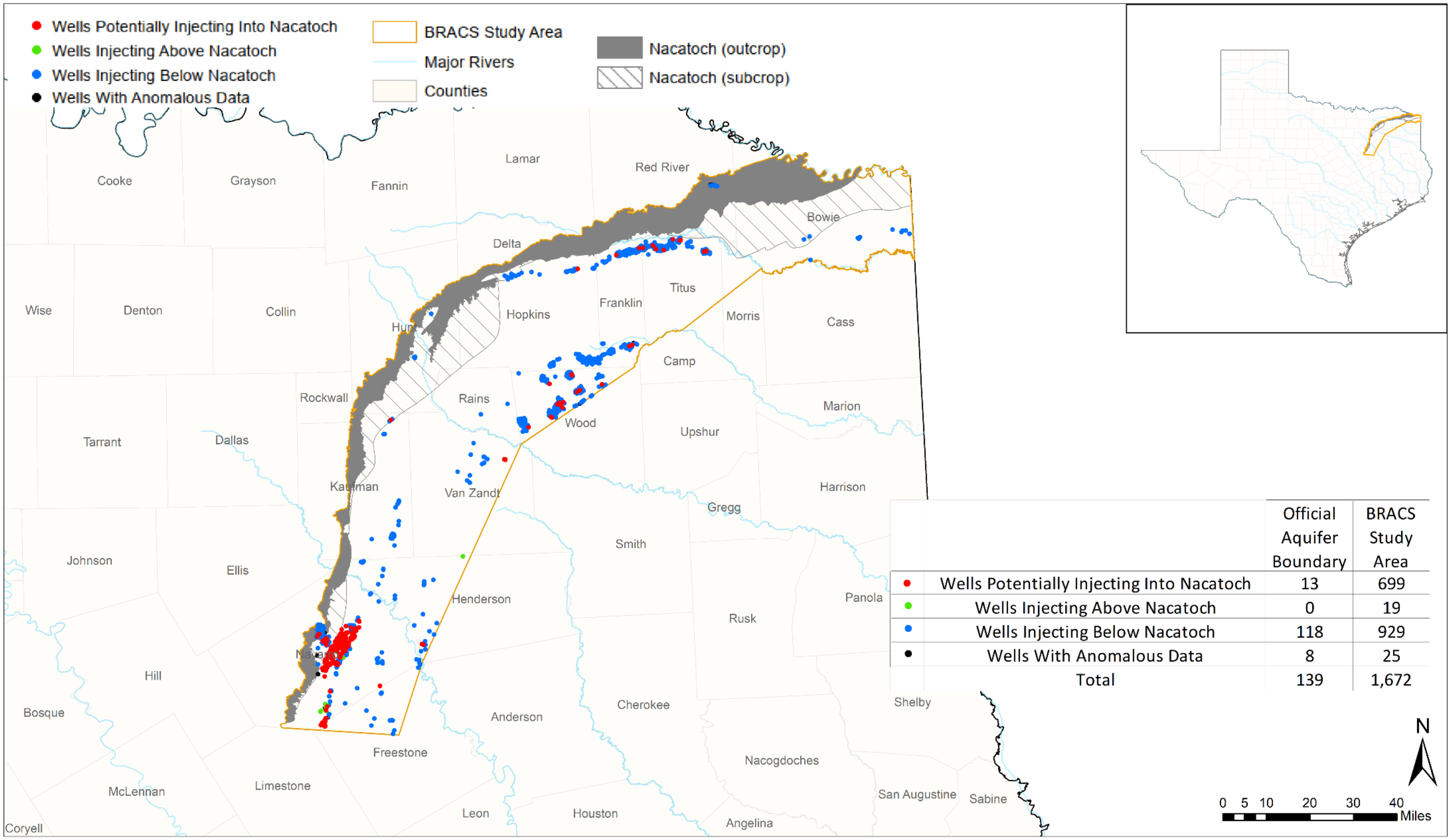
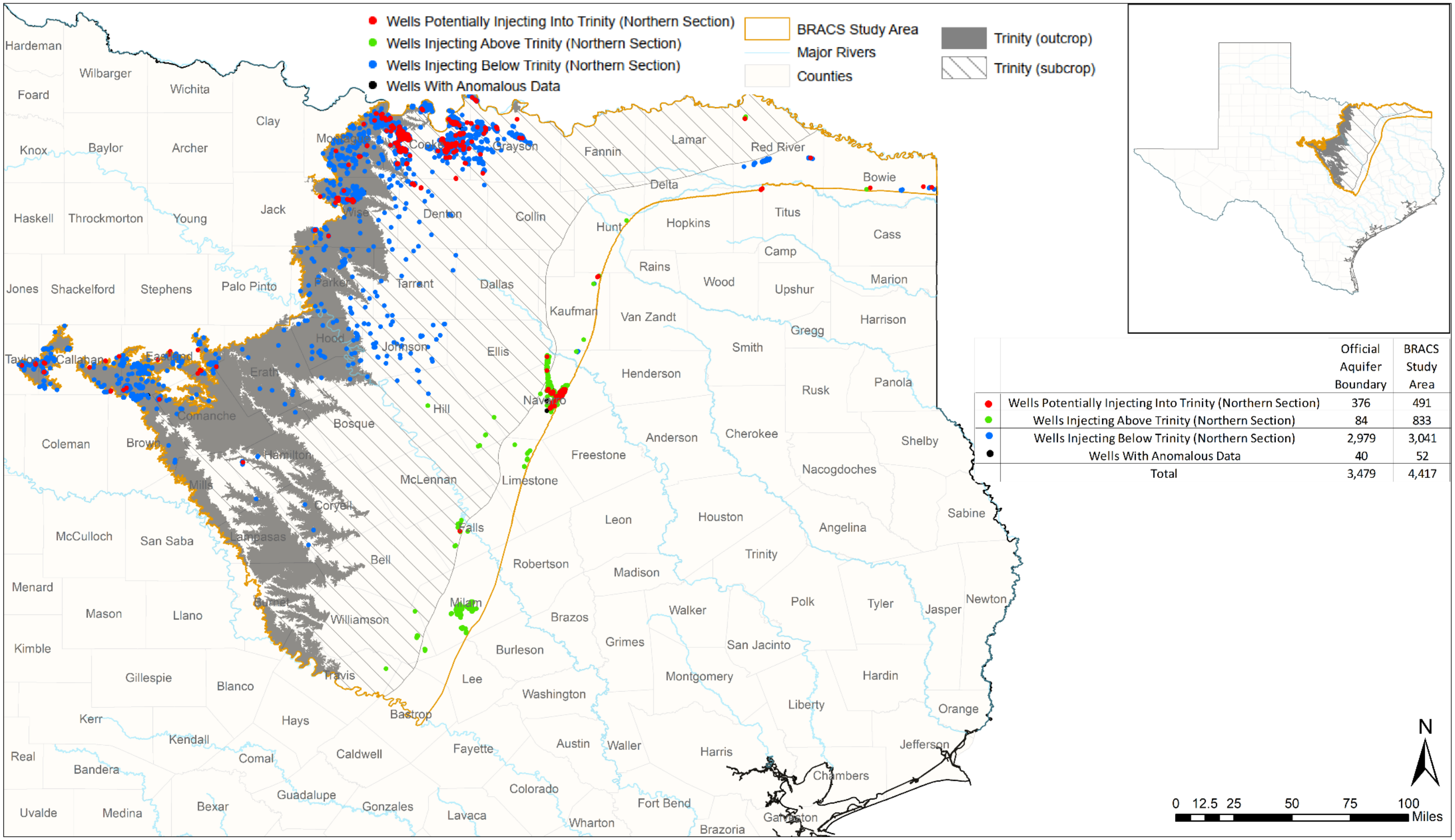
Table 2-3: Well Count Summary of Assessed Aquifers. Category 4 aquifers, as defined in Table 2-1, were not assessed due to insufficient data.

		Class II injections wells within horizontal aquifer boundaries (XY-component)		Class II injections wells within aquifer formation (Z-component)	
	Aquifer	Official Aquifer Boundary	BRACS Study Area	Official Aquifer Boundary	BRACS Study Area
Category 1	Nacatoch	139	1,672	13	699
	Trinity (northern section)	3,479	4,417	376	491
	Blossom	0	50	0	1
	Carrizo-Wilcox (upper coastal plains)	1,643	1,741	141	188
	Gulf Coast (north of the LRGV)	11,233	11,569	1,208	1,265
	Rustler	2,012	-	51	-
Category 2	Carrizo-Wilcox (central section)	N/A	N/A	N/A	N/A
	Gulf Coast (LRGV)	510	664	79	134
	Pecos Valley	12,258	12,258	704	704
	Queen City (central and southern sections)	N/A	N/A	N/A	N/A
	Sparta (central and southern sections)	N/A	N/A	N/A	N/A
	Yegua-Jackson (central and southern sections)	N/A	N/A	N/A	N/A
Category 3	Trinity (Hill Country)	135	1,015 (draft boundaries)	4	35 (draft boundaries)
	Sparta (east section)	731	885	13	28
	Edwards-Trinity Plateau	not assessed	not assessed	not assessed	not assessed



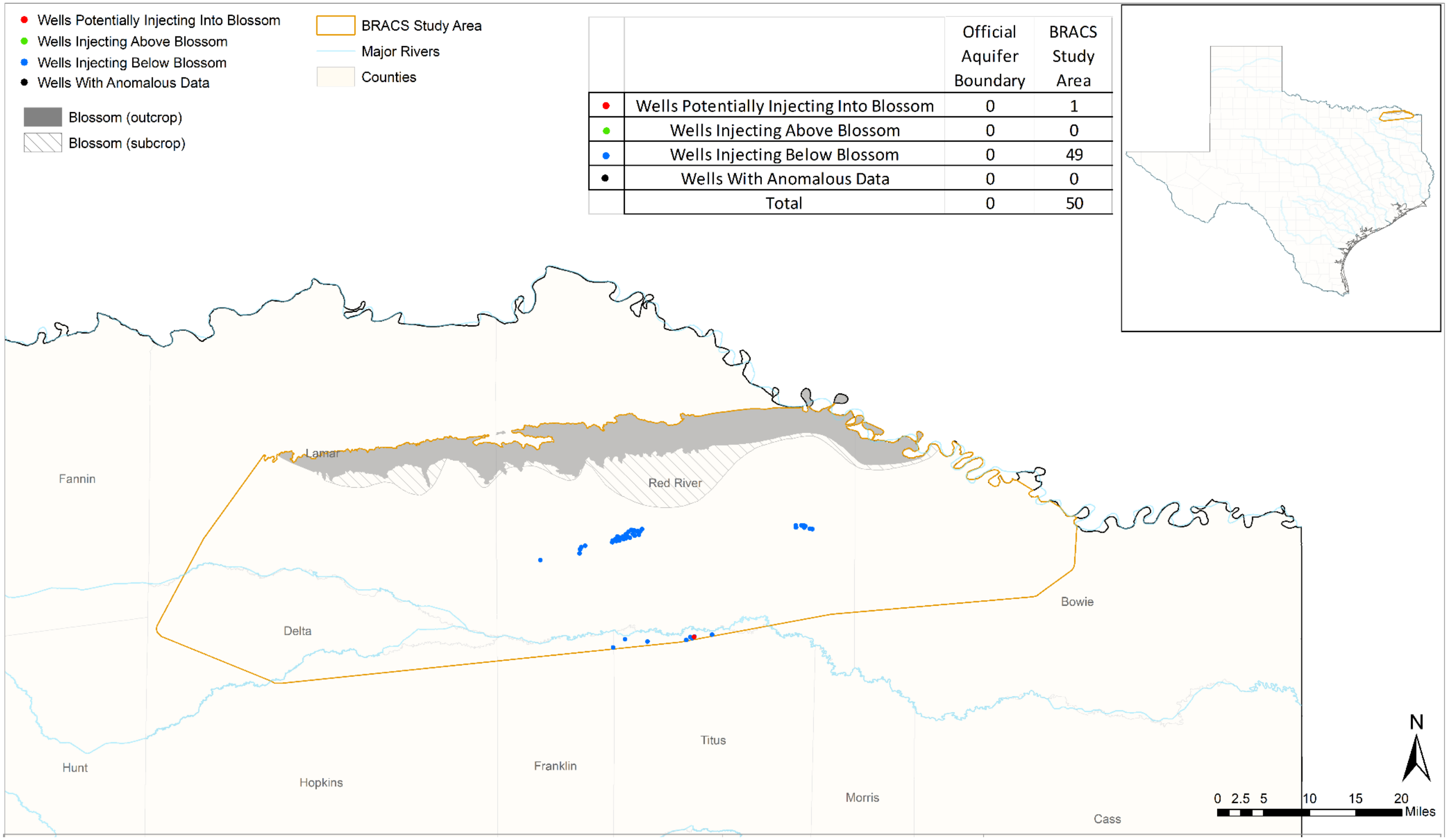
	Official Aquifer Boundary	BRACS Study Area
Wells Potentially Injecting Into Nacatoch	13	699
Wells Injecting Above Nacatoch	0	19
Wells Injecting Below Nacatoch	118	929
Wells With Anomalous Data	8	25
Total	139	1,672

Figure 2-6: Nacatoch Class II Injection Wells



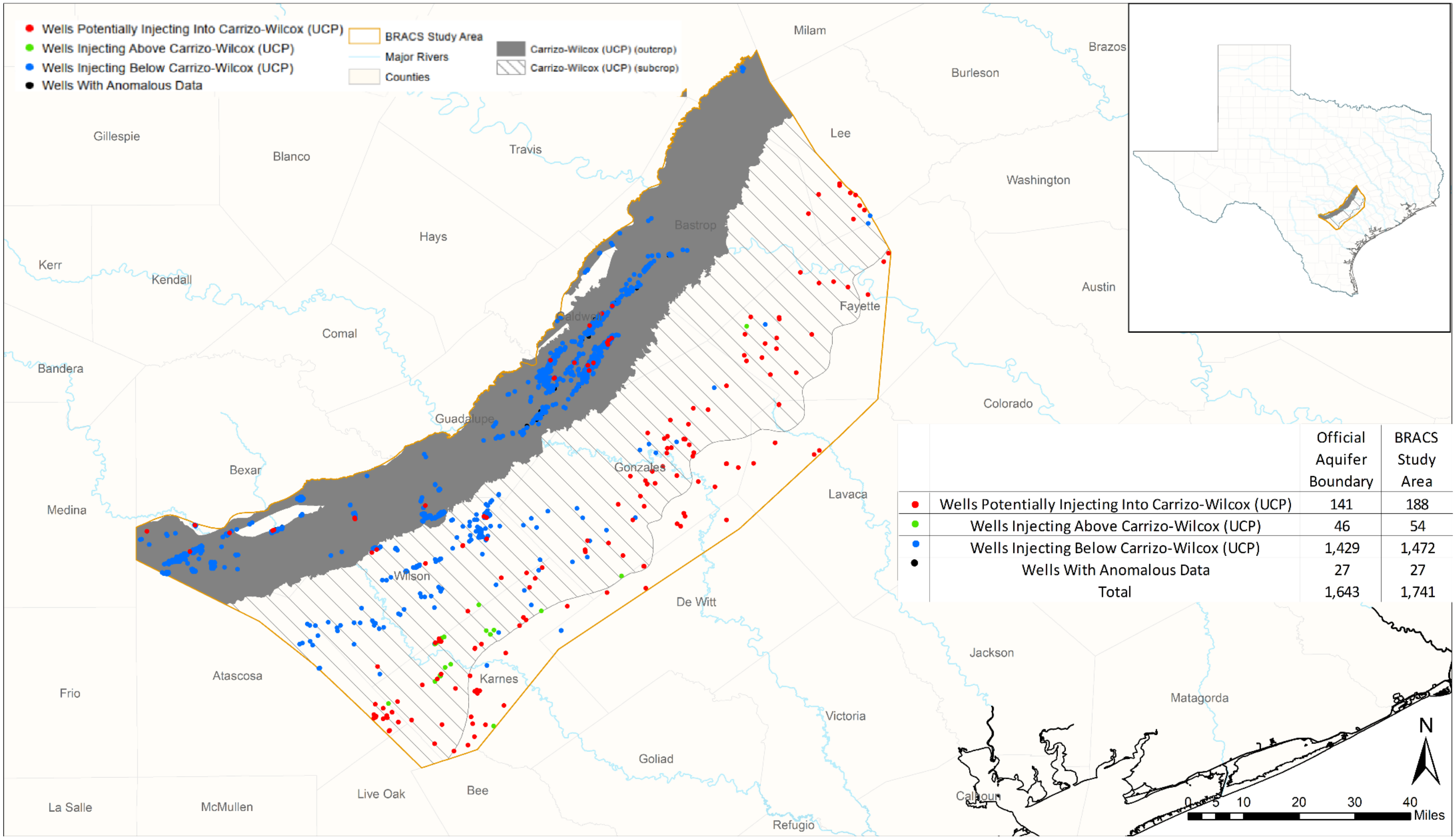
	Official Aquifer Boundary	BRACS Study Area
Wells Potentially Injecting Into Trinity (Northern Section)	376	491
Wells Injecting Above Trinity (Northern Section)	84	833
Wells Injecting Below Trinity (Northern Section)	2,979	3,041
Wells With Anomalous Data	40	52
Total	3,479	4,417

Figure 2-7: Trinity (Northern Section) Class II Injection Wells



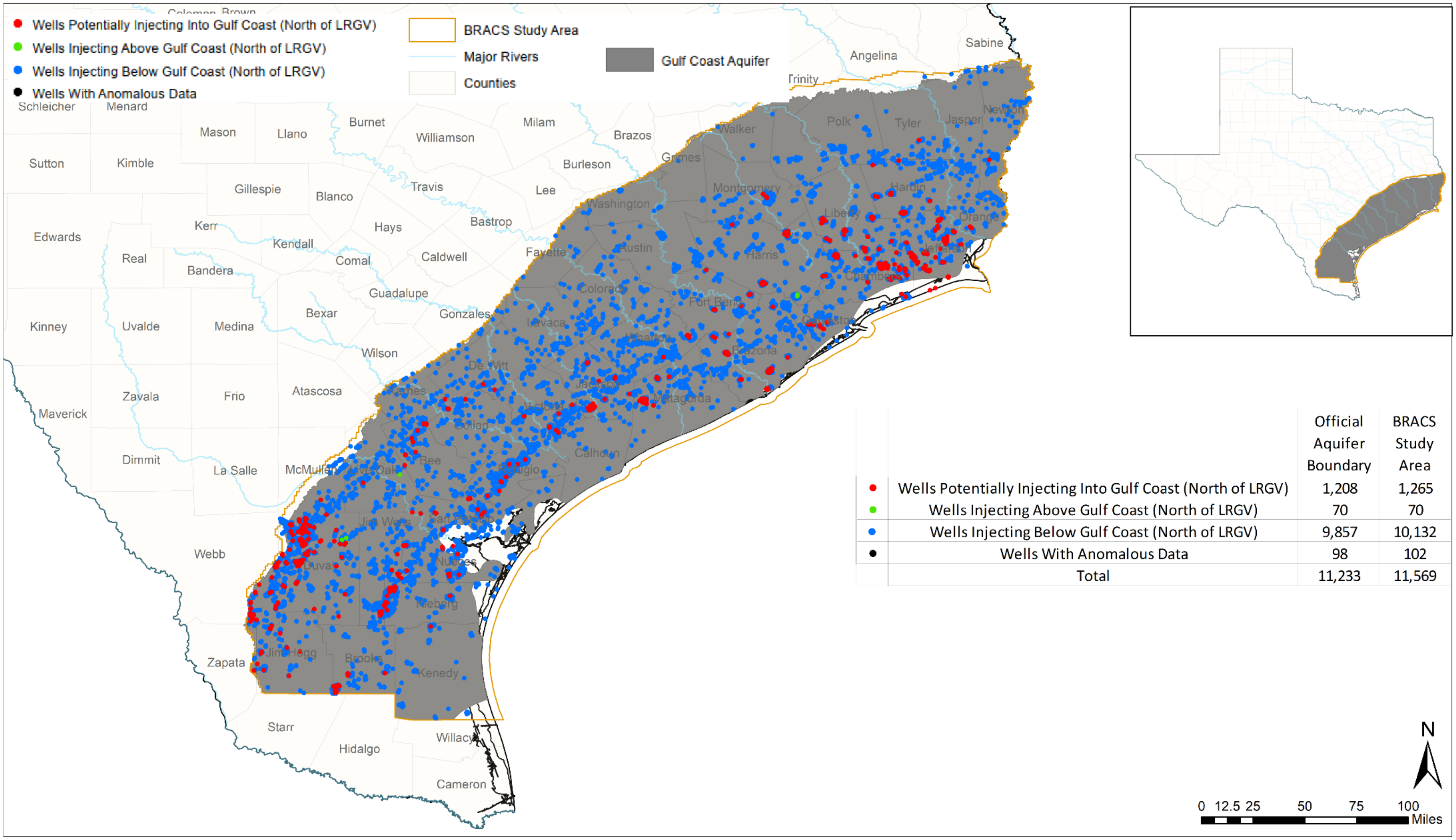
	Official Aquifer Boundary	BRACS Study Area
Wells Potentially Injecting Into Blossom	0	1
Wells Injecting Above Blossom	0	0
Wells Injecting Below Blossom	0	49
Wells With Anomalous Data	0	0
Total	0	50

Figure 2-8: Blossom Class II Injection Wells



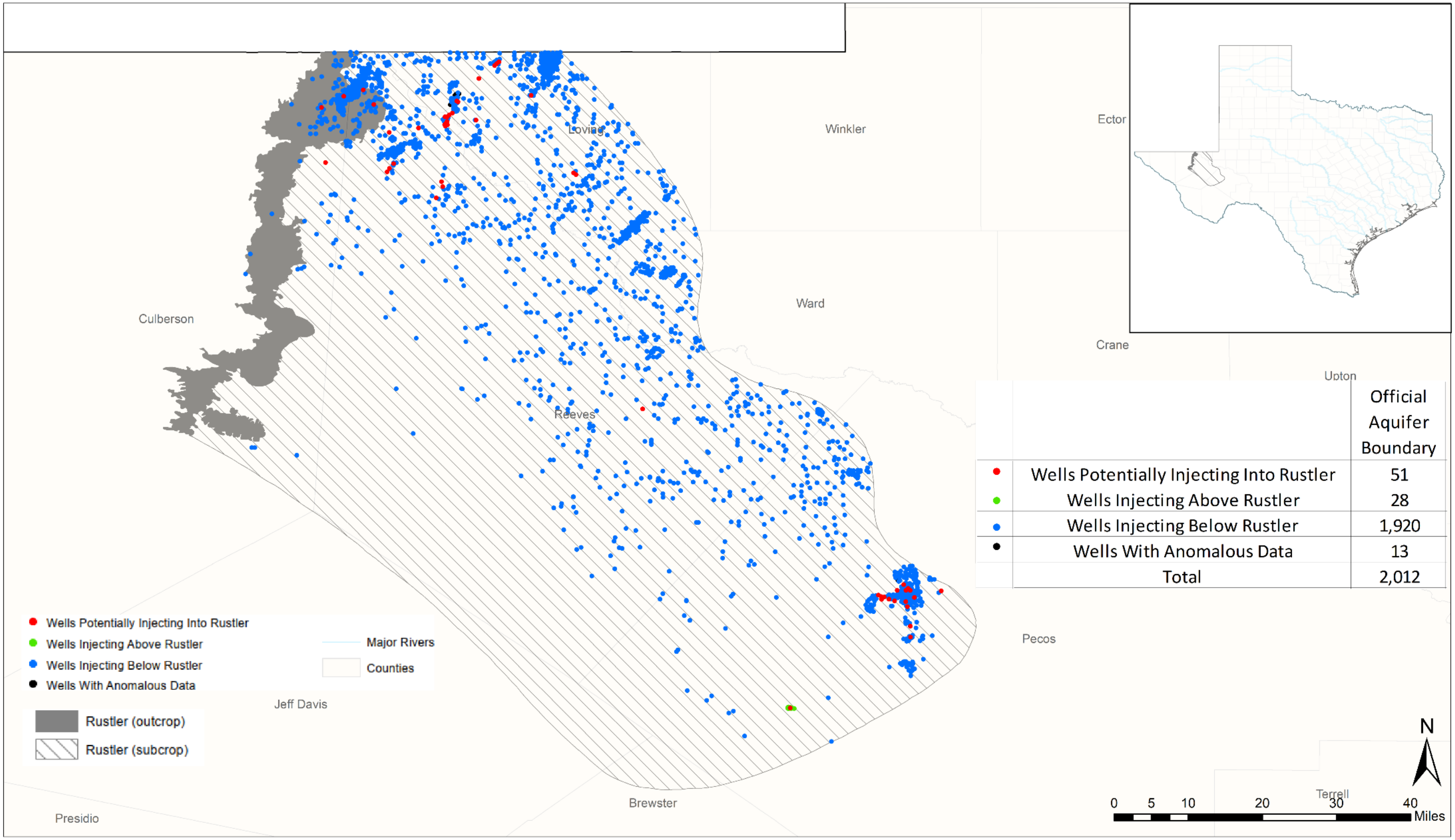
	Official Aquifer Boundary	BRACS Study Area
Wells Potentially Injecting Into Carrizo-Wilcox (UCP)	141	188
Wells Injecting Above Carrizo-Wilcox (UCP)	46	54
Wells Injecting Below Carrizo-Wilcox (UCP)	1,429	1,472
Wells With Anomalous Data	27	27
Total	1,643	1,741

Figure 2-9: Carrizo-Wilcox (Upper Coastal Plains) Class II Injection Wells



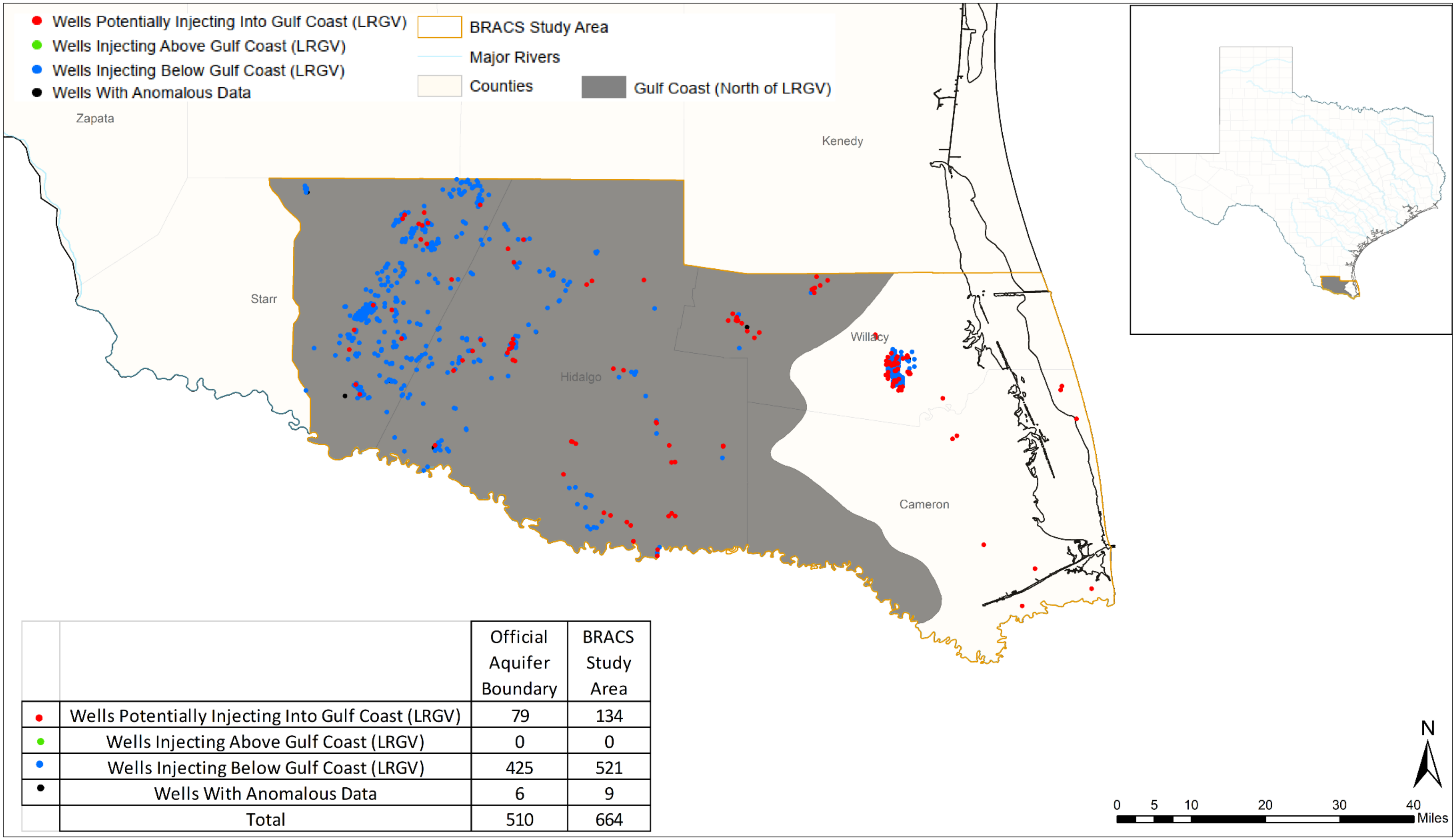
	Official Aquifer Boundary	BRACS Study Area
Wells Potentially Injecting Into Gulf Coast (North of LRGV)	1,208	1,265
Wells Injecting Above Gulf Coast (North of LRGV)	70	70
Wells Injecting Below Gulf Coast (North of LRGV)	9,857	10,132
Wells With Anomalous Data	98	102
Total	11,233	11,569

Figure 2-10: Gulf Coast (North of Lower Rio Grande Valley) Class II Injection Wells



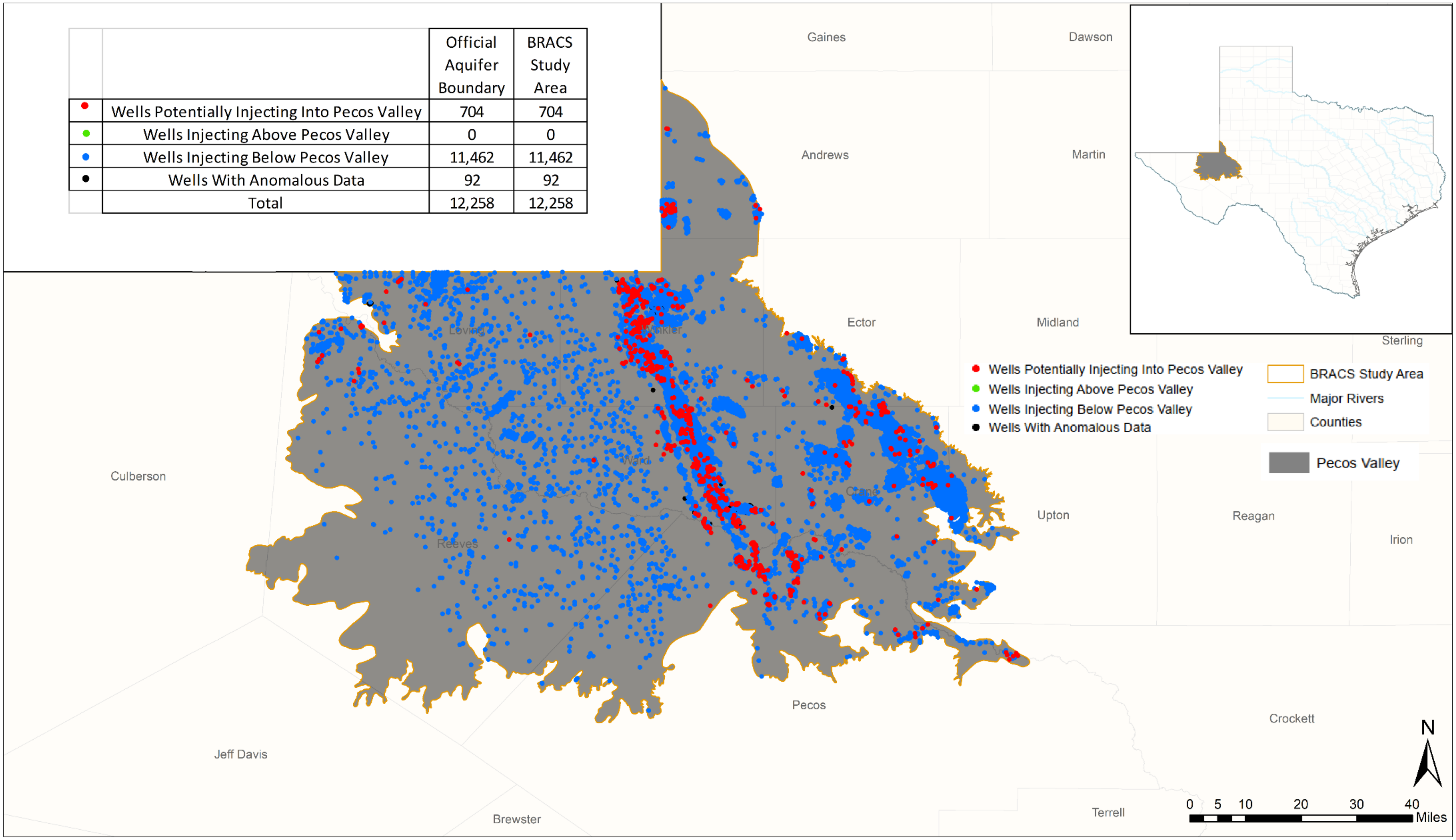
	Official Aquifer Boundary
Wells Potentially Injecting Into Rustler	51
Wells Injecting Above Rustler	28
Wells Injecting Below Rustler	1,920
Wells With Anomalous Data	13
Total	2,012

Figure 2-11: Rustler Class II Injection Wells



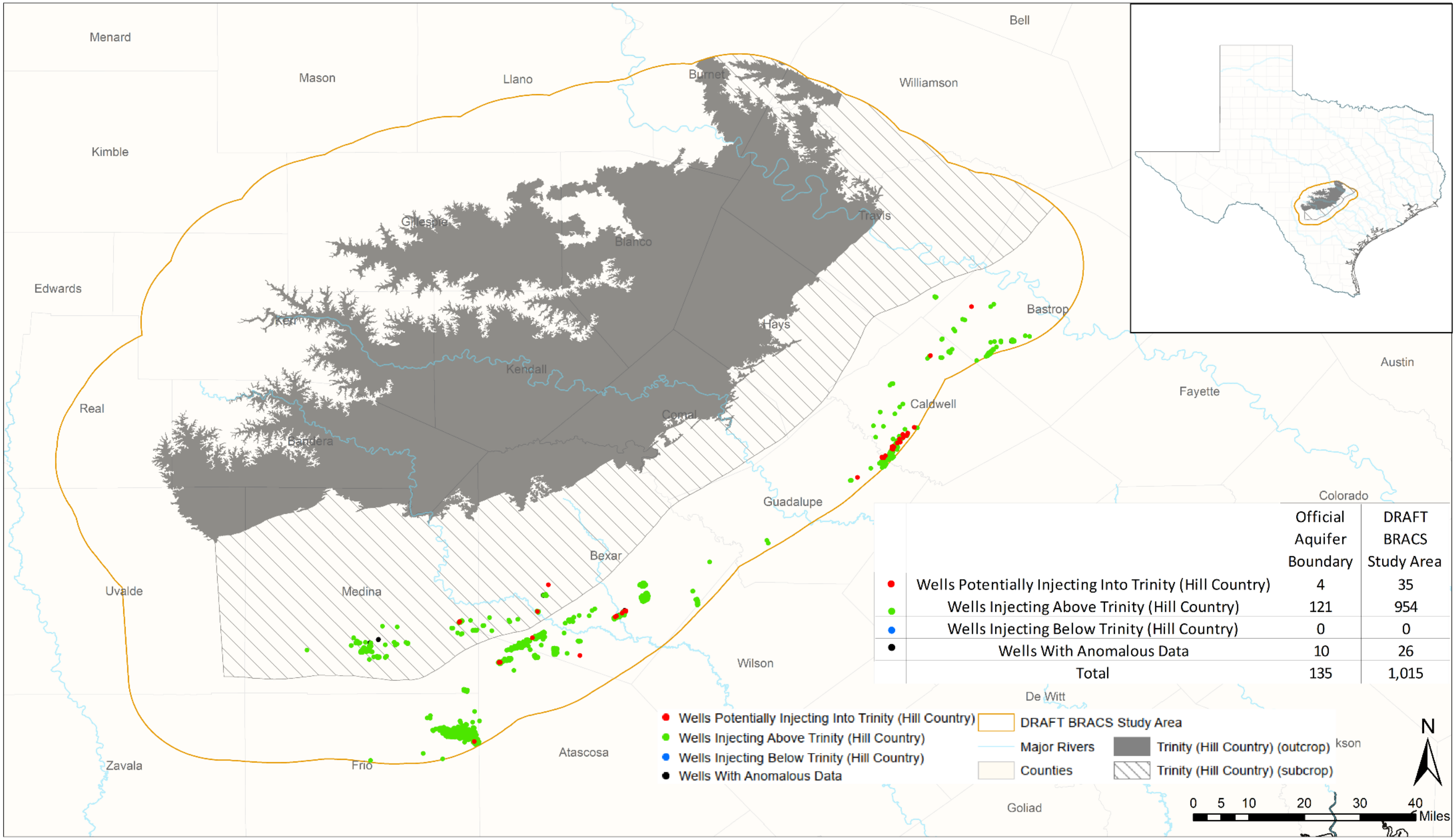
		Official Aquifer Boundary	BRACS Study Area
●	Wells Potentially Injecting Into Gulf Coast (LRGV)	79	134
●	Wells Injecting Above Gulf Coast (LRGV)	0	0
●	Wells Injecting Below Gulf Coast (LRGV)	425	521
●	Wells With Anomalous Data	6	9
	Total	510	664

Figure 2-12: Gulf Coast (Lower Rio Grande Valley) Class II Injection Wells



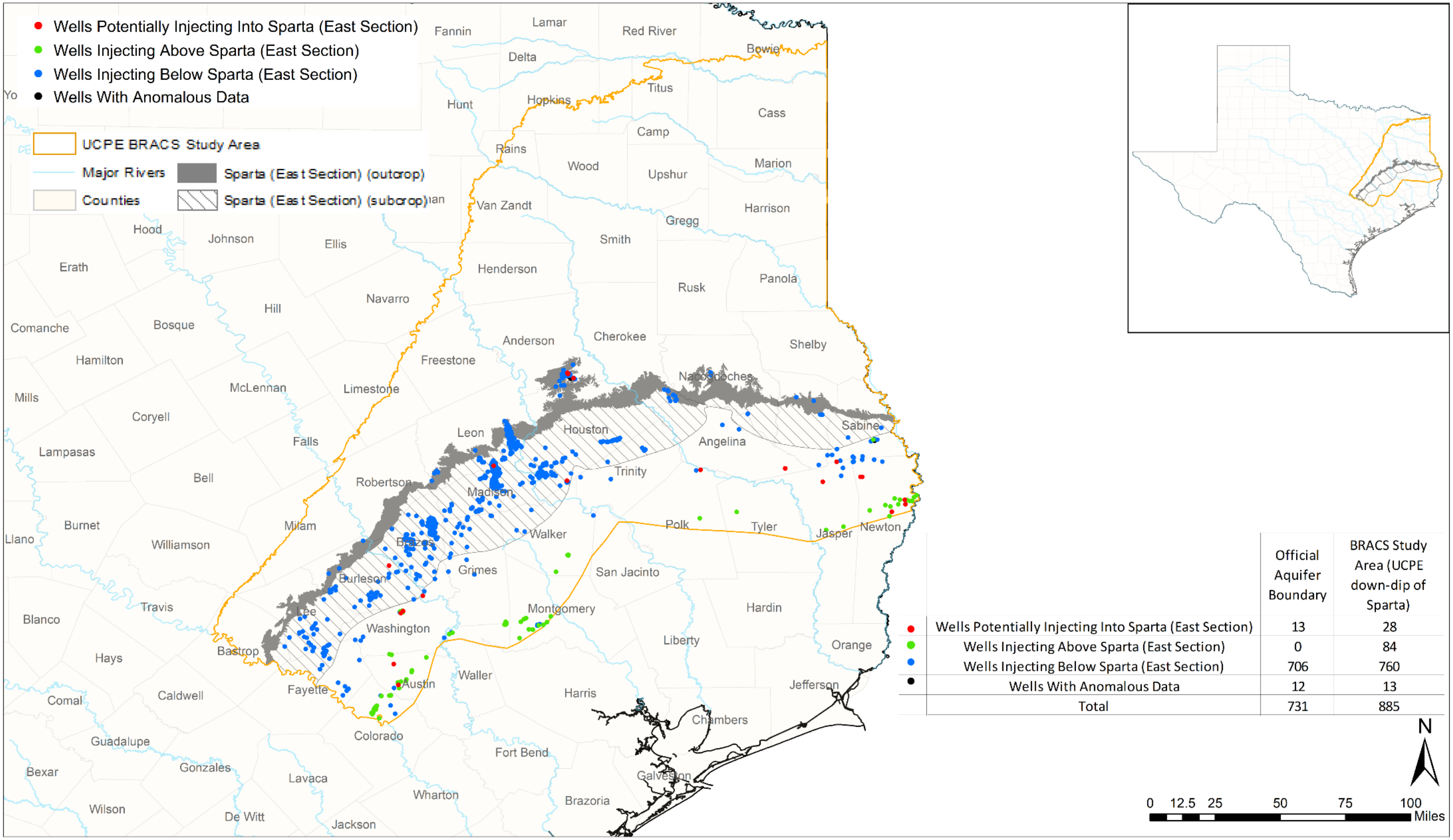
	Official Aquifer Boundary	BRACS Study Area
Wells Potentially Injecting Into Pecos Valley	704	704
Wells Injecting Above Pecos Valley	0	0
Wells Injecting Below Pecos Valley	11,462	11,462
Wells With Anomalous Data	92	92
Total	12,258	12,258

Figure 2-13: Pecos Valley Class II Injection Wells



	Official Aquifer Boundary	DRAFT BRACS Study Area
Wells Potentially Injecting Into Trinity (Hill Country)	4	35
Wells Injecting Above Trinity (Hill Country)	121	954
Wells Injecting Below Trinity (Hill Country)	0	0
Wells With Anomalous Data	10	26
Total	135	1,015

Figure 2-14: Trinity (Hill Country) Class II Injection Wells



	Official Aquifer Boundary	BRACS Study Area (UCPE down-dip of Sparta)
Wells Potentially Injecting Into Sparta (East Section)	13	28
Wells Injecting Above Sparta (East Section)	0	84
Wells Injecting Below Sparta (East Section)	706	760
Wells With Anomalous Data	12	13
Total	731	885

Figure 2-15: Sparta (East Section) Class II Injection Wells. UCPE = Upper Coastal Plains East.

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2.2.5 Likelihood of presence of Class II injection wells

In this section, we provide our opinion on the likelihood of the presence of Class II injection wells in the identified study aquifers based on the assessments completed and described above. The confidence in the opinion is relatively better where completed BRACS studies are available. The horizontal mapping exercise described earlier and other available data are used to determine the potential likelihood of the presence of Class II injection wells for the aquifers without completed BRACS studies. Table 2-4 provides an estimate of the number of potential Class II wells that may exist in single or multiple formations and a corresponding qualitative probability of the presence of these wells.

Table 2-4: Likelihood of presence of Class II injection wells based on horizontal (x,y) and vertical (z) mapping exercise. The numbers marked with * are for aquifers where the BRACS studies have not yet been completed for the entire extent

Aquifer	Well Counts (x,y)	Well Counts (z)	Likelihood	Reason
Blossom	50	1	Significant	presence confirmed
Capitan Reef Complex	4,064	N/A	Significant	high number of potential wells
Carrizo-Wilcox	9,635	188*	Significant	high number of potential wells
Cross-Timbers	22,812	N/A	Significant	high number of potential wells
Dockum	31,717	N/A	Significant	high number of potential wells
Edwards BFZ	135	N/A	Moderate	no presence detected and low number of potential wells
Edwards-Trinity	15,074	N/A	Significant	high number of potential wells
Ellenburger-San Saba	61	N/A	Moderate	no presence detected and low number of potential wells
Gulf Coast	12,233	1,399	Significant	presence confirmed
Hickory	78	N/A	Moderate	no presence detected and low number of potential wells
Nacatoch	1,672	699	Significant	presence confirmed
Pecos Valley	12,258	704	Significant	presence confirmed
Queen City	3,617	N/A	Significant	high number of potential wells
Rustler	2,012	0	Low	no current wells intersecting
Sparta	1,122	28*	Significant	presence confirmed
Trinity (Hill Country)	1,015	35	Significant	presence confirmed
Woodbine	685	N/A	Moderate	no presence detected and low number of potential wells
Yegua Jackson	1,123	N/A	Moderate	no presence detected and low number of potential wells

2.3 Aquifer Parameters Assessment

A list of aquifer parameters and their values is presented in this section. This list was developed based on the research conducted to select the appropriate injectate mapping techniques described in Chapters 1 and 3.

The aquifer parameters identified to be estimated are:

1. Horizontal hydraulic conductivity (K_x and K_y) [ft/day];
2. Vertical hydraulic conductivity (K_z) [ft/day];
3. Transmissivity (T) in [ft^2/day];
4. Effective porosity (ϕ) [dimensionless, -];
5. Specific yield (S_y) [-];
6. Specific storage (S_s) [1/ft]; and
7. Hydraulic gradient (i) [-]: while essential to the mapping exercise, the hydraulic gradient may vary significantly spatially and temporally within an aquifer. Therefore, the project team assumed some default order of magnitude estimates for the injecate mapping exercise.

Multiple sources of information on these aquifer parameters were explored, including published GAMs & BRACS reports from TWDB, United States Geological Survey (USGS) studies, and limited literature review for identification & analysis purposes. Discussions between the project team, workgroup, and TWDB staff resulted in the determination that currently, GAM models and documentation are the most defensible scientific source to obtain the required information on the identified aquifer parameters. The project team used both BRACS and GAM study boundaries for this task. Where an existing BRACS study was not available, the top and bottom elevations values from the GAM models were used for estimating the parameter values.

Note that for the Blossom aquifer, San Antonio segment of the Edwards (Balcones Fault Zone) aquifer, the data are obtained from other sources described above, not the GAMs. No information is currently available for the Cross-Timbers aquifer.

All the aquifer parameters values except for transmissivity values (unless available) are extracted directly from the publicly-available geodatabases or model files for the GAMs. Transmissivity values are estimated by taking the product of hydraulic conductivity and aquifer thickness on a cell-by-cell basis. The thickness of the aquifer is assessed using the top and bottom elevations of the model layer. The GAMs simulate some aquifers using multiple layers. For example, for the Carrizo-Wilcox aquifer: Layer 3 represents Carrizo; Layer 4 represents Upper Wilcox; Layer 5 represents Middle Wilcox, and Layer 6 represents Lower Wilcox; in the multiple available GAMs. The aquifer parameters are extracted for each layer to understand the parameter variability better.

Table 2-5 provides a consolidated list of the assessed aquifer parameters for all the aquifers. Porosity values reported in this table represent effective porosity and should not be mistaken for total porosity or compared with the specific yield values. Please note that specific yield and specific storage values are useful for conducting groundwater modeling under transient flow conditions and not used under assumption of steady flow conditions. Effective porosity values are not part of the GAM data as it is a parameter used in groundwater transport simulations, and GAMs are generally not built to conduct groundwater transport. Therefore, the project team estimated some conservatively default values based on the hydrogeology of each identified aquifer.

A simple statistical analysis of the aquifer parameters produced the maximum, minimum, mean, and median values for the intended aquifer parameters. The maximum and minimum values represent the largest and smallest values respectively used in the model grids from which the range of the estimated parameters can be derived. Mean (average) and median (50^{th} percentile) values are also presented. The median may be more valuable than the mean when extreme values in the data set could create a bias towards these relatively larger or smaller values. The primary objective for conducting the statistical analysis is to develop a default database of aquifer parameter values. This default database for aquifer parameters has been implemented in the injectate mapping tool. However, these aquifer parameter values can be edited within the online tools as new and improved aquifer datasets become available through future studies.

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Table 2-5: Aquifer Parameters for the 18 Identified Aquifers

S.No	Aquifer Name	Layers	Kx (ft/day)				Ky (ft/day)				Kz (ft/day)				Effective Porosity				Transmissivity (ft^2/day)				Specific Yield (Sy)				Specific Storage (Ss)			
			Min	Max	Mean	Median	Min	Max	Mean	Median	Min	Max	Mean	Median	Min	Max	Mean	Median	Min	Max	Mean	Median	Min	Max	Mean	Median	Min	Max	Mean	Median
1	Nacatoch	Layer 2 - Nacatoch	2.5	9.5	5	6	2.5	10	5	6	0.3	1	0.5	0.6	0.1	0.1	0.1	0.1	125	4,150	1,400	2,100	0.05	0.05	0.05	0.05	1.E-05	1.E-05	1.E-05	1.E-05
2	Trinity (northern section)	Layer 1 - Shallow outcrop Northern Trinity	0.03	100	15	2	0.03	100	15	2	1.0E-04	9.1	1	0.2	0.01	0.01	0.01	0.01	2.324	34,000	1,313	752	0.1	0.1	0.1	0.1	2.E-04	3.E-02	8.E-03	8.E-03
		Layer 4 - Paluxy Formation	0.01	9.1	1.5	1.2	0.01	9.1	1.5	1.2	0.006	9.1	1.1	1.2	0.01	0.01	0.01	0.01	0.03	802	82	18	_	_	_	_	1.E-06	2.E-05	1.E-06	1.E-06
		Layer 5 - Glen Rose Formation	0.2	9.1	1.3	1.3	0.2	9.1	1.3	1.3	0.2	9.1	1	1	0.01	0.01	0.01	0.01	388	194	142	27	_	_	_	_	1.E-06	6.E-06	1.E-06	1.E-06
		Layer 6 - Hensell Member	0.02	9	3	3	0.02	9	3	3	0.2	9	0.9	0.9	0.01	0.01	0.01	0.01	1	206	168	46	_	_	_	_	1.E-06	1.E-05	1.E-06	1.E-06
		Layer 7 - Pearsall/Cow Creek/Hammett members	0.01	9	1	1.4	0.01	9	1	1.4	0.009	9	0.6	0.6	0.01	0.01	0.01	0.01	0.3	610	99	14	_	_	_	_	1.E-06	8.E-06	1.E-06	1.E-06
		Layer 8 - Hosston Member	0.6	9.1	3.2	3.2	0.6	9.1	3.2	3.2	4.0E-06	9.1	0.5	0.5	0.01	0.01	0.01	0.01	18	4,276	509	194	_	_	_	_	1.E-06	7.E-06	1.E-06	1.E-06
3	Blossom	_	2.7	7.0	4.4	3.7	_	_	_	_	_	_	_	_	_	_	_	_	85.0	550.0	290.0	205.0	3.0E-05	7.0E-05	1.3E-05	1.3E-05	_	_	_	_
4	Carrizo-Wilcox (southern section)	Layer 3 -Carrizo	1.0E-04	13	1.0	0.5	1.0E-04	13	1.0	0.5	1.0E-04	13	1.0	0.5	0.01	0.01	0.01	0.01	0.03	8,536	920	270	0.2	0.2	0.2	0.2	6.E-04	9.E-03	7.E-03	7.E-03
		Layer 4 - Upper Wilcox	1	1	1	1	1	1	1	1	1	1	1	1	_	_	_	_	11	1,085	303	210	0.1	0.1	0.1	0.1	3.E-05	5.E-03	1.E-03	1.E-03
		Layer 5- Middle Wilcox	0.1	83	10	3	0.1	83	10	3	0.1	83	10	3	0.01	0.01	0.01	0.01	77	59,088	6,285	1,902	0.2	0.2	0.2	0.2	2.E-04	3.E-03	1.E-03	1.E-03
		Layer 6- Lower Wilcox	0.3	3	1.8	3	0.3	3	1.8	3	0.3	3	1.8	3	0.01	0.01	0.01	0.01	6	3,615	786	116	0.2	0.2	0.2	0.2	6.E-05	6.E-03	1.E-03	1.E-03
5	Gulf Coast (north of the LRGV)	Layer 1 - Chicot	0.1	199	21.7	18	0.1	199	21.7	18	0.1	199	21.7	18	_	_	_	_	75	75,000	13,113	2,260	_	_	_	_	2.E-04	1.E-02	6.E-03	6.E-03
		Layer 2 - Evangeline	0.5	27	6.3	5	0.5	27	6.3	5	0.5	27	6.3	5	_	_	_	_	19	22,500	7,289	9,935	_	_	_	_	5.E-04	2.E-02	9.E-03	9.E-03
		Layer 3 -Burkeville	0.01	17	2.7	2	0.0	17	2.7	2	0.0	17	2.7	2	_	_	_	_	0.2	7,336	1,218	646	_	_	_	_	2.E-04	2.E-02	5.E-03	5.E-03
		Layer 4 -Jasper	2	10	6.2	6.3	2.0	10	6.2	6	2.0	10	6.2	6	_	_	_	_	278	26,867	5,037	2,593	_	_	_	_	2.E-04	2.E-02	6.E-03	6.E-03
		Layer 1 - Chicot	0.002	2,877	21.7	85.3	0.002	2,877	21.7	85.3	0.002	2,877	21.7	85.3	_	_	_	_	0.002	2,184	1,140	578	1.0E-04	0.2	0.03	0.03	1.E-04	2.E-01	3.E-02	3.E-02
		Layer 2 - Evangeline	0.001	50	3.7	2.9	1.0E-04	50	3.7	2.9	1.0E-04	50	3.7	2.9	_	_	_	_	0.001	0.3	0.2	0.05	1.0E-05	0.2	0.1	0.1	1.E-05	2.E-01	1.E-01	1.E-01
		Layer 3 -Burkeville	9.0E-06	0.02	0.01	0.01	9.0E-06	0.02	0.01	0.01	9.0E-06	0.02	0.01	0.01	_	_	_	_	_	_	_	_	0.05	0.05	0.05	0.05	5E-02	5E-02	5E-02	5E-02
		Layer 4 -Jasper	9.1E-05	180	1.6	1.6	9.1E-05	180	1.6	1.6	9.1E-05	180	1.6	1.6	_	_	_	_	0.001	14,040	3,188	530	1.0E-05	0.2	0.1	0.1	1.E-05	2.E-01	1.E-01	1.E-01
6	Rustler	Layer 2 - Rustler	0.01	10	0.8	0.8	0.01	10	0.8	0.8	1.4E-05	0.1	8.7E-04	8.7E-04	_	_	_	_	1	4,196	212	212	1.0E-06	0.002	6.4E-05	6.4E-05	1.E-06	2.E-03	6.E-05	6.E-05
7	Gulf Coast (LRGV)	Layer (1-3) - Chicot	0.01	500	358	358	0.01	500	358	358	1.2E-04	67	48	10	0.3	0.3	0.3	0.3	0.003	718,360	141,108	18,780	1.0E-04	0.001	7.6E-04	0.008	1.E-06	1.E-06	1.E-06	1.E-04
		Layer (4-6) - Evangeline	0.01	50	4.5	1.3	0.01	50	5	1	1.2E-04	5.8	2	2	0.3	0.3	0.3	0.3	0.01	16	7	6	1.0E-06	0.001	2.1E-04	2.1E-04	1.E-06	1.E-06	1.E-06	1.E-04
		Layer 7 -Burkeville	0.01	50	2	2	0.01	50	2	2	1.2E-04	2	0.1	0.1	0.3	0.3	0.3	0.3	0.003	6,851	179	31	1.0E-04	0.001	7.7E-04	7.7E-04	1.E-06	1.E-06	1.E-06	1.E-04
		Layer (8-10) -Jasper	0.2	50	18	18	0.2	50	18	18	0.01	2	0.7	0.68	0.3	0.3	0.3	0.3	0.1	15,263	1,061	798	1.0E-04	0.001	7.7E-04	7.7E-04	1.E-06	1.E-06	1.E-06	1.E-04
8	Carrizo-Wilcox (central section)	Layer 2 - Carrizo	0.005	75	12	2	0.005	75	12	2	0.002	0.12	0.006	0.006	_	_	_	_	2.0E-06	24,509	1,376	687	1.0E-05	0.2	0.01	0.01	1.E-06	6.E-04	4.E-05	1.E-04
		Layer (3-5) - Wilcox	0.3	6	1	1	0.3	6	1	1	2.7E-04	0.02	0.002	0.002	_	_	_	_	1.0E-06	1,934	187	54	0.03	0.1	0.05	0.05	1.E-04	1.E-04	1.E-04	1.E-04
9	Pecos Valley	Layer (1-2) - Pecos Valley	1.5	88	3.1	2	1.5	88	3.1	2	_	_	_	_	_	_	_	_	342	22,056	1,035	1,035	_	_	_	_	2.E-04	2.E-04	2.E-04	2.E-04
10	Queen City (central and southern sections)	Layer 3- Queen City Central	0.2	8.5	0.7	0.1	0.2	8.5	0.7	0.1	0.04	0.002	0.002	0.002	_	_	_	_	4.0E-06	1,897	177	53	0.1	0.1	0.1	0.1	2.E-07	5.E-05	1.E-05	1.E-05
		Layer 3- Queen City Southern	1.0E-04	14.8	1.3	1	1.0E-04	14.8	1.3	1	1.0E-04	14.8	1.3	1	_	_	_	_	0.03	8,611	1,058	909	0.2	0.2	0.2	0.2	2.E-01	1.E+00	3.E-01	3.E-01
11	Sparta (central and southern sections)	Layer 1- Sparta Central	27	1,000	134	75	27	1,000	134	75	0.001	100	1	1	_	_	_	_	0.001	85,451	348	2,395	0.2	0.2	0.2	0.2	6.E-04	6.E-04	6.E-04	6.E-04
		Layer 1 - Sparta Southern	1.0E-04	5.6	1.8	0.8	1.0E-04	5.6	1.8	0.8	1.0E-04	5.6	1.8	0.8	_	_	_	_	0.02	1,698	319	237	0.2	0.2	0.2	0.2	5.E-05	1.E+00	9.E-02	2.E-01

S.No	Aquifer Name	Layers	Kx (ft/day)				Ky (ft/day)				Kz (ft/day)				Effective Porosity				Transmissivity (ft^2/day)				Specific Yield (Sy)				Specific Storage (Ss)			
			Min	Max	Mean	Median	Min	Max	Mean	Median	Min	Max	Mean	Median	Min	Max	Mean	Median	Min	Max	Mean	Median	Min	Max	Mean	Median	Min	Max	Mean	Median
12	Yegua-Jackson (central and southern sections)	Layer (1to5)	0.02	12	1.1	0.3	0.02	12	1.1	0.3	0.02	12	1.1	0.3	_	_	_	_	51	13,124	1,445	370	0.03	0.2	0.1	0.1	5.E-04	2.E-01	7.E-02	7.E-02
13	Trinity (Hill Country section)	Layer 2 - Upper Trinity Aquifer	9	150	10.4	9	9	150	10.4	9	_	_	_	_	_	_	_	_	1	2,000	19	28	5.0E-04	5.0E-04	5.0E-04	5.0E-04	1.E-06	1.E-06	1.E-06	1.E-06
		Layer 3- Middle Trinity Aquifer	7.6	15	8.8	7.6	7.6	15	8.8	7.6	_	_	_	_	_	_	_	_	1	2,500	227	73	8.0E-04	8.0E-04	8.0E-04	8.0E-04	1.E-06	1.E-06	1.E-06	1.E-06
		Layer 4- Lower Trinity Aquifer	1.7	17	4.4	1.7	1.7	17	4.4	1.7	_	_	_	_	_	_	_	_	1	2,500	200	56	8.0E-04	8.0E-04	8.0E-04	8.0E-04	1.E-06	1.E-06	1.E-06	1.E-06
14	Sparta (east section)	Layer 1 - Sparta (East Section)	1.0E-04	5.6	1.8	0.8	1.0E-04	5.6	1.8	0.8	1.0E-04	5.6	1.8	0.8	_	_	_	_	0.02	1,698	319	237	0.2	0.2	0.2	0.2	5.E-05	1.E+00	9.E-02	2.E-01
15	Edwards-Trinity Plateau	Layer 1 - Edwards Group	1	50	8	5	1	50	8	5	_	_	_	_	_	_	_	_	5	24,849	2,698	2,900	_	_	_	_				
		Layer 2- Upper and Middle Trinity	2	20	9	9	2	20	9	9	_	_	_	_	_	_	_	_	2	13,095	1,689	370	_	_	_	_	1.E-04	1.E-04	1.E-04	1.E-04
16	Carrizo-Wilcox (eastern section)	Layer 2 - Carrizo	0.005	75	12	2	0.005	75	12	2	0.002	0.12	0.006	0.006	_	_	_	_	2.0E-06	24,509	1,376	687	1.0E-05	0.2	0.01	0.01	1.E-06	6.E-04	4.E-05	4.E-05
		Layer (3-5) - Wilcox	0.3	6	1	1	0.3	6	1	1	2.7E-04	0.02	0.002	0.002	_	_	_	_	1.0E-06	1,934	187	54	0.03	0.1	0.05	0.05	1.E-04	1.E-04	1.E-04	1.E-04
17	Queen City (eastern section)	Layer 3 - Queen City (Eastern Section)	0.2	8.5	0.7	0.1	0.2	8.5	0.7	0.1	0.04	0.002	0.002	0.002	_	_	_	_	4.0E-06	1,897	177	53	0.1	0.1	0.1	0.1	2.E-07	5.E-05	1.E-05	1.E-05
18	Yegua-Jackson (eastern section)	Layer (1to5)	0.02	12	1.1	0.3	0.02	12	1.1	0.3	0.02	12	1.1	0.3	_	_	_	_	51	13,124	1,445	370	0.03	0.2	0.1	0.1	5.E-04	2.E-01	7.E-02	7.E-02
19	Edwards (Balcones Fault Zone, has top of Trinity but not top of Edwards)	Layer 1 - Edwards (Balcones Fault Zone)	3.0E-04	10,000	_	_	_	_	_	_	_	_	_	_	_	_	_	_	0.1	1.0E+07	_	_	0.005	0.2	0.2	0.2	5.E-07	5.E-06	_	_
20	Capitan Reef complex	Layer 5 - Capitan Reef Complex	1.0E-04	12	2.3	0.3	1.0E-04	12	2.3	0.3	0.002	1.2	0.3	0.004	0.01	0.01	0.01	0.01	0.3	58,116	2,658	1,582	0.002	0.01	0.005	0.005	4.E-07	1.E-04	3.E-05	1.E-06
21	Cross-Timbers	_	_	_	_	_	_	_	_	_	_	_	_	_	_	_	_	_	_	_	_	_	_	_	_	_	_	_	_	_
22	Ellenburger-San Saba	Layer 5- Ellenburger - San Saba	0.3	133	8	4	0	133	8	4	0.03	13	0.8	0.4	0.01	0.01	0.01	0.01	4	14,450	407	350	0.02	0.02	0.02	0.02	2.E-05	3.E-02	3.E-03	3.E-03
23	Hickory	Layer 7 - hickory Aquifer	1.7	192	7.2	4.5	1.7	192	7.2	4.5	0.17	19.2	0.7	1	_	_	_	_	10.4	7,843	213	190	_	_	_	_	1.E-06	3.E-01	2.E-03	2.E-03
24	Dockum	Layer (3-4) - Dockum Aquifer	0.001	11.6	0.4	0.02	0.001	4.2	0.5	0.5	2.1E-05	1	0.2	5.0E-05	0.01	0.01	0.01	0.01	0.7	2,207	46	51	0.2	0.2	0.2	0.2	1.E-06	7.E-06	5.E-06	6.E-06
25	Woodbine	Layer 2- Woodbine Aquifer	0.001	9.1	1.3	1.3	0.001	9.1	1.3	1.3	0.001	9.1	1.3	1.3	0.01	0.01	0.01	0.01	6.3	354	33	8	_	_	_	_	1.E-06	1.E-06	1.E-06	1.E-06

2.4 Injection Well Parameters: Injectate Rate and Volumes

Class II injection well parameters for injectate rates and volumes are provided as an MS Excel™ worksheet named "InjectionWellStatistics.xlsx" submitted as part of the data deliverables. The following discussion provides an overview of our injectate volume and rates estimation process. Please note that the results from these assessments apply to the version of RRC database used for this study(October, 2020). The assessments will need to be reconducted for any additional wells added to the RRC databases in the future.

2.4.1 Aquifer Injection Data Description

This is a brief description of the methodology used for the injection well data set, which is based on a comprehensive well list containing approximately 114,330 injection wells. This well count differs from the earlier stated well count since it has been filtered to exclude the duplicate API entries for wells with multiple screens. Therefore, this is the count of unique API numbers in the database. This process extracted the monthly volume and pressure for Brine, Hydrocarbon, and Gas (when available) for the wells in each aquifer through cross-checking the provided injection well list with three databases. The three datasets (in both MS Access™ and CSV formats) included are: *Uif700a-monH10*, *Uif700a-monH10H*, and *unif700a-root*. All relevant "injection statistics" available from the databases are compiled in the "InjectionWellStatistics.xlsx" file, but only the "Volume of fluids injected" (MN_H10_TOTAL_VOL_BBL) field is utilized for injectate mapping purposes; however, the remainder of the data is retained for available information and convenience. Details of source data and list of parameters are listed below in Table 2-6.

Table 2-6: Injection Data Source

		Data Source		
		Database	Table	Field(s)
Actual monthly injection rates and pressures	**Average injection pressure**	Uif700a	monH10	MN_H10_AVG_INJ_PRESSURE
	Maximum injection pressure	Uif700a	monH10	MN_H10_MAX_INJ_PRESSURE
	Volume of fluids injected	Uif700a	monH10	MN_H10_TOTAL_VOL_BBL
	Volume of gas injected	Uif700a	monH10	MN_H10_TOTAL_VOL_MCF
	Maximum hydrocarbon wellhead pressure	Uif700a	monH10H	MN_H10H_MAX_HYDROCARB_PSIG
	Maximum brine wellhead pressure	Uif700a	monH10H	MN_H10H_MAX_BRINE_PSIG
	Net brine volume injected	Uif700a	monH10H	MN_H10H_INJ_BRINE_BBLS
	Net hydrocarbon volume injected	Uif700a	monH10H	MN_H10H_INJ_HYDROCARB_BBLS
	Net gas volume injected	Uif700a	monH10H	MN_H10H_INJ_GAS_MCF
Maximum permitted injection rates and pressures	**Max liquid injection volume (bbl per day)**	Uif700a	root	UIC_BBL_VOL_INJ
	Max gas injection volume (mcf per day)	Uif700a	root	UIC_MCF_VOL_INJ
	Max liquid injection pressure	Uif700a	root	UIC_MAX_INJ_PRESSURE
	Max gas injection pressure	Uif700a	root	UIC_MAX_INJ_PRESSURE2

2.4.2 Guide for Estimating the Injection Well Data

The following table (

Table 2-7) provides the name and description for each sub-tabs in the injection well parameters spreadsheet.

Table 2-7: Description of Sub-Tabs in the "InjectionWellStatistics.xlsx" file

Workbook Name	Description
Injection Statistics	One-line statistic summary for each of the injection wells, with a total well count of 114,330. This count does not include duplicate API entries for wells with multiple screens, i.e. this is a count of unique API numbers in the database as of Oct. 2020.
H10_AvgPres	Minimum, Mean, and Maximum values of Monthly Average Injection Pressure for each injection well of interest, extracted from "Uif700a-monH10". Also include first injection and last injection date and number of months of active injection time.
H10_MaxPres	Minimum, Mean, and Maximum values of Monthly Maximum Injection Pressure for each injection well of interest, extracted from "Uif700a-monH10". Also include first injection and last injection date and number of months of active injection time.
H10_LiqVol	Minimum, Mean, and Maximum values of Total Liquid Injection Volume for each injection well of interest, extracted from "Uif700a-monH10". Also include first injection and last injection date and number of months of active injection time.
H10_GasVol	Minimum, Mean, and Maximum values of Total Gas Injection Volume for each injection well of interest, extracted from "Uif700a-monH10". Also include first injection and last injection date and number of months of active injection time.
Stats_H10H	This table contains statistics of monthly pressure and volumes for a total of 814 wells, which includes certain injection wells. The monthly data does not contain overlap with monH10.
Stats_root	This table contains statistics of monthly permitted pressure and volumes for a total of 114,330 wells, which includes certain injection wells.

3. Injectate Mapping Techniques Description

As stated in Chapter 1, the study's primary goal is to provide a general methodology and tools to estimate the migration of injectate from the identified Class II injection wells. Chapter 2 provided a detailed analysis of the methodology to identify the Class II injection wells that might potentially inject into the brackish groundwater formations within the identified 18 aquifers and the volume/rate of the injection. This chapter describes the mapping techniques considered to achieve the project objective. The approach used for developing mapping techniques, available literature, and proposed techniques are presented in this chapter. A discussion is included on the underlying assumptions, advantages, and limitations of the proposed mapping techniques. The project team developed automated online tools to implement the selected mapping techniques using the processed available data. The online tools can accommodate potential future changes in Class II injection well data and locations. In summary, the mapping techniques considered here are scientifically defensible, utilize all the available aquifer and injection well data, are applicable for a wide variety of hydrogeologic settings, and are practical to use for a state-wide application for Texas.

3.1 Technical Approach

The project team considered mapping techniques that are based on sound theory, could accommodate the use of available aquifer and injection well data, and are capable of delineating injectate migration effectively and conservatively within the study aquifers.

Data are available for eighteen aquifers that span the state of Texas. Data for thousands of Class II injection wells are also available within the designated aquifers for this project. The developed online tools and the associated underlying mapping technique can evaluate the extent of migration for each individual injection well and are sufficiently general for application in a wide variety of hydrogeologic settings. The mapping techniques reviewed here consider practical limitations of the scale and the limitations of available data. We also conducted a case study and a test case showing that the underlying mapping technique can appropriately delineate injectate migration and handle the large amount of data available on a regional scale.

3.2 Background Literature and Identified Techniques

Various modeling techniques and tools are available that can simulate groundwater well injection, and a vast amount of literature deals with extraction and injection wells. Some of the methods used to estimate the migration of groundwater constituents in the subsurface are described in Chapter 1. Here, we distill the information gained from the literature review to help us develop a methodology for the intended tool. Overall, the available modeling techniques to assess migration of subsurface constituents can be broadly classified into:

a. Analytical models; and
b. Numerical models.

In general, analytical models are exact solutions, stable, efficient, robust, and easy-to-use but work with several simplifying assumptions. On the other hand, numerical models are more flexible. They can range from very simple models with similar capabilities and limitations as analytical solutions to very complex models that consider various physical and chemical processes. Numerical models may handle heterogeneities, spatially varying stratigraphy, three-dimensional conditions, time-varying boundary conditions, and several other complexities. Numerical models, however, require fine-tuning, can be unstable, and need extensive data to constrain their results depending on their complexity.

3.2.1 Review of Analytical Models

Examples of analytical models that deal with aquifer and well-pumping analyses include Thiem (1906), Theis (1935), Cooper and Jacob (1946), Hantush (1961), Papadopulos and Cooper (1967), Javandel (1982), Dougherty and Babu (1984), and Faybishenko et al (1995). Several Environmental Protection Agency (EPA) documents are also available that provide guidance and propose using specific analytical solutions to evaluate the radius of pressure influence of injection wells (Warner et al, 1979; EPA, 2021).

It is crucial to make a clear distinction between several of these analytical solutions, the terminology commonly used with these solutions, and injectate migration techniques needed in the current study. EPA often uses terminology such as “area of review”, “radius of pressure influence”, or “zone of endangering influence” to refer to zones in which increases in the water levels in strata occur resulting from injection wells. The term “area of review” is used henceforth in this chapter. These stated analyses are important in dealing with pressure buildup and mounding in the aquifer resulting from injection wells; however, such analyses cannot be used to estimate the extent of injectate migration which is relevant for the current injection migration delineation study. In this study, modeling the extent of injectate migration is a key aspect that needs to be considered.

Figure 3-1 illustrates how injectate migration can extend beyond the “area of review”. The “area of review” concept is based on the assumption that fluid injection pressure is negligible beyond a certain distance from the injection well. Although mounding beyond the “area of review” may be assumed to be negligible, however, the injectate can potentially migrate beyond the limits of the “area of review”. Depending on the duration of injection, injectate migration time, and regional hydraulic gradients, such potential migration may be significant. Therefore, it is essential to distinguish between “area of review” and the migration extents of injectate that are relevant to this study.

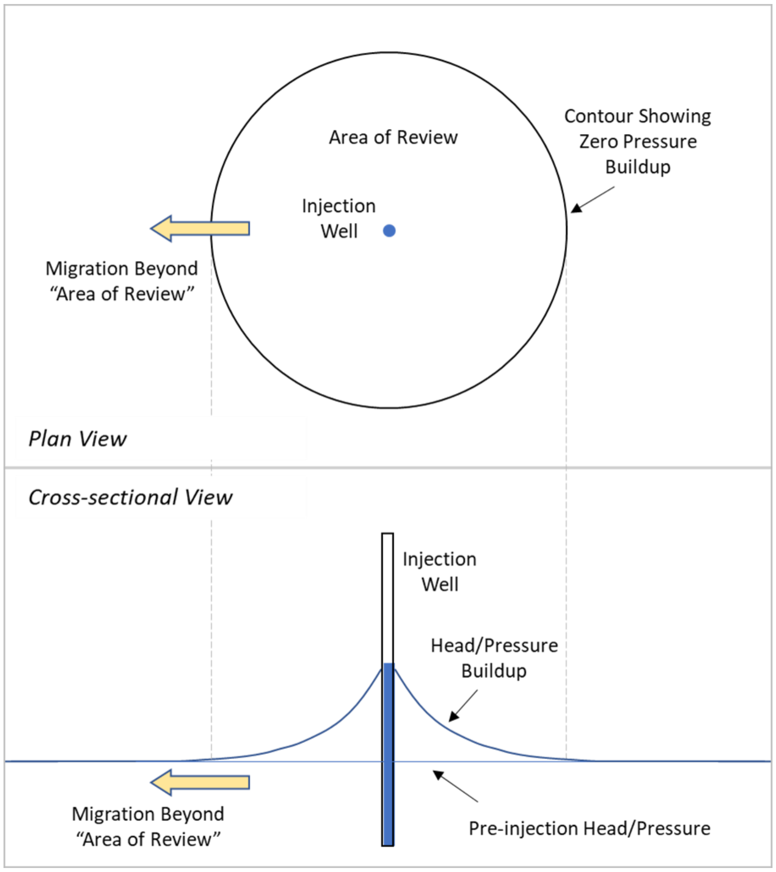

Figure 3-1: Schematic illustrating the "area of review" that is used to designate head or pressure build up due to an injection well. The schematic shows that injectate migration can potentially extend beyond the "area of review".

Two analytical solutions that provide injectate migration analysis are EPA (1994) and Bear and Jacobs (1965). EPA (1994) considers a simple analytical solution that assumes that the volume of injected water displaces the receiving water in an aquifer. Bear and Jacobs (1965) provide an analytical solution that simulates the evolution of the extent of migration of injected water in an aquifer with an ambient hydraulic gradient.

EPA (1994) provides the following simple mass balance equation, which estimates the distance of the front of the injectate from the injection well in any given time:

$$r(t) = \left(\frac{Qt}{\pi\phi b}\right)^{1/2}$$

The quantity $r(t)$ represents the horizontal distance traveled by the injected fluid after an elapsed time t. Here Q is the pumping rate, ϕ is the effective porosity, and b is the thickness of the stratum into which the water is injected. This solution assumes that injection locally overwhelms the ambient groundwater flow. The above expression is derived from a simple mass balance expression where the total water injected over a given time is equal to the volume of water displaced in the aquifer.

Bear and Jacobs (1965) account for an ambient groundwater flow which is a much more realistic scenario for relatively longer time frames of 30 to 50 years in the case of our study. The conceptual model for the Bear and Jacobs (1965) analysis is shown in Figure 3-2. Assuming that the direction of the ambient groundwater flow is known, the distance from the injection well at any time t is written in implicit dimensionless form as:

$$t_D = x_D - ln\{1 + x_D\}$$

Here:

$$t_D = \frac{2\pi q^2 b}{\phi Q} t$$

$$x_D = \frac{2\pi q b}{Q} \bar{x}$$

The quantity $\bar{x}$ denotes the distance between the injection well and the front of the injected fluid along the travel direction of ambient groundwater flow in an elapsed time t. The parameter q is the ambient Darcy flux, the product of the hydraulic conductivity, and the ambient hydraulic gradient. The value of $\bar{x}$ at an elapsed time t is obtained by iterative solution techniques (with root-finding algorithms).

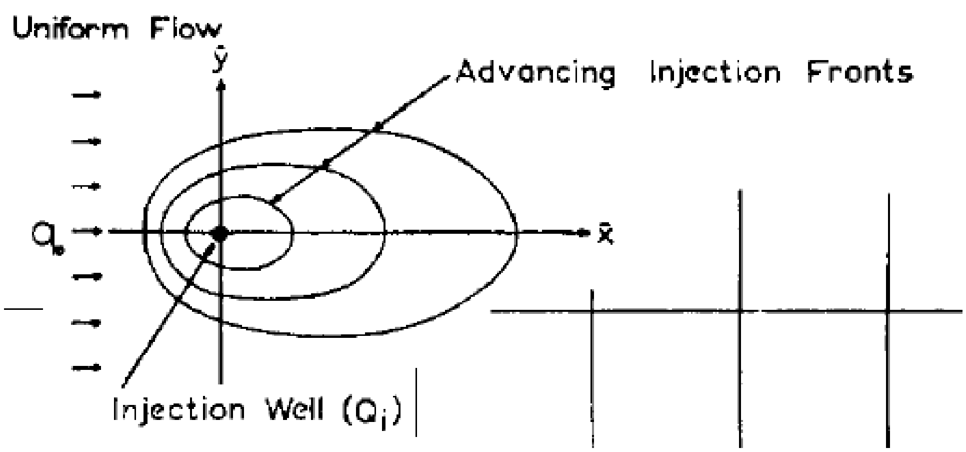

Figure 3-2: Conceptual model for the Bear and Jacobs (1965) analysis of injection with ambient flow. Taken from Bear and Jacobs (1965)

3.2.2 Numerical Models

Several numerical models capable of simulating injection well processes and migration are available. During this study, the project team considered the most widely used, publicly available, and open-source modeling suite of programs developed by the U.S. Geological Survey, MODFLOW and related codes (Langevin et al, 2017; Pollock, 2016; Langevin et al, 2020; Langevin et al, 2021).

3.3 Proposed Techniques and Workflow

3.3.1 Tiered-Approach

A tiered approach has been adopted for the study. The tiers considered for the analyses are listed below. Various features (advantages and disadvantages) associated with these tiers are also summarized in Table 3-1.

Table 3-1: Features of Tiered Analyses

Analysis Feature	Tier 1 Analysis Analytical Solution	Tier 2 Analysis Analytical Solution	Tier 3 Analysis Numerical Method
Can be applied to entire database	Yes	Yes	No
Can accommodate direction of flow	No	Yes	Yes
Can analyze single injection well	Yes	Yes	Yes
Can analyze multiple injection wells	No	No	Yes
Is resource-conservative in its application	Yes	Yes	No

Tier 1 Analysis

This tier will be used as the first screening level analysis to estimate the extent of migration for all injection wells across all aquifers. This analysis will use the method described by the analytical solution EPA (1994), assuming no ambient flow. This analysis will also provide a potential additional mapping extent based on Bear and Jacobs (1965). A maximum injectate migration extent will be assessed for the first tier by considering the hydraulic gradient but ignoring the flow direction. The results from Tier 1 analysis will provide the maximum modeled extent of injectate migration. The Tier 1 analysis will also enable users to quickly assess aquifer-wide conditions and help to determine critical areas that may require more refined assessments potentially with a Tier 2 analysis.

Tier 2 Analysis

Tier 2 analysis will provide a more refined injection transport model for specific wells by considering the direction of flow in addition to the gradient of flow. Tier 2 analysis are based on the Bear and Jacobs (1965) analytical solution. Tier 1 and 2 analyses are illustrated in Figure 3-3.

The project team tested both Tier 1 and Tier 2 analyses during the study and found them to perform correctly for the example dataset. The analytical solutions and their implementation demonstrate efficient and robust computations. Tier 3 analysis was considered to perform detailed evaluation on specific areas of potential concern that need a more detailed site-specific (injection well-specific) analysis. Tiers 1 and 2 analyze each well independently and ignore the combined effects of multiple wells on the injectate migration.

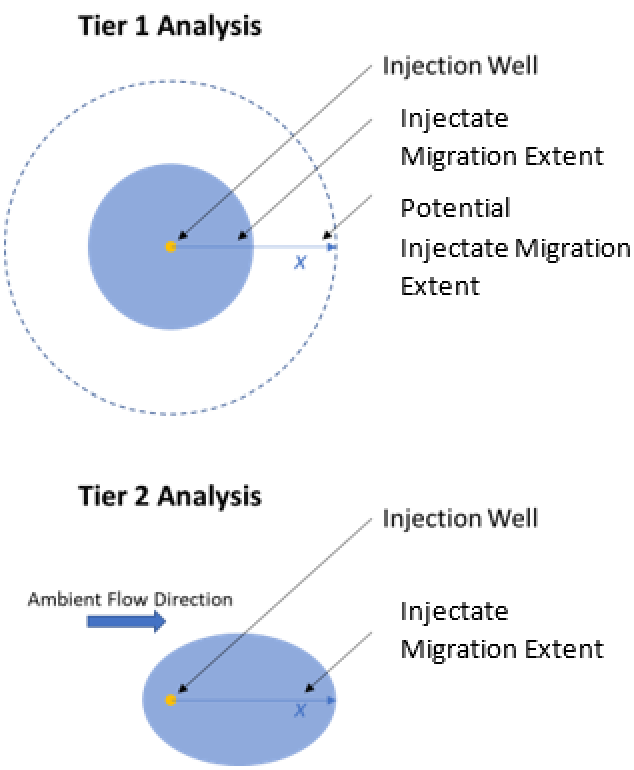

Figure 3-3: Schematic showing the proposed Tier 1 and Tier 2 analyses.

Tier 3 Analysis

Tier 3 analysis may be considered when a more detailed assessment for injection models are needed where the underlying assumptions of the Tier 1 and Tier 2 analyses are too restrictive. If a detailed study needs to be conducted to assess injectate migration in a focused area and requires more complexity than offered by Tier 1 and 2 analyses, it is suggested that a detailed numerical modeling exercise be conducted. This is suggested as a Tier 3 analysis and was considered but not recommended since it would require significant resource investment, including staff training, funding, and time as discussed at the end of Chapter 1. Tier 1 and Tier 2 approaches are significantly more advantageous and require minimal resources.

In the future, TWDB staff may consider using Tier 3 analysis to evaluate the feasibility of a brackish groundwater production well in an area that lies outside but close to the estimated migration zone from Class II well injectate. As described earlier, the Tier 1 and Tier 2 analyses are considered regional in nature, and a focused, more detailed study is required to assess local impacts.

The numerical model suggested for the Tier 3 analysis is the MODFLOW family of codes, such as MODFLOW 6 (Langevin and others, 2017) or MODFLOW-USG (Panday and others, 2013) can simulate both flow and transport. MODFLOW 6 is a freely available, open-source numerical modeling tool released and supported by the U.S. Geological Survey. Other codes, such as FEFLOW, HST3D, etc., are also available, and a detailed description of some of these tools is available in a previous TWDB-funded project (Deeds and Jones, 2011). It is recommended that the numerical model developed using the code be aligned with the flow direction, consider an ambient flow field, and incorporate multiple injection wells. These recommendations align with the state-wide data that are available. The advantage of this approach is the capability to accommodate multiple injection wells in one scenario to assess the migration patterns affected by concurrently injecting wells. The disadvantage of this approach is that because it is a numerical solution, a solution is not guaranteed if the simulation fails to converge, and the model results may not be reliable in such cases. The numerical model will be limited in terms of spatial coverage determined by the number of model cells that a simulation can accommodate due to the computing limitations of the available resources. Other considerations include the appropriateness of the spatial and temporal discretization since they might introduce numerical errors that may be hard to detect. Finally, as mentioned at the end of Chapter 1, a Tier-3 analysis would be significantly resource-intensive as most numerical groundwater models tend to be.

Please note that the specific yield and specific storage values provided in the assessed aquifer parameters table in Chapter 2 (Table 2-5) may be used in the development of the numerical model for Tier 3 analysis. These values are not used in Tier 1 and Tier 2 analyses.

3.3.2 Workflow Process

The databases compiled in previous tasks provide aquifer and injection well data. Missing data was supplemented from default values of aquifer properties and injection well construction and operation tables. The project team has developed the online tools with default data, and a tiered analysis can be performed using the same. The output from the injectate mapping tool consists of a shapefile that can be imported into a GIS interface or be displayed as part of the tool interface. The workflow process is shown as a flow chart in Figure 3-4.

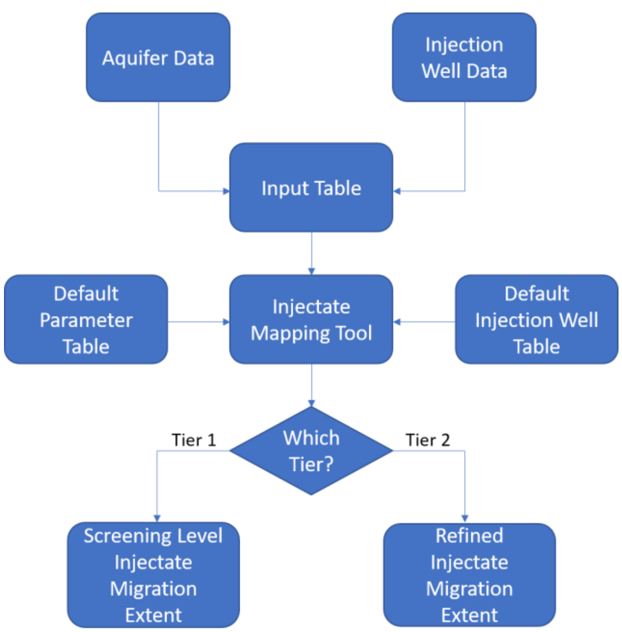

Figure 3-4: Workflow process for the developed tiered analysis.

3.4 Assumptions

The analytical and numerical models proposed in this study are based on several underlying assumptions. Most of these assumptions are valid for the scale and purpose of the analysis being considered here.

Assumptions associated with the aquifers include:

a. Confined aquifer.

b. Homogeneous subsurface properties.

c. Isotropic properties.

d. Negligible vertical hydraulic gradient.

e. Infinite spatial extent in horizontal (x-y) directions.

f. Steady-state flow field; and

g. No recharge or other sources and sinks.

Assumptions associated with the injection well include:

a. Wells assumed fully efficient and have no wellbore storage effects.

b. Multi-screened wells not considered.

c. The injectate fluid has the same density as the fluids in the subsurface.

d. Injectate is assumed to be non-reactive; and

e. No water seeps over or under the injected aquifer resulting from pressure build-up or density impacts of injectate.

Tiers 1 and 2 analyses that are based on analytical solutions assume a single-well analysis and ignore the potential impact of neighboring wells. While not recommended here, a Tier 3 approach with a detailed site-specific numerical model may be developed, where required, to incorporate multiple wells' effect on the injectate migration at a more local scale.

3.5 Examples and Discussion

The previous section listed the various assumptions that were made for the mapping techniques considered for this study. Most of these assumptions are governed by the data available at the scale of the assessment and are appropriate for this study. Selected examples are presented here to demonstrate the applicability of the final tiered methodology and to investigate the impact of certain assumptions on the simulation results.

3.5.1 Verification of Bear and Jacobs (1965)

The project team verified the analytical solution of Bear and Jacobs (1965) against a numerical model developed using MODFLOW 6. The conceptual model used for verification is shown in Figure 3-5 and the results are shown in Figure 3-6. The verification indicates that the analytical solution matches the numerical solution.

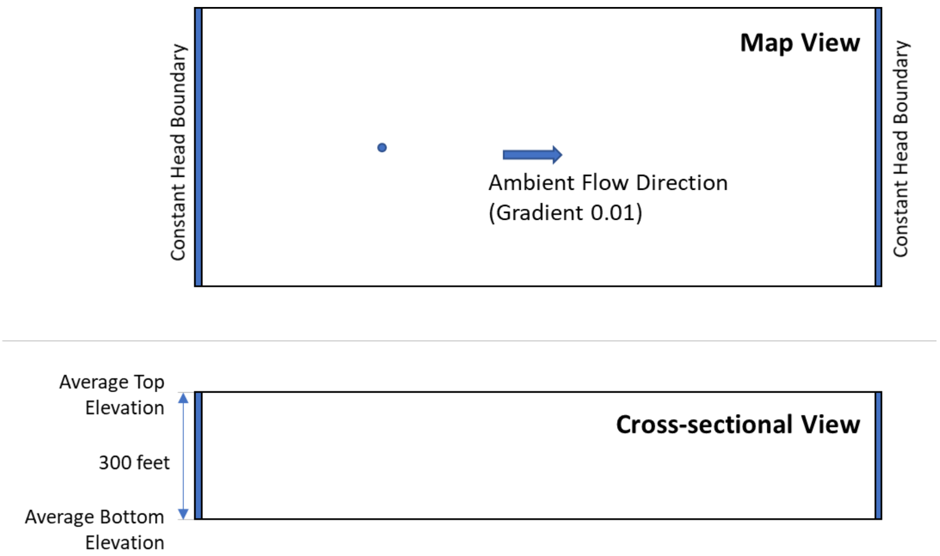

Figure 3-5: Schematic showing a conceptual model used for model verification.

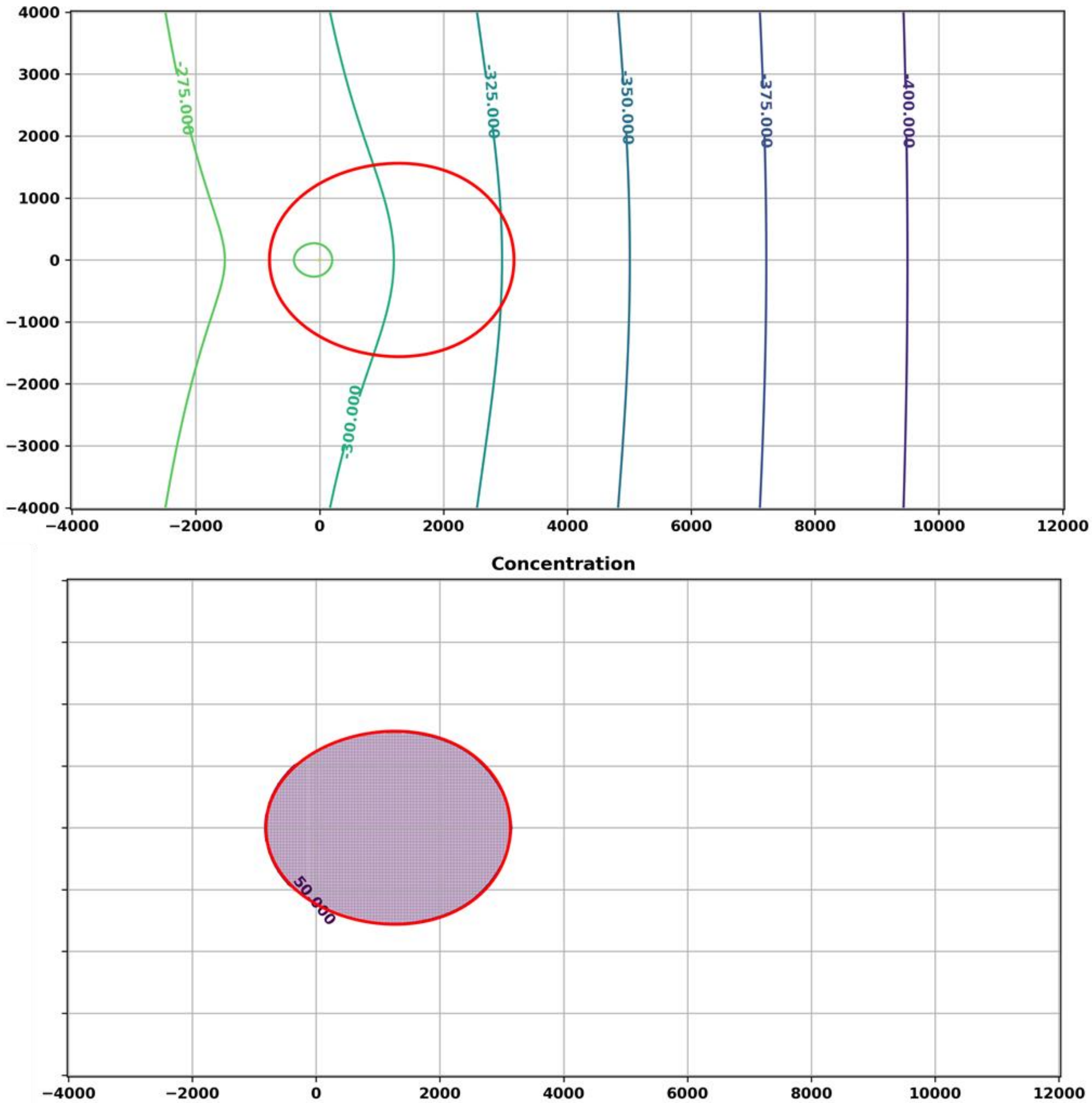

Figure 3-6: Comparison of the analytical solution of Bear and Jacobs (1965) and a numerical solution generated using MODFLOW 6. The plot on top shows head contours and results from the analytical solution. The plot at the bottom shows the extent of injectate migration modeled by the analytical solution (solid line) and the numerical solution (shaded area). The injectate migration model is based on a rectangular area that is 8000 feet wide (y-axis) and 16,000 feet long (x-axis)

3.5.2 Effects of Dispersion

Dispersion does not affect the estimation of the position of the front of injected water. The mean position of the front of injected water is defined as the position of C/C_0 = 0.5, where C_0 is the concentration in the injected water. The mean position of the front is the same with and without dispersion. This is illustrated with the results of an example calculation shown in Figure 3-7. The exact results for advection and dispersion are obtained with the solution of Moench and Ogata (1961). A typical longitudinal dispersity (a_L) of 1.0 m is assumed.

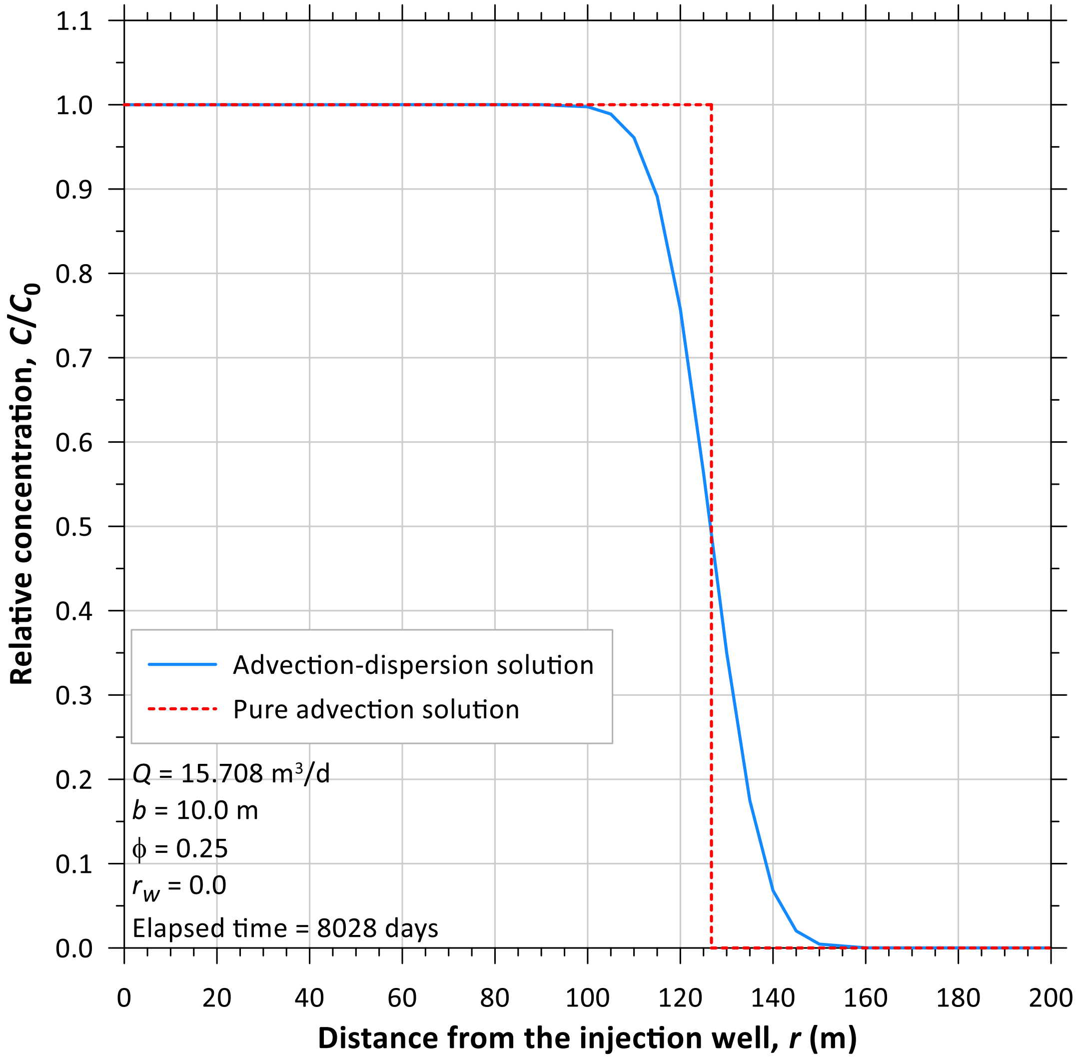

Figure 3-7: Comparison of advection-dispersion and pure advection analyses.

3.5.3 Impact of Multiple Wells

An example is created with multiple wells injecting concurrently in an aquifer. This example demonstrates the potential limitations of an analytical solution that would consider only one well at a time. In this example, injection at five well locations was simulated using Bear and Jacobs's analytical approach (1965). The extent of injectate migration for each well overlaid on top of each other is shown in Figure 3-8. A numerical model is developed with the same aquifer and injection well parameters but with all wells injecting concurrently. Figure 3-9 shows the comparison of an ensemble of all the analytical solutions generated by superposing individual well impacts and the numerical simulation with all wells pumping simultaneously. It is evident that the analytical approach does not simulate the impact of injection wells on the migration patterns of neighboring wells as accurately as it does in the case of a single well. This example is provided here to present a situation when Tier 3 analysis may be considered if Tier 2 analysis reveals overlapping impacts in a critical zone that needs a more detailed analysis.

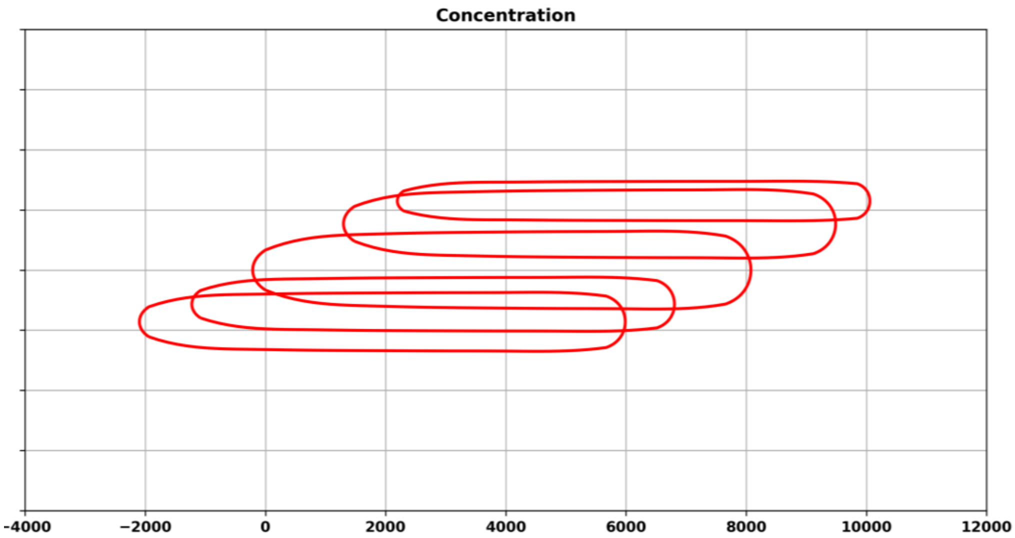

Figure 3-8: Extents of injectate migration from five individual wells generated by an analytical solution by considering one well at a time. Overlapping outlines show a potential for injection wells impacting each other. The plot shows results from the analytical solution (solid line). The injectate migration model is based on a rectangular area that is 8000 feet wide (y-axis) and 16,000 feet long (x-axis)

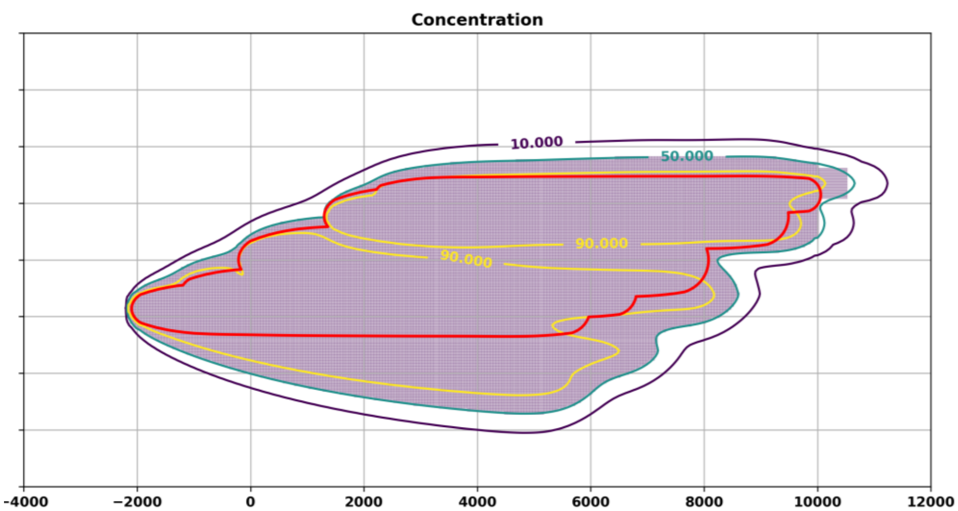

Figure 3-9: Comparison of analytical solutions for each of the five injection wells considered individually against a numerical solution that considers all injection wells pumping concurrently. The red line is an ensemble of all individual outlines shown in Figure 3-8 and the colored (shaded) extent is the equivalent representative extent of the results from the numerical model considering all wells. The injectate migration model is based on a rectangular area that is 8000 feet wide (y-axis) and 16,000 feet long (x-axis)

3.5.4 Density Considerations

An axisymmetric model is developed using MODFLOW 6 to demonstrate the potential effects of contrasts in density between the injectate and the formation fluids. The conceptual axisymmetric model is shown in Figure 3-10. A two-dimensional slice representing a cross-section along the radial direction (R-Z slice) is used to demonstrate results from these example simulations. Isotropic conditions were assumed. This assumption would tend to exaggerate the spread of injectate in the vertical direction because of variable density and is invoked here only for illustrative purposes. Two sets of simulations are considered: (1) a fully penetrating well; and (2) a partially penetrating well. In each set of simulations, three conditions are simulated:

a. Injected water at seawater density (TDS = 35 g/L); receiving water at TDS = 35 g/L (variable density is essentially negligible).

b. Injected water at seawater density (TDS = 35 g/L); receiving water at TDS = 10 g/L; and

c. Injected water at seawater density (TDS = 35 g/L); receiving water at TDS = 70 g/L.

Where 1g/L = 1,000 mg/L.

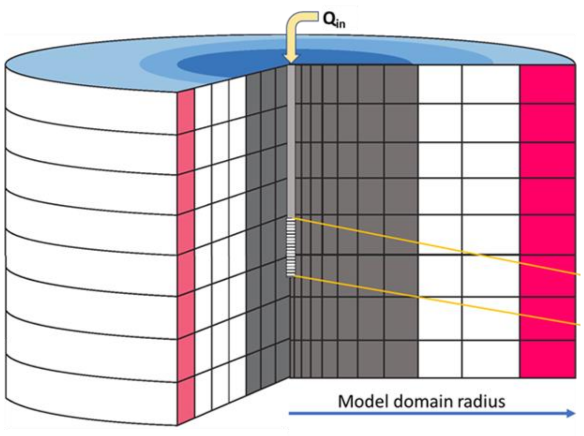

Figure 3-10: Conceptual design of an axisymmetric model used for evaluating variable density flow and transport.

The results for the fully penetrating well are shown in Figure 3-11. The results in Figure 3-11 also include the solution obtained using the analytical solution of Bear and Jacobs (1965). It can be observed that the analytical solution matches the numerical solution when the injected water and receiving ambient aquifer water has the same density, i.e., density effects are negligible. For the cases when injected water is lighter or denser than the ambient water, the spatial spread of injectate is more prominent in some sections of the aquifer (shallower or deeper depending on the density difference) as compared to the proposed analytical solution. It should be noted that the spread is not uniform across the thickness of the aquifer and is exaggerated because of the assumption of isotropy in the simulation. The other aspect to note is that the spread is observed because the well is fully penetrating in a confined aquifer system, and the injectate is assumed to be contained within the injected aquifer. The example is presented to demonstrate the maximum likely effects of variable density on the migration pattern of injectate. In real-world scenarios, anisotropy is expected to limit the vertical spread of injectate compared to the results presented here.

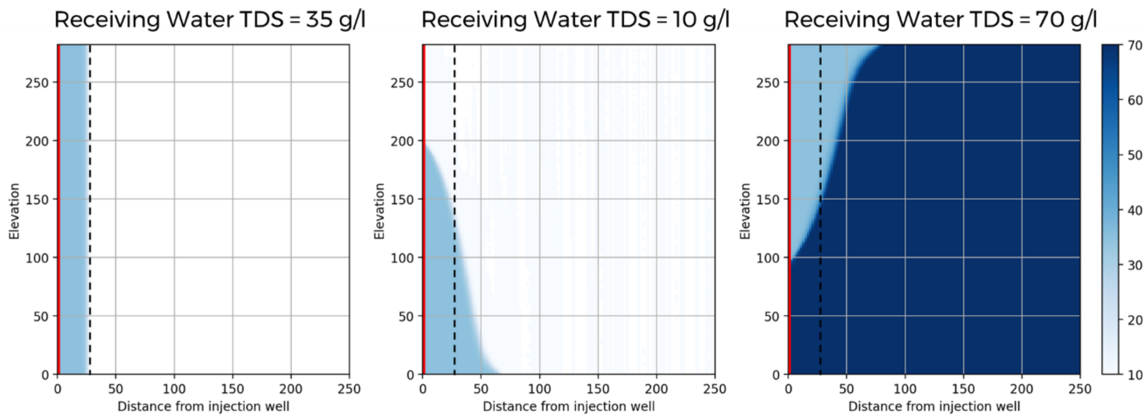

Figure 3-11: **Results showing the effects of variable density flow and transport for a fully penetrating well. The dashed black line shows the analytical solution of Bear and Jacobs (1965) and shaded area represents the results from the numerical model. Water salinity concentrations shown in g/L where 1 g/L = 1,000 mg/L.**

The results for the partially penetrating well are shown in Figure 3-12. Again, the solution obtained using the analytical solution of Bear and Jacobs (1965) is also presented to compare with the numerical variable density solution. In the case of partially penetrating wells, the results from the analytical solution show a more extensive spread than simulating with the numerical solution. The reason for the more extensive spread is that for the analytical solution, only the screened interval is used as the aquifer thickness to assess the injectate migration. In the case of the numerical solution, the horizontal spread is limited because of the vertical spreading of the injectate due to isotropic conditions assumed in the model. The analytical model results show a more conservative (larger) estimate of the spread of injectate in the case of partially-penetrating Class II injection wells.

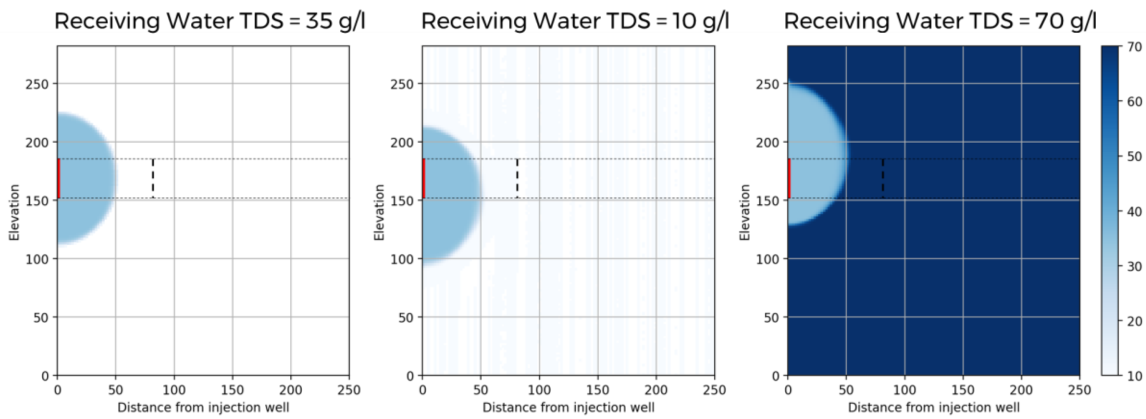

Figure 3-12: **Results showing the effects of variable density flow and transport for a partially penetrating well. The dashed black line shows the analytical solution of Bear and Jacobs (1965) and shaded area represents the results from the numerical model. Water salinity concentrations shown in g/L where 1 g/L = 1,000 mg/L.**

3.5.5 Limitations

The tiered analysis presented in this work has several limitations. The major limitations are summarized below.

- The tool is expected to be general, incorporating certain simplifying assumptions and will not accommodate site-specific details, local well injection effects, other boundary flows, the presence of faults and fractures, formation stratigraphic details, complex hydrogeologic heterogeneities, or physio-chemical processes that can affect the injectate migration.

- The tool ignores contrasts between the injectate and ambient fluid density. Possible sinking of plume into lower formation is ignored. This tool should not be used to assess the fate and transport of brines and possible migration into deeper formations.

- The tool cannot simulate the migration into other aquifer formations. Vertical separation of injected water head within the aquifer cannot be simulated – anisotropy can potentially play an important role in real-world scenarios if continuous clay units are present within the interval across which an injection well is open.

Some of the limitations listed above are also a function of data availability. For example, site specific complex analysis may not be supported by the information available at all injection well sites. Also, even if detailed data are available at specific locations, given the scale of this project, it is impractical to consider site-specific conditions for the tiered analysis presented here.

3.5.6 Communication with Schlumberger software team

A meeting with the Schlumberger Software Team was organized by TWDB staff. The Schlumberger Team provided their insights into the modeling approach typically used for developing and calibrating site-specific models. They acknowledged that such site-specific analyses are not practical given the scale of the modeling efforts considered in this study. The Schlumberger Team agreed with the general approach proposed in this work that was shared with them during the meeting.

3.6 Final Tools and Workflow

Final tool development was conducted based on feedback from TWDB staff and the workgroup during the case study discussed in the next section. The final automated workflow for the injectate mapping process is described in Figure 3-13 below:

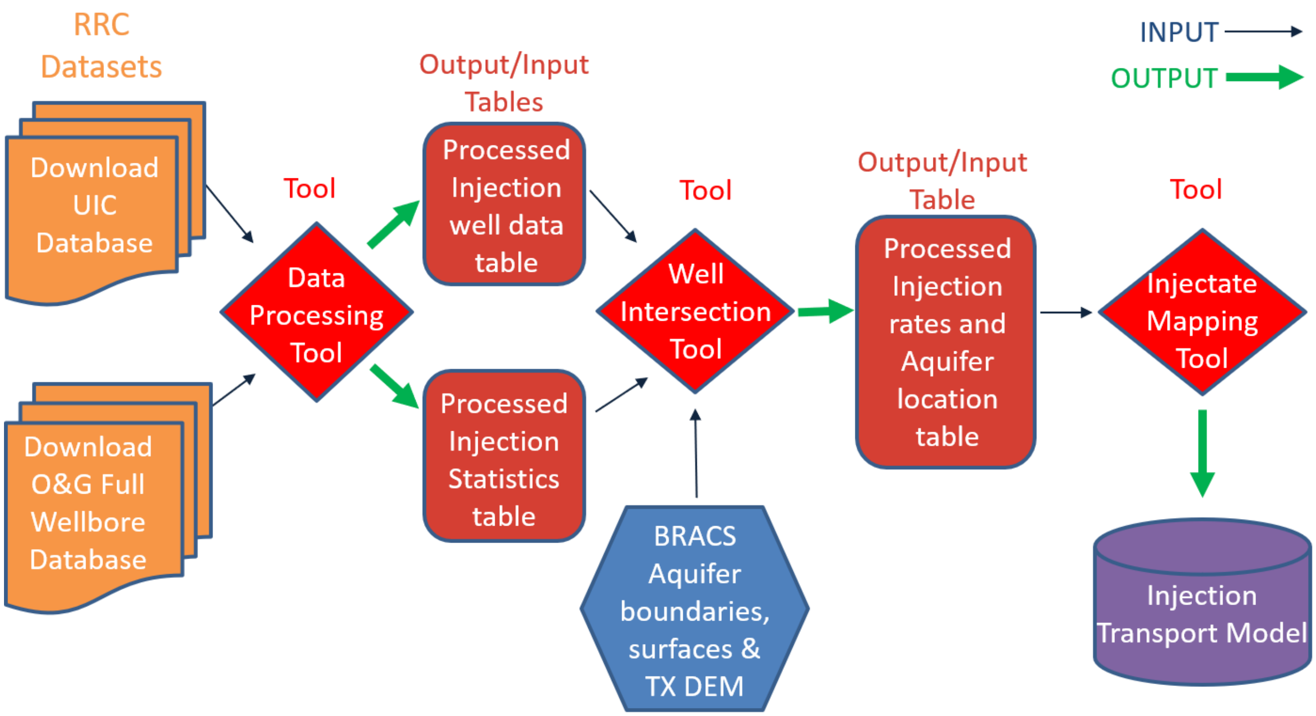

Figure 3-13: Final workflow for the injectate mapping processes and tools

More details on these tools are available in the appendices. Appendices B and C describe the underlying methods for processing the RRC databases and for conducting the injection well intersection analyses, respectively. Appendix D contains the user manual for the automated online RRC data processing and injection well intersection processing tools (FME tools). Appendix E presents the user manual for the online injectate mapping tool.

3.7 Case Study (Northern Trinity Aquifer)

The final tools are developed iteratively process with various features added and modified during the case study and final QA/QC of the online tools. The case study is conducted to estimate injectate mapping for Class II injection wells in the Northern Trinity Aquifer. TWDB staff selected the aquifer based on the available BRACS study and the adequacy of the availability of other required datasets assessed in Chapter 2. The project team conducted the case study, and the TWDB staff repeated it to check the results in an iterative process to evaluate the features and repeatability of the process. Another goal of this process is to ascertain that the automated online tools accurately simulated the manual workflows and methodologies developed during the study. The project team held a workshop to demonstrate the application of the methodologies and online tools developed during the project. Results of the case study were presented to the workgroup assembled by TWDB staff.

Figure 3-14 below provides results from the case study for the Northern Trinity Aquifer. During the case study, a total of 81 Class II injection wells are found to be potentially intersecting the mapped brackish areas of the aquifer based on the data available from the RRC databases and the BRACS study completed for the aquifer. 59 of the 81 Class II injection wells are designated as saltwater disposal wells, and the rest (22) are designated as enhanced oil recovery wells. It should be noted here that enhanced oil recovery wells are flagged by the online tools. TWDB staff can then decide on including or excluding these enhanced oil recovery wells during the injectate mapping process. The project team and TWDB staff used the manual workflows as well as the online (FME) tools to conduct the case study. The underlying assumptions and methodologies for the online tools were updated till both processes yielded the same result. Parameters specific to the injection wells and the aquifer are obtained using the methods described in Chapter 2, and input files prepared for the online injectate mapping tool. The injectate mapping results are provided in Figure 3-14, with the largest injectate migration radius being approximately 1.5 miles (compared to the default 15 miles) for a 50-year period.

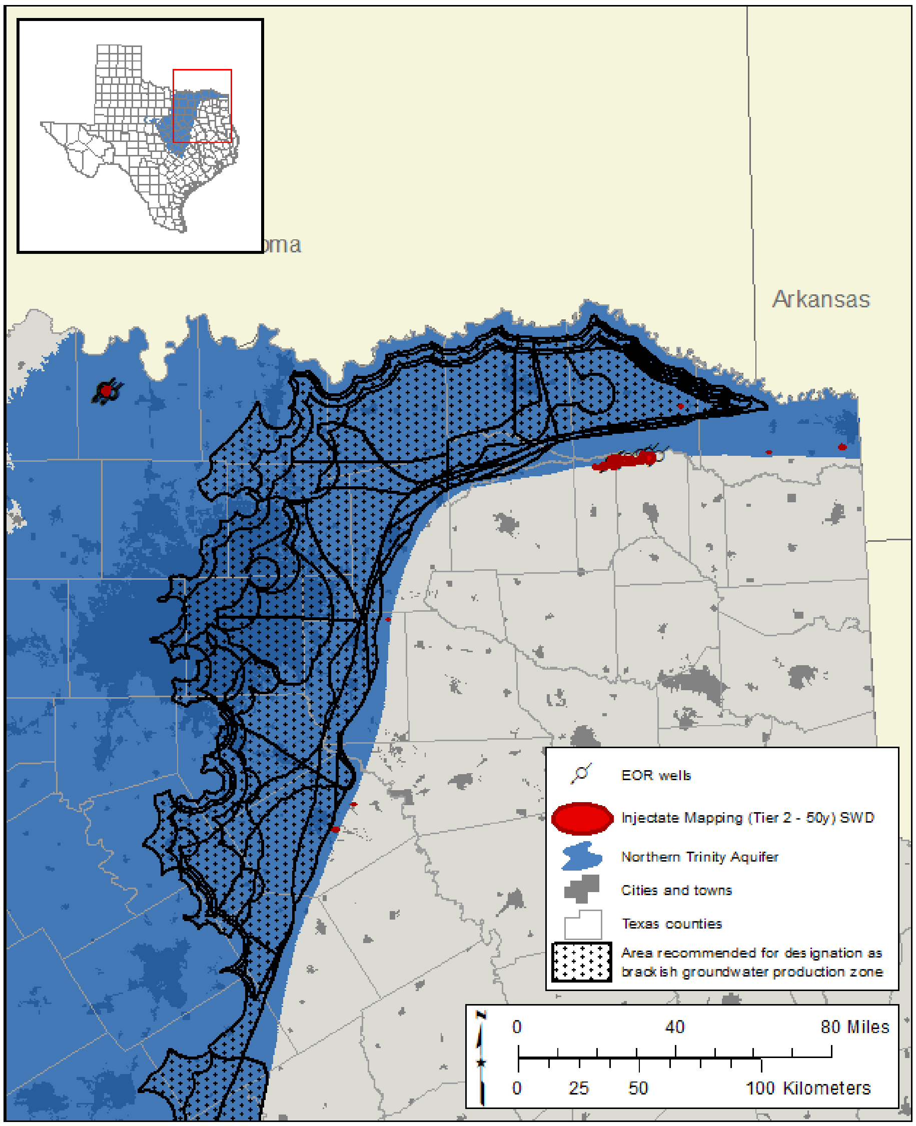

Figure 3-14: Results from the case study conducted for the Northern Trinity Aquifer.

3.8 Case Test (Nacatoch Aquifer)

Further testing conducted by the TWDB staff, in conjunction with the project team, on the Nacatoch Aquifer, yielded the results presented in Figure 3-15. TWDB had contracted a BRACS study which was completed in 2017 (Laughlin and Others, 2017). Assuming a 15-mile extension to the study area, a 2019 analysis conducted by TWDB (Croskrey and Others, 2019) suggested that there were potentially 532 Class II injection wells intersecting the brackish portion of the Nacatoch aquifer. TWDB staff applied a 15-mile default buffer to all but three of these identified Class II wells since those three wells were designated for liquid petroleum gas use. Results from the application of the tools developed during this study identified potentially 425 Class II wells intersecting the brackish portions of the aquifer. For comparative purposes, the 2019 study estimated 84 saltwater disposal wells and 441 enhanced oil recovery wells, whereas the results from the Nacatoch case test estimated 60 saltwater disposal wells and 375 enhanced oil recovery wells. Results from the injectate mapping tool indicated a maximum injectate migration radius of 6 miles (compared to the default 15 miles).

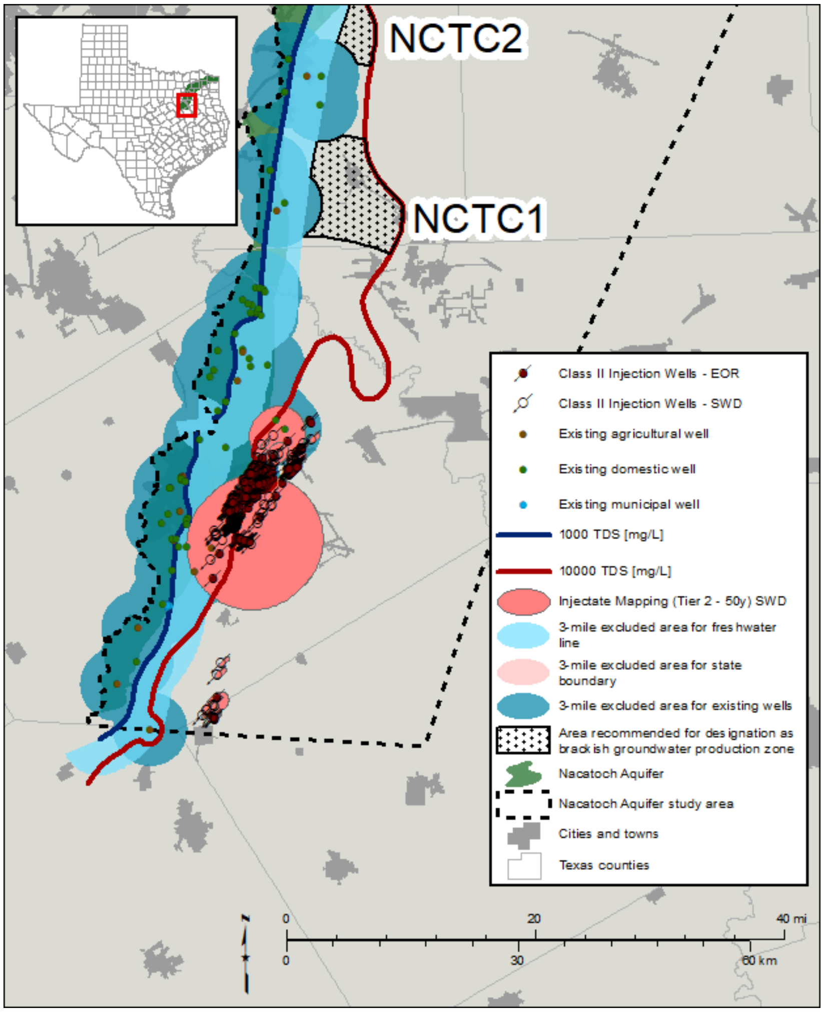

Figure 3-15: Results from the case test conducted for the Nacatoch Aquifer.

3.9 Recommendations for Using the Online Injectate Mapping Tool

The default aquifer parameters described in Chapter 2 have been built into the online injectate mapping tool. However, as discussed earlier, the online injectate mapping tool allows the aquifer parameters to be changed based on different areas of the aquifer being evaluated. The project team developed shapefiles for the various aquifer parameters for all the identified aquifers. These shapefiles can be used as visual aids in estimating the aquifer parameters for specific regions of the aquifers being analyzed in the future, if needed. These shapefiles have been packaged as a geodatabase and delivered along with this project. The description of these shapefiles is available in Appendix F.

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Appendix A: Publications Reviewed During the Study along with Notes, as Applicable

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Appendices A

Publications Reviewed During the Study along with Notes, as Applicable

Regulatory References

1) Environmental Protection Agency (EPA), 2002, Technical Review Program: Underground Injection Control Regulations: Office of Water 4606, EPA 816-R-02-025, revised July 2001, 81p,
https://nepis.epa.gov/Exe/ZyNET.exe/2000E99H.TXT

   - Endangerment of undergroundsources of drinking water (USDW) is the major concern addressed. The EPA identifies 6 possible pathways that must be considered:

     1. Migration of fluids through a faulty injection well casing;
     2. Migration of fluids upward through the annulus located between the casing and the drilled hole);
     3. Migration of fluids from an injection horizon through the confining zone;
     4. Vertical migration of fluids through improperly abandoned or completed wells;
     5. Lateral migration of fluids from within an injection zone into a protected portion of that stratum (aportion that is defined as a USDW); and
     6. Direct injection of fluids into or above an underground source of drinking water.

   - The report refers to appropriate federal regulations (e.g., 40CFR, RCRA, etc.) with Appendix A listingreferences.

   - Appendix C defines underground injection control program well classes (I through V) with examples.Appendix D describes common Class II fluids.

   - Table 1 and Appendix E present Federal regulatory requirements for the various well classes. Appendix Eestablishes minimum permitting requirements (conditions for operation, monitoring, and reporting) for Class I, II, and III wells.

2) Environmental Protection Agency (EPA), 2002, Technical Review Program: Underground Injection Control Regulations: Office of Water 4606, EPA 816-R-02-025, revised July 2001, 81p, https://nepis.epa.gov/Exe/ZyNET.exe/2000E99H.TXT

This report provides basic background information for the WSP project. Endangerment of underground sources of drinking water (USDW) is the major concern addressed. The EPA identifies 6 possible pathways that must be considered:

1. Migration of fluids through a faulty injection well casing;
2. Migration of fluids upward through the annulus located between the casing and the drilled hole);
3. Migration of fluids from an injection horizon through the confining zone;
4. Vertical migration of fluids through improperly abandoned or completed wells;
5. Lateral migration of fluids from within an injection zone into a protected portion of that stratum (a portion that is defined as a USDW); and
6. Direct injection of fluids into or above an underground source of drinking water.

The report refers to appropriate federal regulations (e.g., 40CFR, RCRA, etc.) with Appendix A listing references.

Appendix C defines underground injection control program well classes (I through V) with examples.

Appendix D describes common Class II fluids.

Table 1 and Appendix E present Federal regulatory requirements for the various well classes. Appendix E establishes minimum permitting requirements (conditions for operation, monitoring, and reporting) for Class I, II, and III wells.

Note that Appendix B mis defines aquifer as "a 'geological "formation,' group of formations, or part of a formation that can yield a **significant** amount of water to a well or spring. This definition omits water quality considerations and what is "significant"? This implies that high transmissivity is the only factor that defines an aquifer. The preferred definition of aquifer (Sharp, 2020) is:

1. Consolidated or unconsolidated (saturated) geologic unit (material, stratum, or formation) or set of connected units that yield water of suitable quality to wells or springs in economically usable amounts; or;
2. A formation, group of formations, or part of a formation that yield water of suitable quality to wells or springs in economically usable amounts."

Reference: Sharp, J.M., Jr., 2020, A Glossary of Hydrogeological Terms: Department of Geological Sciences, The University of Texas, Austin, Texas, 107p. EPA, 2004, Understanding the Safe Water Drinking Act: *https://www.epa.gov/sites/production/files/2015-04/documents/epa816f04030.pdf*

This an EPA document/brochure outlining the Safe Drinking Water Act (SDWA) from 1974-2004. The document presents different types of water systems, how the law authorizes the EPA to set national drinking water standards to protect drinking water, amendments to the law over the years, and roles and responsibilities of SDWA.

The document also mentions that the SDWA sets framework for the Underground Injection Control (UIC) program to control the injection of wastes into groundwater. US EPA and states implement the UIC program which sets standards for safe waste injection practices.

3) EPA, 2006, Drinking Water Treatment Residual (DWTR) Injection Wells Technical Recommendations: https://www.epa.gov/sites/production/files/2015-08/documents/dwtr_final_report_01-19-07.pdf

Discusses the use of wells, including Class II wells for waste injection, but noted that existing regulations do not allow the use of non-EOR Class II wells for the injection of DWTR.

4) EPA, 2016, Underground Injection Control Well Classes, https://www.epa.gov/uic/underground-injection-control-well-classes

This is very basic reference and one of the keys for the WSP study. The document defines 6 classes of wells.

- **Class I –** wells used to inject hazardous and non-hazardous wastes into deep, isolated rock formations, typically drilled thousands of feet below the lowermost underground source of drinking water (USDW).

- ***Class II** - wells used exclusively to inject fluids associated with oil and natural gas production and are a target of the WSP project.* Class II fluids are primarily brines (salt water) that are brought to the surface while producing oil and gas. 80 % of these are wells used for enhanced hydrocarbon recovery; 20% are disposal wells. There are numerous Class II wells in Texas and over 30,000 in the USA (Ellsworth, 2013). Hincks et al. (2018) state that there are over 10,000 in Oklahoma alone.

- ***Class III** - wells used to inject fluids to dissolve and extract minerals (uranium, salt, copper, sulfur).*

- ***Class IV** - wells are shallow wells used to inject hazardous or radioactive wastes into or above a geologic formation that contains a USDW.* These wells may only operate as part of an EPA- or state-authorized groundwater clean-up action. Less than 32 waste clean-up sites with Class IV wells exist in the United States.

- ***Class V** - wells used to inject non-hazardous fluids underground. Most Class V wells are used to dispose of wastes into or above underground sources of drinking water. If a Class V well receives hazardous waste, it becomes a Class IV well.*

- ***Class VI** - wells used for injection of carbon dioxide (CO_2) into underground subsurface rock formations for long-term storage or geologic sequestration of CO_2.*

Note: The EPA website has several links that give considerable details, including regulatory requirements.

Comment: There is no a priori technical reasons why Class II disposal wells could not be considered for disposing of wastewaters and not exclusively for fluids associated with oil and natural gas production.

5) EPA, 2021, Part 144- Underground injection control program: Electronic Code of Federal Regulations, https://www.ecfr.gov/cgi-bin/text-idx?node=pt40.25.146&rgn=div5#se40.25.144

Sets the basic framework for the program. Many portions are repeated in subsequent portions of the regulation.

6) EPA, 2021, Part 146 - Underground injection control program: criteria and standards: Electronic Code of Federal Regulations, Safe Drinking Water Act, 42 U.S.C. 300f *et seq.;* Resource Conservation and Recovery Act, 42 U.S.C. 6901 *et seq.*SOURCE: 45 FR 42500, June 24, 1980[accessed January 2021], https://www.ecfr.gov/cgi-bin/text-idx?node=pt40.25.146&rgn=div5#se40.25.146_15

Subpart A- General Provisions - 146.3 Definitions; 146.4 Criteria for exempted aquifers; 146.5 Classification of injected wells; 146.6 Area of review; 146.7 Corrective action; 146.8 Mechanical integrity; 146.9 Criteria for establishing permitting priorities; 146.10 Plugging and abandoning Class I, II, III, IV, and V wells..

Subpart C—Criteria and Standards Applicable to Class II Wells - 146.22 Construction requirements; 146.23 Operating, monitoring, and reporting requirements; 146.24 Information to be considered by the Director.

Note: 146.6 established criteria for the zone of endangering influence of an injection well.

7) Railroad Commission of Texas, 2020, Injection/Disposal Well Permitting, Testing, and Monitoring Manual, https://www.rrc.state.tx.us/oil-gas/publications-and-notices/manuals/injectiondisposal-well-manual/

The manual outlines basic compliance and reporting requirements for oil and gas operators engaged in underground injection operations.

Chapter iii gives the permitting process for all Class II wells. It is stated that "The authorized injection or disposal strata must be isolated from overlying usable quality water by a sufficient thickness of relatively impermeable strata, which is generally considered to be an accumulative total of at least 250 feet of clay or shale." Note there is nothing about horizontal (intrastratal) variations.

8) Railroad Commission of Texas, 2020, Water Use in Association with Oil and Gas Activities: https://www.rrc.texas.gov/about-us/resourcecenter/faqs/oil-gas-faqs/faq-water-use-in-association-with-oil-and-gas-activities/

This is a retrieved webpage from the Railroad Commission of Texas' (RRC) website that lists ten frequently asked questions and answers related to the water use in association with oil and gas activities. The webpage discusses the jurisdiction of RRC, the quantity, quality, and sources of water for the operations of oil and gas industry, and regulations and the role of various regulatory bodies that manage the use of water in Texas. Among other things, the Texas Department of Licensing and Regulation (TDLR) regulates drilled water wells and requires drillers to submit drilling logs and other required information to the TDLR and the Texas Commission on Environmental Quality (TCEQ). A RRC drilling permit is required to drill an injection water source well that penetrates the base of usable quality water.

There is no specific discussion regarding Class II injection wells.
https://www.rrc.state.tx.us/oil-gas/publications-and-notices/manuals/injectiondisposal-well-manual/chapter-iii/

9) Texas Commission on Environmental Quality, 2021, Injection Wells Regulated by the Railroad Commission of Texas:
https://www.tceq.texas.gov/permitting/radmat/uic_permits/RRCT_wells.html

This introduces the types of injection wells and their regulation by the TCEQ and the RRC. Class II wells are regulated specifically for:

1. injecting waste arising out, of or incidental to, drilling for or production of oil and gas.
2. injecting waste arising out of, or incidental to, the underground storage of hydrocarbons other than storage in artificial tanks or containers
3. underground storage of hydrocarbons that are liquid at standard temperature and pressure.
4. injecting waste arising out of, or incidental to, the operation of gasoline plants, natural gas processing plants, or pressure-maintenance or repressurizing plants. The injected waste fluid (usually salt water) may be commingled with wastewaters from gas plants, unless those waters are classified as hazardous waste at the time of injection.
5. enhanced recovery (secondary recovery) of oil or natural gas.

Note: Class II wells are not (yet) authorized for injection of desalination residual concentrates. The site also discusses regulation of Class I, III, and V injection wells.

10) Texas Water Code, 1981, Chapter 27, Subchapter C §§ 27.031.

This is the Chapter 27 of the Texas Water Code and is cited as the Injection Well Act. This chapter deals with injection wells in the state of Texas and the purpose of this chapter is "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, to prevent underground injection that may pollute fresh water, and to require the use of all reasonable methods to implement this policy."

11) Texas Water Development Board, 2014, Manual for Permitting Process

http://www.twdb.texas.gov/publications/reports/contracted_reports/doc/1004831106injectionwells.pdf

This is a manual for the permitting process of Class I and Class II wells. The manual focuses on the disposal of non-hazardous desalination concentrate and drinking water treatment residual (DWTR) using existing Class II wells. The manual provides the following relevant information:

Definitions of various classes and types of injection wells including:

- Base of Usable Quality Groundwater (BUQW) – lowest formation with TDS concentration <3,000 mg/l Brackish water: 1,000 to 10,000 mg/l
- Underground Source of Drinking Water (USDW) – any aquifer with <10,000 mg/l TDS concentration
- A detailed discussion on the permitting roadmap for various classes of wells;
- A summary of Class II wells in Texas;
- A case study for the San Antonio Water System (SAWS) brackish groundwater desalination project;
- A copy of House Bill (HB) 2654 that provides the regulatory framework;
- Various detailed maps of Class II wells in Texas; and
- Permitting process and regulatory framework for RRC and TCEQ.
    - One of the permitting requirements is for drillers to provide well information (depth, screens, casing) and regional and local hydrogeology (stratigraphy, aquifer formations, water quality zones), which is relevant information.

General Articles

12) Beach, J.A., Kreitler, C.W., and Klemt, W.B., 2002, Brackish Water Resources of the Gulf Coast Aquifers in Texas [abs.]: Gulf Coast Association of Geological Societies Transactions, v. 52, p. 38.

13) Brown, H. S., Cook, B. J., Krueger, R., Shatkin, J. A., 1997, Reassessing the History of U.S. Hazardous Waste Disposal Policy – Problem Definition, Expert Knowledge and Agenda-Setting: RISK: Health, Safety & Environment, v. 8, p. 249 – 272 https://scholars.unh.edu/cgi/viewcontent.cgi?article=1332&context=risk

This study examines the history and evolution of US hazardous waste disposal science and policy at the state and local level beginning in the 1940s over several decades leading up to the development of national level policies in the form of RCRA in 1976 and CERCLA in 1980. The paper also discusses the role of various organizations in the policy development process.

14) Collier, H.A., 1993a, Borehole geophysical techniques for determining the water quality and reservoir parameters of fresh and saline water aquifers in Texas, Volume I: Texas Water Development Board, Report 343, 414p., 1 Appendix, 5 plates, http://www.twdb.texas.gov/publications/reports/numbered_reports/doc/r343/r343vol1_1.pdf

15) Collier, H.A., 1993b, Borehole geophysical techniques for determining the water quality and reservoir parameters of fresh and saline water aquifers in Texas, Volume II: Texas Water Development Board, Report 343, 216p.

These 2 volumes, in 4) and 5) above, discuss geophysical techniques that can be used for characterizing brackish water resources.

16) Aksoy, Niyazi & Serpen, Umran & Filiz, Şevki. (2008). Management of the Balcova–Narlidere geothermal reservoir, Turkey. Geothermics. 37. 444-466. 10.1016/j.geothermics.2007.12.003.

1. Injection will not be used in areas where seismic activity could potentially occur.
2. Injected waste fluids must be compatible with the mechanical components of the injection well system and the natural formation water.
3. High concentrations of suspended solids (typically >2 ppm) can lead to plugging of the injection interval.
4. Corrosive media may react with the injection well components, with injection zone formation, or with confining strata with very undesirable results.
5. High iron concentrations may result in fouling when conditions alter the valence state and convert soluble to insoluble species.
6. Organic carbon may serve as an energy source for indigenous or injected bacteria resulting in rapid population growth and subsequent fouling.
7. Waste streams containing organic contaminants above their solubility limits may require pretreatment before injection into a well.
8. Site assessment and aquifer characterization are required to determine suitability of site for wastewater injection.
9. Extensive assessments must be completed prior to receiving approval from regulatory authority.

17) Ellsworth, 2013, Injection-induced Earthquakes: Science, v. 342 https://science.sciencemag.org/content/341/6142/1225942

This paper is an excellent introduction/review of injection-induced earthquakes. Figures 1 and 2 show seismicity the USA and in the "stable" central and eastern USA, respectively. Humaninduced earthquakes can be caused by surface loading (e.g., impoundments), mining, and by either fluid withdrawals or injection. There are a few cases of quakes with magnitude (M) > 5. Larger faults can host larger magnitude quakes and that hydraulic connection between the injection zone and faults in the (crystalline) basement is an important factor (also found by Hincks et al., 2018, in Oklahoma).

The paper discusses 3 well documented case histories (Rocky Mountain Arsenal, Rangely oil field, and Paradox Valley), which confirm the theory of how increasing fluid pressures by injection cause earthquakes.

It is noted that consideration of the "diffusion" of pressure into underling faults is **not** considered in US regulations and suggests in addition to fracture pressure (not to be exceeded), monthly injection volume, and average injection pressure, monitoring should include:

1. Initial stress state and pore pressure.
2. Tracking injection history,
3. Careful seismic monitoring, which includes lowering the magnitude -detection threshold in regions of injection to M<2.

There are also a few points relevant to the project. These are:

1. Seismic activity has been related to reservoir depressurization or over pumping aquifers. However, these have been less frequent and generally lower in magnitude than those caused by fluid injection.2) Earthquakes induced by fluid injection are generally small and even the "largest fracking induced earthquakes have all been below the damage threshold for modern building codes."
2. The majority of Class II injection wells appear to be aseismic.
3. The largest seismic events (M>3) have occurred along faults deeper than the injection intervals.
4. This diffusion of pressure into basement faults is not considered in Class II wells federal regulations, which stress protection of overlying aquifers.
5. The author suggests lowering the "magnitude-detection threshold for injection wells to areas with M < 2, would "certainly help."

Finally, it is noted that regulations have stressed protection of overlying aquifers from deeper wastewater injection and, generally ignored not deeper seismic activity.

Earthquake potential exists within stable continental interior because shear stress levels within plate interiors is commonly near the strength limit of the crust so that small perturbations can trigger seismic events.

Although rare higher magnitude examples (M>5) have been cited, note that:

The fact that the great majority of UIC Class II injection wells in the United States appear to be aseismic, at least for earthquakes of M>3, suggests that ambient conditions for geologic formations commonly approved for disposal are far enough removed from failure that injection can be done at low risk, provided that the pressure perturbation remains confined within the intended formation.

18) Elsawah, S., Pierce, S.A., Hamilton, S.H., van Delden, H., Haase, D., Elmahdi, A., & Jakeman,

19) A.J., 2017, An overview of the system dynamics processes in the context of integrated modelling and environmental decision making for integrated modelling of socio-ecological systems: Lessons on good modelling practice from five case studies: Environmental Modelling and Software, v. 93, p. 127–145, https://doi.org/10.1016/j.envsoft.2017.03.001

Use of system dynamics to contribute to system understanding and decision making depending upon the practices applied by the modeler.

20) EPA, 2001, Class I Underground Injection Control Program: Study of Risks Associated with Class I Underground Injection Wells: EPA 816-R-01-007, https://www.epa.gov/sites/production/files/2015-07/documents/study_uic-class1_study_risks_class1.pdf

Review of risks and causes of failure for Class I wells.

21) EPA, 2006, Drinking Water Treatment Residual Injection Wells Technical Recommendations, 72p., https://www.epa.gov/sites/production/files/2015-08/documents/dwtr_final_report_01-19-07.pdf

*The paper sets the basic background and suggestions for EPA policy on disposa*l wells for drinking water treatment residuals (DWTR) from desalination, specifically reverse osmosis.

Note: the paper states that, "Class II-D wells could be dually permitted with either an additional Class I or Class V permit to enable the disposal DWTR. Class II-D permit/authorization wells cannot accept DWTR wastes without dual permitting (see UIC Program Guidance #24 for additional information)."

22) EPA, 2014, Minimizing and Managing Potential Impacts of Injection-induced Seismicity from Class II Disposal Wells: Practical Approaches, Underground Injection Control National Technical Workgroup U.S. Environmental Protection Agency Washington, DC, 415p, https://www.kdheks.gov/geo/download/NTW_Report_2014.pdf

Extensive review of seismicity induced by Class II well injections and mitigation/prevention measures.

23) EPA, 2021, Class I Industrial and Municipal Waste Disposal Wells, [accessed January 2021], https://www.epa.gov/uic/class-i-industrial-and-municipal-waste-disposal-wells

Class I wells inject hazardous and non-hazardous wastes into confined rock formations, typically thousands of feet below the lowermost underground source of drinking water (USDW). Approximately 800 operational Class I wells exist in the USA. Class I wells inject fluids from petroleum refining; metal, chemical, food, and pharmaceutical production; commercial disposal; and municipal wastewater treatment. Based upon the characteristics of the fluids injected, Class I wells fall into one of four subcategories:

1. *Hazardous waste disposal wells*
2. *Non-hazardous industrial waste disposal wells*
3. *Municipal wastewater disposal wells*
4. *Radioactive waste disposal wells*

24) EPA, 2021, Class II Oil and Gas Related Injection Wells [accessed January 2021], https://www.epa.gov/uic/class-i-industrial-and-municipal-waste-disposal-wells

Class II wells are used only to inject fluids associated with oil and natural gas production. The fluids are primarily brines or saline waters that are brought to the surface while producing oil and gas. Over 2 billion gallons of fluids are injected in the USA daily, primarily in Texas, California, Oklahoma, and Kansas.

25) EPA, 2021, Class V Wells for Injection of Non-Hazardous Fluids into or Above Underground Sources of Drinking Water, [accessed January 2021], https://www.epa.gov/uic/class-v-wells-injection-non-hazardous-fluids-or-above-underground-sources-drinking-water

EPA estimates that there are > 650,00 Class V wells in the USA are in operation mostly for stormwater drainage, septic system leach fields, and agricultural drainage. Complex Class V well types include those for aquifer storage and recovery (ASR), geothermal energy, and experimental wells used for pilot geologic sequestration.

26) Ericson, J., 1965,*The stability and mixing of a density-stratified horizontal flow in a saturated porous medium:* unpub. PhD dissertation, California Institute of Technology, Pasadena, https://resolver.caltech.edu/CaltechETD:etd-09302002-124434

This dissertation models how fluid density affects flows in horizontal strata.

27) Frohlich, C., 2012, Two-year survey comparing earthquake activity and injection-well locations in the Barnett Shale, Texas: PNAS, v. 109, p. 13934 – 13938, https://www.pnas.org/content/109/35/13934

The study focuses on a two-year survey over a 70-km grid covering the Barnette Shale in Texas. The survey recorded regional earthquakes and correlated to the spatial location of injection wells. Earthquakes were recorded near wells with high injection rates but not all high-injection wells resulted in earthquakes. The study concluded that there was correlation between injection rates and earthquakes and also hypothesized that the earthquakes are triggered when injected fluids reached formations that are conducive to regional tectonic stresses that could lead to earthquakes.

28) Frohlich, C., Brunt, M., 2013, Two-year survey of earthquakes and injection/production wells in the Eagle Ford Shale, Texas, prior to the M_W4.8 20 October 2011 earthquake: Earth and Planetary Science Letters, v. 379, p. 56-63, https://www.sciencedirect.com/science/article/pii/S0012821X13004007

This is 2-year (November 2009 to September 2011) survey of earthquakes in the Eagle Ford Shale play. Using seismic station data, they identified 62 probable earthquakes that occurred at 14 foci. 8 of these were near wells that recently increased extracting fluids (oil or water); 2 were near wells that recently increased injection of water; and 4 were not sited close to wells with recent increase of extraction or injection of fluids. There were also seismic events attributed to blasting at rock quarries. The study concentrated on the Fasching and Dimmit County areas. The Fasching area hosted the largest reported quake in south-central Texas (M = 4.8) on 20 October 2011.

The "principal result" of the study is that ~90% of the quakes occurred near active production or injection wells. Of these 85%occurred near wells where injection or extraction had significantly increased in the previous 12 months.

The authors contrast these results with those for the Barnett Shale in the Fort Worth Basin. Here the earthquakes are more strongly associated with injection wells. They speculate that in the Fort Worth Basin production from the Barnett took place only since 2003 (and especially since 2008, Hennings et al., 2019), whereas the South-Central Texas, production and injection into other formations, such as the Edwards Group, has been going on for over 60 years.

They recommend the deployment of permanent seismic stations, including some densely instrumented networks in selected areas.

29) Hamlin, H.S. and de la Rocha, L., 2015, Using electric logs to estimate groundwater salinity and map brackish groundwater resources in the Carrizo-Wilcox Aquifer in south Texas: Gulf Coast Association of Geological Societies Transactions, v. 65, p. 625-626.
Geophysical methods that map brackish groundwater.

30) Hennings, P. H., Snee, J. L., Osmond, J. L., DeShon, H. R., Dommisse, R., Horne, E., Lemons, C., Zoback, M. D., 2019, Injection-Induced Seismicity and Fault-Slip Potential in the Fort Worth Basin, Texas: Bulletin of the Seismological Society of America, v. 109, p. 1615 – 1634, https://pubs.geoscienceworld.org/ssa/bssa/article-abstract/109/5/1615/572191/Injection-Induced- Seismicity-and-Fault-Slip?redirectedFrom=fulltext

This study focusses on identification of faults in the Fort Worth Basin (FWBB) and injection-induced seismicity associated with the development of the Mississippian Barnett Shale petroleum resources. Most disposal wells inject into the Ordovician Ellenburger Group. The authors state the seismicity is strongly linked to faults in the Precambrian crystalline bedrock as shown on their Figure 2, section (a)-A' through the center of the basin.

Injection-Induced Seismicity and Fault-Slip Potential in the Fort Worth Basin, Texas 3

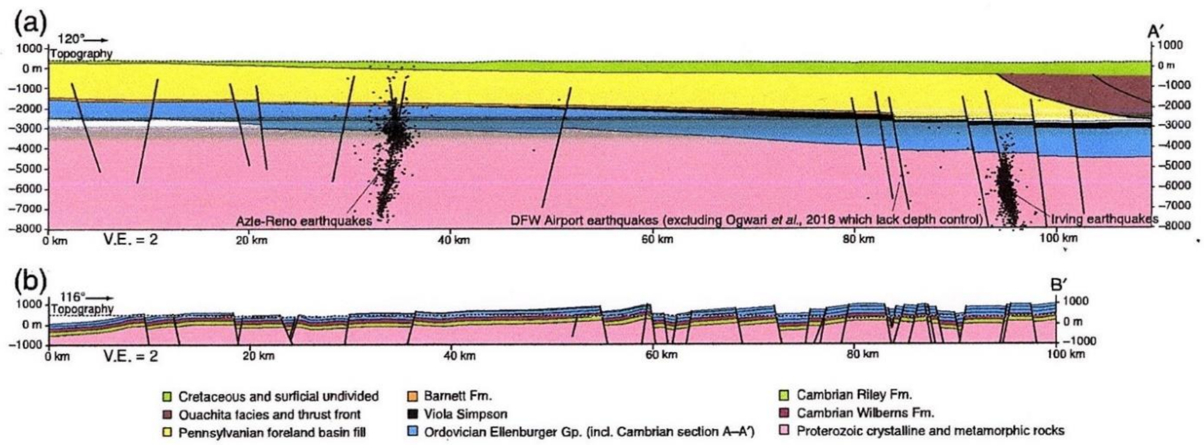

Figure 2. Cross-section traces (a) A–A′ (though the center of the basin) and (b) B–B′ (through the outcropping domain) illustrate the general structural style and spatial variability of basement-rooted normal faults. Cross section A–A′ shows recent earthquakes projected into the line of section from nearby sequences (Fig. 1). V.E., vertical exaggeration.

The study used seismic geophysics and mapping to find more faults than had previously been mapped. Over 251 faults striking generally NNE were identified. Their fault-slip potential values indicate that modest increases in pore pressure (1 MPa or 145 psi). They also found that the mist recent FWB quakes occurred on faults less than 8 km in length.

31) Hincks, T., Aspinall, W., Cooke, C., Gernon, T., 2018, Oklahoma's induced seismicity strongly linked to wastewater injection depth: Science, v. 359, p. 1251 – 1255, https://www.researchgate.net/publication/322880364

This paper evaluates the significant increase in Oklahoma's seismic activity since 2009 using a Bayesian network numerical model. They found that these earthquakes are not caused by fracking per se but by injection of wastewater at depth. No mention was made of seismic activity related to fluid withdrawal. Furthermore, the closeness the injection depth to the crystalline rock bedrock strongly correlated with the larger events. They also correlated seismic activity with the total and annual volumes of injected wastewater.. The largest earthquakes (one near Pawnee, OK, in 2016 had a 5.8 magnitude) are near high volume injection wells close to the basement.

They report that there were > 10,000 Class II wells in OK the inject > 2.3 x 10^9 barrels of fluid for both EOR and saltwater disposal.

The authors suggest restricting injection depths to 200 -500 m or more above the crystalline bedrock.

They note the importance of understanding the local geological system.

32) LBG-Guyton Associates, 2003, Brackish Groundwater Manual for Texas Regional Water Planning Groups: Report to the TDWB, 188p., https://www.twdb.texas.gov/publications/reports/contracted_reports/doc/2001483395.pdf

An extensive general review of potential for and costs of using brackish waters and the brackish water resources in Texas.

33) Lemons, C., McDaid, G., Smye, K., Acevedo, J., Hennings, P., Scanlon, B., Banerji, A.,2019, Spatiotemporal and Stratigraphic Trends in Saltwater Disposal Practices of the Permian Basin, Texas and New Mexico, U.S.: AAPG Environmental Geosciences, v. 26, p. 107– 124, https://www.beg.utexas.edu/files/texnetcisr/pubs/LemonsEtAl_2019_PermianSWD_EnvGeosc.pdf

This paper reviews the history of salt-water disposal in the Permian Basin of Texas and New Mexico with estimates of disposal volumes by formation and by basin subregions as shown on their Fig.1. It is noted that Texas RRC classifies 2 types of Class II (salt-water disposal or SWD) wells: RRC 1 wells inject into zones that do not produce oil & gas; RRC 2 wells inject into a zone that does produce oil and gas. There are over 8,200 SWD wells in the basin.

The paper lists RRC permit values for Class II wells:

1. Maximum wellhead injection pressure - in Texas this must be < 0.5 psi/ft, except for one unit in the Delaware Basin (< 0.25 psi/ft.);
2. Top and bottom depths of injection interval;
3. Packer depth; but may also include:
4. Formation name;
5. Permitted fluids; and
6. Casing integrity test frequency.

It is noted that the highest number of earthquakes in Texas is near the City of Pecos, but there is little discussion of basin seismicity.

Permian Guadalupian units receive the most salt water, but that operators are looking at the underlying Ordovician Ellenburger, which is closer to the Precambrian basement.

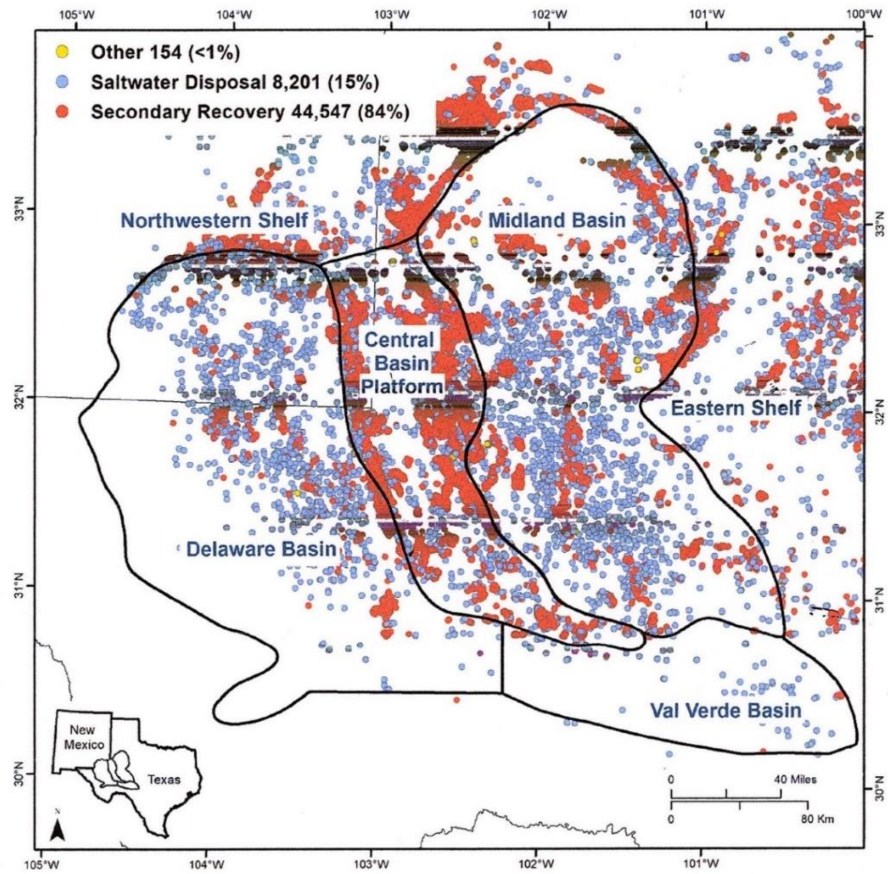

Figure 1. The Permian study has six subregions of focus, with class II wells in the Permian Region actively injecting water any time from 1978–2016. Wells are mapped according to their surface hole location. If a well was active as more than one Underground Injection Control (UIC) class II type, the well is mapped twice. Permits were extracted from the New Mexico Oil Conservation Division and Railroad Commission of Texas websites and are classified by the UIC class II permit types. New Mexico injection wells are combined with Texas secondary recovery wells and are shown in orange.

34) Hovorka et al. 2014, Expert-based development of a standard in CO2 sequestration monitoring technology: Gulf Coast Carbon Center (GCCC) Digital Publication Series #14-07, https://cfpub.epa.gov/ncer_abstracts/index.cfm/fuseaction/display.abstractDetail/abstract/9056

CO_2 sequestration has been proposed as a mechanism to control greenhouse gases. The effectiveness of the sequestration requires monitoring that ensures:

1. the site characterization on which sequestration permits were granted is correct; &
2. CO_2 injection operations in Class VI wells are being conducted as planned to assure CO_2 /

The same rationale will apply to wastewater injection in Class II disposal wells, but recognizing the wastewater and CO2 have different properties.

The study:

1) Modeled the sensitivity of selected representative monitoring strategies to the

expected variability of 28 sites;

2) Tested the evaluation against field measurements.

3) Proposed improvements in mechanisms for matching monitoring methods to sites, which it maintains or "builds a consensus" that these are properly applied and adequate; &

4) Compiled a workbook of test cases for training practitioners in applying the strategies to an array of sites.

The study proposes a term, assessment of low probability material impact (ALPMI), to facilitate the discussion of unexpected but possible outcomes that would fail to meet the project goals and recommended that the ALPMI be modeled as a step in the design of a robust monitoring program. It also suggests that monitoring can fill in the "white space" where high magnitude events and longtime scales are not constrained by existing data.

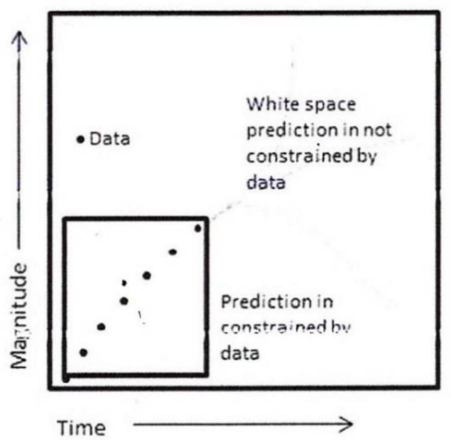

Figure 4. Prediction of system response is well defined where it is constrained by data (solid dots); however, modeling high magnitudes and longer time frames is more conjectural (dotted lines). Monitoring is one method of filling in the "white space" with data.

The paper reviews a number of monitoring methods for deep CO_2 sequestration projects: seismic, gravity, pressure sensing, thermal methods, direct fluid sampling (reservoir chemistry), wireline logging, tilt & surface deformation, and soil gas chemistry. These would have varying degrees of applicability to the BRACS project. There is also an extensive bibliography on CO_2 sequestration.

35) Hutchinson, W.R., 2008, Deep-well injection of desalination concentrate in El Paso, Texas: Southwest Hydrology, March/April issue, 3p., http://www.swhydro.arizona.edu/archive/V7_N2/feature7.pdf

Short review of deep-well injection DWTR fluids at the El Paso desalination plant.

36) Mace, R.E., Nicot, J.P., Chowdhury, A.H., Dutton, A.R., and Kalaswad, S., 2006, Please pass the salt: Using oil fields for the disposal of concentrate from desalination plants: Texas Water Development Board, Report 366, 198 p.,2

https://www.usbr.gov/research/dwpr/reportpdfs/report112.pdf

It is technically feasible to inject concentrate into depleted oil and gas fields, but the concentrate may require pretreatment to prevent clogging of the formations. Concentrate can be so injected only if certain conditions are met (such as more stringent well construction requirements and purpose of injected water). Permitting the injection of concentrate could be made easier through general permitting of a special non-hazardous Class I injection well. It may also be possible to create a special category of Class I or Class V injection well. Figure 1 shows major Texas oil & gas reservoirs; Fig 2 shows brackish water resources; Fig. 3 shows Class II injection well locations; and Fig. 4 shows Texas C counties with water supply needs

37) Maliva, R.G., and Manahan, S., 2013, Desalination Concentrate Disposal Using Injection Wells: Technical Challenges: GWPC UIC Conference Sarasota, Florida (January 22-24, 2013), http://www.gwpc.org/sites/default/files/event-sessions/Manahan_ScottFINAL.pdf

This is a Power Point slide presentation, but it is a good introduction to the challenges of using injection wells. It did not address Class II wells, only Class I and V wells.

1) Concentrate disposal is often the critical factor for desalination project feasibility. 2.
2) Concentrate disposal must be:
    a. Permittable. All required regulatory approvals can be obtained (environmental and water quality issues).
    b. Reliable over desalination system life (20+ years)
    c. Economically viable
3) Key technical issues:
    a. Feasibility and system type depend upon local hydrogeology
    b. Optimization of design and operation
4) Deep high-capacity injection well system characteristics:
    a. Depths => 500 m (1,500 ft)
    b. Capacities => 3,800 m 3/d (1 Mg/d)
    c. One well may dispose of entire concentrate flow
    d. Key technical issues:
        i. Requires high-transmissivity injection zone (uncommon?) to accept concentrate flows.

ii. Upward migration of injected concentrate is retarded by density stratification.

5) Deep high-pressure injection well technical issues:

a. These injection wells are more complicated that other injection and production wells!

b. Low transmissivity media– vulnerability to clogging

c. Geochemical compatibility (scaling) – high TDS and ion concentrations

d. Temperature and salinity viscosity effects

e. Management of pressure – high pressures can induce fracturing and low-level seismicity

f. Optimization of completion (perforated vs. liner or screened; hydraulic fracturing)

g. Improper design or geochemical incompatibility can damage well.

6) Fundamental injection well issues:

a. Location of an injection zone and designing injection well system to provide target disposal rate and volume over life of the plant (20+ years)

b. Avoiding adverse impacts to the environment or groundwater resources from the migration of injected water out of the injection zone

c. Maintaining well performance (management of clogging) - Specific injectivity (injection rate/injection pressure) - O&M (workover/rehabilitation program needs to be effective and affordable)

d. Regulatory issues - Obtaining project approval - Monitoring requirements

7) Technical issues:

a. Management of clogging is the critical injection well system design and operational issue. Additional causes of clogging:

i. Clay mineral dispersion and swelling

ii. Air entrapment

iii. Particle rearrangement

8) Optimization of well design – high efficiency completions are critical.

a. Maximization of screen open area

b. Use of open hole completion

c. Accurate identification of most permeable strata for perforation

d. Proper development – material left in well or near borehole wall will be forced into the formation during injection

9) Injection Well Issues and Opportunities

a. Clogging Management:

i. Characterization of injected fluids and analysis of its compatibility with injection zone water and rock (geochemical modeling) pretreatment (e.g., filtration and chemical adjustments)

ii. Assessment of causes of clogging:

1. Pressure transient testing for formation damage

2. Borehole geophysics

Well rehabilitation (workover) is part of normal operations and maintenance Injection wells typically require more frequent rehabilitation than production wells

The study concludes that injection wells are a valuable tool for the sustainability of desalination by providing an environmentally safe means for concentrate disposal. However, injection well systems require favorable hydrogeologic conditions that may not be locally present. Also, technical challenge is the optimization of design and operation of wells to ensure reliable long-term performance. Projects must be approached with an understanding of their complexity.

38) Maliva, R.G. and Missimer, T.M., 2011, Improved aquifer characterization and the optimization of the design of brackish groundwater desalination systems. Desalination & Water Treatment, v. 31, no. 1-3, p190-196, https://www.tandfonline.com/doi/abs/10.5004/dwt.2011.2357

This paper doesn't address disposal options directly, but instead on the analyses of the source water systems for desalination. It stresses the need for hydrogeological investigations of aquifer characteristics and for well system design. The chief risks (potential negative effects) of brackish water production listed were upcoming of more saline fluids and subsidence.

39) Maliva, R.G. and Shanahan, S. 2013, Desalination Concentrate Disposal Using Injection Wells: Technical Challenges: GWPC UIC Conference Sarasota, Florida, Power Point presentation, http://www.gwpc.org/sites/default/files/event-sessions/Manahan_ScottFINAL.pdf

This is an excellent review, but doesn't consider Class II wells, but rather Class I and Class V wells. It does discuss deep high-pressure injection wells.

40) Mancha, E., and Walker, W.S., 2019, Desalination: Growing Opportunities in Texas: in The Edwards Aquifer – The Past, Present, and Future of a Vital Water Resource (Sharp. J.M., Jr., Green, R.T., and Schindel, G.M., eds.), Geol. Soc. America Memoir 215, Ch. 22, p. 259-265, https://doi.org/10.1130/2019.1215(22)

Recent review of desalination in Texas with special reference to the Edwards Aquifer.

41) Meyer, J.E., 2020, Brackish Resources Aquifer Characterization System Database Data Dictionary: Texas Water Development Board Open File Report 12-02 (5th ed.) https://www.twdb.texas.gov/innovativewater/bracs/doc/TWDB_OpenFileReport_12_02_FifthEdition_BRACSDataDictionary.pdf

The data dictionary supports studies characterizing Texas brackish water resources. It describes primary tables and key fields in the data base and then provide custom tables from completed BRACS studies.

42) Nassar, M.K.K., El-Damak, R.M., and Ghanem, A.H.M., 2008, Impact of desalination plants brine injection wells on coastal aquifers: Environmental Geology, v. 54, p. 445–454, doi: 0.1007/s00254-007-0849-9
https://link.springer.com/article/10.1007/s00254-007-0849-9

The paper states that brine disposal is the main environmental problem in desalination of seawater; brine injection wells may be environmentally sound. It uses SEAWAT as a simulation model. It proposes scenarios for brine injection based upon relative salt concentrations, production and injection rates, well spacings, and time.

43) Nicot, J.-P., Chowdhury, A.H., and Alan R. Dutton, A.R., 2015, Please Pass the Salt: Using Oil Fields for the Disposal of Concentrate from Desalination Plants: Bureau of Economic Geology, Report for Texas Water Development Board, Contract No. IA 2004-0001-012, 259p., https://www.beg.utexas.edu/files/content/beg/research/water/Report-Final7.pdf

This extensive report examines the potential to inject of desalination residual fluids into depleted oil & gas reservoirs. The report "found no technical drawback to allowing injection of desalination concentrates into depleted oil or gas fields using existing wells."

44) Nielsen-Gammon, J. W., Banner, J. L., Cook, B. I., Tremaine, D. M., Wong, C. I., Mace, R. E., et al., 2020, Unprecedented drought challenges for Texas water resources in a changing climate: What do researchers and stakeholders need to know? Earth's Future, v. 8, e2020EF001552. https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2020EF001552

An analysis of drought factors and s climate projections for Texas. Climate models are found to be robust predictors of 21st century climate.

45) Okandan, E., Gümrah, F., Demiral, B., 2001, Pollution of an aquifer by produced oil field water: Energy Sources, v. 23, no.4, p. 27-36, https://www.tandfonline.com/doi/abs/10.1080/009083101300110878

This is a modeling study based upon injection of oil field saline waters into an aquifer in Turkey.

The results are not startling and follow general hydrogeological principles. The study is not directly applicable to our project as Texas currently does not inject brines into aquifers. Here injecting into units that are brackish or deeper into oil-field reservoirs. However, the same general transport findings would also apply in these units.

The statement "total protection of ground water from waste materials is impossible because of all the flow paths from waster to aquifers, except casing leaks, is beyond reliable control." Implies that the risks of contamination can never be totally eliminated.

46) Pyne, R.D.G., 2005, Aquifer and Storage Recovery (2nd ed.): ASR Press, Gainesville, FL, 608p. Ch 4.3 outlines issues of well plugging & well redevelopment. Although the book is on aquifer storage and recovery (ASR), the basic principles apply to injection of desalination residual concentrates by Class II wells.

47) Railroad Commission of Texas, 2021, Injection and Disposal Welles: https://www.rrc.state.tx.us/about-us/resource-center/faqs/oil-gas-faqs/faq-injection-and-disposal-wells/ [accessed January 2021].

This fact sheet defines Class II wells as disposal or injection wells.

1. Disposal wells - these inject mineralized water produced with oil and gas into the subsurface for the purpose "safely and efficiently disposing of the fluid."

2. Injection wells – these inject fluids into a petroleum reservoir for enhanced oil recovery (EOR) from the reservoir.

The website states that there are 54,700 permitted Class II wells of which ~34,200 were active as of July 2015. 8,100 of the active wells are disposal wells.

48) Railroad Commission of Texas, 2020, Water Use in Association with Oil and Gas Activities: https://www.rrc.texas.gov/about-us/resourcecenter/faqs/oil-gas-faqs/faq-water-use-in-association-with-oil-and-gas-activities/

This is a retrieved webpage from the Railroad Commission's (RRC) website that lists ten frequently asked questions and answers related to the water use in association with oil and gas activities. The webpage discusses the jurisdiction of RRC, the quantity, quality, and sources of water for the operations of oil and gas industry, and regulations and the role of various regulatory bodies that manage the use of water in Texas. Among other things, the Texas Department of Licensing and Regulation (TDLR) regulates drilled water wells and requires drillers to submit drilling logs and other required information to the TDLR and the Texas Commission on Environmental Quality (TCEQ). A RRC drilling permit is required to drill an injection water source well that penetrates the base of usable quality water. There is no specific discussion regarding Class II injection wells.

49) Richter, B.C., and Kreitler, C.W., 1993, Geochemical Techniques for Identifying Sources of Ground-Water Salinization: CRC Press, Boca Raton, FL, Edition 1. https://www.beg.utexas.edu/files/publications/contract-reports/CR1991-Richter-1.pdf

The book was not available for the review purpose, however, another source (BEG) by the same authors and essentially the same title with likely the same information was reviewed. Table of contents of the book were identical to the table of contents of this alternate source and therefore, the alternate source was reviewed.

The book/report examines the various sources of salinization of groundwater. This report reviews geochemical techniques that can be used to identify different sources. Seven major salinization sources identified in this report are:

a. Natural saline groundwater;

b. Halite solution;

c. Seawater intrusion;

d. Oil and gas field brines;

e. Agricultural effluents;

f. Saline seep; and

g. Road salting.

Geographic distribution of these various sources in the US and statistics by each state are also discussed in the report. See tables and figures below. Geochemical characteristic curves are also presented in this report.

Table 3. Mineral composition of salt from domes in Louisiana and Texas (data from Pierce and Rich, 1962).

	Coastal domes, Louisiana				Interior domes, Texas	
	1	2	3	4	5	6
Sodium chloride (NaCl)	92.750	96.405	99.252	95.720	98.883	98.926
Calcium sulfate ($CaSO_4$)		0.694	0.694	3.950	1.099	1.041
Magnesium chloride($MgCl_2$)		0.012	0.012	0.008	Trace	
Magnesium carbonate ($MgCO_3$)	0.201					
Sodium carbonate (Na_2CO_3)	0.067					
Sodium sulfate (Na_2SO_4)	0.837				0.008	0.023
Calcium carbonate ($CaCO_3$)	1.804				0.010	0.100
Calcium chloride ($CaCl_2$)	0.000	0.226	0.042	0.140		
Iron and aluminum oxide (Fe_2O_3-Al_2O_3)	0.500	0.025		0.012		
Insoluble matter	3.325	0.059		0.030	Trace	

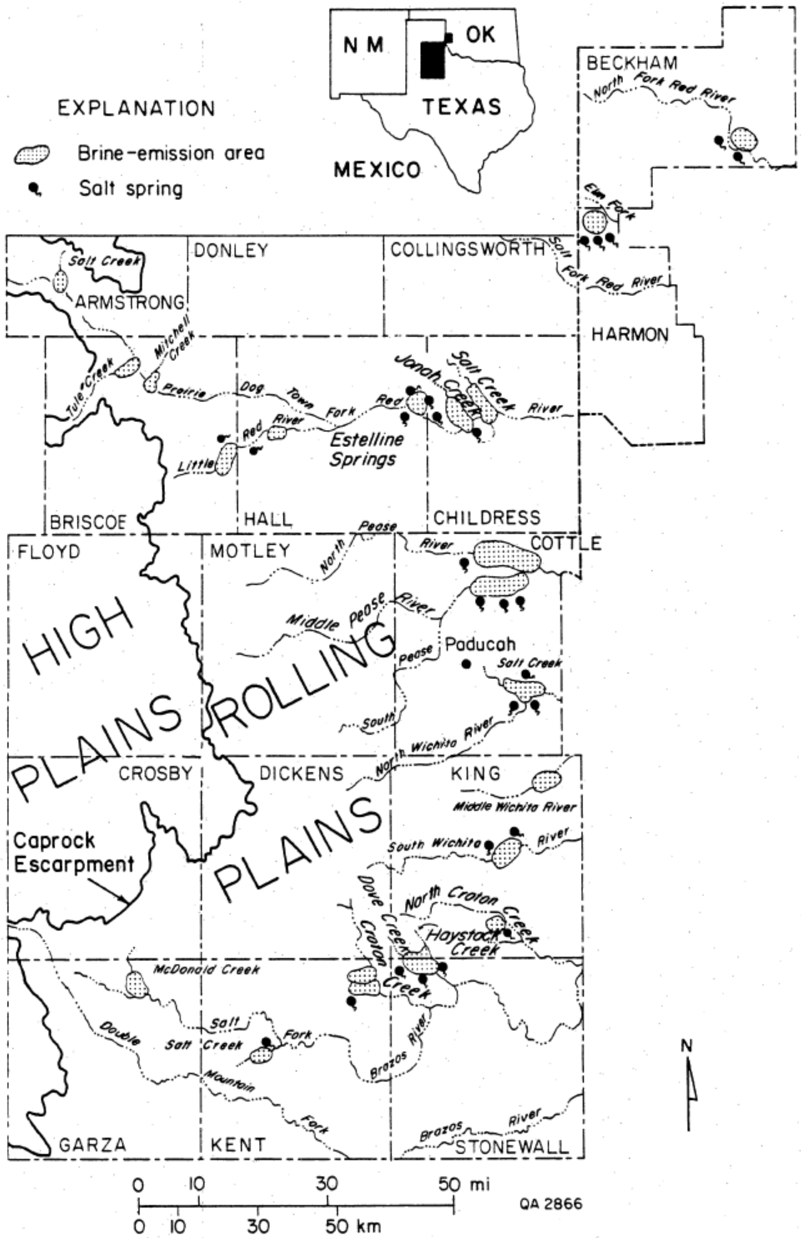

Figure 21. Discharge points of halite-solution brine at land surface in the Rolling Plains of north-central Texas and southwestern Oklahoma (from Richter and Kreitler, 1986a,b).

59

50) Scanlon, B. R., Weingarten, M. B., Murray, K. E., Reedy, R. C., 2019, Managing Basin – Scale Fluid Budgets to Reduce Injection – Induced Seismicity from the U.S. Shale Oil Revolution: Seismological Research Letters, v. 90, p. 171 – 182, https://doi.org/10.1785/0220180223

The study identifies linkage between produced water volumes, disposal and seismicity, and provides strategies to mitigate injection-induced seismicity. The study focuses on Oklahoma and suggests reducing injection rates and regional injection volumes to reduce seismicity.

51) Shammas, N., Sever, C.W., and Wang, L.K., 2010, Deep-Well Injection for Waste Management:

in (Wang, L., Shammas, N., and Hung, Y.-T., eds.) Advanced Biological Treatment Processes, Springer, Ch. 14, p. 521-582, doi: 10.1007/978-1-60327-170-7_14

Underground injection is an effective and environmentally safe method to dispose of wastes in wells that are properly sited, constructed, and operated,. This chapter covers regulations for managing injection wells; basic well design;, evaluation of proposed injection site;, ways to prevent, detect, and correct potential hazard; economic evaluation; use of injection wells for wastewater and hazardous wastes management; protection of usable aquifers; case studies; and practical examples.

52) Shirazi, S., and Arroyo, J., 2011, Desalination database updates for Texas: Texas Water Development Board White Paper, 25p.
http://www.twdb.texas.gov/innovativewater/desal/doc/2011_03_desaldb_whitepaper.pdf

53) Simon, M. ,accessed October 2020, Desalination Is Booming. But What About All That Toxic Brine? https://www.wired.com/story/desalination-is-booming-but-what-about-all-that-toxic-brine/

This posting is not a peer-reviewed article, but it does bring up key points that need to be considered.
These include:

1. Desalination is increasing because of increasing water scarcity;
2. Desalination used lots of energy, but with RO and using less saline input fluids, energy requirements are lessened;
3. We don't have good numbers on how much brine must be disposed; &
4. Discharge fluids may contain "precious elements like uranium"

The article doesn't discuss disposal options, nut assumes discharge to the sea.

54) Thornhill, J.T., Short, T.E., and Silka, L., 1982, Application of the Area of Review Concept, Ground Water, v. 20, no. 1, https://doi.org/10.1111/j.1745-6584.1982.tb01327.x

Analytical equations for calculating pressure buildup in injection zones. In areas of review characterized by numerous injection wells, the effect of every injection well on pressure buildup must be accounted for to prevent the migration of fluids to USDWs.

55) Whittemore, D. O., 2007, Fate and identification of oil-brine contamination in different hydrogeologic settings: Applied Geochemistry, v. 22, p. 2099 – 2114.

The study discusses a methodology to identify and quantify the contribution of natural and oil-field sources to the saline water contamination of surface water and groundwater. The study also focuses on the role of hydrogeologic settings on the movement of saline water. The general conclusions are:

a. Low-permeability soils exhibit less infiltration as compared to unconsolidated aquifers causing surface runoff;

b. Brine seeped into the aquifer acts like a reservoir and finds pathways to sink deeper if high permeability zones are available and if sufficient density contrast is present, otherwise migrates laterally;

c. Surface runoff of brine occurs within months to a few years after disposal whereas groundwater contamination could take up to a century or more in the study conducted in Kansas;

d. Use of mixing curves of Br^-/Cl^- ratio versus Cl^- concentration, SO_4^{2-}/Cl^- ratio and concentration of NO_3^- and NH_4^+ provide a means to identify and differentiate between different sources of contamination.

56) Wolthek, N., Raat, K., de Ruijter, J.A., Kemperman,. A., and Oosterhof, A., 2013, Desalination of brackish groundwater and concentrate disposal by deep well injection: Desalination and Water Treatment, 51:4-6, 1131-1136, https://www.tandfonline.com/doi/abs/10.1080/19443994.2012.694205

This brackish water extraction was used to prevent upconing into overlying aquifers. The brackish water was treated with RO. The injection of the supersaturated concentrate did not lead to mineral precipitation in the target hots rocks. They found that deep well injection is technically feasible without risks of injection well or aquifer clogging.

Texas Water Development Board (Publications or Communications)

57) Designation of brackish groundwater production zones: Memo dated 6 October 2016, 33p., https://www.twdb.texas.gov/innovativewater/bracs/doc/2016_10_06_HB_30_Board_Memo_Final.pdf

This memo identified the Carrizo-Wilcox Aquifer between the Colorado River and the Rio Grande, Gulf Coast Aquifer and sediments bordering that aquifer, the Blaine Aquifer, and the Rustler Aquifer as brackish water production zones. The TDWB staff "discovered that a number of Class II injection zones are installed above, below, lateral to, or overlap with geologic stratum containing brackish groundwater. However, information needed to determine the distance that injected fluids may have traveled both laterally and vertically from these wells is lacking, necessitating staff to adopt a conservative approach (a 15-mile buffer) when recommending brackish groundwater production zones."

58) Designation of brackish groundwater production zones in four aquifers: Memo dated 14 March 2019, 32p., 2014, 32p., https://www.twdb.texas.gov/innovativewater/bracs/doc/20190328_Brd_Memo_BGPZ_Designation_Final.pdf

This memo identifies potential brackish groundwater production zones in the Blossom, Lipan, Nacatoch, and Northern Trinity aquifers. The TDWB BRACS staff again "discovered that several Class II injection zones are installed above, below, lateral to, or overlapping with geologic stratum containing brackish groundwater. The TWDB will continue to adopt a conservative approach to estimating the distance traveled by injected fluids and place a 15-mile buffer around Class II (type 1, 2,3) injection wells."

59) Texas Water Development Board, 2017, Water for Texas 2017 State Water Plan, Ch . 7, https://www.twdb.texas.gov/waterplanning/swp/2017/index.asp

Figure 7.2 shows predicted water needs by county in 2070. There's also a map of water scarcity that is not dependent upon county population.

60) Texas Water Development Board, 2019, Brackish Resources Aquifer Characterization System (BRACS) Program, h https://www.twdb.texas.gov/innovativewater/bracs/index.asp

Current information on the BRACS program.

Aquifer-specific Texas Studies

61) Andrews, A.G., and Croskrey, A., 2019, Brackish Groundwater Production Zone Recommendations for the Blossom Aquifer, Texas: Texas Water Development Board Open File Report 19-01, 19p., https://www.twdb.texas.gov/publications/reports/Open-File/doc/Open-File19-01.pdf

The study identified three brackish groundwater production zones with slightly and moderately saline groundwater in place in the Blossom Aquifer.

62) Croskrey, A., Suydam, A., Robinson, M., and Meyer, J.E. 2019, Brackish Groundwater Production Zone Recommendations for the Nacatoch Aquifer, Texas: Texas Water Development Board Open File Report 19-01, 19p., https://www.twdb.texas.gov/publications/reports/Open-File/doc/Open-File19-02.pdf

The study evaluated the entire aquifer and identified five potential brackish groundwater production zones in the Nacatoch Aquifer.

63) Robinson, M.C., and Deeds, N.E., 2019, Identification of Potential Brackish Groundwater Production Areas – Northern Trinity Aquifer: Texas Water Development Board Technical Note 19-1, 143p., https://www.twdb.texas.gov/publications/reports/technical_notes/doc/TechnicalNote19-01.pdf

The study identified evaluated 15 potential production areas. using the Northern Trinity Aquifer GAM to estimate productivity of each potential production area and to evaluate potential impacts. The Hosston Formation has the represents the best potential for high production rates of brackish groundwater, the Pearsall, Paluxy, and the Glen Rose formations have moderate potential; and the Hensell has the lowest production potential.

Literature Identified through Ground Water Protection Council (GWPC)

64) Arthur, J.D., 2017, Oilfield Water Injection: A Summary of Issues, PowerPoint presentation at February 2017 GWPC UIC Conference, 23 slides, http://www.gwpc.org/sites/default/files/event-sessions/Dan%20Arthur.pdf

General review of issues and history of injection wells. It is noted that "well planned and properly constructed Class II disposal wells will continue to be the best practice for managing flowback and produced water in the shale plays" and that Class II wells in these regions were being converted from EOR to flowback water disposal.

65) Frailey, S.M., 2020, Analyses of Step Rate Tests for Estimating Maximum Injection Pressure, PowerPoint presentation, 2020 GWPC Meeting San Antonio, 18 slides, http://www.gwpc.org/sites/default/files/event-sessions/Frailey-ClassII.pdf

Presentation shows how step tests can estimate fracture propagation pressures and lists causes of overestimating and underestimating fracture pressures.

66) GWPC, 2014, State Oil and Natural Gas Regulations Designed to Protect Water Resources, 122p., http://www.gwpc.org/sites/default/files/files/Oil%20and%20Gas%20Regulation%20Report%20Hyperlinked%20Version%20Final-rfs.pdf

This document is based on review of 27 state oil and gas agencies and describes selected areas and related elements of state oil and gas regulations designed to protect water resources and to generally describe the rule language and agency approaches related to those areas.

67) GWPC, 2015, Potential Injection-Induced Seismicity Associated with Oil & Gas Development, http://www.gwpc.org/sites/default/files/finalprimerweb.pdf

Document addresses technical and regulatory considerations associated with the evaluation of and response to seismicity, seismic monitoring systems, information sharing, and the use of ground motion metrics.

68) GWPC, 2016, Well Integrity Regulatory Elements, 10p., http://www.gwpc.org/sites/default/files/Well%20Integrity%20%20Full%20Publication%202016.pdf

Based upon the 2012 and 2013 GWPC meetings, this document provides regulators with a set of ideas to consider when improving oversight of the permitting, construction, and plugging of wells.

69) GWPC, 2016, A White Paper Summarizing a Special Session on Induced Seismicity, 39p., http://www.gwpc.org/sites/default/files/white%20paper%20-%20final_0.pdf.

Document discusses induced seismicity associated with hydraulic fracturing and disposal wells.

70) Veil. J., 2015, Class II Injection Wells Are an Integral Part of U.S. Oil and Gas Production,

PowerPoint presentation at GWPC UIC Conference, Austin, 12 slides, http://www.gwpc.org/sites/default/files/event-sessions/Veil_John1.pdf

Good general introduction to Class II wells.

71) Veil, J., 2020, Produced Water Volumes and Management Practices for 2017, PowerPoint presentation at GWPC UIC Conference, San Antonio, 29 slides, http://www.gwpc.org/sites/default/files/event-sessions/Veil%20-%20Produced%20Water.pdf

Report focuses solely on produced water volumes and the types of water management practices that are used. In its data submittal for 2017, estimates of total produced water volume from approximately 1 million U.S. oil and gas wells in 2017 is 24.4 billion barrels (bbl), the volume injected for enhanced recovery (4,557,819,641 bbl), and volume injected into non-commercial disposal wells (3,586,674,633 bbl). The RRC reported that commercial disposal well facilities injected 1,716,310,350 bbl of water in 2017.

Analytical Flow Modeling References

72) Bear, J. and Jacobs, M., 1965, On the movement of water bodies injected into aquifers: Journal of Hydrology, v. 3, no. 1, p. 37-57, https://doi.org/10.1016/0022-1694(65)90065-X.

73) Bear, J. (1979), Hydraulics of Groundwater, McGraw-Hill, ISBN: 0-07-004170-9.

74) Chan, C., and Javandel, I., 1996, Two-dimensional analytical solutions for chemical transport in aquifer: Parts 1 and 2: Lawrence Berkeley National Laboratory Report LBNL-38825,67p., https://www.osti.gov/servlets/purl/272510

75) Cooper, H.H. Jr., ,and Jacob, C.E., 1946, A generalized graphical method for evaluating formation constants and summarizing well field history: Transactions, American Geophysical Union, v. 27, no. 4, p. 526-534, http://dx.doi.org/10.1029/TR027i004p00526

76) Dougherty D.E., and Babu, D.K., 1984, Flow to a partially penetrating well in a double-porosity reservoir: Water Resources Research, v,. 20, no. , 8, p. 1116-1122, https://www.osti.gov/biblio/5967122-flow-partially-penetrating-well-double-porosity-reservoir

77) Faybishenko, B.A., Javandel, I.,, and Witherspoon, P.A., 1995, Hydrodynamics of the capture zone of a partially penetrating well in a confined aquifer: Water Resources Research, v. 31, n. 4, p. 859-866, https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/94WR02707

78) Hantush, M., 1961, Drawdown around a partially penetrating well: Journal of the Hydraulics Division, Proceedings, American Society of Civil Engineers, HY4, p.83-988, https://cedb.asce.org/CEDBsearch/record.jsp?dockey=0012298

79) Javandel, I., 1982, Analytical solutions in subsurface flow: in Recent Trends in Hydrogeology (Narasimhan, T,N., ed.,) Geological Society of America Special Paper 189, p.,

223-235,
https://doi.org/10.1130/SPE189

A review of mathematical methods for solving equations of groundwater flow subject to different boundary conditions.

80) Papadopulos, S.S., and Cooper, H.H., Jr., 1967, Drawdown in a well of large diameter: Water Resources Research, v. 3, no. 1, p.241-244, https://doi.org/10.1029/WR003i001p00241

81) Theis, C.V, 1952, The Relation Between the Lowering of the piezometric Surface and the Rate of Duration of Discharge of a well Using Groundwater Storage: U.S. Geological Survey, Water Resources Division, 10p., https://pubs.er.usgs.gov/publication/70198446

82) Reprint of Theis, C.V., 1935, Trans., American Geophysical Union, v.2, p. 519-524.

The classic analysis of transient flow to a well in a confined aquifer. This serves as an initial model for Class II injection wells.

83) Wenzel, L.K., 1936, The Thiem method for determining permeability of water-bearing materials and its application to the determination of specific yield; results of investigations in the Platte River Valley, Nebraska: U.S. Geological Survey Water-Supply Paper 679A, 70p., https://doi.org/10.3133/wsp679A

This paper extends the original Thiem method that estimates confined aquifer drawdown from a pumping under steady state conditions to unconfined conditions and the calculation of hydraulic conductivity and estimating specific yield.

Numerical Flow Modeling References

84) Deeds, N.E., and Jones, T.L., 2011, Assessment of Groundwater Modeling Approaches for Brackish Aquifers: INTERA Inc. Final Report to the Texas Water Development Board, 50p. Plus appendices.
https://www.twdb.texas.gov/publications/reports/contracted_reports/doc/1100011196_brackishaquifers.pdf

The report assessed numerical codes that might be applicable for “brackish water applications”; summarized the hydrogeologic features of the brackish water aquifers in Texas: and analyzed how the characteristics of the various codes could affect the suitability of a code for each type of hydrogeologic feature.

85) Langevin, C.D., Provost, A.M., Panday, S., & Hughes, J.D., 2021, Documentation for the MODFLOW 6 Groundwater Transport Model: U.S. Geological Survey Techniques and Methods, book 6, chap. A55.

86) Langevin, C.D., Panday, S., & Provost, A.M., 2020, Hydraulic-head formulation for density-

dependent flow and transport: Groundwater, v. 58, p. 349-362. https://doi.org/10.1111/gwat.12967.

87) Langevin, C.D., Hughes, J.D., Banta, E.R., Niswonger, R.G., Panday, S., & Provost, A.M., 2017, Documentation for the MODFLOW 6 Groundwater Flow Model: U.S. Geological Survey Techniques and Methods, book 6, chap. A55, 197 p., https://pubs.usgs.gov/tm/06/a55/tm6a55.pdf.

88) Panday, Sorab, Langevin, C.D., Niswonger, R.G., Ibaraki, Motomu, and Hughes, J.D., 2013, MODFLOW-USG version 1: An unstructured grid version of MODFLOW for simulating groundwater flow and tightly coupled processes using a control volume finite-difference formulation: U.S. Geological Survey Techniques and Methods, book 6, chap. A45, 66 p., https://doi.org/10.3133/tm6A45

89) Pollock D.W. (1994), User's Guide for MODPATH/MODPATHPLOT,version 3: A particle tracking post processing package for MODFLOW, the U.S. Geological Survey finite difference ground-water flow model, U.S. Geol. Survey Open-File Rept. 94-464.

90) Reilly, T.E. and Harbaugh, A.W. (2004), Guidelines for Evaluating Ground-Water Flow Models, U.S. Geol. Survey Scientific Investigations Report 2004-5038, 37p.

91) Warner, D., Koederitz, l., Simon, A., & Yow, M., 1979, Radius of Pressure Influence of Injection Wells. U.S. Environmental Protection Agency, Washington, D.C., EPA/600/2-79/170 (NTIS PB80100498), https://cfpub.epa.gov/si/si_public_record_Report.cfm?Lab=ORD&dirEntryID=43152.

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Appendix B: Workflow for Manual Downloading and Processing Texas Railroad Commission (RRC) Database Files

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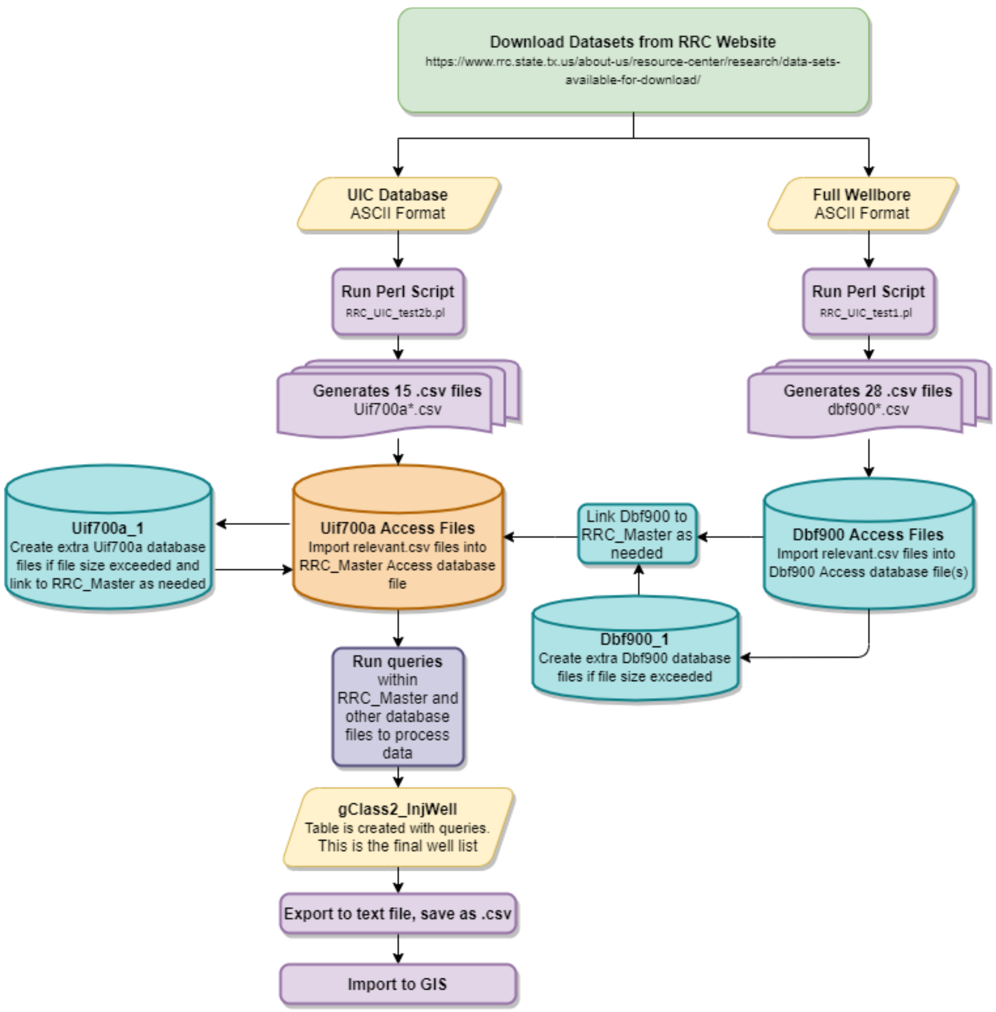
Appendix B

Workflow for Manual Downloading and Processing Texas Railroad Commission (RRC) Database Files

This workflow document summarizes the manual steps required to process the RRC databases via Perl scripts, load the resulting CSV files into Access database files, and perform queries within Access to generate the "gClass2_InjWell" table, which can be utilized in Arcmap to display Class II injection wells in Texas, and can be utilized in the "well intersection" determination. This manual workflow has been automated and developed into an online tool. Further details on the online tool are available in the Appendix D. An overview of the manual workflow is provided in the flowchart below. Following is a more detailed discussion of each step involved in the workflow.



(Overview of workflow)

Download RRC Database Files

The two databases of interest for this workflow are available for download from the RRC website: https://www.rrc.state.tx.us/resource-center/research/data-sets-available-for-download/. The two databases of interest are the Underground Injection Control (UIC) database and the Oil & Gas Full Wellbore database. These databases may be referred to as the "Uif700a database" (also referred to as "Uif database" or

"UIC database") and the "dbf900 database" (also referred to as "Full Wellbore database" or "DbfF database"), respectively. These databases are updated monthly, so it is strongly suggested that the user employ a file naming convention that includes a date stamp (this could be as simple as creating folders with the date included in the folder name or renaming csv files to include the date). Two file formats are available for each database download: ASCII and EBDIC. The ASCII file format (file extension is .txt) will be utilized in this workflow.

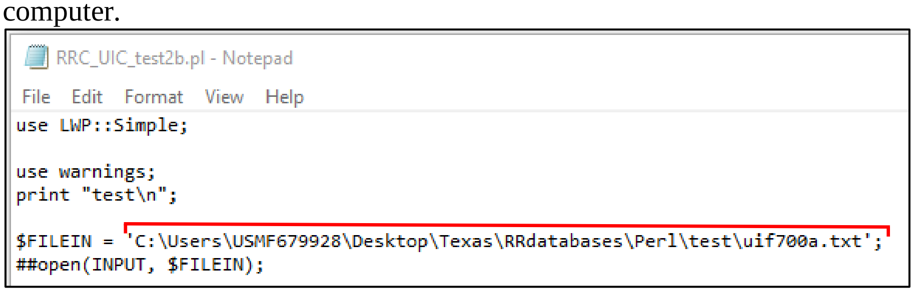
(1) Download Underground Injection Control (UIC) database ASCII file.
   a. Direct link to ASCII file download page: https://mft.rrc.texas.gov/link/445ce1ae-233d-4590-92a2-e71f5908f3a1.
   b. While viewing the download page, note the date stamp in the "Last Modified" column at the time of download for the "uif700a.txt.gz" file.
   c. Download the file "uif700a.txt.gz".
   d. Unzip the contents of "uif700a.txt.gz" to an appropriate location (i.e. C:\UIC or C:\uif700a).

(2) Download Oil & Gas Full Wellbore database ASCII file.
   a. Direct link to ASCII file download page: https://mft.rrc.texas.gov/link/9ef1955f-cf26-4bd4-8030-1253eb772cf9.
   b. While viewing the download page, note the date stamp in the "Last Modified" column at the time of download for the "dbf900.txt.gz" file.
   c. Download the file "dbf900.txt.gz".
   d. Unzip the contents of "dbf900.txt.gz" to an appropriate location (i.e. C:\FullWellbore or C:\dbf900).

Run Perl Scripts on Uif700a.txt and dbf900.txt Files

TWDB previously created Perl scripts to process the ASCII database files. The Perl scripts have not been modified for this workflow, other than changing the file path within the script files to point to the location of the ASCII files on the user's computer. Perl must be installed on the user's machine in order to run the Perl scripts. Perl can be installed via download from the Perl website (https://www.perl.org/get.html) or through installation of an Integrated Development Environment (IDE) such as Strawberry Perl (https://strawberryperl.com/). WSP utilized Strawberry Perl (64-bit) 5.32.0.1-64bit to execute the Perl scripts. Some scrolling text may be displayed in the Perl command window while the scripts are running, but this seems to be trivial, and the scripts should be allowed to fully execute regardless of the text displayed in the command window.

(1) Process the UIC database ASCII file.
   a. Locate the Perl script "RRC_UIC_test2b.pl".
   b. Right-click on the "RRC_UIC_test2b.pl" file and select Edit.
   c. Modify the file path on the "$FILEIN" line to the location of the uif700a.txt file on the user's computer.



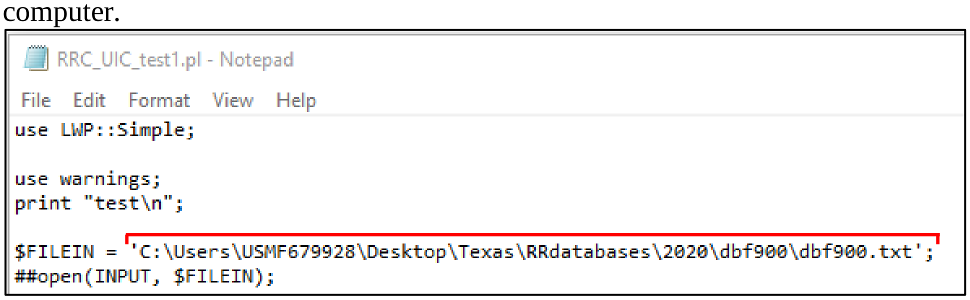
   d. Save and close the "RRC_UIC_test2b.pl" file.
   e. Double-click the "RRC_UIC_test2b.pl" file to execute the Perl script.
      i. If this doesn't work, user may need to run the script via command line.
   f. A command window with scrolling text should automatically open, indicating the script is running. As the script runs, CSV files will be created and populated in the same directory in which "RRC_UIC_test2b.pl" is located.

g. Allow the script to continue to run until the command window automatically closes or indicates that the process is complete. The run time of this script should be 5 minutes or less.
h. Fifteen CSV files should be generated, totaling approximately 3.5 GB. The CSV files should include:

- uif700a_enf.csv
- uif700a_enfact.csv
- uif700a_enfoth.csv
- uif700a_enfrmk.csv
- uif700a_H5.csv
- uif700a_H5_rmk.csv
- uif700a_H10vio.csv
- uif700a_mon_rmk.csv
- uif700a_mon10H.csv
- uif700a_ monH10A.csv
- uif700a_ monH10B.csv
- uif700a_ monH10H.csv
- uif700a_ montr.csv
- uif700a_rmk.csv
- uif700a_ root.csv

(2) Process the Full Wellbore database ASCII file.

a. Locate the Perl script “RRC_UIC_test1.pl”.
b. Right-click on the “RRC_UIC_test1.pl” file and select Edit.
c. Modify the file path on the “$FILEIN” line to the location of the dbf900.txt file on the user’s computer.



RRC_UIC_test1.pl - Notepad

File Edit Format View Help

```
use LWP::Simple;

use warnings;
print "test\n";

$FILEIN = 'C:\Users\USMF679928\Desktop\Texas\RRdatabases\2020\dbf900\dbf900.txt';
##open(INPUT, $FILEIN);
```

d. Save and close the “RRC_UIC_test1.pl” file.
e. Double-click the “RRC_UIC_test1.pl” file to execute the Perl script.
    i. If this doesn’t work, user may need to run the script via command line.
f. A command window with scrolling text should automatically open, indicating the script is running. As the script runs, CSV files will be created and populated in the same directory in which “RRC_UIC_test1.pl” is located.
g. Allow the script to continue to run until the command window automatically closes or indicates that the process is complete. The run time of this script should be approximately 5-10 minutes.
h. Twenty-eight CSV files should be generated, totaling approximately 4 GB. The CSV files should include:

- dbf900_01root.csv
- dbf900_02compl.csv
- dbf900_03date.csv
- dbf900_04rmks.csv
- dbf900_05tube.csv
- dbf900_06case.csv
- dbf900_07perf.csv
- dbf900_08line.csv
- dbf900_09form.csv
- dbf900_10sqeze.csv
- dbf900_11fresh.csv
- dbf900_12oldloc.csv
- dbf900_13newloc.csv
- dbf900_14plug.csv
- dbf900_15plrmks.csv
- dbf900_16plrec.csv
- dbf900_17plcase.csv
- dbf900_18plperf.csv
- dbf900_19plname.csv
- dbf900_20drill.csv
- dbf900_21wellid.csv
- dbf900_22_14B2.csv
- dbf900_23_H15.csv
- dbf900_24_H15rmk.csv
- dbf900_25SB126.csv
- dbf900_26dastat.csv
- dbf900_27W3C.csv
- dbf900_28_14B2rm.csv

Import CSV Files into MS Access

The CSV files generated in the previous step need to be imported into MS Access for data processing via queries.

Most of the relevant queries are saved in an Access database template "RRC_Master_Template.accdb". A blank copy of the table "gClass2_InjWell" with appropriate fields and structure is also included in the template. The "gClass2_InjWell" table will be populated automatically by running queries as outlined in the following steps. At the beginning of the workflow, prior to importing any files into Access, **make a copy of RRC_Master_Template.accdb and rename the copy** with a file name including a date stamp, for example RRC_Master_YYYYMMDD.accdb where MM is month, DD is day, and YYYY is year. Due to file size limitations of Access (~2 GB max file size), multiple database files are required to store all the data from the RRC databases. In addition to RRC_Master_YYYYMMDD.accdb, the following Access database file templates are provided, and some include pre-loaded queries. Copy and rename each of these with a date stamp, such as Dbf900_1_YYYYMMDD:

- Dbf900_1_Template.accdb
- Dbf900_2_ Template.accdb
- Dbf900_3_ Template.accdb
- Dbf900_4_ Template.accdb
- Uif700a_1_ Template.accdb
- Uif700a_2_ Template.accdb
- Uif700a_3_ Template.accdb
- Uif700a_4_ Template.accdb

The general steps for importing CSV files into MS Access include:

(1) Within the RRC_Master_YYYYMMDD database (or other desired database file), click on the "External Data" tab, click "New Data Source", "From File", "Text File".
(2) Click the "Browse…" button next to "File name", navigate to and select "uif700a_ root.csv".
    a. Make sure the "Import the source data into a new table in the current database" option is selected in the "Get External Data – Text File" menu.
(3) Click ok, select "delimited" and click next, select "comma" and check the box for "First Row Contains Field Names", make sure the "Text Qualifier" is set to ", then click next, change "Indexed" to "no", click next, select "No primary key", click "Next", name the table "Uif700a_root" under the "Import to Table box" otherwise it will select a random table name, click "Finish".

Notes:

- If Access gives an ambiguous error when attempting to import CSV files, try the following fixes:
    - Within the Access file, go to the "Database Tools" tab and select "Compact and Repair Database".
        - Also, whenever a table is deleted within Access for any reason, running this tool is highly recommended.
    - Close and re-open the Access file.
    - If all else fails, delete the Access file and re-create from the appropriate template.
- If Access gives an error related to "system resources exceeded", try closing other applications, close and re-open the Access file and try the operation again; however, the import may succeed with this error and the error can be ignored.
- If Access creates a table of errors indicating certain rows were not imported for a particular table, WSP believes this is likely due to unreadable characters in the database file or erroneous entries in the database file, and these entries cannot be corrected. The user may retain the table of errors or delete the table, then compact and repair the database.

The general steps above should now be performed to import all the CSV files into the Access database files using the following structure:

(1) **RRC_Master_YYYYMMDD.accbd** (Main database containing most of the relevant UIC database tables and queries.)
    - Uif700a_enfact
    - Uif700a_enfoth
    - Uif700a_enfrmk
    - Uif700a_H10vio
    - Uif700a_H5
    - Uif700a_H5_rmk

- Uif700a_mon10H
- Uif700a_monH10H
- Uif700a_montr
- Uif700a_rmk
- Uif700a_root

(2) **Dbf900_1_YYYYMMDD.accdb** (These tables will be linked to RRC_Master_MMYYYY.accbd and used in queries.)
- dbf900_01root
- dbf900_03date
- dbf900_07perf
- dbf900_11fresh
- dbf900_13newloc
- dbf900_14plug
- dbf900_23_H15

(3) **Dbf900_2_YYYYMMDD.accdb** (These tables can be used to append the injection formation and the well operation dates to the RRC_Master_MMYYYY.accbd.)
- dbf900_03date
- dbf900_09form

(4) **Dbf900_3_YYYYMMDD.accdb** (Supplemental at this time, these tables are not used in queries.)
- dbf900_02compl
- dbf900_04rmks
- dbf900_05tube
- dbf900_06case
- dbf900_08line
- dbf900_09form
- dbf900_10sqeze
- dbf900_12oldloc
- dbf900_15plrmks

(5) **Dbf900_4_YYYYMMDD.accdb** (Supplemental at this time, these tables are not used in queries.)
- dbf900_16plrec
- dbf900_17plcase
- dbf900_18plperf
- dbf900_19plname
- dbf900_20drill
- dbf900_21wellid
- dbf900_24_H15rmk
- dbf900_25_SB126
- dbf900_26dastat
- dbf900_27W3C
- dbf900_28_14B2rm
- dbf900_22_14B2 (This one could be buggy. If importing the CSV gives odd characters or if it takes a long time to load, try opening the CSV in Excel and save it as an .xlsx file, then use the "From File -> Excel" option in Access.)

**The 04 record ID from the UIC database is the monthly injection data, and this is split into two tables by the Perl script: Uif700a_monH10A.csv and Uif700a_monH10B.csv. Uif700a_monH10A.csv must be manually split using a text editor, such as the free version of EmEditor https://www.emeditor.com/#download. Recommended steps for manually splitting Uif700a_monH10A.csv: (1) Right-click Uif700a_monH10A.csv and open with EmEditor (2) Note the total number of lines (roughly 10,000,000) and navigate to approximately half way down (line 5,000,000) and place cursor at the beginning of a row where a new API number begins (3) Hold CTRL-SHIFT-END to select the records from this row to the end of the file, press CTRL-X to cut the selected records (4) Open a new file and CTRL-V to paste the records (5) Go back to Uif700a_monH10A.csv and save it as Uif700a_monH10A_part1.csv, also press CTRL-Home to navigate to line 1 (6) With cursor at beginning of row 1, press SHIFT-END to select the headers, press CTRL-C to copy (7) Go back to the new file with pasted data, press CTRL-HOME to move cursor to beginning of file, press ENTER to create a blank line, and then CTRL-V to paste the headers into the new blank line (8) Save the new file as Uif700a_monH10A_part2.csv (9) Optionally delete the original Uif700a_monH10A.csv, as it will not fit into an Access database file.

(6) **Uif700a_1_YYYYMMDD.accdb** (Contains one of three parts of the monthly injection data.)
- Uif700a_monH10B

(7) **Uif700a_2_YYYYMMDD.accdb** (Contains one of three parts of the monthly injection data.)
- Uif700a_monH10A_part1

(8) **Uif700a_3_YYYYMMDD.accdb** (Contains one of three parts of the monthly injection data.)
- Uif700a_monH10A_part2

(9) **Uif700a_4_YYYYMMDD.accdb** (Contains remaining UIC tables as supplement, not used in queries)
- Uif700a_enf
- Uif700a_enfrmk
- Uif700a_mon_rmk

Link Access Database Files
A limited workaround regarding Access file size limitations is the ability to link tables from different Access database files to any other desired Access database file. This allows the user to view tables from other Access database files and run queries on other external database tables. At this time, the only linked tables will be all tables from DBF_1_YYYYMMDD and DBF_2_YYYYMMDD linked to RRC_Master_YYYYMMDD. The following steps are provided to link the tables:

(1) Open the RRC_Master_MMDDYYYY.accdb file, click the "External Data" tab, click the "Linked Table Manager".
(2) Within the Linked Table Manager, click "Add", leave the "Data source name:" blank, select "Access", click "Next".
(3) Click "Browse…" next to "File name *:", navigate to and select Dbf900_1_YYYYMMDD.accdb, click "Finish".
(4) A "Link Tables" window will pop up. Select all tables (Dbf900_01root, Dbf900_03date, Dbf900_07perf, Dbf900_11fresh, Dbf900_13newloc, Dbf900_14plug, Dbf900_23_H15), click "Ok", click "Close"
(5) Repeat steps (1), (2), and (3) but instead select the Dbf900_2_YYYYMMDD.accdb file, click "Finish".
(6) A "Link Tables" window will pop up. Select only tables "Dbf900_03date_NoDup" and "Dbf900_09form", click "Ok", click "Close".

Perform Queries in Access to Populate gClass2_InjWell Table
The UIC database uses a 10-digit API number to reference wells; however, the Full Wellbore database utilizes an 8-digit API number system. The only difference between the 8-digit and 10-digit numbers is "42" is added to the front of the 8-digit API number to make it 10-digits. Most of the following queries simply create a new field for a 10-digit API number within the Full Wellbore tables and append "42" to the front of the WB_API_NUMBER. This allows the databases to relate to each other using a common 10-digit API number and perform queries on both databases simultaneously to append data to the gClass2_InjWell table.

(1) Open the DBF_1_YYYYMMDD.accdb. The following queries create a new 10-digit API number field for the relevant tables and populate the new fields by add "42" to the front of the existing 8-digit API number in each table. Double-click the following queries in order, click "Yes" through menus:
    a. **qry1_Add10digitAPIfield_01root** – adds 10-digit API number field
    b. **qry2_Add10digitAPIfield_07perf** – adds 10-digit API number field
    c. **qry3_Add10digitAPIfield_13newloc** – adds 10-digit API number field
    d. **qry4_Append42API_01root** – Populates 10-digit API number field with '42'+[WB_API_NUMBER]
    e. **qry5_Append42API_07perf** – Populates 10-digit API number field with '42'+[WB_API_NUMBER]
    f. **qry6_Append42API_13newloc** – Populates 10-digit API number field with '42'+[WB_API_NUMBER]
    g. Close the DBF_1_YYYYMMDD.accdb file.

(2) Open the DBF_2_YYYYMMDD.accdb. The following queries are related to determining the beginning active date and ending active date for each unique API number. Subsequent queries will be performed on

these tables in the RRC_Master_YYYYMMDD.accdb file to append the information to the gClass2_InjWell table. Double-click the following queries in order, click “Yes” through menus:

a. **qry1_Add10digitAPIfield_03date** – adds 10-digit API number field
b. **qry2_Add10digitAPIfield_09form** – adds 10-digit API number field
c. **qry3_Append42API_03date** – Populates 10-digit API number field with '42'+[WB_API_NUMBER]
d. **qry4_Append42API_09form** – Populates 10-digit API number field with '42'+[WB_API_NUMBER]
e. **qry5_Sort03date** – Sorts the 03date table by API number first and Elevation second
f. **qry6_FindDuplicatesDbf900_03date_SORTED** – Creates a list of duplicate API entries
g. **qry7_RemoveDuplicates_03date_SORTED** – Removes duplicates from table per list in qry6
h. Close the DBF_2_YYYYMMDD.accdb file.

(3) Open the DBF_4_MMDDYYYY.accdb and double-click the following queries in order, click “Yes” through menus:

a. **qry1_Add10digitAPIfield_18plperf** – adds 10-digit API number field
b. **qry2_Append42API_18plperf** – Populates 10-digit API number field with '42'+[WB_API_NUMBER]
c. Close the DBF_4_YYYYMMDD.accdb file.

(4) Open the RRC_Master_YYYYMMDD.accdb file and double-click the following queries in order, click “Yes” through menus:

a. **qry01_gClass2_InjWell_del** – This deletes the contents of the gClass2_InjWell table but retains the table structure (field names and types, etc.). It should already be empty from the template but run this query if it’s not empty.
b. **qry02_gClass2_InjWell_append_uic -** This query appends relevant information from the Uif700a_root table to the gClass2_InjWell table, including all API entries in the current version of the UIC database, but beware there will be duplicate API entries, so the number of rows does not reflect the actual number of unique API numbers (total wells).
c. **qry03_gClass2_InjWell_update_loc** – Populates the LATDD and LONGDD fields
d. **qry04_gClass2_InjWell_Perf_TD** – Creates the zzgClass2_Perf_TD table
e. **qry05_gClass2_InjWell_Perf_BD –** Creates the zzgClass2_Perf_BD table
f. **qry06_gClass2_InjWell_Perf_TD_Update** – Populates the PERF_Z_TD field in gClass2_InjWell
g. **qry07_gClass2_InjWell_Perf_BD_Update** – Populates the PERF_Z_BD field in gClass2_InjWell
h. **qry08_gClass2_InjWell_AddSurfaceElevation** – Populates surface elevation field in gClass2_InjWell
i. **qry09_gClass2_InjWell_AddFormationName** – Adds formation name to gClass2_InjWell. Caution is advised because there are multiple formation names per API, but only the first occurrence is currently included in gClass2_InjWell.
j. **qry10_gClass2_InjWell_AddFormationDepth** – Adds formation depth to gClass2_InjWell. Caution is advised because there are multiple formation names per API, but only the first occurrence is currently included in gClass2_InjWell.
k. **qry11_gClass2_InjWell_AddFormationCounter** – Adds formation counter to gClass2_InjWell. Caution is advised because there are multiple formation names per API, but only the first occurrence is currently included in gClass2_InjWell. The counter field indicates the position of this entry out of the number of occurrences.
l. **qry12_gClass2_InjWell_ScreenTopElevation** – Populates screen top elevation field in gClass2_InjWell
m. **qry13_gClass2_InjWell_ScreenBotElevation –** Populates screen bottom elevation field in

gClass2_InjWell

n. **qry14_gClass2_InjWell_ScreenFMElevation** – Populates formation elevation field in gClass2_InjWell
o. Export gClass2_InjWell as text or other desired format.
    i. Right-click the gClass2_InjWell table, go to "Export, "Text File", click "Browse" to select desired output location, click "OK", "Delimited", check "Include Field Names on First Row", set the "Text Qualifier" to "{none}".
p. Close the RRC_Master_YYYYMMDD.accdb file.
q. Utilize the exported gClass2_InjWell.txt (or other format) as desired, it is ready to be imported into GIS using "Add XY data…"

Methodology and General Workflow for Manually Developing the Estimated Injection Well Data

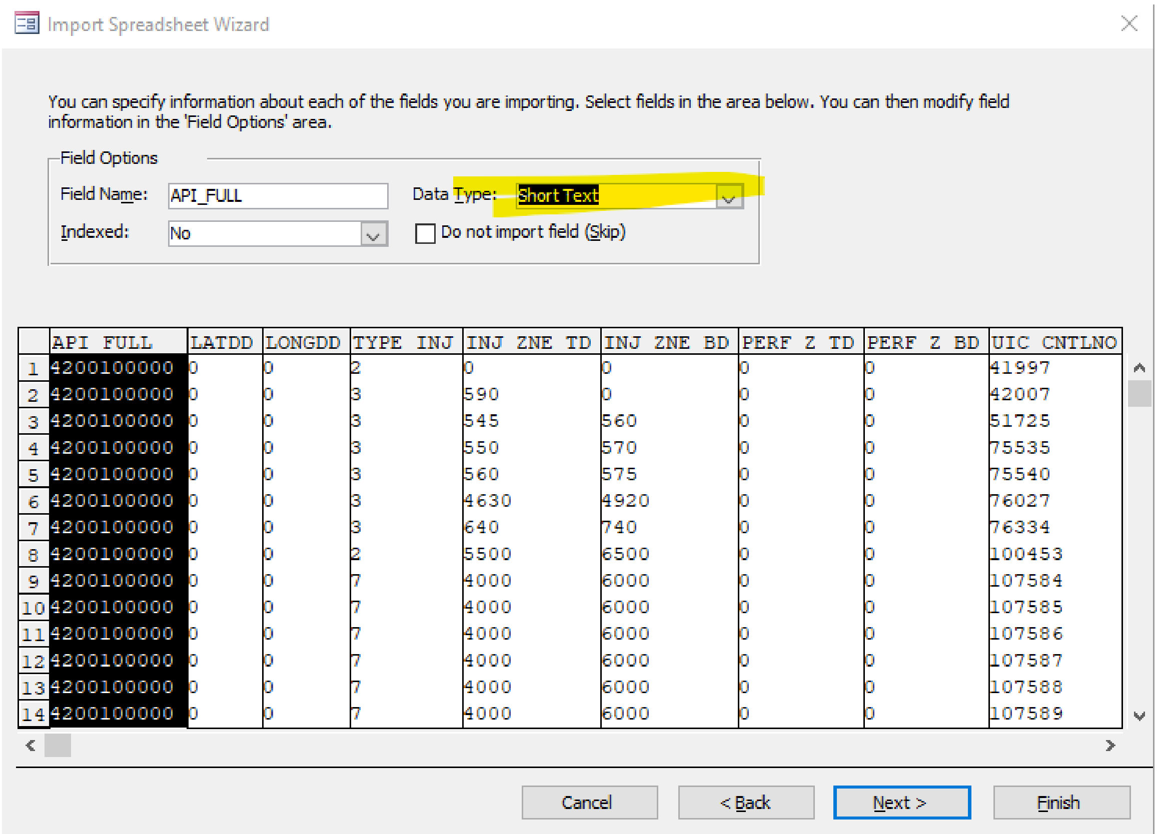
This section provides a general workflow of generating injection well statistics included in the summary "InjectionWellStatistics.xlsx"

- *Uif700a-monH10*: Due to the 2Gigabyte size limit of Access database, the dataset Uif700a-monH10 was split into three Access sub databases. The provided injection well list was imported into these three sub databases: *04amonH10A_part1.accdb, 04amonH10A_part2_new03242021.accdb, 04bmonH10B0_new03242021.accdb*, and used to run queries to extract the required data in Table 4.6.1. These data were saved in different workbooks: H10_MaxPres, H10_MaxPres, H10_LiqVol, H10_GasVol, which are also listed in Table 4.6.2 above.

- *Uif700a-monH10H* and *Uif700a-root*: Table *Uif700a-monH10H* provides supplementary injection information while table Uif700a-root provides permitted/allowable injection pressure and volumes. These two tables were imported into Access database *monH10H_and_root.accdb*, which was then used for extraction of injection statistics for selected list of injection wells.

Below is a simple example of step-by-step procedure of extracting injection statistics for selective injection well list:

Import well list of interest. Data type can be defined when imported or changed later after import. API is the major index/identifier for queries in this exercise and we defined the format of the API and majority of the properties as "Short Text". Note that API is the major index/identifier for queries and the format cannot be set as "Long Text", which would cause a failure in queries execution.



	API FULL	LATDD	LONGDD	TYPE INJ	INJ ZNE TD	INJ ZNE BD	PERF Z TD	PERF Z BD	UIC CNTLNO
1	4200100000	0	0	2	0	0	0	0	41997
2	4200100000	0	0	3	590	0	0	0	42007
3	4200100000	0	0	3	545	560	0	0	51725
4	4200100000	0	0	3	550	570	0	0	75535
5	4200100000	0	0	3	560	575	0	0	75540
6	4200100000	0	0	3	4630	4920	0	0	76027
7	4200100000	0	0	3	640	740	0	0	76334
8	4200100000	0	0	2	5500	6500	0	0	100453
9	4200100000	0	0	7	4000	6000	0	0	107584
10	4200100000	0	0	7	4000	6000	0	0	107585
11	4200100000	0	0	7	4000	6000	0	0	107586
12	4200100000	0	0	7	4000	6000	0	0	107587
13	4200100000	0	0	7	4000	6000	0	0	107588
14	4200100000	0	0	7	4000	6000	0	0	107589

Figure: Import Well List into Access Database

After importing the selected well list named as "Option1WellList" in figure below, we can set up queries to each injection property per well per month. Note that a criterion of "<>0000" was applied to exclude the zero values for the purpose of generating true average values. Different properties might have different values to represent zero value such as "00000" or "00000000". In this example a query for monthly average injection pressure per well is set up and saved as "Monthly_Avg_Pressure"

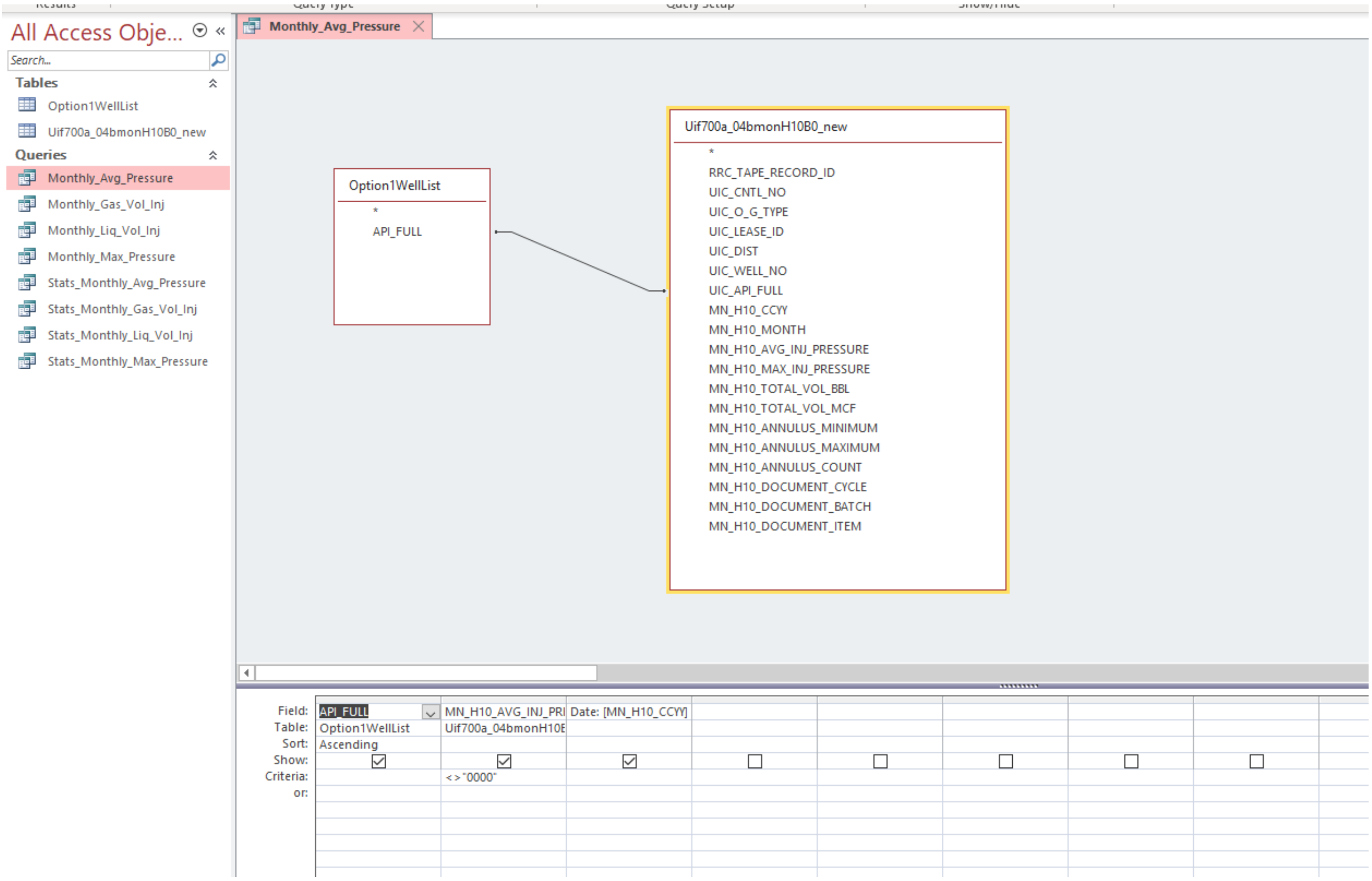


Figure: Set up Query for Monthly Average Well Injection Pressure

Another query named “Stats_Monthly_Avg_Pressure” is set up after “Monthly_Avg_Pressure” is generated. This is to calculate statistical properties based on each well’s monthly data (shown in the Figure above). The SQL command for statistical analysis is shown as the following:

SELECT Monthly_Avg_Pressure.API_FULL, Min(Monthly_Avg_Pressure.MN_H10_AVG_INJ_PRESSURE) AS MinOfMN_H10_AVG_INJ_PRESSURE, Avg(Monthly_Avg_Pressure.MN_H10_AVG_INJ_PRESSURE) AS AvgOfMN_H10_AVG_INJ_PRESSURE, Max(Monthly_Avg_Pressure.MN_H10_AVG_INJ_PRESSURE) AS MaxOfMN_H10_AVG_INJ_PRESSURE, Min(Monthly_Avg_Pressure.Date) AS MinOfDate, Max(Monthly_Avg_Pressure.Date) AS MaxOfDate, Count(Monthly_Avg_Pressure.Date) AS CountOfDate

FROM Monthly_Avg_Pressure

GROUP BY Monthly_Avg_Pressure.API_FULL

ORDER BY Monthly_Avg_Pressure.API_FULL;

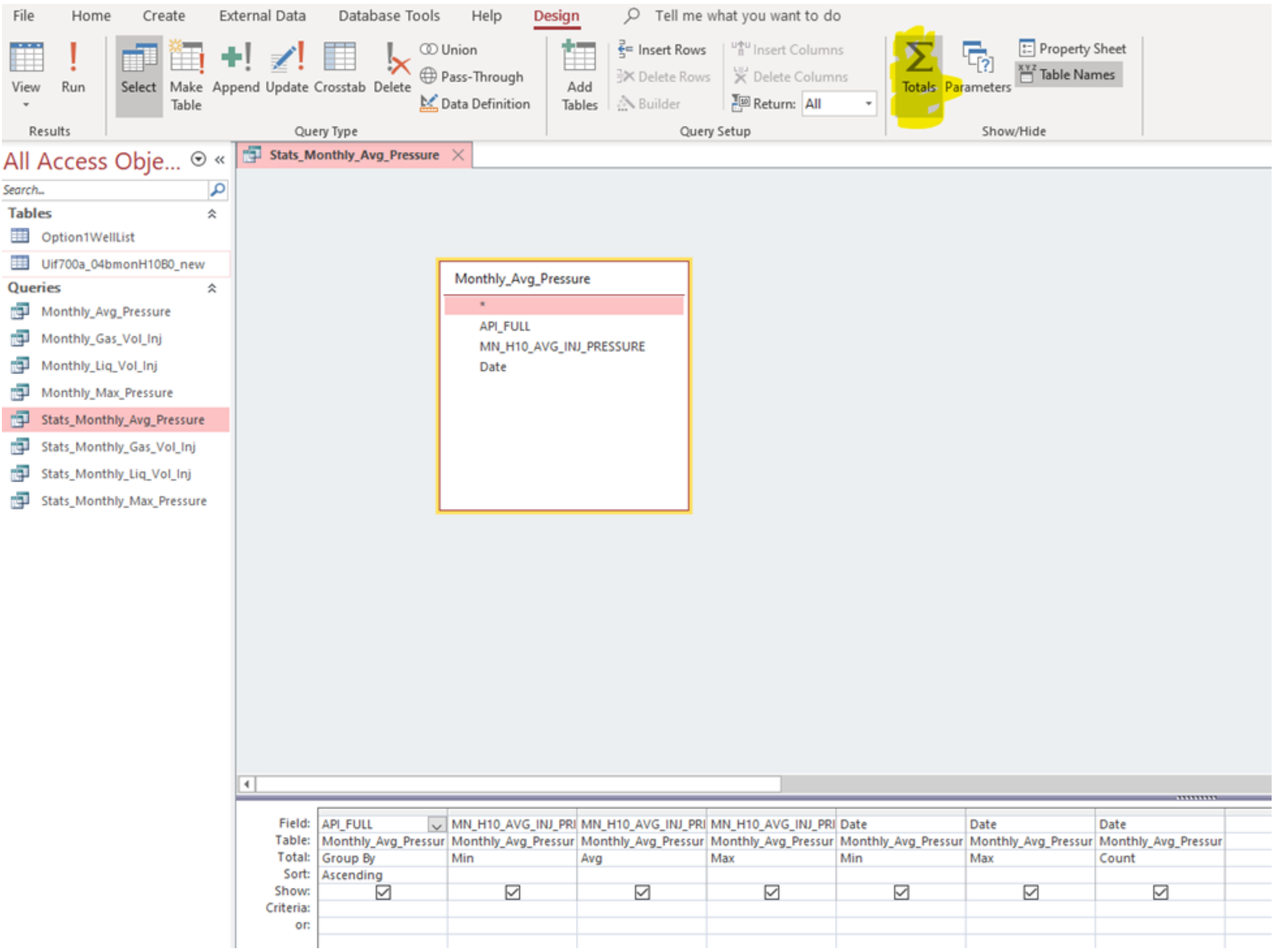


Figure: Set up Query for Calculation of Statistics of Monthly Average Well Injection Pressure

The table generated from statistical analysis query can be exported and saved into excel file. Then, one-line summary of statistics for each well can be extracted and arranged using "Vlookup" command.

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Appendix C: Workflow for Performing Manual Well Intersection Analysis

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Appendix C

Workflow for Performing Manual Well Intersection Analysis

This document provides a workflow for performing the "Well Intersection Analysis" utilized in the Texas Water Development Board (TWDB) project: "Develop Procedures and Tools to Delineate Areas Designated or Used for Class II Well Wastewater Injectate". This document is a follow-up to the "Workflow for Downloading and Processing Texas Railroad Commission (RRC) Database Files", and some files resulting from that documentation are utilized in this workflow. References to the Northern Trinity case study, performed by WSP, are utilized as examples throughout this document. Associated example files and templates are provided in "TemplatesAndNorthernTrinityWellIntersectionExamples.zip".

Input Files

The following input files are utilized in this workflow:

(1) Files Utilized From Previous Workflow Documentation
   a. **gClass2_InjWell table -** The "gClass2_InjWell" table generated in the previous workflow documentation, "Workflow for Downloading and Processing Texas Railroad Commission (RRC) Database Files", is utilized in this workflow.
   b. **Statistics table** – The statistics table generated by FME is utilized in this workflow.
   c. The RRC database version utilized in the case study workflow is May 31, 2021.

(2) External Files
   a. **Study area boundary shapefile(s)** – Study area (XY boundary) shapefiles, in GAM projection.
   b. **Aquifer surfaces** – All relevant aquifer top/bottom surfaces, in raster format, in elevation (feet or meters AMSL) or depth (feet or meters below land surface), and in GAM projection.
   c. **Digital Elevation Model (DEM)**, either in feet AMSL or meters AMSL, and in GAM projection.

XY Intersection

The "XY Intersection" is performed utilizing the gClass2_InjWell table and desired study area boundary shapefile. The result of the steps in this section is a table of Class II Injection wells that are located within the footprint of the desired study area.

(1) Clean up the gClass2_InjWell table and save as CSV.
   a. The gClass2_InjWell table has extraneous fields not utilized in this workflow and removing these fields will limit clutter and make processing less cumbersome.
   b. The fields that should be retained for this workflow and their column order are:
      i. API_FULL (A)
      ii. LATDD (B)
      iii. LONGDD (C)
      iv. TYPE_INJ (D)
      v. PERF_Z_TD (E)
      vi. PERF_Z_BD (F)
      vii. INJ_ZNE_TD (G)
      viii. INJ_ZNE_BD (H)
      ix. INJ_TD_COR (I) – rename INJ_ZNE_TD_COR to INJ_TD_COR otherwise Arcmap will ambiguously rename due to 10-character maximum for field names. To be incorporated in FME.
      x. INJ_BD_COR (J) – rename INJ_ZNE_BD_COR to INJ_BD_COR otherwise Arcmap

will ambiguously rename due to 10-character maximum for field names. To be incorporated in FME.

c. Re-order columns in the gClass2_InjWell table according to the list above, delete other fields, and save as a new CSV file, suggested name: gClass2_InjWell_Clean_Date.csv
d. Remove duplicates on API_FULL (Column A)
    i. Select all data (CTRL+A), go to Data tab, Remove Duplicates, check My data has headers, click Unselect All, put a check only next to API_FULL, click OK, OK. Should be approximately 115,000 unique values remaining.
e. Filter out entries with no LATDD LONGDD values. *If there are blank cells at the top of the table, Arcmap will not recognize these fields as being numerical, and the user will not be able to perform step 2 below.*
    i. Click the Sort & Filter drop-down menu, select Filter, click new drop-down button in cell B1, scroll to bottom of list and uncheck value of "(Blanks)", click OK.
    ii. Select all data (CTRL+A) and copy (CTRL+C), create a new sheet within the file by clicking the + sign at the bottom of the workbook, paste (CTRL+V) the filtered data into the new sheet, right-click the original sheet and delete, save the file.
f. Examples provided: gClass2_Inj_Well_05312021.csv and gClass2_InjWell_Clean_05312021.csv
    i. gClass2_InjWell_Clean_05312021.csv, RRC database version 05/31/2021, was utilized in the Northern Trinity case study

(2) Add gClass2_InjWell_Clean_Date.csv to Arcmap using the "Add XY Data…" feature.

a. Utilize an existing map document (.mxd) or create a new document, make sure the map layer coordinate system is set to GCS_WGS_1984 so the wells plot in the correct location using the LONGDD LATDD fields.
    i. **GCS_WGS_1984 Coordinate System Information**: GCS_WGS_1984, WKID: 4326 Authority: EPSG, Angular Unit: Degree (0.0174532925199433), Prime Meridian: Greenwich (0.0), Datum: D_WGS_1984, Spheroid: WGS_1984, Semimajor Axis: 6378137.0, Semiminor Axis: 6356752.314245179, Inverse Flattening: 298.257223563
b. Within ArcMap, click File -> Add Data -> Add XY Data…
c. Select the gClass2_InjWell_Clean_Date.csv table, X Field is LONGDD, Y Field is LATDD, set coordinate system to GCS_WGS_1984, click OK.
d. Verify the wells have plotted in the correct location.
e. Export to shapefile
    i. Within ArcMap, right-click the "gClass2_InjWell_Clean_Date.csv Events" layer in the Table Of Contents, go to Data -> Export Data…, make sure to export "All features", select desired location and file name, click OK, click Yes when prompted to add to the map.

(3) Add study area shapefile to the map.

(4) Perform "Select By Location" function in ArcMap and export to shapefile.

a. Click "Selection" on the ArcMap main toolbar, click "Select By Location…"
b. Selection method: select features from
c. Target layer: gClassII_InjWell table
d. Source layer: Desired study area boundary shapefile
e. Spatial selection method for target layer feature(s): intersect the source layer feature.
f. Click OK
g. Verify that the correct subset of wells has been selected
h. Right-click the gClass2_InjWell layer in the Table of Contents within Arcmap, go to Data, Export Data…, Export: Selected features, choose save destination and file name (e.g. gClass2_InjWell_NorthernTrinity_Date), click Save, click OK, click Yes to add the exported data to the map as a layer. Turn off or remove the gClass2_InjWell_Clean_Date layer and verify that the new shapefile has only wells that plot within the study area boundary.

Aquifer Layer Intersection (Z Component)

The aquifer layer intersection is performed utilizing the XY gClass2_InjWell shapefile for the desired study area, from step 3h above, and all relevant aquifer surfaces for the desired study area. The results of the steps in this section are tables of wells intersecting each aquifer layer, and a master table with the compiled tables of wells intersecting each aquifer layer.

(1) Add relevant files to Arcmap session.

a. gClass2_InjWell_Aquifer_Date shapefile for the desired study area from step 4h above.

b. All relevant aquifer surface rasters.

    i. Can either be in elevation (m or ft AMSL) or depth (ft or m below land surface).

    ii. Only need top raster surface of shallowest layer and bottom raster surfaces of other layers OR only bottom raster surface of deepest layer and top raster surfaces of other layers.

    iii. For example (diagram below), the Northern Trinity is comprised of the Paluxy, Glen Rose, Hensell, Pearsall, and Hosston hydro stratigraphic units (HGUs). The aquifer surfaces utilized for the case study include: Paluxy top, Glen Rose top, Hensell top, Pearsall top, Hosston top, Hosston bottom because bottom of Paluxy = top of Glen Rose, etc.

Age m.y.	Period	Group	Formations: North and West	Formations: Central		Formations: South		Hydrostratigraphic Units
65	Upper Cretaceous	Eagle Ford	not present	undifferentiated		undifferentiated		
		Woodbine	not present	undifferentiated		undifferentiated		
		Washita	Grayson Mainstreet Pawpaw Weno Denton Fort Worth Duck Creek	Buda Del Rio Georgetown		Buda Del Rio Georgetown		
100	Lower Cretaceous	Fredericksburg	Kiamichi Goodland Walnut	Kiamichi Edwards Comanche Peak Walnut		Kiamichi Edwards Comanche Peak Walnut		
		Trinity	Antlers	Paluxy Glen Rose		Paluxy Glen Rose		Paluxy Glen Rose
				Twin Mountains	Hensell Pearsall Hosston	Travis Peak	Hensell Pearsall Cow Creek Hammett Sligo Hosston	Hensell Pearsall Hosston
127								
Pre-Cretaceous								

c. Digital Elevation Model (DEM) raster, if aquifer surface rasters are in elevation.

(2) Run the Extract Values to Points (Spatial Analyst) tool.

a. Navigate to ArcToolbox, Spatial Analyst Tools, Extraction, double-click Extract Values to Points.

b. Input point features: gClass2_InjWell_AquiferName from step 3h above.

c. Input raster: Need to run this tool multiple times using each relevant aquifer surface raster.

d. Output point features: Need to save multiple, one for each relevant aquifer surface raster, suggested naming convention: AquiferName_LayerName_TopBottom, e.g. NorthernTrinity_Paluxy_Top

e. Click OK.

    i. If error occurs, save map document, and either close and re-open the map document or restart Arcmap.

f. A new shapefile is created, which is a copy of the shapefile input in 2b, but with the addition of field "RASTERVALU", which is the value of the aquifer surface raster (elevation or depth) at each well location.

g. Right-click on the new shapefile layer in the Table of Contents, Open Attribute Table, select the upper-left drop-down menu, click Export…Export: All records, click the folder icon under Output table:, change Save as type: to Text File, enter desired file name and path (e.g. NorthernTrinity_Paluxy_Top), click Save, click OK, do not add table to map.
    i. The RASTERVALU field will be extracted from each text file in the next section.
h. Perform steps 2a-2g for each relevant aquifer surface raster, and for the DEM if aquifer surface rasters are provided in elevation.

(3) Process Raster Surface Tables in Excel

a. Open Windows File Explorer (or similar) and navigate to the folder where the tables in Step 2 are located.
b. Create a new Excel file named Aquifer_SurfaceProcessing.xlsx or similar
    i. Open this file and keep it open - the data from the tables in step 2 will be assembled here.
    ii. Create a new worksheet for every aquifer surface
        1. e.g. Northern Trinity needs the following worksheets: “Paluxy”, “Glen Rose”, “Hensell”, “Pearsall”, “Hosston”.
c. Open the first text file table from step 2 (NorthernTrinity_Paluxy_Top in the case study example).
    i. Should have been saved by Arcmap as a .csv file, but if it is a .txt file, will need to right-click the txt file, open with Excel, select column A, text to columns, comma delimited and “ text qualifier, next, finish.
d. Copy all data (CTRL+A to select all, CTRL+C to copy), paste into cell A1 of appropriate sheet in Aquifer_SurfaceProcessing.xlsx
    i. e.g. Copy/paste all data from NorthernTrinity_Paluxy_Top into the “Paluxy” worksheet within the NorthernTrinity_SurfaceProcessing.xlsx workbook.
e. Delete column A (FID).
f. Rename the RASTERVALU (Column K header) cell K1 to the name of the raster surface plus _TE if the value is top elevation, _BE if the value is bottom elevation, _TD if the value is top depth, _BD if the value is bottom depth.
    i. e.g. Rename it to “Paluxy_TE” in the example case.
g. Perform a VLOOKUP to populate column L with the corresponding top or bottom raster surface data.
    i. Populate header in cell L1 as the name of the corresponding raster surface and indicate whether it is _TE, _BE, _TD, _BD as in the previous step.
        1. e.g. Fill in cell L1 with “Paluxy_BE” in the example case
    ii. (Optional if need to select the VLOOKUP range manually) Open the aquifer surface top or bottom table corresponding to that in the previous step.
        1. e.g. Open the NorthernTrinity_GlenRose_Top.csv because bottom of Paluxy = top of Glen Rose.
    iii. Switch view back to the current worksheet in the Aquifer_SurfaceProcessing.xlsx workbook, enter the VLOOKUP formula into cell L2:
        1. Formula template: =VLOOKUP([API], [Range of data in corresponding csv file], [column number of RASTERVALU data], FALSE)
        2. e.g. for the case study:
           =VLOOKUP(A2,
           NorthernTrinity_GlenRose_Top.csv!$B$1:$K$4319,11,FALSE)
h. Insert a new column K by right-clicking existing column K and click Insert.
    i. Make K1 = “Aquifer_HGU”
    ii. Populate K2 with Aquifer_HGU and copy to bottom of table.
        1. e.g. type in “NorthernTrinity_Paluxy” into cell K2, press enter, select the cell,

double-click radio button at bottom-right of cell to populate to bottom of table.

i. (Required if raster surfaces are in elevation) Insert DEM data into column L.
    i. Insert a new column L by right-clicking existing column L and click Insert.
    ii. Make L1 = "DEMelevFT" or "DEMelevM"
    iii. Open the table containing DEM values at each well location from Step 2h.
        1. NorthernTrinity_DEM.csv in the example case.
    iv. Switch view back to the current worksheet in the Aquifer_SurfaceProcessing.xlsx workbook, enter a VLOOKUP formula into cell L2:
        1. = VLOOKUP([API], [Range of data in DEM csv file], [column number of RASTERVALU data], FALSE)
        2. e.g. for the case study: =VLOOKUP(A2, NorthernTrinity_DEM.csv!$A$1:$K$4319,11,FALSE)
    v. If DEM values are in meters, convert to feet, keeping the data in column L.
    vi. Columns O and P will be populated with raster surface depth values, calculated from the DEM and raster surface elevation values.
        1. Make O1 = HGU_TD, Make P1 = HGU_BD
            a. e.g. in example case, O1 = "Paluxy_TD", P1 = "Paluxy_BD"
        2. Enter the following formula into O2: =L2-M2
        3. Enter the following formula into P2: =L2-N2
        4. Select cells O2 and P2, double-click radio button on bottom-right of cell to populate all rows.

j. Repeat steps 3c through 3i until a top and bottom raster value is processed for each aquifer layer.

k. Create a new worksheet in the processing workbook, rename it "AllProcessed"
    i. Copy/paste row 1 from one of the aquifer surface worksheets into row 1 of the AllProcessed worksheet to populate headers.

l. Copy/paste data from each aquifer surface worksheet into the AllProcessed worksheet.
    i. Prior to copy/pasting, set filters for columns M and N on each aquifer surface worksheet and filter out the -9999 entries (or other "null placeholder" value). This filters out wells where there is no aquifer surface raster coverage.
        1. Highlight cells M1 and N1, click the Sort & Filter drop-down menu, click Filter
        2. Click the Filter drop-down menu in M1 and N1, uncheck the -9999 value for both (if applicable), click OK.
    ii. Select the first cell under A1, press SHIFT+CTRL+END to select all filtered data below the row 1 headers.
    iii. Select cell A2 in the AllProcessed worksheet, CTRL+V to paste
    iv. Repeat steps a through c above for the remainder of aquifer surface worksheets, pasting the filtered data from each worksheet below the previous data, without pasting headers.
    v. (Required if raster surfaces are in elevation) Delete columns L, M, N on the AllProcessed worksheet after all data has been assembled.
    vi. Keep workbook open for next step.

(4) Perform Z-Intersection Logic on Data From Step 3.

a. Open the WellIntersect_Logic_Template.xlsx, make a copy by performing SAVE AS WellIntersect_Aquifer_Date
    i. Case study example saved as WellIntersect_NorthernTrinity_07082021.xlsx

b. Switch view to AllProcessed worksheet from step 3.

c. Select cell A2, press SHIFT+CTRL+END to select all data without headers, CTRL+C to copy

d. Switch view to WellIntersect_Aquifer_Date.xlsx, Template worksheet.

e. Select cell A2, press CTRL+V to paste data.

f. Select cells N2 through AR2, double-click the radio button at the bottom right of the selected cells to copy all cells (formulas) down to bottom of table.

g. Insert new column B and populate with API_Aquifer
    i. Right-click existing column B, click Insert, Enter "API_Aquifer" into cell B1, enter formula into B2 and copy down: =A2 & "_" & L2
h. Scroll down through table to make sure all cells have been populated.
i. Turn on filters by clicking Sort & Filter on the ribbon, Filter.
j. Select cell AE1 (Well Intersects Fm) filter drop-down, place checkbox next to "1", uncheck others, OK
    ii. Wells that intersect the aquifer are displayed; others are filtered out.
k. Select column A (API_FULL), CTRL+C to copy, switch view to InjectionStatsTemplate, left click the top of column A to select the entire column and CTRL+V to paste.
l. Select column L (Aquifer), CTRL+C to copy, switch view to InjectionStatsTemplate, left click the top of column B to select the entire column and CTRL+V to paste.
m. Populate columns C through I by utilizing VLOOKUP on the injection statistics table generated by FME.
    i. Case study example injection statistics table provided as InjectionStatistics_FME_06082021.xlsx
    ii. Open the injection statistics table, but switch view back to InjectionStatsTemplate worksheet.
    iii. Enter formula into cell C2, but adjust the second parameter, the file location, to the file location and data range on the user's computer: =VLOOKUP(A2,[InjectionStatistics_FME_06082021.xlsx]InjectionStatistics!$A$3:$AA$114657,16,FALSE)
    iv. Enter formula into cell D2: =C2*$J$2
    v. Enter formula into cell E2: =D2/$J$1
    vi. Enter formula into cell F2, but adjust the second parameter, the file location, to the file location and data range on the user's computer: =VLOOKUP(A2,[InjectionStatistics_FME_06082021.xlsx]InjectionStatistics!$A$3:$AA$114657,17,FALSE)
    vii. Enter formula into cell G2, but adjust the second parameter, the file location, to the file location and data range on the user's computer: =VLOOKUP(A2,[InjectionStatistics_FME_06082021.xlsx]InjectionStatistics!$A$3:$AA$114657,18,FALSE)
    viii. Enter formula into cell H2: =DATE(LEFT(F2,4),RIGHT(F2,2),1)
    ix. Enter formula into cell I2: =DATE(LEFT(G2,4),RIGHT(G2,2),1)
    x. Select cells C2 through I2, double-click the radio button at the bottom right to populate remainder of table.
n. Populate the InjectateMappingInput_Template worksheet.
    i. Switch view to InjectionStatsTemplate, select columns A and B, CTRL+C to copy
    ii. Switch view to InjectateMappingInput_Template, select columns A and B, CTRL+V to paste, change header name for A1 back to previous value, A1 = "WellName"
    iii. Select cell C2, double-click radio button to populate all rows.
        1. Formula in cell C2 should be =A2 & "_" & B2 (API_Aquifer)
    iv. Enter formula into cell D2, but adjust the second parameter, the data range portion, to the current data range on the Template worksheet: =VLOOKUP(C2,Template!$B$319:$AR$18685,2,FALSE)
    v. Enter formula into cell E2, but adjust the second parameter, the data range portion, to the current data range on the Template worksheet: =VLOOKUP(C2,Template!$B$319:$AR$18685,3,FALSE)
    vi. Enter formula into cell F2, but adjust the second parameter, the data range portion, to the current data range on the Template worksheet:

=VLOOKUP(C2,Template!$B$319:$AR$18685,42,FALSE)

vii. Enter formula into cell G2, but adjust the second parameter, the data range portion, to the current data range on the Template worksheet:
=VLOOKUP(C2,Template!$B$319:$AR$18685,43,FALSE)

viii. Enter formula into cell H2, but adjust the second parameter, the data range portion, to the current data range on the InjectionStatsTemplate worksheet:
=VLOOKUP(A2,InjectionStatsTemplate!$A$2:$M$62,8,FALSE)

ix. Enter formula into cell I2, but adjust the second parameter, the data range portion, to the current data range on the InjectionStatsTemplate worksheet:
=VLOOKUP(A2,InjectionStatsTemplate!$A$2:$M$62,9,FALSE)
    1. Make sure the resulting value is in date format: MM/DD/YYYY

x. Enter formula into cell J2, but adjust the second parameter, the data range portion, to the current data range on the InjectionStatsTemplate worksheet:
=VLOOKUP(A2,InjectionStatsTemplate!$A$2:$M$62,5,FALSE)
    1. Make sure the resulting value is in date format: MM/DD/YYYY

xi. Select cells D2 through J2, double-click the radio button at the bottom right to populate remainder of table.
    1. Make sure the resulting values in columns I and J are in date format: MM/DD/YYYY

xii. Turn on filters by clicking the Sort & Filter drop-down button on the ribbon, select Filter

xiii. Click the filter for StateDate, scroll down and uncheck the #VALUE! entry, click OK

xiv. Press CTRL+A to select all data, CTRL+C to copy, switch view to InjectateMappingInput_Final, select cell B1, CTRL+V to paste.
    1. If not using a blank template, make sure there is no existing data in rows further down the page that may be partially overwritten if the new dataset is smaller.

xv. Select cells A2 and A3, double-click radio button to populate all rows.

xvi. Delete column D (Aquifer_API)
    1. Right-click column D, click delete

xvii. Save the data from the InjectateMappingInput_Final as a CSV file for input into the injectate mapping tool.
    1. Right-click the InjectateMappingInput_Final worksheet, select Move or Copy…, To book: (new book), check the Create a copy checkbox, click OK, save new file as CSV.

<u>NOTES/LOGIC UPDATES</u>

Injection Statistics

Only maximum liquid injection included, converted bbl/month to ft3/d

Screen Thickness

Determined as the portion of well screen intersecting the respective aquifer layer. If screen thickness is >0 to 10 ft, set it to 10ft. Screen thickness should not exceed aquifer thickness.

Aquifer Thickness

Agnostic to well screen location, determined as (aquifer HGU bottom depth – aquifer HGU top depth) at each well location. If aquifer thickness is >0 to 10 ft, set it to 10ft. Implemented the 10 ft check to coincide with screen thickness check, because if aquifer thickness is 5 ft, screen would initially be calculated as 5ft but would get adjusted to 10 ft and there would be a mismatch because screen thickness should always be less than or equal to aquifer thickness.

Ongoing injection

The latest injection data is 4/1/2021. There is only one API number (4213337824) with injection data on that date, and it intersects three layers. We manually replaced the three entries with -999.

Well intersection logic updates:

(1) If injection zone top depth OR bottom depth is 0, well does **not** intersect due to data gap, but gets flagged for QC review.
(2) Added check to all scenarios, if bottom depth > top depth, well does not intersect, gets flagged for QC review. This QC flag was already in but added logic to intersect determination as it seems some of these cases were making it through.
(3) Modified scenarios I and J to be deemed intersecting the aquifer if within 10 feet above/below aquifer.
    a. Added QC flag if I or J is true and there is some separation from the aquifer.
(4) Added QC flag 14g for screens > 2000 ft in length.
(5) Added QC flag 14h to check if screen thickness is less than or equal to aquifer thickness. Should never get flagged based on how the thickness calculations are implemented but will provide more robust QC.

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Appendix F: Shapefiles Description for Aquifer Parameters

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Appendix F

Shapefiles Description for Aquifer Parameters

The geodatabase for the aquifer parameters shapefiles can be obtained from the TWDB website or by contacting TWDB staff

Things to Note

Below are some of the salient features and things to note about the submitted shapefiles:

- All the shapefiles are in the GAM projection
- The shapefiles were extracted from the GAM models or available geodatabases from TWDB, https://www.twdb.texas.gov/groundwater/models/download.asp
- We considered data from active cells only.
- White spaces within the shapefiles for hydraulic conductivities or thickness are the "no flow cells" in the GAMs
- For aquifers with multiple layers, the cell-by-cell maximum hydraulic conductivity is estimated across the aquifer
- The shapefiles are saved in the following format "AquiferName_LayerNumbers_AquiferParameters.shp"

Attribute Table Description

To avoid confusion for GAMs with multiple layers, layer numbers are added to the column headings.

- Row: GAM cell row ID
- Column: GAM cell column ID
- Zone(LayerNumber): Mainly represents the layer number
- Kx(LayerNumber): Horizontal Hydraulic Conductivity (ft/day) (Kx) for the Layer Number
- Ky(LayerNumber): Horizontal Hydraulic Conductivity (ft/day) (Ky) for the Layer Number
- Kz(LayerNumber): Vertical Hydraulic Conductivity (ft/day) (Kz) for the Layer Number
- S(LayerNumber): Specific Storage (Ss) for the Layer Number
- Sy(LayerNumber): Specific Yield (Sy) for the Layer Number
- Porosity(LayerNumber): Porosity for the particular Layer Number
- Bottom(LayerNumber): Bottom Elevation in feet below ground level for the particular Layer Number
- Top(LayerNumber): Top Elevation in feet below ground level for the particular Layer Number
- T(LayerNumber): Transmissivity ft2/day for the Layer Number

Shapefile Description Table

#	Aquifer Name	Shapefile Name	GAM	Layers	Source	Comments
1	**Nacatoch**	**Nacatoch_Layer2_AquiferParameters**	Nacatoch Aquifer GAM	Layer 2 - Nacatoch	GAM Files Groundwater Vistas	
2	**Trinity (northern section)**	**Trinity_(northern_section)_Layer 1,4,5,6,7,8,AquiferParameters**	Northern Trinity and Woodbine Aquifers GAM	Layer 1 - Shallow outcrop Northern Trinity	GAM Files Groundwater Vistas	
				Layer 4 - Paluxy Formation	GAM Files Groundwater Vistas	
				Layer 5 - Glen Rose Formation	GAM Files Groundwater Vistas	
				Layer 6 - Hensell Member	GAM Files Groundwater Vistas	
				Layer 7 - Pearsall/Cow Creek/Hammett members	GAM Files Groundwater Vistas	
				Layer 8 - Hosston Member	GAM Files Groundwater Vistas	
3	**Blossom**	**Blossom_AquiferParameters**	Blossom BRACS Study	–	BRACS Geodatabase	Data in a point shapefile
4	**Carrizo-Wilcox (southern section)**	**Carrizo-Wilcox_(southern_section)_Layer 3,4,5,6_AquiferParameters**	GAM for the Southern Portion of the Carrizo-Wilcox, Queen City, and Sparta Aquifers	Layer 3 - Carrizo	GAM Files Groundwater Vistas	
				Layer 4 - Upper Wilcox		
				Layer 5- Middle Wilcox		
				Layer 6- Lower Wilcox		

5	**Gulf Coast (north of the LRGV)**	**Gulf Coast (north of the LRGV)_Layer1,2,3,4_AquiferParameters**	GAM for Northern Part of the Gulf Coast Aquifer System	Layer 1 - Chicot	GAM Files Vistas	Data in a table format
				Layer 2 - Evangeline		
				Layer 3 - Burkeville		
				Layer 4 - Jasper		
6	**Rustler**	**Rustler_Layer2_AquiferParameters**	GAM Report for the Rustler Aquifer	Layer 2 - Rustler	GAM Files Vistas	
7	**Gulf Coast (LRGV)**	**Gulf_Coast_(LRGV)_Layer1to10_AquiferParameters**	Lower Rio Grande Valley Groundwater Transport Model	Layer (1-3) - Chicot	GAM Files Vistas	
				Layer (4-6) - Evangeline		
				Layer 7 - Burkeville		
				Layer (8-10) -Jasper		
8	**Carrizo-Wilcox (central section)**	**Carrizo-Wilcox_(central_section)_Layer2,3,4,5_AquiferParameters**	GAM for Central portion of the Sparta, Queen city, and Carrizo Wilcox aquifers	Layer 2 - Carrizo	GAM Files Vistas	
				Layer (3-5) - Wilcox	GAM Files Vistas	
9	**Pecos Valley**	**Pecos_Valley_AquiferParameters**	GAM for Edwards-Trinity (Plateau) and Pecos Valley	Layer (1-2) - Pecos Valley	GAM Geodatabase	Data in a point shapefile
10	**Queen City (central and southern sections)**	**Queen_City_(central_sections)_Layer3_AquiferParameters**	GAM for Central Part of the Carrizo-Wilcox Aquifer	Layer 3-Queen City Central	GAM Files Vistas	
		Queen_City_(Southern_sections)_Layer3_AquiferParameters	GAM for Southern Part of the Carrizo-Wilcox Aquifer	Layer 3-Queen City Southern	GAM Files Vistas	

11	**Sparta (central and southern sections)**	**Sparta_(central_sections)_Layer1_AquiferParameters** **Sparta_(Southernl_sections)_Layer1_AquiferParameters**	GAM for Central Part of the Carrizo-Wilcox Aquifer	Layer 1-Sparta Central	GAM Files Groundwater Vistas	
			GAM for Southern Part of the Carrizo-Wilcox Aquifer	Layer 1 - Sparta Southern	GAM Files Groundwater Vistas	
12	**Yegua-Jackson (central and southern sections)**	**Yegua-Jackson_(central_and_southern_sections)_Layer1to5_AquiferParameters**	GAM for the Yegua-Jackson Aquifer	Layer (1to5)	GAM Files Groundwater Vistas	
13	**Trinity (Hill Country section)**	**Trinity_(Hill_Country_section)_Layer2,3,4_AquiferParameters**	Hill Country Trinity GAM	Layer 2 - Upper Trinity Aquifer	GAM Geodatabase	Data in a table format
				Layer 3-Middle Trinity Aquifer	GAM Geodatabase	
				Layer 4-Lower Trinity Aquifer	GAM Geodatabase	
14	**Sparta (east section)**	**Sparta_(East_sections)_Layer1_AquiferParameters**	GAM for the Queen City and Sparta Aquifers	Layer 1 - Sparta (East Section)	GAM Files Groundwater Vistas	
15	**Edwards-Trinity Plateau**	**Edwards-Trinity_Plateau_AquiferParameters**	GAM for Edwards-Trinity (Plateau) and Pecos Valley Aquifers	Edwards-Trinity Plateau	GAM Geodatabase	Data in a point shapefile
16	**Carrizo-Wilcox (eastern section)**	**Carrizo-Wilcox_(eastern_section)_Layer2,3,4,5_AquiferParameters**	GAM for Central Part Of The Carrizo-Wilcox Aquifer	Layer 2 - Carrizo	GAM Files Groundwater Vistas	
				Layer (3-5) - Wilcox	GAM Files Groundwater Vistas	
17	**Queen City (eastern section)**	**Queen_City_(easternl_sections)_Layer3_AquiferParameters**	GAM for Queen City and Sparta Aquifers	Layer 3 - Queen City (Eastern Section)	GAM Files Groundwater Vistas	

18	**Yegua-Jackson (eastern section)**	**Yegua-Jackson_(eastern_sections)_Layer 1to5_AquiferParameters**	GAM for the Yegua-Jackson Aquifer	Layer (2-5) - Yagua - Jackson (eastern section)	GAM Files Groundwater Vistas	
19	**Edwards (Balcones Fault Zone, has top of Trinity but not top of Edwards)**	**NA**	Report and data for the Edwards Aquifer, San Antonio Region, Texas	Layer 1 - Edwards (Balcones Fault Zone)	USGS Report	No GAM files
19	**Capitan Reef complex**	**Capitan_Reef_complex_AquiferParameters**	GAM for Capitan Reef Aquifer	Layer 5 - Capitan Reef Complex	GAM Files Groundwater Vistas	
21	**Cross-Timbers**	**NA**	Draft Conceptual Model for the Cross Timbers Aquifer	–	Refer Draft Conceptual Model Report	No GAM files
22	**Ellenburger-San Saba**	**Ellenburger-San_Saba_Layer5,AquiferParameters**	GAM for Llano Upfit Region of Texas	Layer 5- Ellenburger - San Saba	GAM Files Groundwater Vistas	
23	**Hickory**	**Hickory_Layer7_AquiferParameters**	GAM for Llano Upfit Region of Texas	Layer 7 - hickory Aquifer	GAM Files Groundwater Vistas	
24	**Dockum**	**Dockum_Layer3,4_AquiferParameters**	GAM for the High Plains Aquifer System	Layer (3-4) - Dockum Aquifer	GAM Files Groundwater Vistas	
25	**Woodbine**	**Woodbine_Layer2_AquiferParameters**	GAM for Northern Trinity and Woodbine Aquifers	Layer 2- Woodbine Aquifer	GAM Files Groundwater Vistas	