Application for Class V Underground Injection Control (UIC) Wells for an Aquifer Storage and Recovery (ASR Project)

Submitted by

Example City, Texas

Submitted to:

TEXAS COMMISSION ON ENVIRONMENTAL QUALITY

Date of Submittal

Signature Page of Those Who Prepared Report

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ATTACHMENTS

For TCEQ Use only
Authorization/Permit No. ___________
Date Received_________________
Date Authorized________________

Section I. General Information

A. Type of Application *(Self explanatory)*
- a. Initial ____
- b. Amendment_____

B. For an application for amendment of an authorized or permitted ASR, please provide a brief description of the requested revisions. *(Self explanatory)*

____Not Applicable

C. Type of authorization requested *(Self explanatory)*
- a. Individual permit___
- b. Authorization by rule ____
- c. General permit_____

D. Operator *(Self explanatory)*
1. Name: ____
2. Address: ____
3. Telephone Number: ____
4. Email Address: ____

5. If the application is submitted on behalf of a corporation or other business organization with filing requirements, please identify the Charter Filing Number as recorded with the Office of the Secretary of the State of Texas. *(Self explanatory)*

____

6. If the application is submitted by a business organization that is required to designate and maintain a registered agent, the applicant must provide the name and address of the registered agent. *(Self explanatory)*

Name: ____
Address: ____
____

E. Site Owner (if different from Permittee)
If the ASR operator is different from the site owner, please provide verification that the site owner has granted the permittee permission to construct and operate an ASR project on the proposed site. The application must include a completed application signature page from both the ASR operator and the site owner. *(Self explanatory)*

1. Name: ______________________________
2. Address: ______________________________
3. Telephone Number: ______________________________
4. Email Address: ______________________________

6. Status of the facility *(Self explanatory)*
    a. Private
        i. Corporation ___
        ii. Partnership ___
        iii. Proprietorship ___
        iv. Nonprofit Organization ___
    b. Public
        i. Military ___
        ii. State ___
        iii. Regional ___
        iv. County ___
        v. Municipal ___
        vi. Federal ___

F. Facility *(Self explanatory)*
1. Name of Facility: ______________________________
2. Street Address: ______________________________
3. City (if applicable): ______________________________
4. County: ______________________________

5. Give a description of the location of the facility site with respect to known or easily identifiable landmarks. Detail the access routes from the nearest U.S. or State Highway to the facility. *(Self explanatory)*

Description: ____

____

____

____

6. Provide the location of the facility relative to established surveys. *(Self explanatory)*

Provide the geographical coordinates of the centroid of the facility *(Indicate ASR well location. If the authorization is for more than one well, provide the location of the center of the well field.)*
    a. Latitude 99.999999
    b. Longitude -99.99

G. List those persons or firms authorized to act for the applicant during the processing of the permit application. Indicate the capacity in which each person may represent the applicant (engineering, legal, geology, for example). The person listed first will be the primary recipient of correspondence regarding this application. Include complete mailing addresses, telephone numbers, and email addresses. *(Additional authorized persons/firms can be listed as desired)*

Project Management

Name:
Title: ______________________
Address: ______________________
City, State, and Zip Code: ______________________
Telephone Number: ______________________
Email Address: ______________________

Engineering

Name: ______________________
Title: ______________________
Address: ______________________
City, State, Zip Code: ______________________
Telephone Number: ______________________
Email Address: ______________________

Geology

Name: ______________________
Title: ______________________
Address: ______________________
City, State, Zip Code: ______________________
Telephone Number: ______________________
Email Address: ______________________

H. Confidential Material

The designation of material as confidential is frequently carried to excess. The Commission has a responsibility to provide a copy of each application to other review agencies and to interested persons upon request and to safeguard confidential material from becoming public knowledge. Thus, the Commission requests that the applicant be prudent in the designation of material as confidential, and (2) submit this material only when it might be essential to the staff in their development of a recommendation. The commission suggests that the applicant not submit confidential information as part of the permit application. However, if this cannot be avoided, the confidential information should be described in non-confidential terms throughout the application, submitted as a document or binder with each page conspicuously marked **"Confidential"**.

I. All chemical analyses submitted with this application shall be performed by a laboratory accredited in accordance with the requirements of Title 30 of the Texas Administrative

Code (TAC) Chapter 25.

J. The TCEQ is not authorized to issue an individual permit, general permit, or authorization-by-rule for an ASR project on Indian Lands in the State of Texas. Contact the Environmental Protection Agency, Region 6 for ASR requirements for ASR projects on Indian Lands.

K. Please indicate if the groundwater in the proposed injection zone contains greater than 3,000 milligrams per liter total dissolved solids (TDS): *(Self explanatory)*

Proposed injection zone contains groundwater with:
Greater than 3,000 milligram per liter (mg/l) TDS____
Less than or equal to 3,000 mg/l TDS____

If the groundwater in the proposed injection zone contains greater than 3,000 mg/l TDS, contact:

Groundwater Advisory Group
Texas Railroad Commission
1701 North Congress Avenue
Austin, Texas 78701
512-463-2741

L. TCEQ Core Data Form

The TCEQ requires that a Core Data Form (Form TCEQ-10400) be submitted with all new applications. For all other applications, if a Regulated Entity Number (RN) and Customer Reference Number (CN) have been issued by the TCEQ and core data information has not changed, a core data form is not required. If a core data form is not submitted, please provide the RN and CN for your facility. *(Note: The core data form is a 3-page TCEQ form requiring customer information, well information, affected TCEQ programs, and preparer information)*

Response: *Place the completed TCEQ Core Data Form in Appendix A.*

M. Legal Description

Submit as "Attachment A" a legal description of the tract or tracts of land upon which the ASR project referenced in this application will be located. Although a legal description is required, a metes and bounds description is not necessary for urban sites with appropriate "lot" descriptions. In accordance with the Texas Water Code (TWC), §27.153(c), all wells associated with a single ASR project must be located within a continuous perimeter boundary of one parcel of land, or two or more adjacent parcels of land under the common ownership, lease, joint operating agreement, or contract. (*Self explanatory*)

N. Indicate if the location of the proposed ASR project is within the areas identified in the following legislation: (*Self explanatory*)

a. Chapter 626, Acts of the 73rd Legislature, Regular Session, 1993, for the Edwards Aquifer Authority;

b. Chapter 8801, Special District Local Laws Code, for the Harris-Galveston Subsidence District;
c. Chapter 8834, Special District Local Laws Code, for the Fort Bend Subsidence District;
d. Chapter 8802, Special District Local Laws Code, for the Barton Springs-Edwards Aquifer Conservation District; or
e. Chapter 8811, Special District Local Laws Code, for the Corpus Christi Aquifer Storage and Recovery Conservation District.

Signature Page

I (Signatory Name) ____________________, (Title) __e.g., City Manager____ of __Example City__, certify under penalty of law that this document and all attachments were prepared under my direction or supervision in accordance with a system designed to assure that qualified personnel properly gather and evaluate the information submitted. Based on my inquiry of the person or persons who manage the system, or those persons directly responsible for gathering information, the information submitted is, to the best of my knowledge and belief, true, accurate, and complete. I am aware there are significant penalties for submitting false information, including the possibility of fine and imprisonment for knowing violations.

Signature: ____, Date: ___________________________

See 30 TAC §305.44 for signatory authority.

Hazardous waste permit applications must be signed by both the owner (facility owner and landowner) an operator of the facility. Duplicate this page for additional signatories.

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To Be Completed by the Applicant if the Applicant Is a Corporation and the Responsible Corporate Officer Is Assigning or Delegating Signature Authority to a Manager in Accordance with 30 TAC §305.44(a)(1)

I (Signatory Name) _________________________________ (Title)________________________________ (Company) _________________________________ hereby designate (Agent Name and/or Title) ______________________________ as my agent and hereby authorize said agent to sign any application, submit additional information as may be requested by the Commission, and/or appear for me at any hearing or before the Texas Commission on Environmental Quality in conjunction with this request for a Texas Water Code or Texas Solid Waste Disposal Act permit. I further understand that I a responsible for the contents of this application, for oral statements given by my agent in support of the application, and for compliance with the terms and conditions of any permit which might be issued based on this application.

Signature: ____ Date: _________________________

- -

Note: Application Must Bear Signature and Seal of Notary Public

SUBSCRIBED AND SWORN to before me by the said

_________(e.g., City Manager Name)____________________

on this _______ day of _______ , ___________.

My commission expires on the _______ day of ____Month___, __Year__.

SEAL HERE

___Notary Signature Here__

Notary Public

Section II. Information Required to Provide Notice

If the ASR project is proposed to be located within the jurisdictional boundary of a groundwater conservation district, provide the following information:

Name of District:	XXX Groundwater Conservation District
Contact Person:	________________
Address:	________________
City, State, Zip Code:	________________
Email address:	________________

For an application for an individual ASR permit, the applicant is required to provide notice of the application by first class mail to any groundwater conservation district in which the wells associated with the ASR project will be located and by publishing notice in a newspaper of general circulation in county in which the wells will be located [(Texas Water Code, §27.153(d)]. Notice must meet the requirements in 30 TAC §39.651(h). Please identify the person who will be responsible for causing notice to be published in the newspaper [30 TAC §39.405(f)(2)]. Include the complete mailing address, telephone number, fax number and email address for the contact person.

Response: *If applicable:*

Name:	________________
Address:	________________
Telephone:	________________
Fax:	________________
Email:	________________

(This requirement applies to an application for a permit for an ASR project. It does not apply to an application for an authorization for an ASR project.)

For an application for an authorization by rule for Class V wells associated with an ASR project, the TCEQ will notify a groundwater conservation district of an ASR project that is proposed to be located within the jurisdictional boundary of that groundwater conservation district [30 TAC §331.7(h)].

Section III. ASR Project Area

Please provide a map for the ASR project area that includes the following information:

A. The property boundary for the proposed ASR project;
B. Main cultural features, including highways and roads, railroads, cities and towns; and
C. Surface water bodies, rivers and streams.

Response: *This is the first figure, and can be labeled **Figure 1**. You can use USGS Topographic Map, Google maps or other map application software to obtain. Label the location of the ASR well(s). Changes to the application for multiple ASR wells should be noted as applicable.*

Section IV. Area of Review

Please provide a map of the area of review (AOR), as determined in accordance with the requirements in 30 TAC §331.182. This map must include the following information:

A. The proposed ASR project area, including

1. The extent of the ASR area described in Attachment A;
2. The boundary of the AOR; and
3. The location of all artificial penetrations with the AOR.

Response: *This is the second figure (e.g., **Figure 2**). It should show the ASR well(s), the extent of the ASR area, and the boundary of the AOR. It should also show any other existing wells that are in the same formation, and within the boundary of the AOR. The ASR area represents the area associated with all activities to access, construct, and operate the ASR well. The AOR represents:*

> *"the area determined by a radius of 1/2 mile from the proposed ASR injection well. For an ASR project that includes more than one proposed injection well, the area of review is the area determined by a radius of 1/2 mile from the centroid of the injection well field. If the extent of the underground stored water of the ASR project will exceed the area determined by the 1/2 mile radius as described in this section, the area of review is the area determined by the projected extent of the underground stored water as calculated by using site-specific hydrogeologic information"*

The AOR should also include land area above groundwater whose potentiometric head is projected to be significantly altered by ASR operations. Guidance for determining the extent of underground stored water and groundwater potentiometric changes are in sections VI-VIII of this document.

B. For all artificial penetrations identified in Section III.A.3 above, provide the following information:

1. Whether the artificial penetration intersects or transects the injection zone of the proposed ASR;

Response: *Provide information as appropriate.*

2. For artificial penetrations that intersect or transect the injection zone of the proposed ASR, provide a well schematic with the following information

a. Depth;
b. Completion information (casing, screens); and
c. Use of well (domestic, irrigation, disposal, oil and gas production, other injection).

Response: *The well schematic(s) can be provided as Appendix B.*

Section V. Well Construction and Closure Standards

A. Please provide a map with the locations of all proposed ASR injection wells, ASR production wells, and all monitoring wells. (*Self explanatory*)

B. Please provide the number of ASR injection wells that are being requested in this application. (*Self explanatory*)

C. Please provide a discussion of how each *new* ASR injection well and each *new* well that will serve both as an ASR injection well and an ASR recovery well will be constructed to meet the requirements of 30 TAC §331.183. With regards to the design of each ASR injection well, the discussion must include, but is not limited, to the following information:

1. Well schematic;
   Response: *A schematic of the ASR well (e.g.,* ***Figure 3****) showing well components, their dimensions, and materials of construction should be provided.*
2. Depth of the well;
   Response: *This can be shown in the schematic, or indicated in the text.*
3. Borehole diameter
   Response: *This can be shown on the schematic, or indicated in the text. Borehole diameter changes with depth in a given well should be shown or indicated.*
4. Casing material and diameter;
   Response: *Indicate if casing materials and casing diameters change with depth. See 30 TAC §331.132 for TCEQ requirements of casing material.*
5. Casing setting depth(s);
   Response: *As before, indicate if this parameter varies when multiple ASR wells are being proposed. Also, see 30 TAC §331.132 for TCEQ requirements of casing dimensions.*
6. Cement type, volume, and top of cement;
   Response: *Include differences in cement types and volumes, as well as the top of different cement sections, for different segments of a well, and across different wells. See 30 TAC §331.132 for TCEQ requirements regarding well seals.*
7. Screen interval; and
   Response: *Indicate if each ASR well has one or multiple screened intervals. See 30 TAC §331.132 for TCEQ requirements regarding seals between screened intervals accessing water in chemically different environments.*
8. Surface completion (30 TAC §331.132(c) through (f)).

   Response: *See surface completion requirements in 30 TAC §331.132.*

D. For each *existing* well that will serve as an ASR injection well and each *existing* well that will serve both as an ASR injection well and an ASR recovery well, provide all information, as available, required in Section V.B.

Response: *Indicate for existing wells that will be used for ASR the same information discussed in V.C, i.e.,: 1) well schematic, 2) depth of well, 3) borehole diameter, 4) casing material and diameter, 5) casing setting depth, 6) cement type, volume, and top of cement,* *7) screen interval, and 8) surface completion. Well logs if available can be provided in Appendix C.*

E. Please provide a discussion of how each ASR production well and each ASR production well that also serves as an ASR injection well that provides water to a public water system will comply with the applicable requirements in 30 TAC §290.41 (relating to water sources).

Response: *The requirements specified in 30 TAC §290.41 include but are not limited to:*

-ASR wells must satisfy a number of setbacks from potential pollution sources for safety (e.g., sanitary sewer plant, feed lots).

-ASR wells must meet a number of requirements regarding construction, disinfection, protection, and testing.

F. Please provide a discussion of how each ASR injection well and each well that will serve both as an ASR injection well and an ASR recovery well will be closed to meet the requirements of 30 TAC §331.183.

Response: The *requirements specified in 30 TAC §331.183 include one of the following:*

-Removing all removable casing and the pressure filling the entire well via a tremie pipe with cement from bottom to the land surface.

-Or if a Class V well is not completed through zones containing undesirable groundwater, the well may be filled with fine sand, clay, or heavy mud followed by a cement plug extending from land surface to a depth of not less than ten feet below the land surface.

-Or if a Class V well is completed through zones containing undesirable groundwater, either the zone(s) containing undesirable groundwater or the fresh groundwater zone(s) shall be isolated with cement plugs and the remainder of the wellbore filled with bentonite grout followed by a cement plug extending from land surface to a depth of not less than ten feet below the land surface.

G. If monitoring wells are required, please provide the information in Section V.B for each proposed monitor well, and the number of monitor wells that will be installed.

Response: *Indicate the number of monitoring wells, and for each of them provide the same information requested in V.B, i.e., 1) well schematic, 2) depth of well, 3) borehole diameter, 4) casing material and diameter, 5) casing setting depth, 6) cement type, volume, and top of cement, 7) screen interval, and 8) surface completion. Well logs can be provided in Appendix C. Please note, one or more monitoring wells are helpful in determining if the AOR has been appropriately determined, and if (and possibly where) water quality in the formation is being negatively altered. The water extracted from the ASR well(s) should be regularly monitored to ensure water quality criteria are being met.*

Please note that ASR production wells are not authorized under a Class V individual permit, general permit, or authorization by rule. However, please provide the number of ASR production wells that will be associated with this ASR project. *(Self explanatory)*

Section VI. Injection Well Operation

A. Please provide a discussion of the methods by which the proposed ASR injection wells will be operated to ensure that injection will not endanger drinking water sources, as required under 30 TAC §331.184(a). This discussion must include, but is not limited to the following:

1. Calculation of maximum injection pressure to ensure movement of injected water from the injection zone does not occur [30 TAC §331.184(b)];

   Response*: Identify the maximum injection pressure, per 30 TAC §331.184(b), which ensures there is no movement of fluid out of the injection zone, and explain how this maximum pressure was determined.*

2. Notification to the TCEQ within 30 days when an ASR injection well has not been used for more than two years [30 TAC §331.184(c)];

   Response: *(Self explanatory)*

3. Maintenance of mechanical integrity [30 TAC §331.184(d)];

   Response: Describe how mechanical integrity of the ASR well(s) will be maintained.

4. Water quality requirements [30 TAC §331.184(e)]; and

   Response: *Confirm that the quality of the water injected at an ASR project will meet the requirements in §331.186(a)(1). Relevant water quality results if available could be presented in this section, along with with accompanying data, in Appendix D.*

5. Installation of flow meters [30 TAC §331.184(f)].

   Response: *Per 30 TAC §331.184(f), confirm that all ASR injection and ASR production wells will be installed with a flow meter for measuring the volume of water injected and the volume of the water recovered.*

B. Provide a discussion of ASR project operations with regards to:

1. Maximum volume of water injected;

   Response: *Explain how the volume was calculated. Include in Attachment B any supporting data, figures, or calculations. One possible approach is to calculate the different maximum volumes using the approaches below, and to take the smallest volume among them as the maximum.*

   - Calculate the volume of injected water needed to displace native groundwater to the AOR boundary. The can be done using the web-based model applications

developed by the University of Texas at Austin for relatively simple cases, or using a numerical model for more complex scenarios[1]*.*

- Calculate the volume of ASR water available for injection during wet periods.

- Calculate the volume of ASR water needed to address water needs during dry periods.

- Calculate the maximum injection rate, Q_{max}, based on the criteria that the potentiometric head cannot exceed the ground surface[2]*, and multiply this by the maximum time period for injection during the wet period when water is in excess.*

Example calculations and/or simulations for determining the extent of native groundwater for displacement by injected water, and the change in groundwater head, are in Attachment B.

2. Residence time of injected water;

Response: *The residence time of injected water is defined as the period of time after injection and before pumping begins. The residence time is also called the storage time or delay time. As a first approximation, it can be set equal to the time period between when excess water is no longer available for injection, and when extraction begins to meet water demands during dry periods. It is important to recognize that different residence times affect the percent of injected water that is recovered due to regional groundwater flow. Example simulations showing the effects of different residence times are in Attachment B.*

3. Maximum horizontal and vertical extent of injected water; and

Response: T*he horizonal extent is determined by the extent of the injection bubble and the vertical extent is determined by changes in piezometric surface. Approaches to*

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[1] *A web-based model application was developed by the University of Texas for estimation of the amount of injected water and native water that is recovered upon pumping (i. TxASR app). The model is based on an analytical solution provided by Jacob Bear (1965), and is applicable when ASR can be approximated by a single injection and recovery well, and by homogeneous and isotropic aquifer conditions. The model requires as input hydraulic conductivity, hydraulic gradient, porosity, aquifer thickness, injection volume, injection time, storage time, extraction volume, and extraction time. For the conditions stated, this model can be used to estimate the volume of water needed to displace native water to the AOR boundary.*

For ASR projects involving more than one ASR well, or involving one ASR well with nearby pumping wells that alter the hydraulic gradient in time, or alter the hydraulic gradient in an anisotropic manner, a more complex model just be used. Numerical models are typically used for such cases.

[2] *The change in the potentiometric surface can be calculated using the confined well function derived by Theis (1935), or via numerical simulation for more complex scenarios.*

determine these values are introduced in VI.B.1, and example results are provided in Attachment B.

4. Maximum horizontal and vertical extent of buffer zone.

Response: *The simulation of injection volumes in VI.B.1 can be extended to simulate extraction. The extraction volumes can be set such that the native fraction pumped during recovery is 0%, and there is a buffer zone of non-native water in the aquifer whose minimum thickness is at least 10% of the radius of the injected water.* Examples are shown in Attachment B. In subsequent injection cycles, the injected water volume would be less than the maximum water volume due to the buffer water. Also, some buffer water may be lost over time, so the injection volume may need to be adjusted in subsequent injection cycles.

C. Provide a discussion on the effect injection of water will have on native groundwater, including:

1. The effect of the ASR project on existing offsite water wells;

Response: *The extent of increased pressure head and drawdown during injection and pumping, respectively, can be calculated as a function of distance from a single ASR well in a homogeneous and isotropic aquifer using the following confined well function.*

$$h_o - h = \frac{Q}{4 * \pi * T} \int_{u}^{\infty} \frac{e^{-u}}{u}\, du$$

$$u = \frac{r^2 S}{4 * T * t}$$

For systems with multiple ASR wells, the drawdown can be determined, for example, using TTIM or numerical model simulation. TTIM solves for transient multi-aquifer flow for a variety of boundary conditions, and is based on the Laplace-transform analytic element method. It was developed at the Delft University of Technology and is free.

The drawdown can be calculated as a percent of the aquifer thickness, and large drawdowns (e.g,. >20% of the aquifer thickness) at other pumping well locations could be cause for concern and prompt possible steps for mitigating negative impacts on other water pumping wells.

2. The effect that injection will have on native groundwater with respect to the considerations in 30 TAC §331.186(a)(4); and

3. Whether the injected water will comply with the standards set forth under the federal Safe Drinking Water Act (42 United States Code, §§300f, et seq). Describe any mitigating measures (such as monitoring wells and a groundwater monitoring program that will be employed to ensure compliance with this standard.

Section VII. Project Geology, Hydrogeology, and Geochemistry

A. Geology Report

1. Describe the regional geology and hydrogeology of the proposed ASR project area, including regional stratigraphy, structure, lithology, and hydrogeology. Regional geology should be rendered on a scale capable of accurately depicting the geology of the region. Maps and cross-sections from commercial mapping companies may be used, provided they adequately characterize the geology (including faulting) of the region. Major aquifers, stratigraphic units, general lithology, confining zones and the injection zone should be indicated on all cross-sections. Cross-sections should be constructed with well logs and to scale. The injection well location(s) should be indicated on all maps and cross-sections. Maps and figures should be referenced in the description, where applicable.

Response: *This response can be divided into sections on stratigraphy, structure, lithology, and hydrogeology, with a focus on the regional scale. Maps and cross sections should be used, and these can be constructed from both well logs and geophysical logs. A source of well logs and geophysical logs is TWDB BRACS database. <http://www.twdb.texas.gov/innovativewater/bracs/database.asp>. A source of regional stratigraphy is the TWDB Groundwater Available Models (GAMs) <http://www.twdb.texas.gov/groundwater/models/gam/index.asp>.* A source of general data on groundwater levels, driller reports, lithology, and chemistry is <https://www2.twdb.texas.gov/apps/WaterDataInteractive/GroundWaterDataViewer>. Drillers reports can be found in the TWDB electronic database <http://www.twdb.texas.gov/groundwater/data/drillersdb.asp> A *source of groundwater levels is the TWDB groundwater reports <http://www.twdb.texas.gov/groundwater/data/gwdbrpt.asp>. Include the ASR well(s) on all maps and relevant cross sections. Maps and cross sections can be put into Appendix E.*

Regional Stratigraphy

Provide details on regional stratigrapy, indicating depth and thickness of ASR target zone, and its relationship to other formations.

Regional Structure

Provide details on regional structure.

Regional Lithology

Provide details on regional lithology.

Regional Hydrogeology

Provide details on regional hydrogeology. Identify the ASR target formation. Identify recharge and discharge areas/points. Include potentiometric and streamline maps as relevant.

2. Describe the geology and hydrogeology of the proposed ASR project site, including local stratigraphy, structure, lithology, and hydrogeology pertinent to the proposed ASR project site (include potentiometric maps for the injection zone and for any aquifers

that may be affected by injection). Information must be integrated into a coherent and complete summary, not merely listed. Maps should cover the area of review (AOR). Maps should conform to a uniform system of identification numbers for wells that will key the wells to tables, cross-sections and other figures. The injection well location should be indicated on all maps and cross-sections. Maps and figures should be referenced in the description, where applicable. Well locations, major aquifers, USDW base, confining bed below the USDW, stratigraphic units, general lithology, confining zones, injection zone, and injection interval should be indicated on all cross-sections. Cross-sections should be on a scale necessary to depict the local geology and hydrogeology. Cross-sections should be constructed with well logs and to scale. Sufficient well data must be used to accurately depict the local geology. When necessary to accurately portray the geology of the area, maps or cross-sections should extend beyond the AOR. The data must be of sufficient quality and quantity to accurately delineate the faulting in the area.

Response: *This response can be divided into sections on stratigraphy, structure, lithology, and hydrogeology, with a more local focus that covers the Area of Review (AOR). Maps and cross sections should be used (Appendix E), where the latter are constructed from well logs and geophysical logs. Possible data sources are noted in VII.A.1. Include the ASR well(s) and other relevant wells on all maps and relevant cross sections. It's likely that there will be overlap with the previous response.*

Local Stratigraphy

Provide details on local stratigrapy.

Local Structure

Provide details on local structure.

Local Lithology

Provide details on local lithology.

Local Hydrogeology

Provide details on local hydrogeology. Identify the ASR target formation. Identify recharge and discharge areas/points. Include potentiometric and streamline maps as relevant.

B. Provide a description of the zone into which water will be injected and produced for this ASR project. Include the following in this description:

1. Name of aquifer;
   a. Depth below ground level to the top and base of the injection zone;
   b. Geology of the injection zone, including:
      1. Lithology;
      2. Pertinent stratigraphic features, such as sedimentary facies, channels, pinch-outs, and overall continuity of the injection zone over the ASR project area;
      3. Pertinent structural elements, such as faults;
   c. Porosity and permeability of the injection zone;
   d. Potentiometric map for the injection zone;

Response: *Relevant maps / figures can be placed into Appendix E. Possible data sources are noted in VII.A.1.*

2. Water chemistry within the injection zone;
    a. Total dissolved solids concentration;
        Response: *As data allow, discuss range and mean values, as well as any constituents that dominate TDS and/or contribute to common precipitates. Possible sources of local chemistry are noted in VII.A.1.*

    b. Concentration of other dissolved constituents;
        Response: *Discuss any constituents of concern, including metals, metalloids, total organics, and individual volatile and semivolatile organic compounds. Identify ions that are near the saturation limit for any common mineral precipitates. Identify the pH. Possible sources of local chemistry are noted in VII.A.1.*

    c. Biological constituents; and
        Response: *Discuss any pathogetic concerns. Discuss any reactants that could stimulate biological growth, and any reaction products that indicate biological growth.*

    d. Radiological constituents.
        Response: *Discuss overall radioactivity, as well as individual radionuclides of concern. A list of counties where radionuclide testing is required can be found at <https://www.tceq.texas.gov/drinkingwater/chemicals/radionuclides/pdw_rad.html>.*

C. Provide a discussion of the source and characteristics of the water to be injected in this proposed ASR project. This discussion must include the following:
    a. Source of injected water
        i. Groundwater (identify source aquifer)
        ii. Surface water (identify source, such as river, lake, creek, stormwater, or reservoir)
        iii. Reclaimed water (identify source facility)

    Response: *Indicate quantities expected to be available and when available. Identify and/or address any general concerns regarding water quality. The response to this question will have some overlap with VI.B.*

    b. Chemistry of injected water
        i. Total dissolved solids concentration;
        ii. Concentration of other dissolved constituents;
        iii. Biological constituents; and
        iv. Radiological constituents.

    Response: *Similar to prior question except for injection water. Highlight concentrations relative to drinking water standards. Identify any potential mineral precipitation concerns. Identify pH, ionic strength, and oxygen concentration relative to native groundwater. Potential data sources are listed in VII.A.1.*

D. Provide a discussion on the Injected Water/Aquifer Water/Well Material Compatibility.

i. Injected water/formation water compatibility

Response: *Consider risks associated with precipitation driven by mineral ions that are near saturation. Note differences in pH and consider whether this could promote precipitation.*

ii. Injected water/formation compatibility

Response: *Consider risks stemming from injecting a more acidic water into the formation and promoting dissolution of toxic ions like arsenic or barium.*

iii. Injected water/well material compatibility

Response: *Consider risks stemming from injecting acidic water and/or water with a high TDS promoting corrosion of well materials.*

iv. Formation water/well material compatibility

Response: *Consider risks stemming from formation water being acidic and/or having a high TDS, and promoting corrosion of well materials.*

E. Identify the volume of water that will be injected as part of the ASR Project.

Response: *This response is related to that in VI.B.1, where the maximum injection volume of water was identified. The volume of water injected after the first injection period could be reduced by the amount of buffer water remaining in the formation.*

F. Provide any available aquifer test data and a discussion of these data.

Response: *Such data would be injection and/or extraction test data in the same formation showing parameters such as: 1) injection and/or extraction rate, 2) injection and/or extraction volume, 3) drawdown with pumping, 4) hydraulic conductivity, 5) storativity, etc. This could be provided in Appendix F. Nearby pumping test data can be used to provide some of this information, and specific capacity data (i.e., pumping rate, drawdown) is especially important. Possible data sources are listed in VII.A.1.*

G. Provide any available geophysical logs of wells within the ASR project area.

Response: *Provide as available in Appendix C. These can provide important information regarding injection zone location and heterogeneity. Possible data sources are listed in VII.A.1.*

Section VIII. Demonstration of Recoverability

In order for the commission to make a determination as to whether injection of water into a geologic formation will result in a loss of injected water or native groundwater, as required under TWC, §27.154(b), please provide an analysis of the volume of injected water that will be recovered. This analysis should consider the geologic, hydrogeologic, and hydrochemistry of the injection zone, the quality of the injected water, and the operational conditions proposed for the project. The commission anticipates that this analysis will require groundwater modeling. Please provide a detailed discussion of how the applicant estimated the percentage of injected water that will be recovered. If this estimated percentage of the injected water volume that is estimated is based on groundwater modeling, please describe the modeling performed, with justification for all assumptions and input parameter values.

Response: *A web-based model was developed by the University of Texas for estimation of the amount of injected water and native water that is recovered upon pumping. The model is based on an analytical solution provided by Jacob Bear (1965), and is applicable when ASR can be approximated by a single injection and recovery well, and by homogeneous and isotropic aquifer conditions. The model requires as input hydraulic conductivity, hydraulic gradient, porosity, aquifer thickness, injection volume, injection time, storage time, extraction volume, and extraction time. Several different modeling scenarios using the model are illustrated in the Attachment B.*

For ASR projects involving more than one ASR well, or involving one ASR well with nearby pumping wells (e.g., within the AOR) that alter the hydraulic gradient in time, or alter the hydraulic gradient in an anisotropic manner, a more complex model just be used. Numerical models are typically used for such cases, and examples using such a model are shown in Attachment B.

ATTACHMENT B:
ASR WELL OPERATION DETAILS

Prepared for:

Sample County Conservation District

Prepared by:

Sample Incorporated

Table of Contents

PART I. EXAMPLE RESULTS USING THE TXASR APP, A WEB-BASED APPLICATION DEVELOPED BY THE UNIVERSITY OF TEXAS AT AUSTIN

**Note that the example calculations in Part I are for ASR cases that can be approximated by a single injection and recovery well, and by homogeneous and isotropic aquifer conditions. Example calculations for ASR projects involving more than one ASR well or involving one ASR well with nearby pumping wells that alter the hydraulic gradient in time, or alter the hydraulic gradient in an anisotropic manner, are in Part II of this document, and were performed using numerical models.*

SECTION VI.B.1: MAXIMUM VOLUME OF WATER INJECTED

Extent of the potentiometric surface:

- A simulation of the extent of the potentiometric surface was conducted using the *confined well function* derived by Theis (1935).
- As seen in **Figure 1** the potentiometric surface has not exceeded the ground level.
- The maximum $Q_{max,i}$ is the rate prior to when the potentiometric surface has exceeded the ground surface. The selected Q_i that is based on an estimated volume and time of injection does not exceed the $Q_{max,i}$ rate.
  - $Q_{max,i}$ = 279,777.80 ft/day for an injection period of 90 day
  - V_{max}= 25,180,002 ft^3

- TABLE 1: INPUT PARAMETERS REQUIRED TO DETERMINE THE EXTENT OF THE POTENTIOMETRIC SURFACE FOR INJECTED WATER. MOUNDING EFFECTS.

Q_i	Injection rate	220000	ft^3/day
t_i	Injection time	90	days
K	Hydraulic conductivity	20	ft/day
B	Thickness of aquifer	200	ft
T	Transmissivity	K*B	ft^2/day
S	Storage coefficient	0.005	-
r	Radius of well	0.65	ft
Dswl	Depth to static water level below ground surface	110	ft

Extent of injection front 'bubble':

- A simulation of the extent of the injection bubble (i.e., front) was conducted using the *complex potential function* derived by Bear and Jacobs (1965) via the TxASR app.
- The area of influence is shown in **Figure 2**. The maximum area of injected water is as follows: Up dip is 300 ft, down dip is 348 ft, and lateral dip is 322 ft.

- TABLE 2: INPUT PARAMETERS REQUIRED TO DETERMINE THE EXTENT OF THE INJECTION BUBBLE

Q_i	Injection rate	220000	ft^3/day
t_i	Injection time	90	days
K	Hydraulic conductivity	20	ft/day
B	Thickness of aquifer	200	ft
dh/dx	Hydraulic gradient	0.001	ft/ft
n	Porosity	0.3	-

SECTION VI.B.2: RESIDENCE TIME OF INJECTED WATER

- A simulation with these delay times was conducted using the TxASR app to determine the effects of regional groundwater flow on the movement of the injected bubble. We assume that the residence time (i.e., storage time, delay time) of injected water after injection may vary from 100 to 300 days.
- The series of graphs in **Figure 3** illustrate the movement of the injection bubble during 100-day delay intervals. **Figure 3** indicates that the injected bubble moves 6.67 ft per 100 days in the direction of regional groundwater flow. It indicates that for a maximum of 300 days of storage the bubble will move 13.34 ft in the direction of regional groundwater flow.
- A simulation of recoverability (**Figure 4**) shows that the recovery efficiency when ($V_{injected}$=V_{pumped}) varies from 97.1% to 94.5%. Therefore, the residence time of 300 days shows a reduced recovery efficiency of only 2.6%.

- TABLE 3: INPUT PARAMETERS REQUIRED FOR DETERMINING THE EFFECTS OF RESIDENCE TIME ON INJECTED WATER. NOTE THE VARIED DELAY TIMES.

Q_i	Injection rate	220000	ft^3/day
Q_p	Pumping rate	220000	ft^3/day
t_i	Injection time	[90,90,90]	days
t_d	Delay time	[100, 200, 300]	days
t_p	Pumping times	1 - 120	days
K	Hydraulic conductivity	20	ft/day
B	Thickness of aquifer	200	ft
dh/dx	Hydraulic gradient	0.001	ft/ft
n	Porosity	0.3	-

SECTION VI.B.3: MAXIMUM HORIZONTAL AND VERTICAL EXTENT OF INJECTED WATER

- Results showing the horizontal and vertical extent of injected water along with appropriate methods for simulation are presented in Section VI.B.1. of this document. Specifically, **Figures 1 and 2** provide detailed information on the horizontal and vertical extent of injected water.

- Note that the horizonal extent is determined by the extent of the injection bubble and vertical extent is determined by changes in piezometric surface (mounding). The vertical extent of the injection cannot be determined with the TxASR app because it is a 2-D simulation and assumes uniformity through the thickness of the aquifer. More complex, 3-D simulations are required for a vertical extent of the injection bubble.

SECTION VI.B.4: MAXIMUM HORIZONTAL AND VERTICAL EXTENT OF BUFFER ZONE

- A simulation of a buffer zone where the native fraction is 0% (i.e., no native groundwater is pumped) and there is a buffer zone of non-native water in the aquifer whose minimum thickness is at least 10% of the radius of the injected water was determined using the TxASR app.
- **Figure 5** shows that native fraction is 0% and the radius of extracted water upstream of the aquifer is 10% of the radius of injected water
- This simulation indicates that the first cycle of operation would only yield 66.67% recovery efficiency. Pumping time would be limited to 60 days. See **Figures 6** for recovery efficiencies vs time.
- Vertical extent is not presented but the potentiometric surface would be determined by using the calculated pumping time of 60 days. Again, more complex, 3-D simulations are required for a vertical extent of the injection bubble.

- TABLE 4: INPUT PARAMETERS REQUIRED TO DETERMINE THE HORIZONTAL EXTENT OF THE BUFFER ZONE.

Q_i	Injection rate	220000	ft^3/day
Q_p	Pumping rate	220000	ft^3/day
t_i	Injection time	90	days
t_d	Delay time	300	days
t_p	Pumping times	1 - 120	days
K	Hydraulic conductivity	20	ft/day
B	Thickness of aquifer	200	ft
dh/dx	Hydraulic gradient	0.001	ft/ft
n	Porosity	0.3	-

SECTION VI.C.1: THE EFFECT OF THE ASR PROJECT ON EXISTING OFFSITE WATER WELLS

- Mounding during injection was previously presented in Section VI.B.1 and **Figure 1.**
- Drawdown was determined in a similar fashion by simulating the extent of the potentiometric surface using the *confined well function* derived by Theis (1935).
- **Figure 7** depicts drawdown vs distance from well. As seen, the effects of drawdown on existing offsite water wells is negligible.

- TABLE 5: INPUT PARAMETERS USED TO DETERMINE THE EFFECTS OF ASR WELLS ON EXISTING OFFSITE WATER WELLS. PARAMETERS ARE PRESENTED FOR DRAWDOWN ONLY.

Q_p	Pumping rate	220000	ft^3/day
t_p	Pumping time	90	days
K	Hydraulic conductivity	20	ft/day
B	Thickness of aquifer	200	ft
T	Transmissivity	K*B	ft^2/day
S	Storage coefficient	0.005	-
r	Radius of well	0.65	ft
Dswl	Depth to static water level below ground surface	110	ft

SECTION VIII. DEMONSTRATION OF RECOVERABILITY

- The recovery efficiency of injected water was determined using the required inputs solved for and presented in Section VI.
- First, we present recovery efficiency values for when volume injected is equal to volume pumped
    - **Figure 8** indicates that during a 30-day injection period and 300 day delay a **recovery efficiency (RE) of 92.2%** may be obtained with a **native recovery (NR) of 7.71%.** Due to the fact that Qi=Qp in this scenario a pumping time of 30 days resulted in Vi=Vp.
    - **Figure 9** indicates that during a 60-day injection period and 300-day delay a **RE of 93.91%** may be obtained with a **NR of 6.09%.** Due to the fact that Qi=Qp in this scenario a pumping time of 60 days resulted in Vi=Vp.
    - **Figure 10** indicates that during a 90-day injection period and 300-day delay a **RE of 94.5%** may be obtained with a **NR of 5.5%.** Due to the fact that Qi=Qp in this scenario a pumping time of 90 days resulted in Vi=Vp.
    - We note that the recovery efficiencies at Vi=Vp require 5-8% of native water to be extracted. This water is most likely buffer zone water, that is established during the implementation of the buffer zone. This may not be ideal if multiple cycles are conducted, unless the buffer zone is replenished. Monitoring of extracted ground water will provide additional information regarding the extent to which we are impacting buffer and/or native groundwater.
- A range of recovery efficiencies with respect to pumping time is presented in **Figure 11.**
    - As seen, a recovery efficiency of 100% may not be obtained unless a significant amount of native water is pumped. Additionally, a recovery efficiency of 100% may not be obtained unless a larger volume of water is pumped than was initially injected.
- Second, we present recovery efficiencies if no native water is extracted. This data is obtained from **Figure 11.**
    - During a 30-day injection period and 300 day delay a maximum **recovery efficiency (RE) of 80%** may be obtained to ensure that native recovery **(NR) is 0%.** Pumping may only occur for 24 days at the current pumping rate to ensure that no native water is recovered.

- During a 60-day injection period and 300-day delay a maximum recovery **efficiency (RE) of 85%** may be obtained to ensure that native recovery **(NR) is 0%.** Pumping may only occur for 51 days at the current pumping rate to ensure that no native water is recovered.
- During a 90-day injection period and 300-day delay a maximum **recovery efficiency (RE) of 87%** may be obtained to ensure that native recovery **(NR) is 0%.** Pumping may only occur for 78 days at the current pumping rate to ensure that no native water is recovered.

- TABLE 6: INPUT PARAMETERS REQUIRED FOR DEMONSTRATION OF RECOVERABILITY

Q_i	Injection rate	220000	ft^3/day
Q_p	Pumping rate	220000	ft^3/day
t_i	Injection time	[30,60,90]	days
t_d	Delay time	[300,300,300]	days
t_p	Pumping times	1 - 120	days
K	Hydraulic conductivity	20	ft/day
B	Thickness of aquifer	200	ft
dh/dx	Hydraulic gradient	0.001	ft/ft
n	Porosity	0.3	-

FIGURES: PART I - EXAMPLE RESULTS USING THE TXASR APP

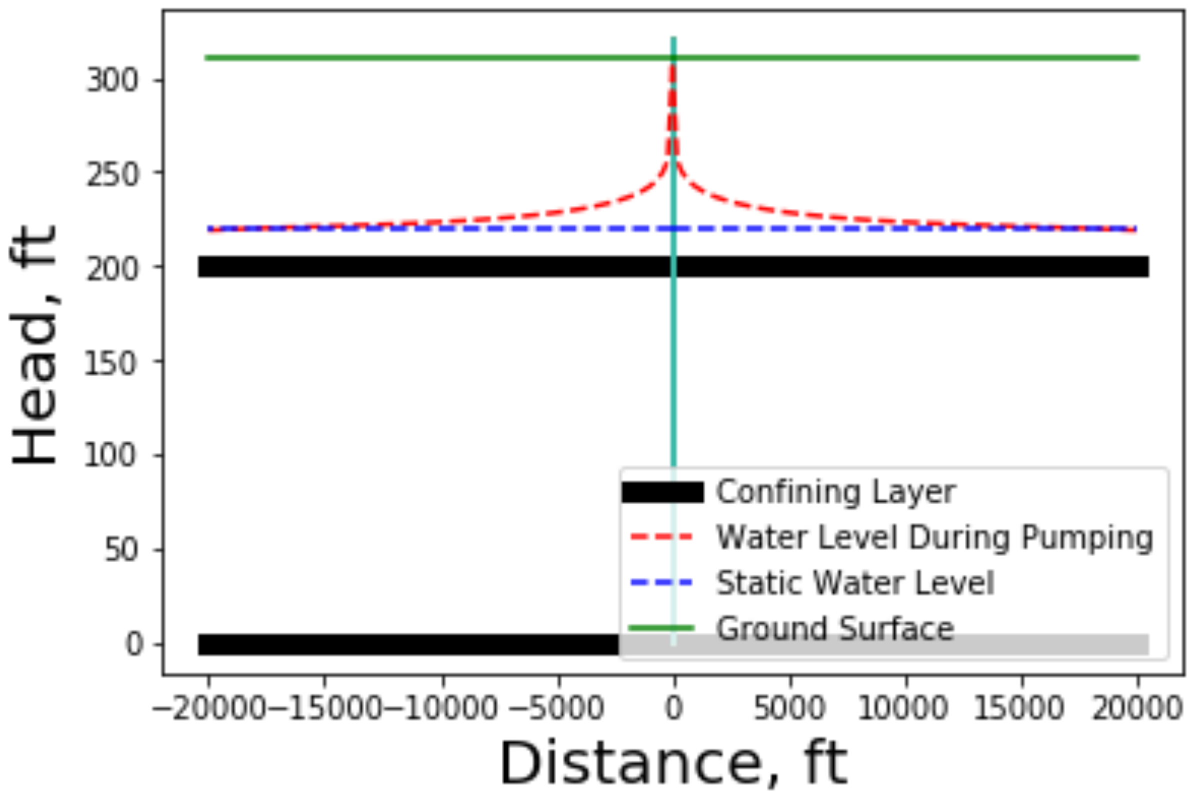

FIGURE 1: ILLUSTRATION OF POTENTIOMETRIC SURFACE DURING INJECTION. MOUNDING EFFECTS.

EXAMPLE Attachment B

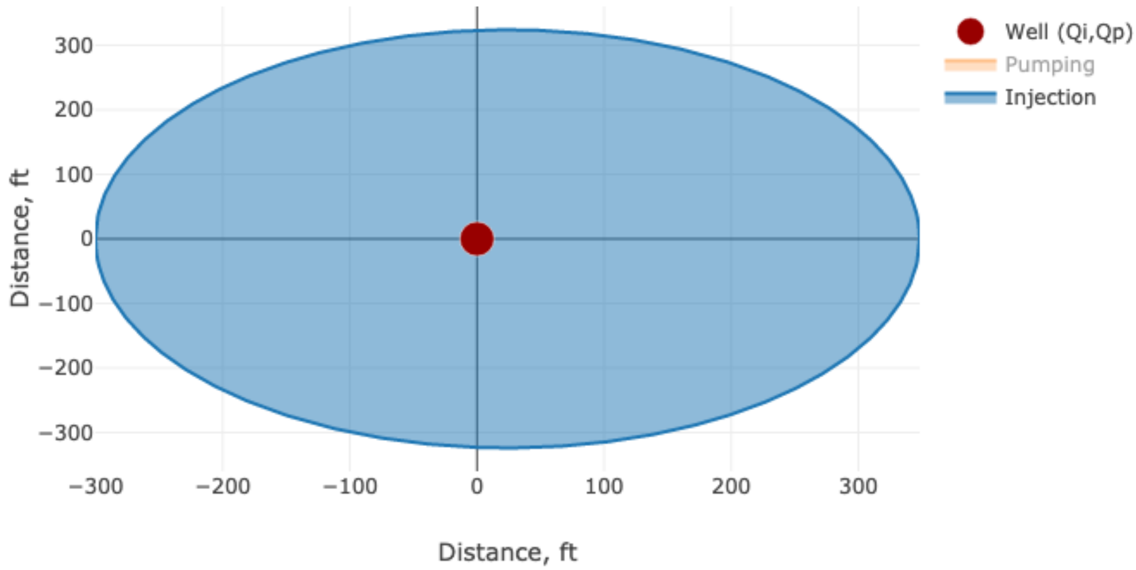

FIGURE 2: INJECTION FRONT ('INJECTION BUBBLE')

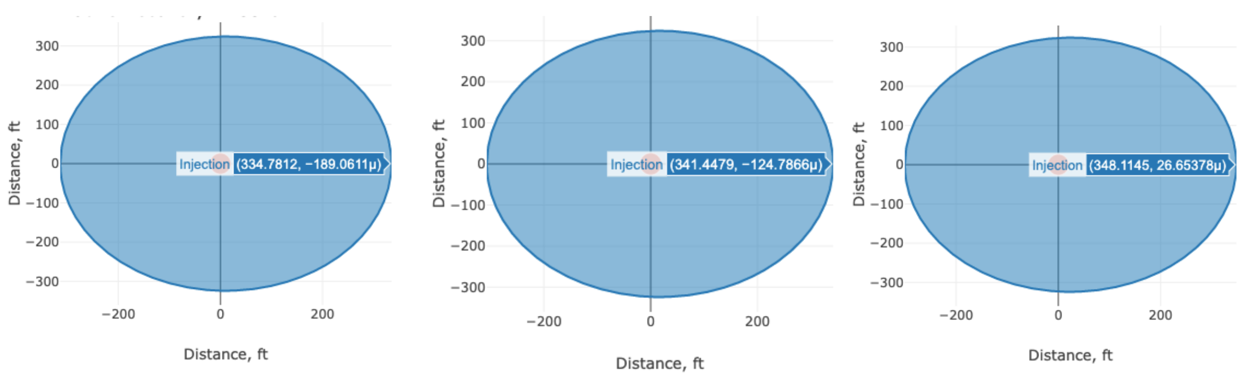

FIGURE 3: INJECTED BUBBLE POSITION AFTER 100, 200, AND 300 DAYS OF STORAGE. THE FRONT POSITIONS ARE 334.78, 341.45, AND 348.11 FT.

****EXAMPLE Attachment B****

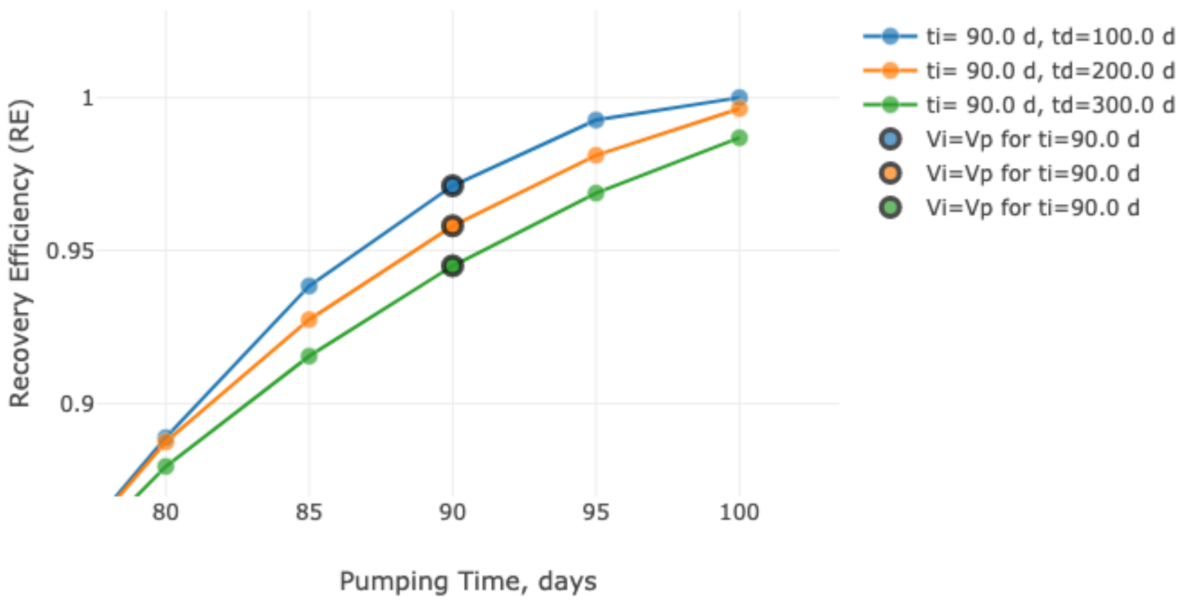

FIGURE 4: RECOVERY EFFICIENCY WITH VARIED DELAY (100, 200, 300 DAYS DELAY)

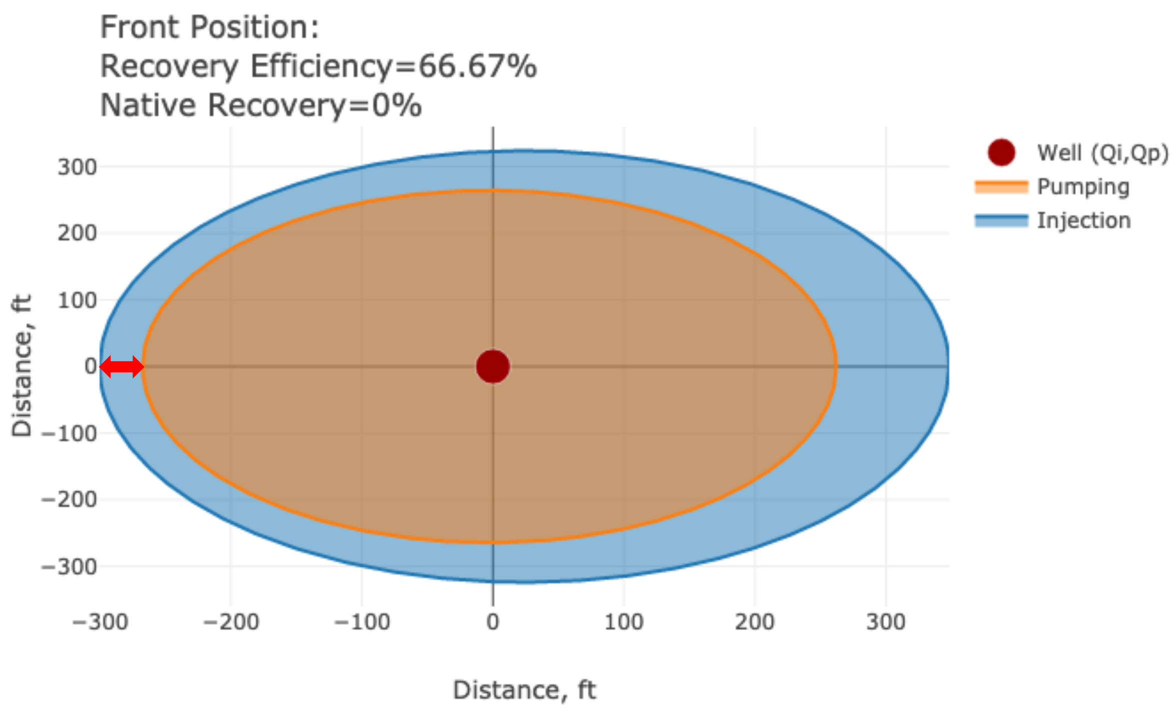

FIGURE 5: INJECTION AND PUMPING FRONTS DURING BUFFER ZONE GENERATION. THE RED ARROWS INDICATE WHERE THE RADIUS OF EXTRACTED WATER UPSTREAM OF THE AQUIFER IS 10% OF THE RADIUS OF INJECTED WATER

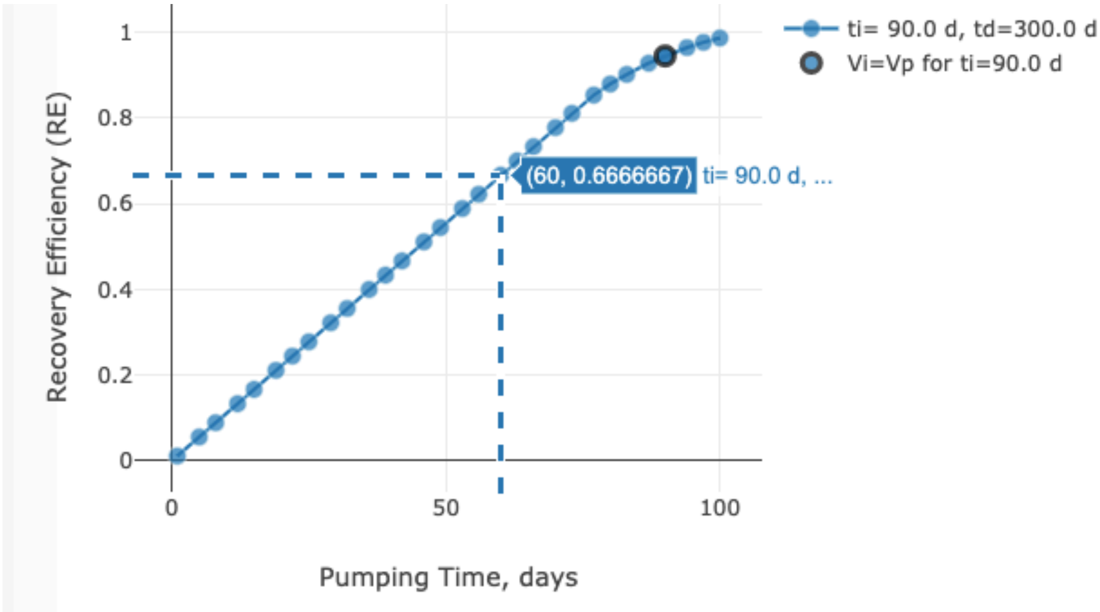

FIGURE 6: RECOVERY EFFICIENCY VS PUMPING TIME. SELECTED POINT INDICATES MAXIMUM PUMPING TIME TO ESTABLISH THE BUFFER ZONE.

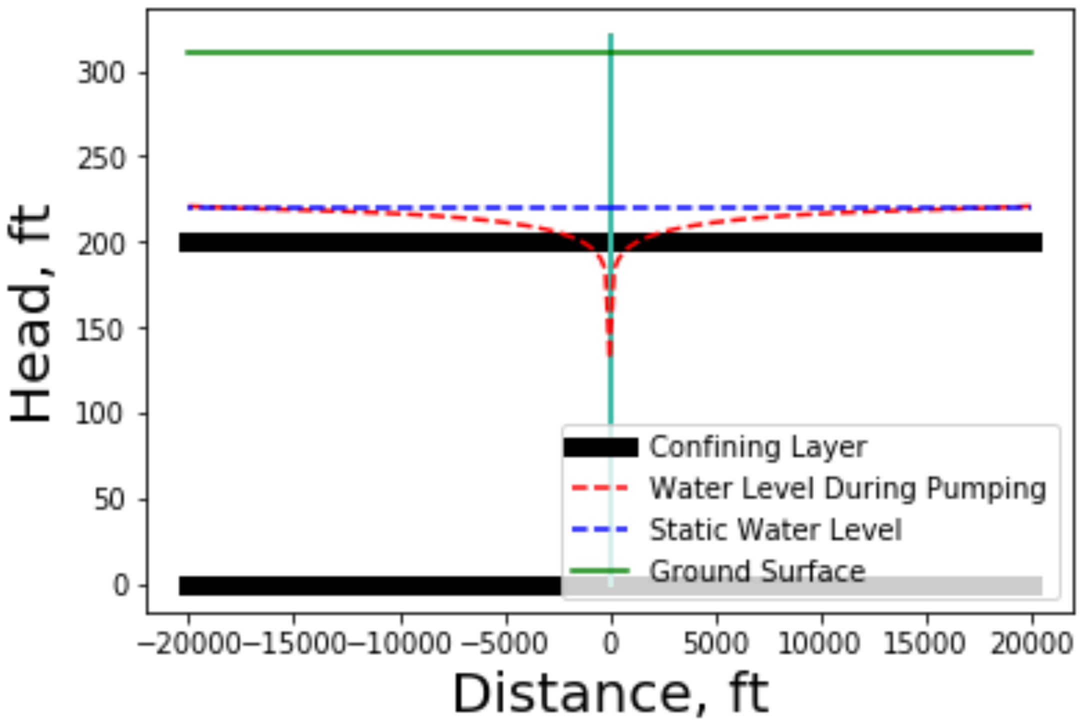

FIGURE 7: ILLUSTRATION OF POTENTIOMETRIC SURFACE DURING PUMPING. DRAWDOWN EFFECTS.

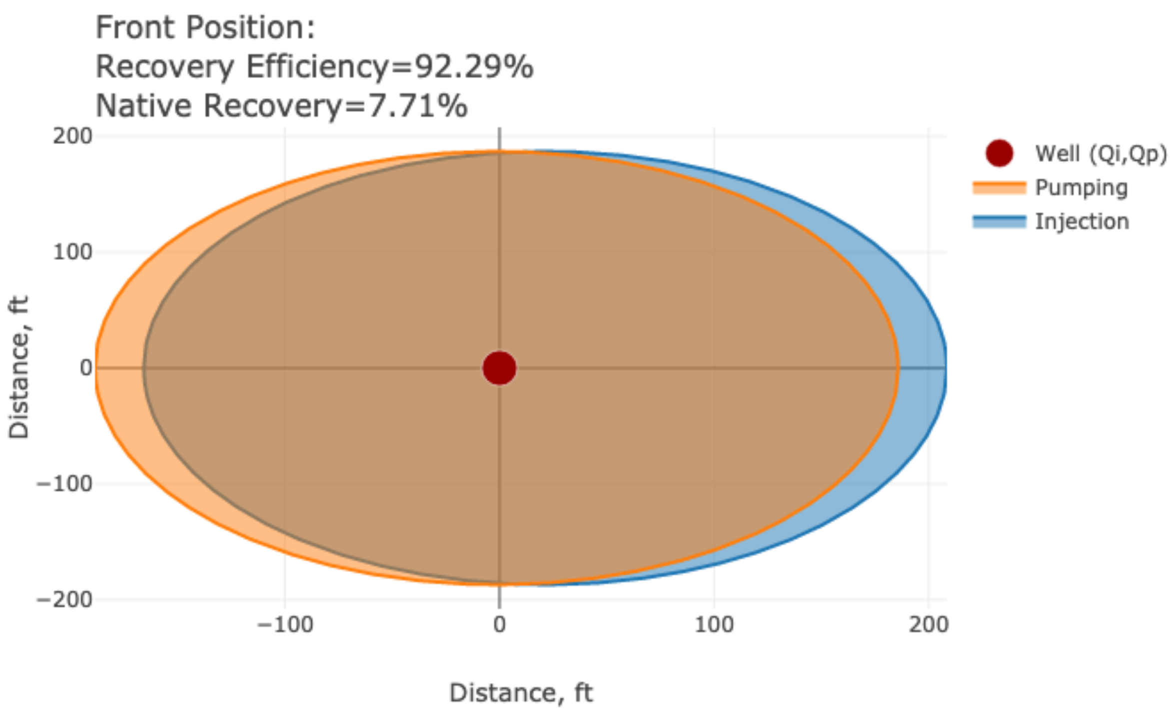

FIGURE 8: INJECTION AND PUMPING FRONTS FOR A 30-DAY INJECTION, 300-DAY DELAY, AND 30-DAY PUMPING PERIOD.

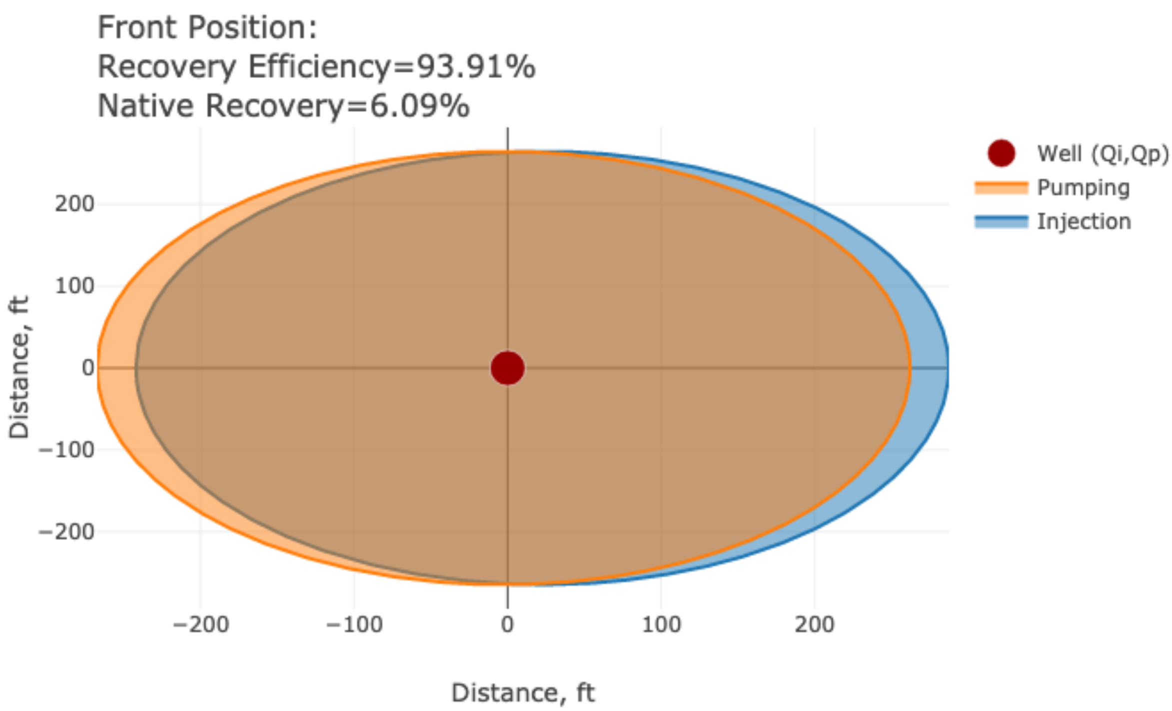

FIGURE 9: INJECTION AND PUMPING FRONTS FOR A 60-DAY INJECTION, 300-DAY DELAY, AND 60-DAY PUMPING PERIOD

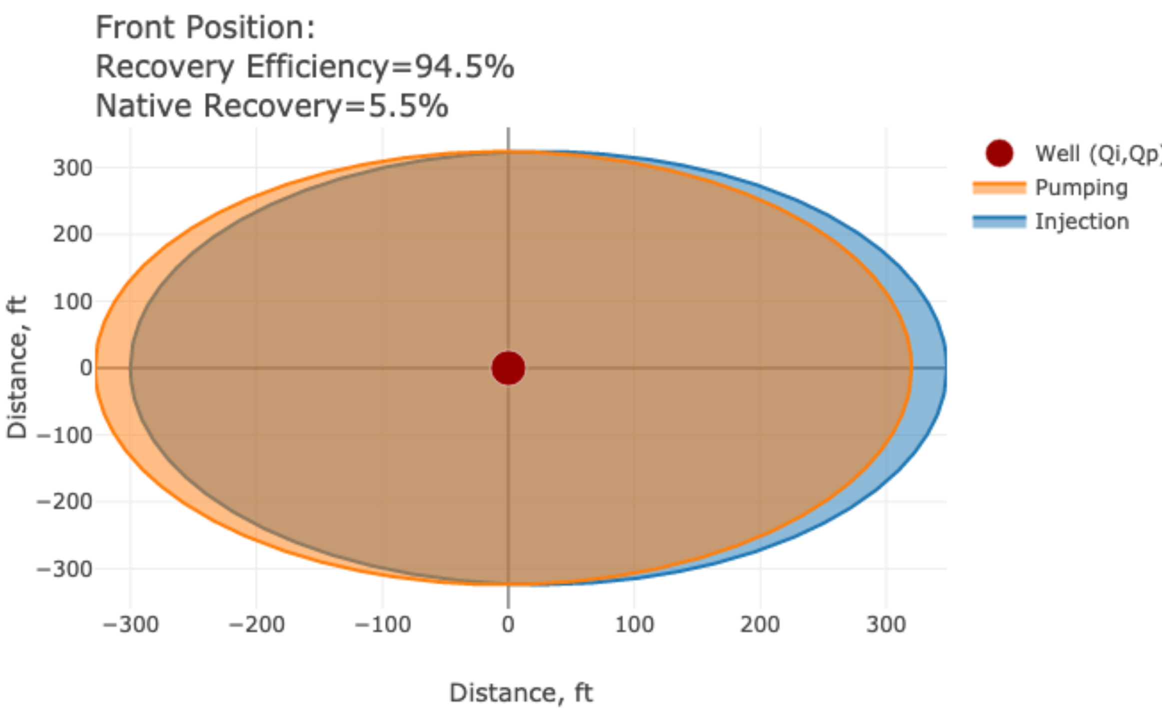

FIGURE 10: INJECTION AND PUMPING FRONTS FOR A 60-DAY INJECTION, 300-DAY DELAY, AND 60-DAY PUMPING PERIOD.

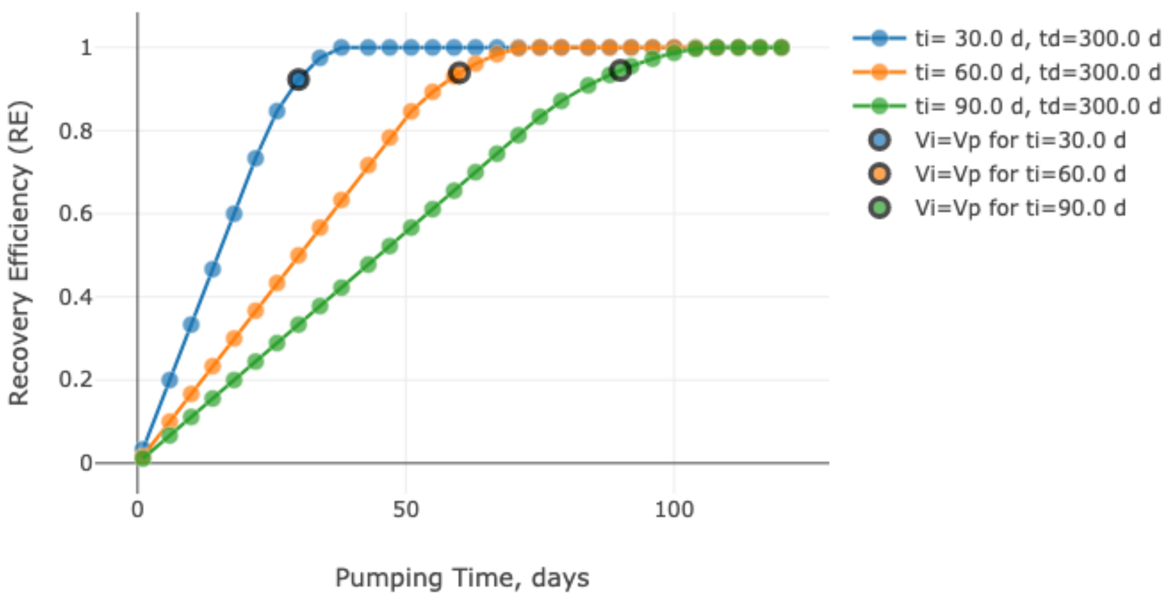

FIGURE 11: RECOVERY EFFICIENCY VS PUMPING TIME FOR THREE REPRESENTATIVE INJECTION TIMES AND A DELAY PERIOD OF 300 DAYS.

PART II. EXAMPLE RESULTS USING COMPLEX NUMERICAL SIMULATIONS

**Note that the example calculations in Part II are for ASR projects involving more than one ASR well or involving one ASR well with nearby pumping wells that alter the hydraulic gradient in time or alter the hydraulic gradient in an anisotropic manner.*

INTRODUCTION

The numerical modeling approach involved presented coupling a MODFLOW for groundwater flow and MODPATH for particle-tracking flow paths. It is important to ensure that numerical approaches are reproducible and accurate. Numerical models are most easily validated with analytical models. Prior to conducting complex simulations for the proposed project, a sensitivity analysis comparing a simple one-well case was conducted. Here, the TxASR app was used to validate the MODFLOW/MODPATH numerical approach using a base-case scenario. The sensitivity analysis is considered a "one-off" sensitivity analysis. The parameters for the base-case scenario are listed in **table 7.** The results for the sensitivity analysis are presented in **table 8**, as seen aquifer parameters were varied, and recovery efficiencies were compared for validation. The results indicate that the recoveries predicted with the numerical model are very similar to that of the analytical solution (TxASR App). With this data we can more confidently move forward with complex numerical simulations.

TABLE 7: PARAMETERS THAT DESCRIBE AN ASR SCENARIO USED FOR BENCHMARKING AND VALIDATING THE RECOVERABILITY SIMULATED BY THE ANALYTICAL AND NUMERICAL APPROACHES

Qi	Injection rate	20,000	ft^3/day
Qp	Pumping rate	220,000	ft^3/day
ti	Injection time	330	days
td	Delay time	0	days
tp	Pumping time	30	days
n	Porosity in aquifer	0.3	-
K	Hydraulic conductivity	20	ft/day
dh/dx	Regional hydraulic gradient	0.001	ft/ft
B	Thickness of aquifer	100	ft
Vi	Injection Volume	6.60E+06	ft^3
Vp	Pumping Volume	6.60E+06	ft^3

TABLE 8: THE SENSITIVITY OF SIMULATED RECOVERABILITY TO CHANGES IN AQUIFER PARAMETERS AND ASR OPERATIONS USED IN THE BASE-CASE MODELING SCENARIO

Sensitivity Parameter	Numerical Model	Analytical Model
Hydraulic Gradient		
0.01	63.6%	63.6%
0.001	**96.0%**	**96.2%**
0.0001	99.5%	99.6%
Thickness		
50 feet	97.0%	97.3%
100 feet	**96.0%**	**96.2%**
200 feet	94.3%	94.6%
Hydraulic Conductivity		
6.8 ft/day	98.5%	98.8
20 ft/day	**96.0%**	**96.2%**
60 ft/day	82.4	82.9
Porosity		
30%	**96.0%**	**96.2%**
20%	95.1%	95.3%
15%	93.0%	93.3%
Injected Volume		
2.2E+06 ft3	92.8%	93.0%
6.6E+06 ft3	**96.0%**	**96.2%**
1.2E+07 ft3	97.5%	97.8%
Storage Period		
No Delay	**96.0%**	**96.2%**
100 days	94.4%	94.6%
200 days	92.7%	92.9%

SECTION VI.B.1: MAXIMUM VOLUME OF WATER INJECTED

Extent of the potentiometric surface:

- A simulation of the extent of the potentiometric surface was conducted using MODFLOW NWT groundwater model developed by Young and Kushnereit (2018). **Figure 12** show the location of 5 proposed ASR wells (red dots) along with the location of other surrounding existing offsite wells (black dots). **Figure 13** and the potentiometric surface prior to pumping of existing offsite wells (pre-development scenario). **Figure 14** shows the potentiometric surface during pumping of existing offsite well locations. Note that figure 14 considers the pumping of pumping wells not the proposed ASR wells. As seen, the surrounding wells have a strong effect on the regional groundwater flow. **Figure 15b** shows the potentiometric surface during injection of ASR well #5 when the existing offsite wells are not pumping. **Figure 16b** shows the potentiometric surface during injection of ASR well #5. The difference between **figure 15b and 16b** is as a result of pumping in nearby existing offsite wells.

Extent of injection front 'bubble':

- A simulation of the extent of the injection bubble was conducted using MODFLOW and MOD-PATH3DU. **Figure 17** shows the extent of the injection bubble of an arbitrary ASR well by particle tracking. ASR well in the down dip distance, up dip distance, and lateral distance, which are 282, 252, and 264 ft, respectively for the arbitrary scenario presented.

SECTION VI.B.2: RESIDENCE TIME OF INJECTED WATER

- A graphical representation of residence (i.e., delay, storage) time is not presented. **Table 8** show numerical calculations of the effects that residence time has on injected water.

SECTION VI.B.3: MAXIMUM HORIZONTAL AND VERTICAL EXTENT OF INJECTED WATER

- Results for the maximum horizontal and vertical extent of injected water are presented in previous figures. **Figure 17** previously provided an example of the horizontal extent of injected water in terms of the extent of the injection bubble. **Figure 15b and 16b** provide examples of the vertical extent of injected water in terms of hydraulic heads. Note that ore complex, 3-D simulations are required for a vertical extent of the injection bubble.

SECTION VI.B.4: MAXIMUM HORIZONTAL AND VERTICAL EXTENT OF BUFFER ZONE

- The horizontal and vertical extent of the buffer zone can be calculated in a similar manner as that of section VI.B3.

SECTION VI.C.1: THE EFFECT OF THE ASR PROJECT ON EXISTING OFFSITE WATER WELLS

- An example of effects on existing offsite water wells is presented in **figure 16b and 16c** during operations of ASR wells. In this scenario there are small effects during injection (**figure 16b**) but rather large drawdown effects during pumping (**figure 16c**). The effects are most effectively represented by indicating the change in hydraulic head at the offsite well locations.

SECTION VIII. DEMONSTRATION OF RECOVERABILITY

- **Figure 18** provides path lines for particle that were recovered and for particles that escaped during an ASR cycle that consisted of 64-moth injection and 4-month extraction. Effects of nearby pumping wells can be seen. Here two recovery efficiencies are noted. A **97.8% recovery efficiency** was estimated when the surround wells are not operational but when surrounding wells are operational (as shown in **figure 18**) a **recovery efficiency of 72.5%** was determined. This example denotes the importance of complex groundwater simulations when there are surrounding wells affecting the regional groundwater flow.

FIGURES: PART II - EXAMPLE RESULTS USING COMPLEX NUMERICAL SIMULATIONS

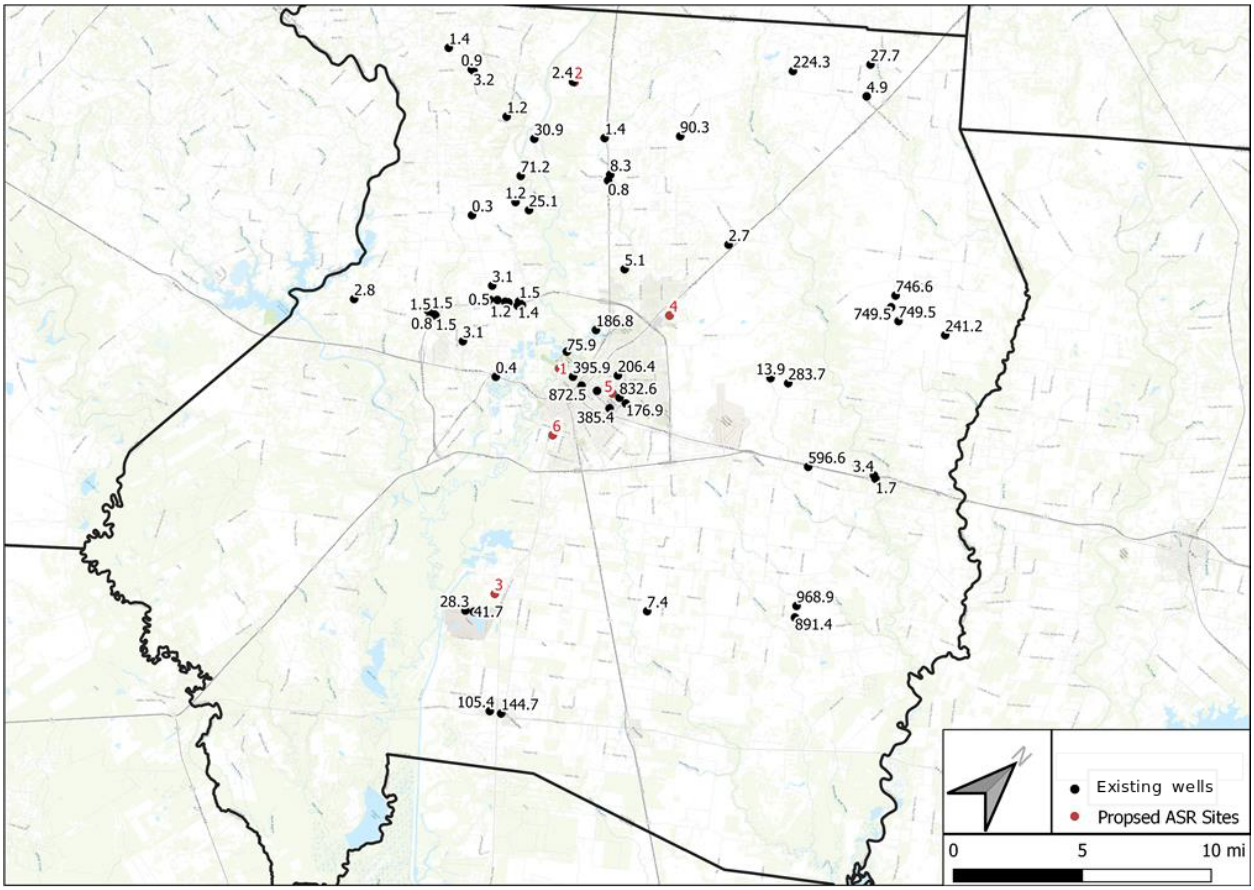

FIGURE 12: EXAMPLE MAP OF THE LOCATION OF 6 PROPOSED ASR WELLS (RED DOTS) ALONG WITH THE LOCATION OF EXISTING OFFSITE WELLS (BLACK DOTS).

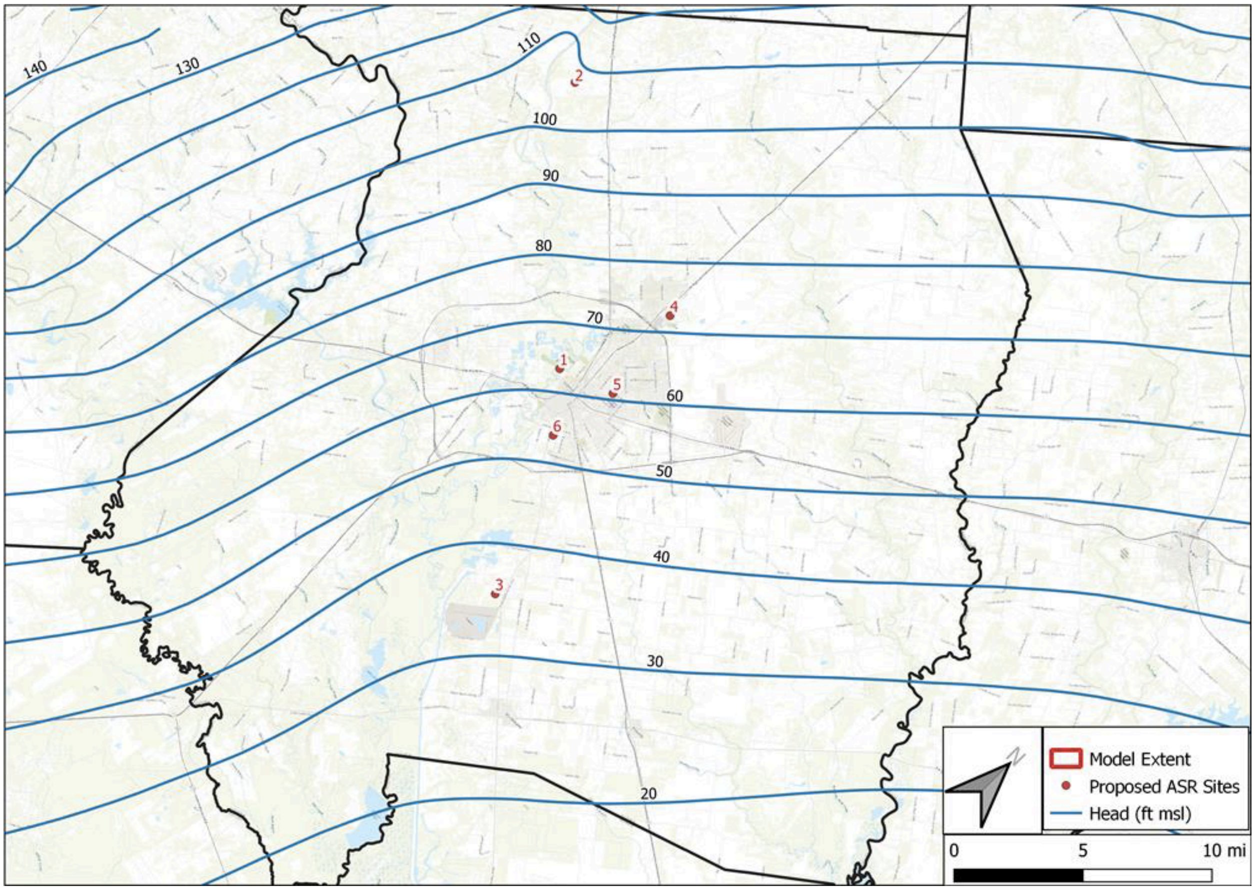

FIGURE 13: EXAMPLE MAP OF HYDRAULIC HEAD CONTOURS PRIOR TO PUMPING OF EXISTING OFFSITE WELL.

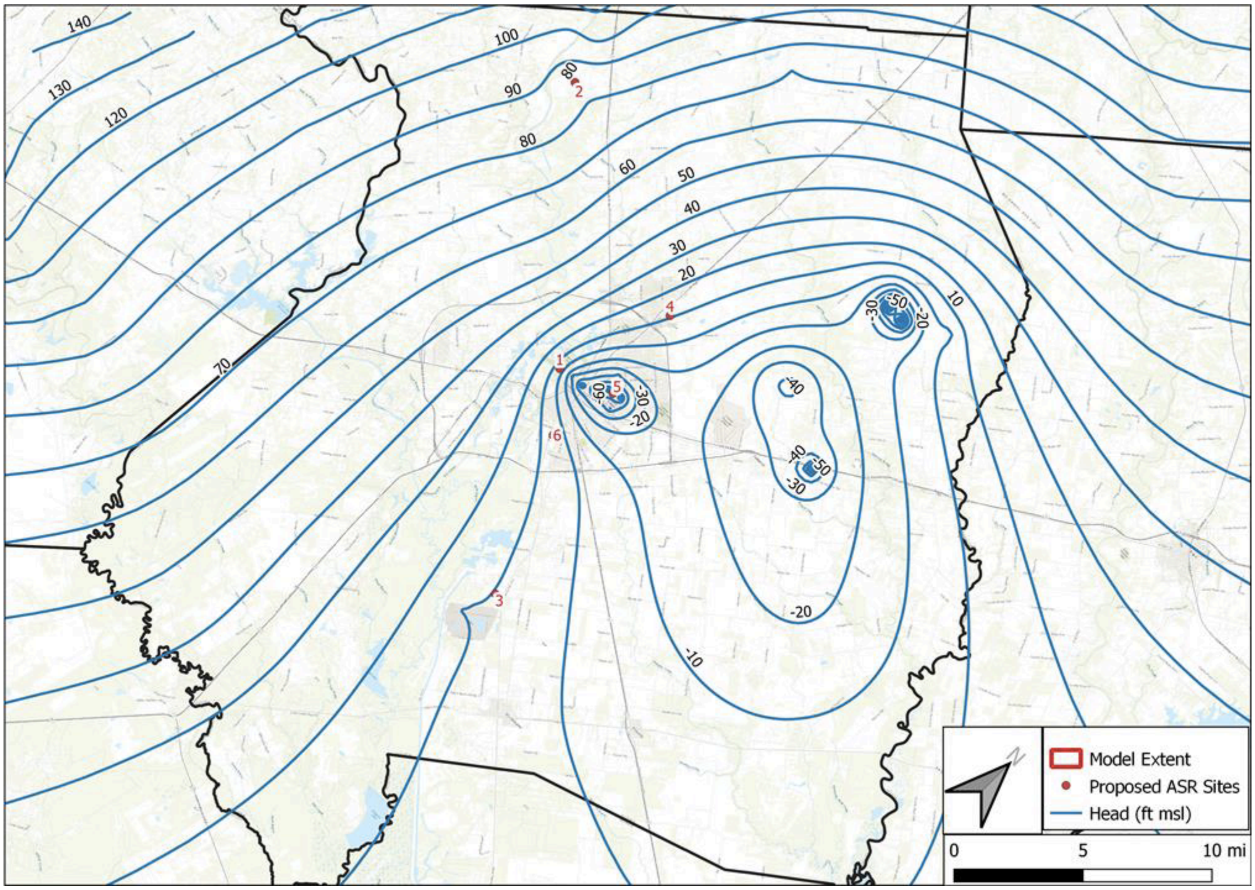

FIGURE 14: EXAMPLE MAP OF POTENTIOMETRIC SURFACE DURING PUMPING OF EXISTING OFFSITE WELL LOCATIONS. NOTE THAT MAP DENOTES THE EFFECTS ON POTENTIOMETRIC SURFACE DURING PUMPING EXISTING WELLS NOT ASR WELLS.

EXAMPLE Attachment B

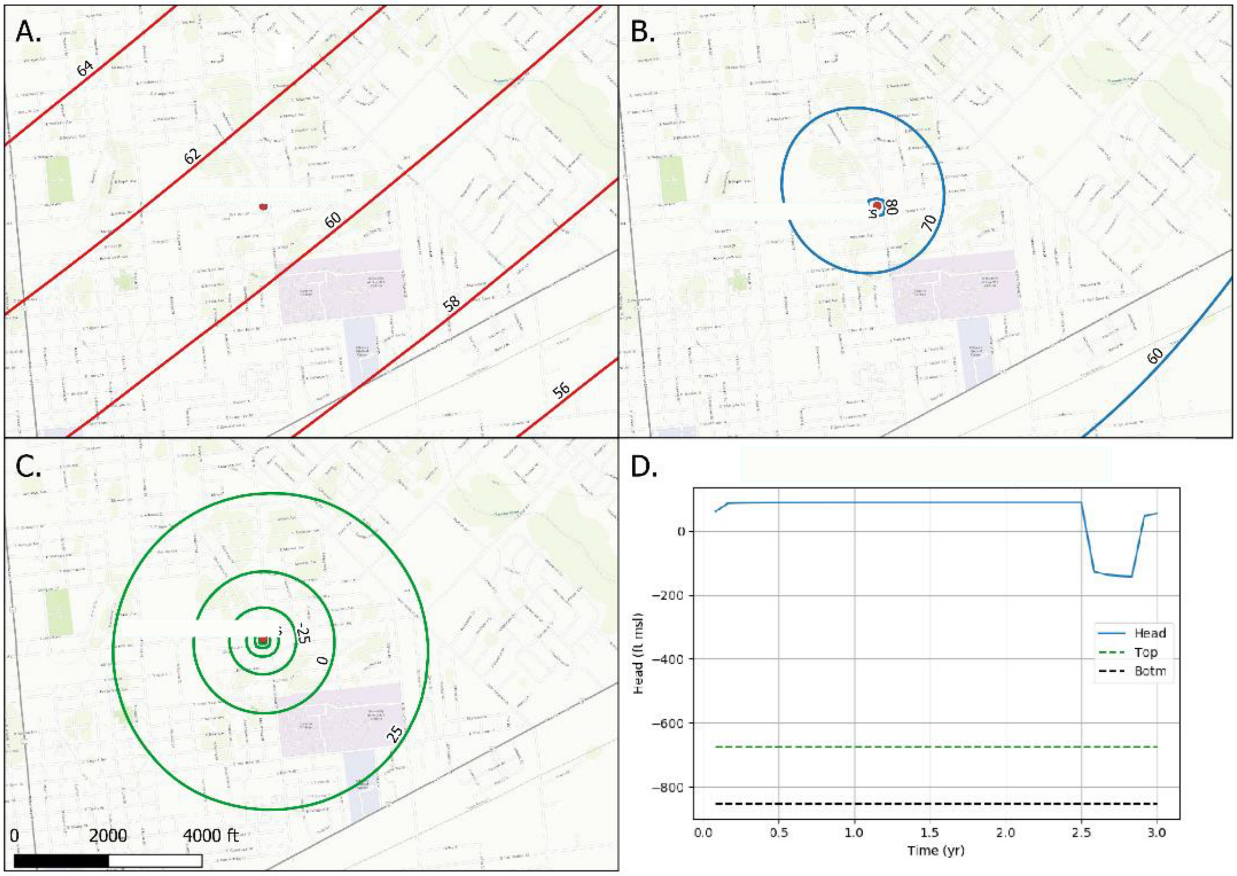

FIGURE 15: POTENTIOMETRIC SURFACE OF ASR WELL #5 ASSUMING THERE IS NO PUMPING OF EXISTING OFFSITE WELLS. (A) REGIONAL GROUNDWATER FLOW. (B) AFTER 29 MONTHS OF INJECTION. (C) AFTER 4 MONTHS OF PUMPING. (D) OPERATIONAL SCHEDULE FOR THE ASR WELL.

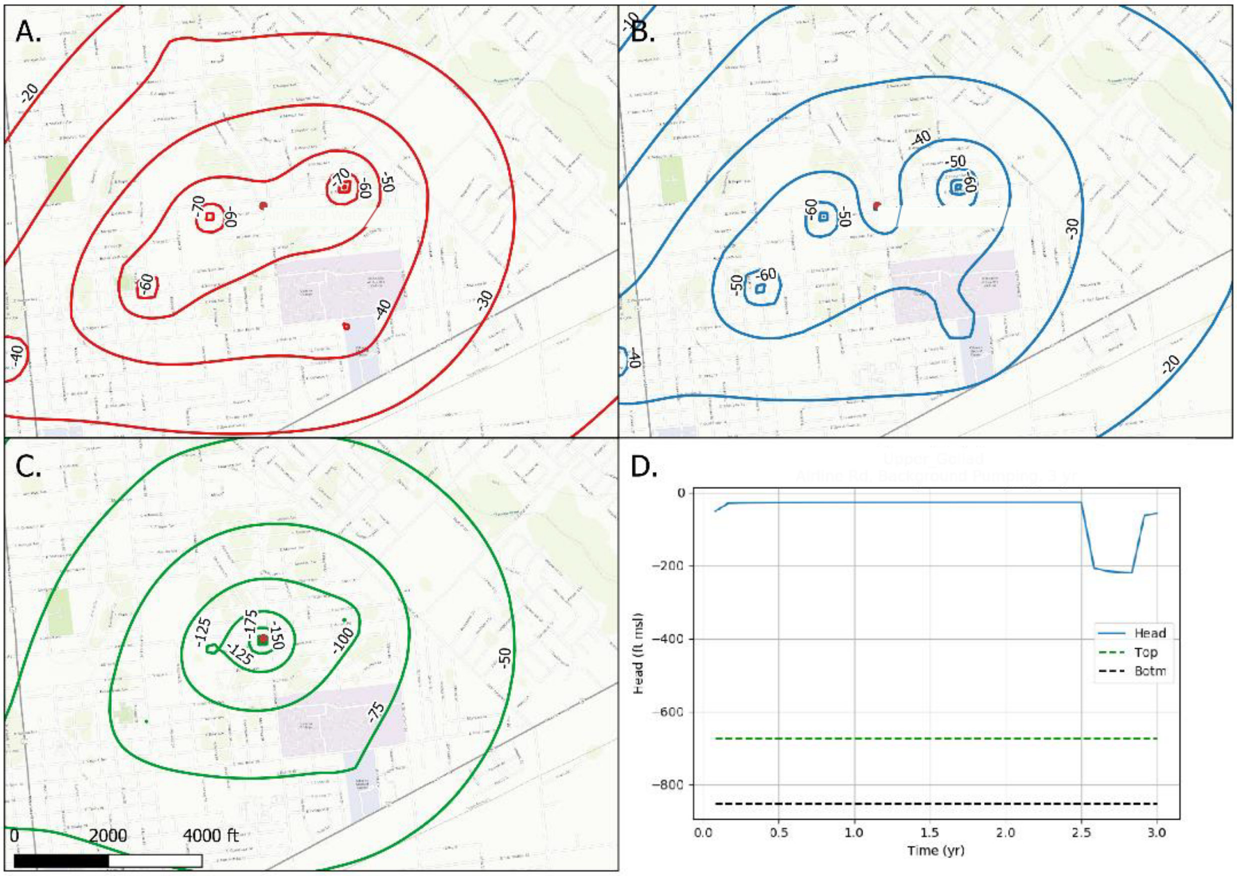

FIGURE 16: POTENTIOMETRIC SURFACE OF ASR WELL #5 ASSUMING EXISTING OFFSITE WELLS ARE ALSO OPERATIONAL AND PUMPING. (A) REGIONAL GROUNDWATER FLOW. (B) AFTER 29 MONTHS OF INJECTION. (C) AFTER 4 MONTHS OF PUMPING. (D) OPERATIONAL SCHEDULE FOR THE ASR WELL.

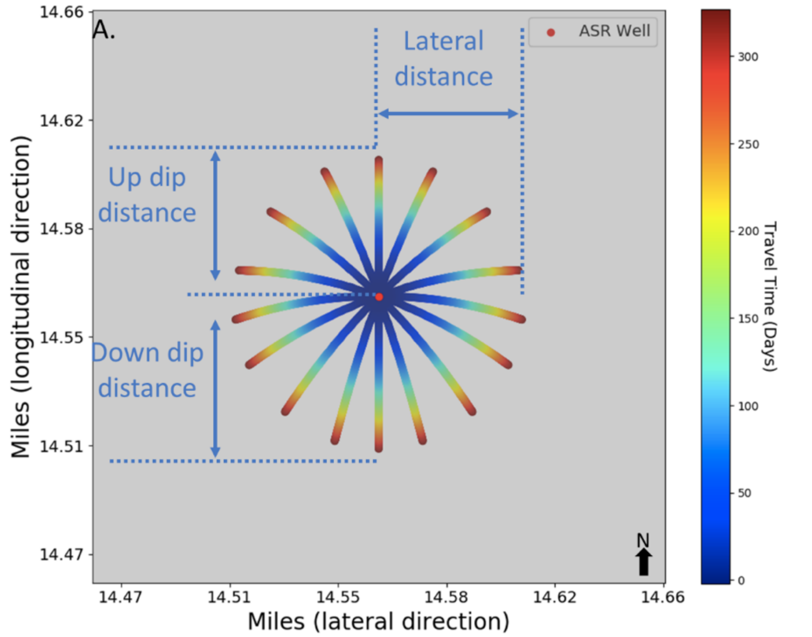

FIGURE 17: PARTICLE TRACKING RESULTS AN ARBITRARY ASR WELL USING MODFLOW AND MOD-PATH3DU. EXTENT OF THE INJECTION BUBBLE AFTER 330 DAYS OF INJECTION; DOWN DIP DISTANCE, UP DIP DISTANCE, AND LATERAL DISTANCE, ARE 282, 252, AND 264 FT, RESPECTIVELY.

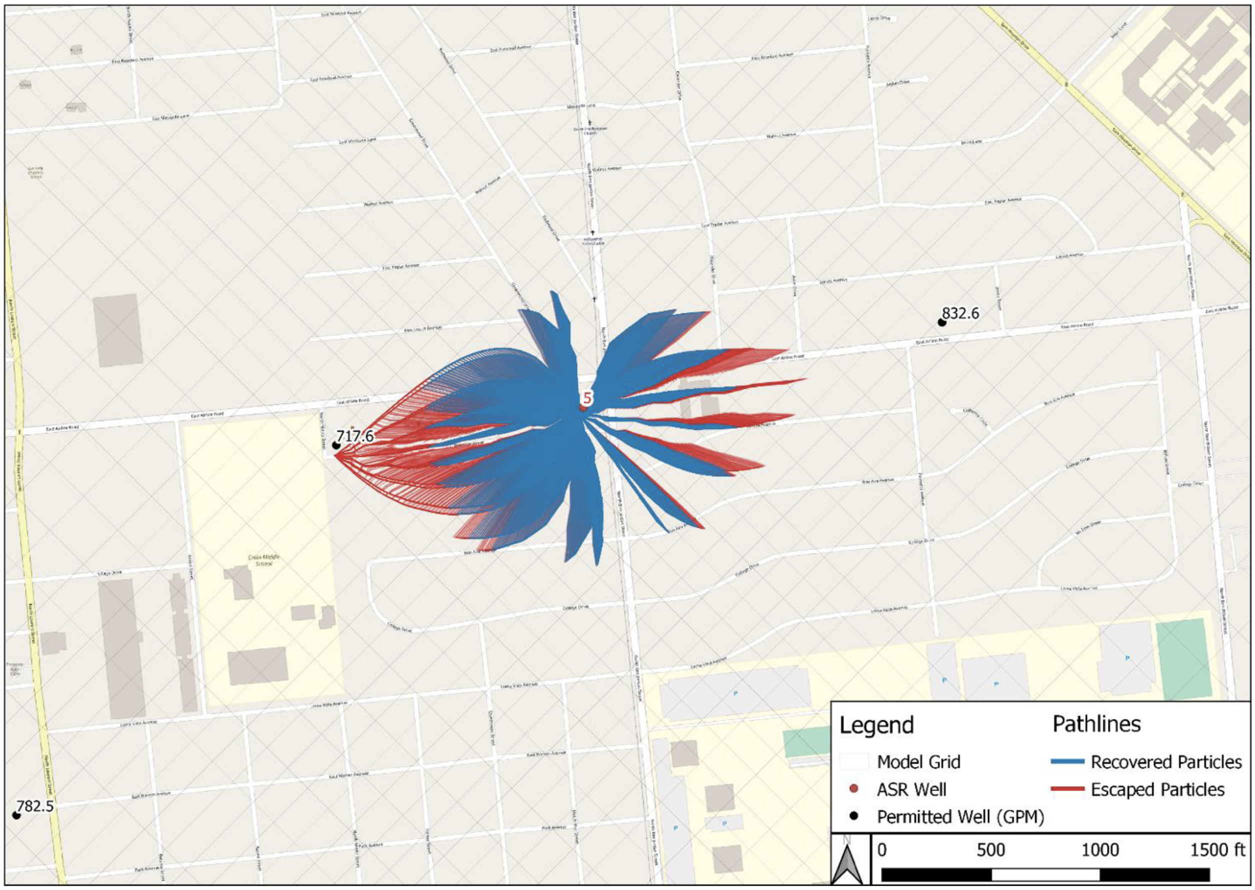

FIGURE 18: PATH LINES FOR PARTICLE THAT WERE RECOVERED AND FOR PARTICLES THAT ESCAPED DURING AN ASR CYCLE THAT CONSISTED OF 64-MOTH INJECTION AND 4-MONTH EXTRACTION. A RECOVERY EFFICIENCY OF 72.5% WAS DETERMINED.