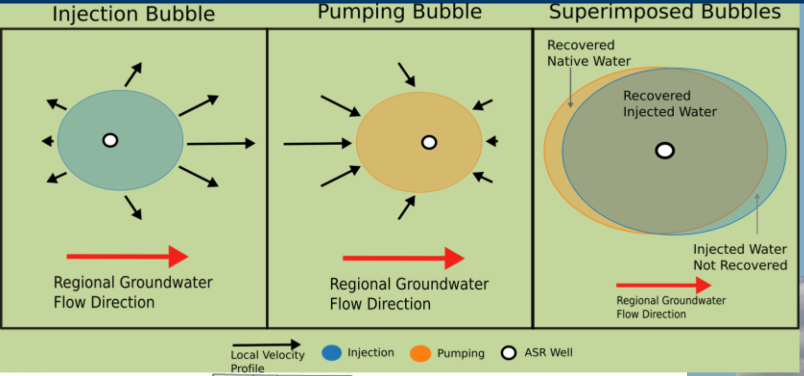
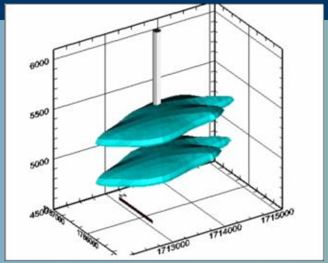
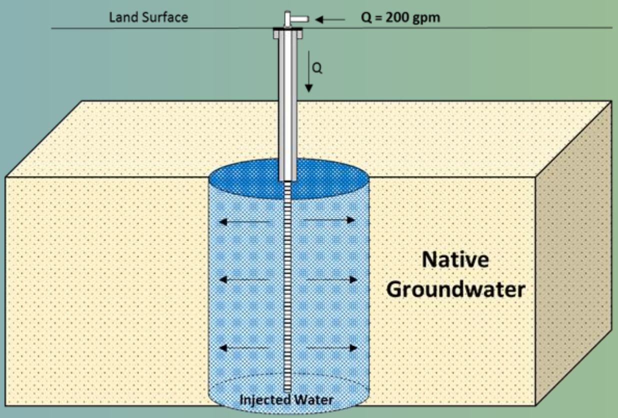
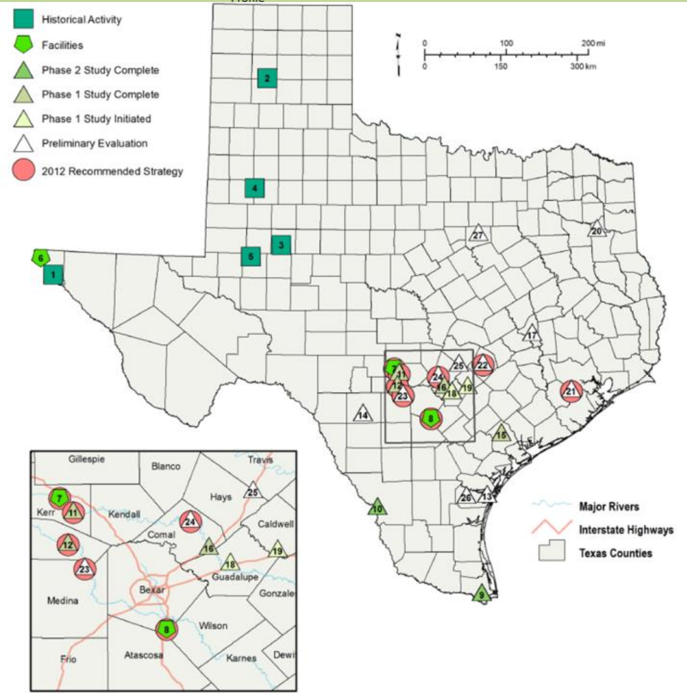
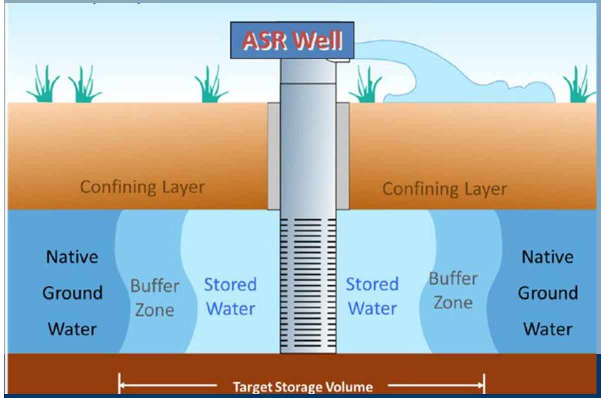
Aquifer Storage and Recovery: Calculating Recoverability











Presented By:

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August 9, 2018

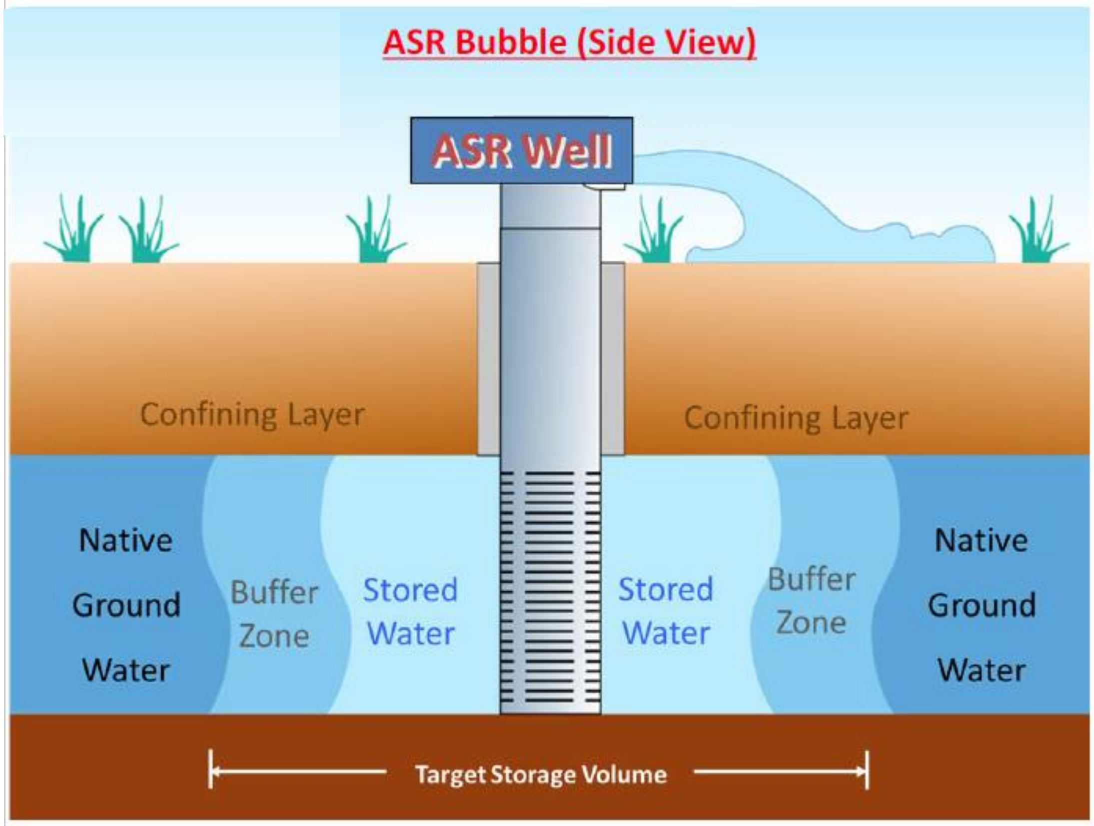
Outline

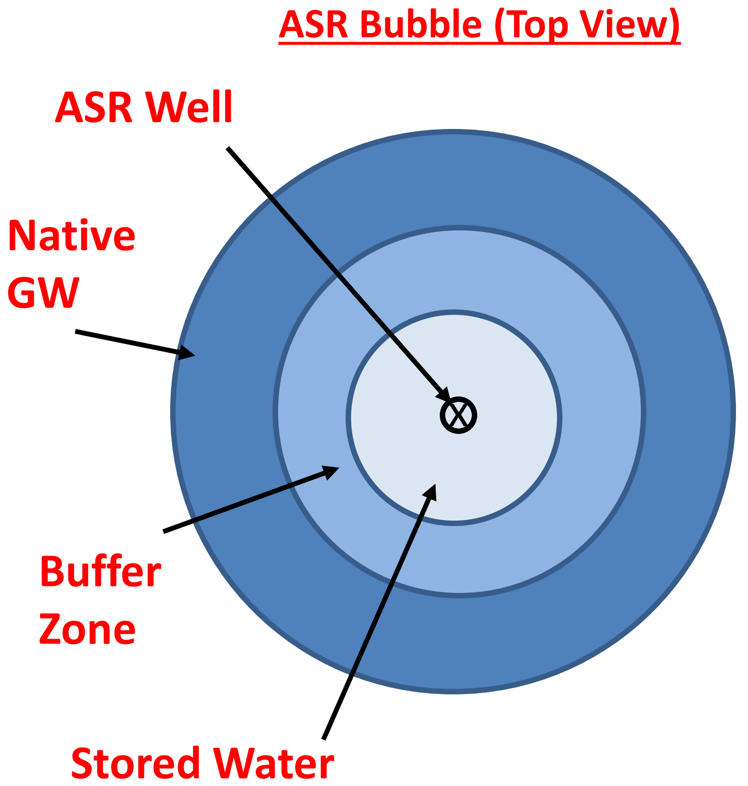
- What is Recoverability?
- Why is Recoverability Important?
- Approaches to Calculating Recoverability
- Example Application of Calculating Recoverability
  - Two-dimensional model
  - Three dimensional model
- Summary

Idealized Diagram of Stored ASR Water

ASR: The injection of water into a geologic formation, group of formations, or part of a formation that is capable of underground storage of water ***for later retrieval and beneficial use.***

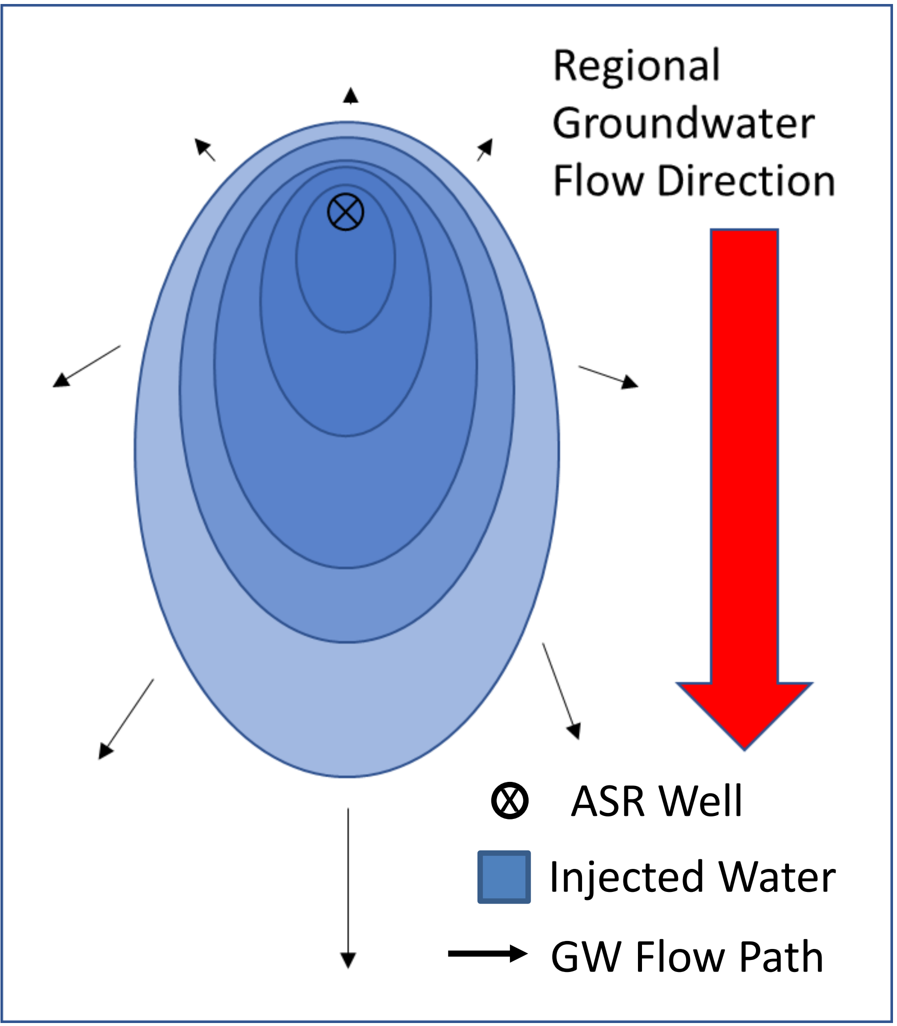
- TCEQ: 30TAC 331.2(8)



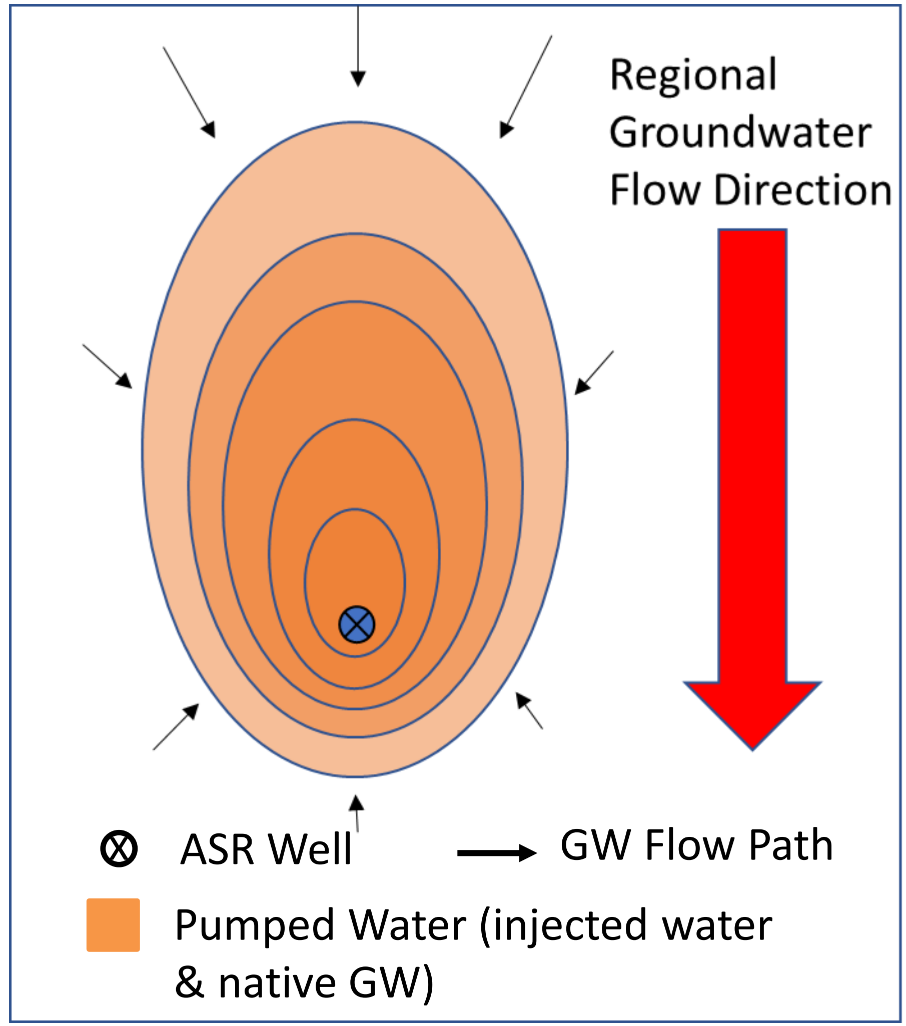


Aquifer Storage and Recovery Flow Fields

Injection of Water



Recovery of Groundwater



Recoverability of Injected Water (RE)

$$RE = \frac{V_r}{V_i} * 100\ \%$$

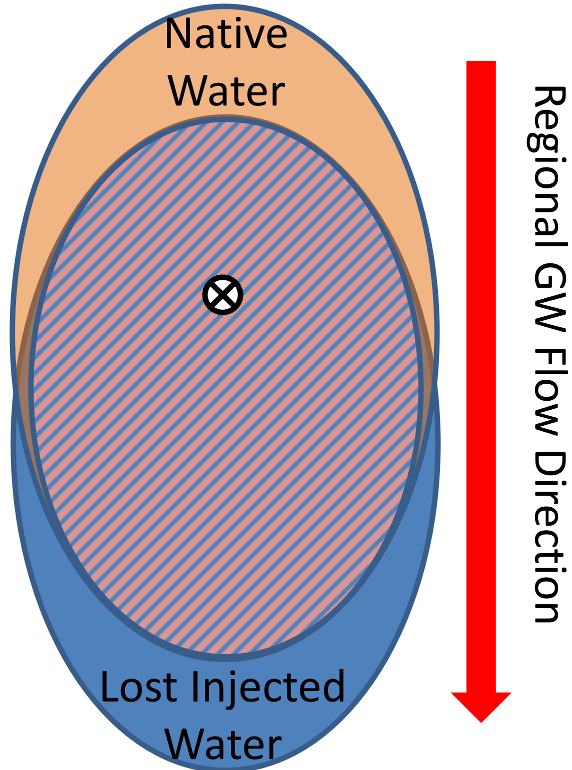
V_i = injected volume of water
V_r = recovered volume of injected water
V_p = pumped volume

Example

V_i = 100 acre-ft
V_r = 80 acre-ft
V_p = 95 acre-ft

$$\text{Recoverability} = \frac{80}{100} * 100\ \% = 80\%$$

$$\text{Lost Injection volume} = \frac{(100 - 80)}{100} * 100\ \% = 20\%$$



Pumped Groundwater

- Injected Water Recovered
- Native GW Recovered
- ⊗ ASR Well
- Injected Water Not Recovered

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Recovery of Native Groundwater (RNG)

$$RNG = \frac{(V_P - V_r)}{V_P} * 100\ \%$$

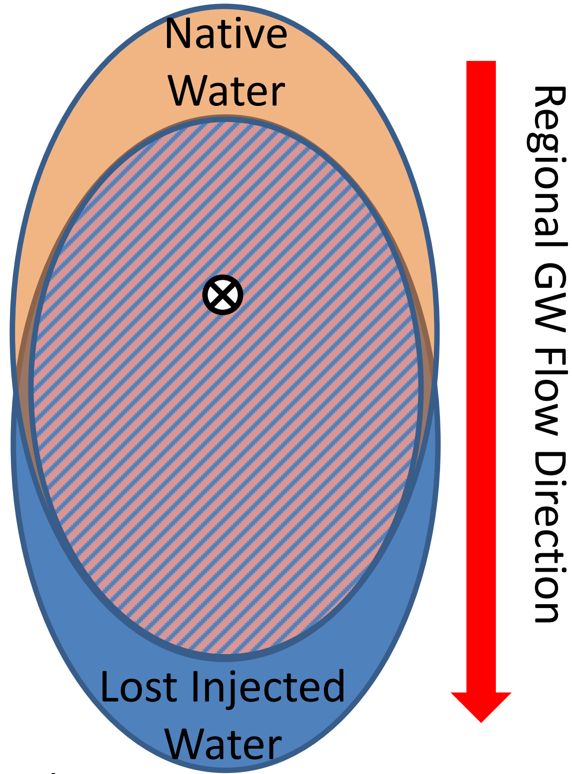
V_i = injected volume of water
V_r = recovered volume of injected water
V_p = pumped volume

Example

V_i = 100 acre-ft
V_r = 80 acre-ft
V_p = 95 acre-ft

Recovered Native GW = $\frac{(95-80)}{95} * 100\ \% = 15.8\ \%$

Recovered Injected Water = $\frac{80}{95} * 100 = 84.2\%$



Pumped Groundwater

- Injected Water Recovered
- Native GW Recovered
- ⊗ ASR Well
- Injected Water Not Recovered

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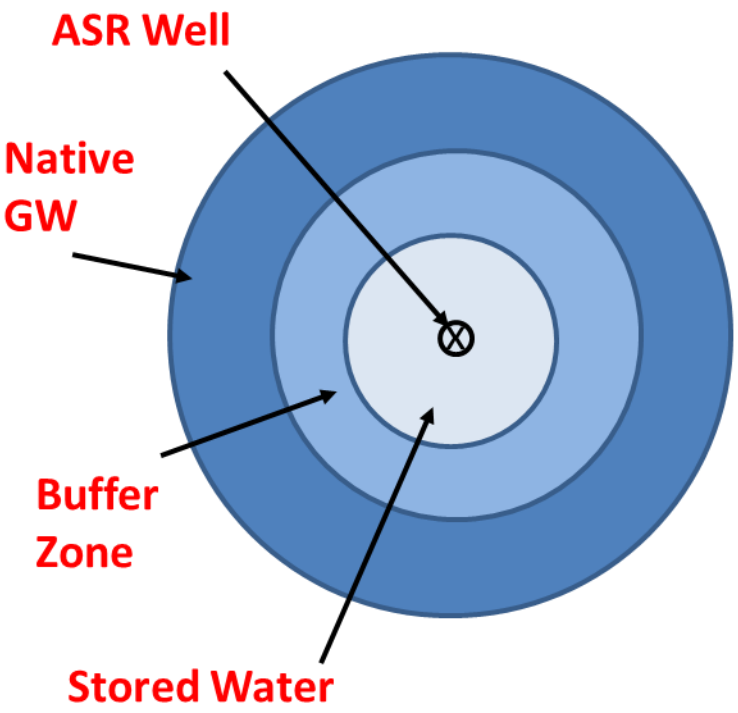
TCEQ ASR Authorization Application

- The **purpose of ASR is the underground storage of water and the subsequent retrieval of that *same* water. ASR is not injection of a volume of water and the subsequent retrieval of a like volume of water with no regard as to the source of the recovered water.**

- An ASR **project should be designed and operated to isolate the injected water from native groundwater.**

ASR Bubble (Top View)



TCEQ ASR Authorization Application

Required Elements:

- General Facility/Operator Information
- ASR Project Area
- Area of Review & Artificial Penetrations
- Well Construction & Closure
- Injection Well Operation
- Project Geology, Hydrogeology, and Geochemistry
- Demonstration of Recoverability

TCEQ Application for Class V Underground and Injection Control (UIC) Well for ASR

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.**

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.**

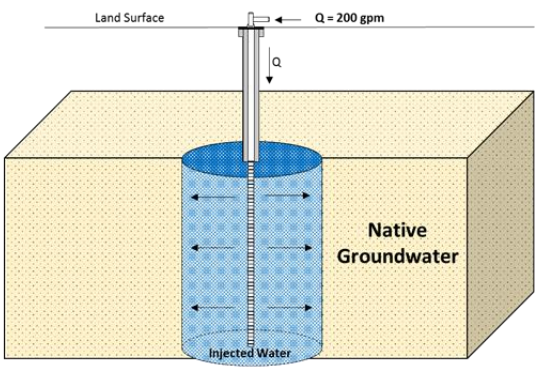
* From TCEQ application

Groundwater Flow Models For Pumping Impacts

Groundwater Models: Computational mathematical approximations describing groundwater flow and transport

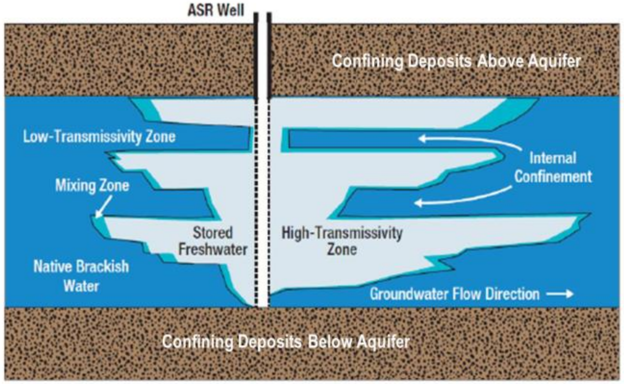
- Analytical Model
  (Theis Equation)
  - Equations have exact solution
  - Simplification of aquifer conditions
  - Typically assume homogeneous conditions
  - Risk for misuse is low

Homogenous Aquifer Conditions



- Numerical Model
  (MODFLOW – Groundwater Availability Model)
  - Equations approximate exact solution
  - Adaptable for complex groundwater flow systems
  - Labor intensive to set up
  - Risk for misuse is significantly greater than analytical modes

Heterogeneous Aquifer Conditions



(modified from Maliva et al., 2006).

University of Texas Development of 2-D Analytical Model (Bear and Jacob; 1965)

ASR App

Aquifer Storage and Recovery (ASR) Applet

The **ASR app** provides a simple way to assess the feasibility of water injection, storage and recovery.

Operational Parameters:

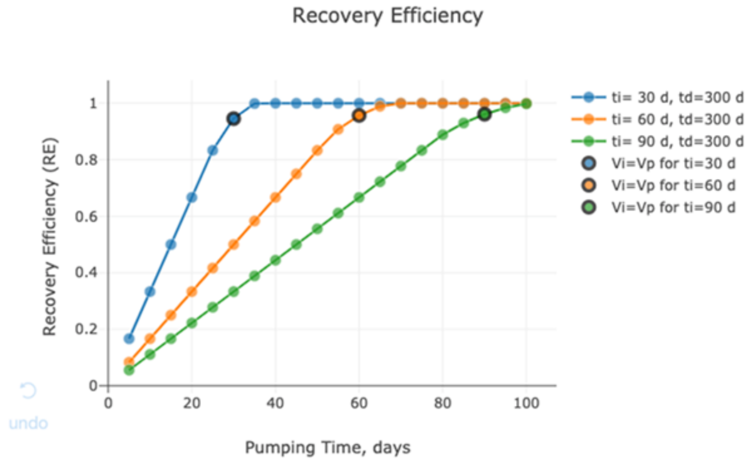
Injection Rate, ft^3/day	Puming Rate, ft^3/day	Time of Injection, day	Delay time, day	Time of Pumping, days
220000	220000	30,60,90	300,300,300	5,10,15,20,25,30,35,40,4

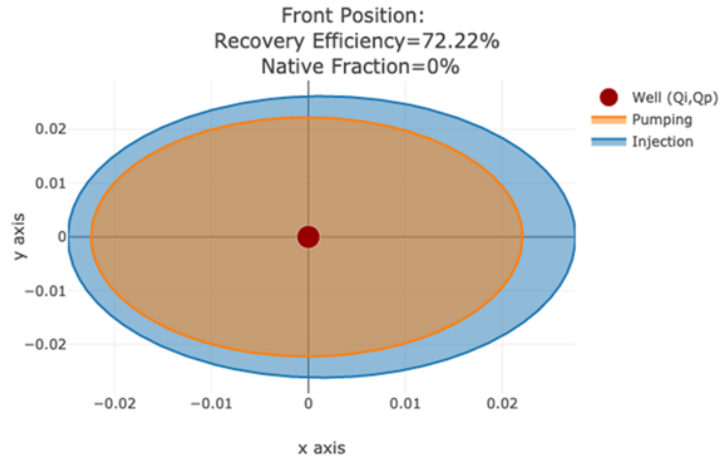
Physical Parameters:

Hydraulic Conductivity (Kd), ft/day	Hydraulic Gradient (dh/dx), ft/ft	Porosity (n), -	Thickness of Aquifer, ft	
20	0.001	0.3	100	SUBMIT

parameter options:

input option





From: TCEQ 2019 Trade Fair, Austin Texas

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University of Texas Development of 2-D Analytical Model (Bear and Jacob; 1965)

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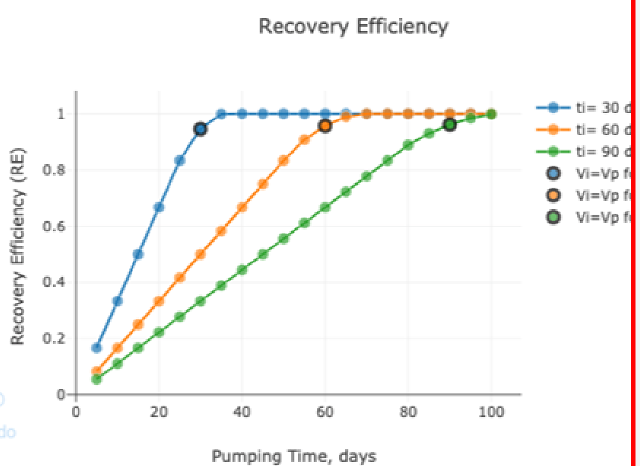
20	0.001	0.3	100

SUBMIT

parameter options:

input option



Input Parameters:

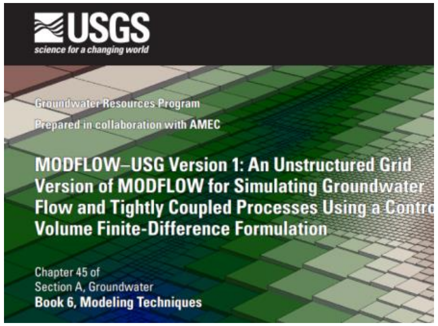
- Qi= injection rates
- Qp= pumping rates
- ti= injection time *(Multiple inputs supported)*
- tp= pumping time *(Multiple inputs supported)*
- td= delay time *(Multiple inputs supported)*
- B= thickness of aquifer
- n= porosity in aquifer
- K= hydraulic conductivity
- dh/dx = regional hydraulic gradient

From: TCEQ 2019 Trade Fair, Austin Texas

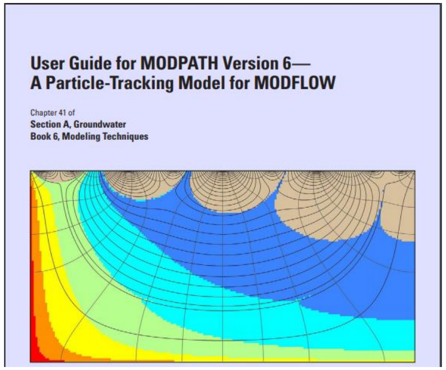
Numerical Model Approach

- MODFLOW for GW Flow
  - 2-dimensional or 3-dimensional
  - Homogeneous or Heterogeneous
  - Injection and Pumping Schedule
  - Grid refinement around ASR is required
- MODPATH for Flow Paths
  - Associate a particle with a volume of injected water
  - Assume slug flow – injected water fully displaces native water as it migrates outward into aquifer
  - Track capture of particles by wells to calculate recoverability
  - Geochemical reactions are ignored

Aquifer conditions, pumping rates



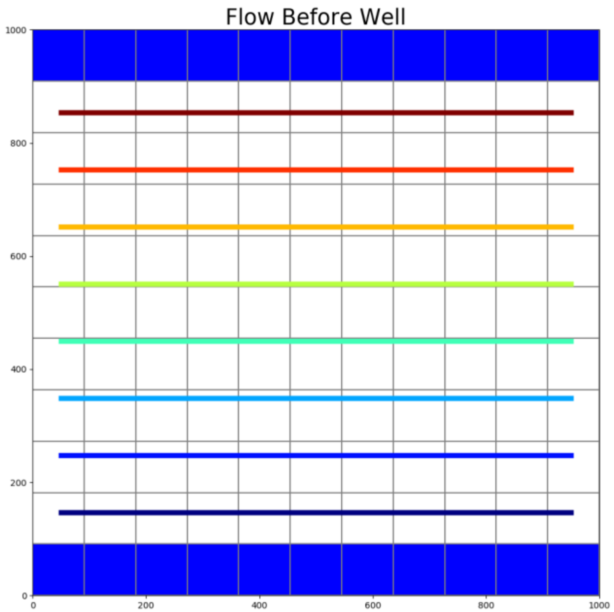
Groundwater velocities



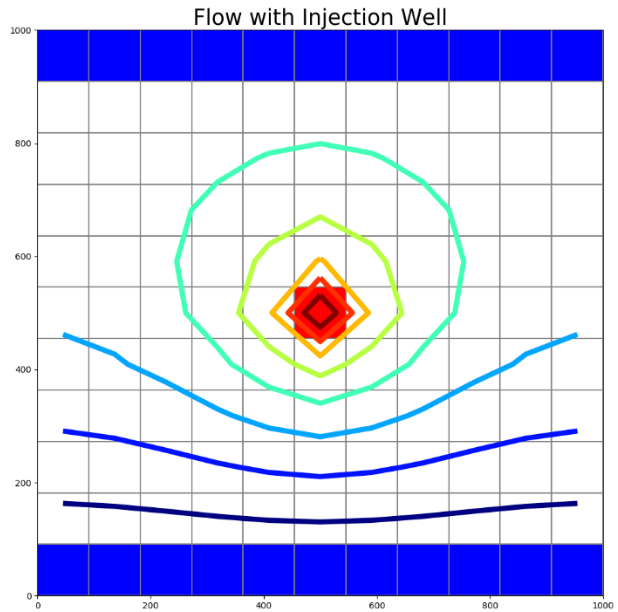
Flow paths and ASR recoverabilities

Methodology: Calculate Groundwater Water Levels using MODFLOW

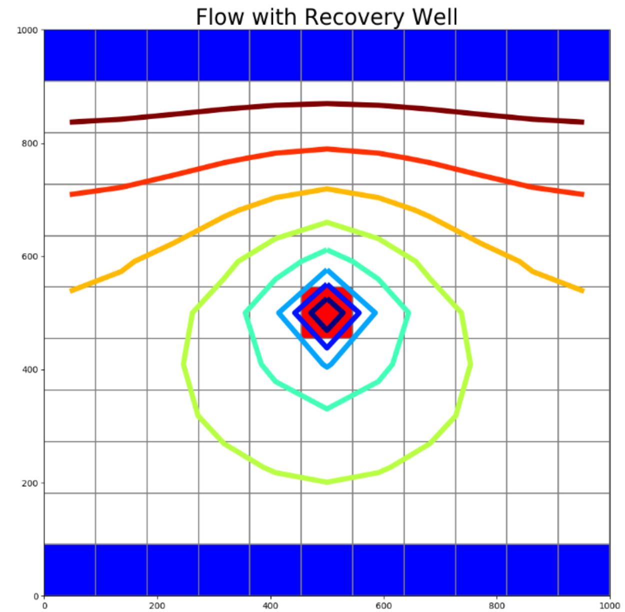
Ambient Water Levels



Water Levels During Injection



Water Levels During Recovery



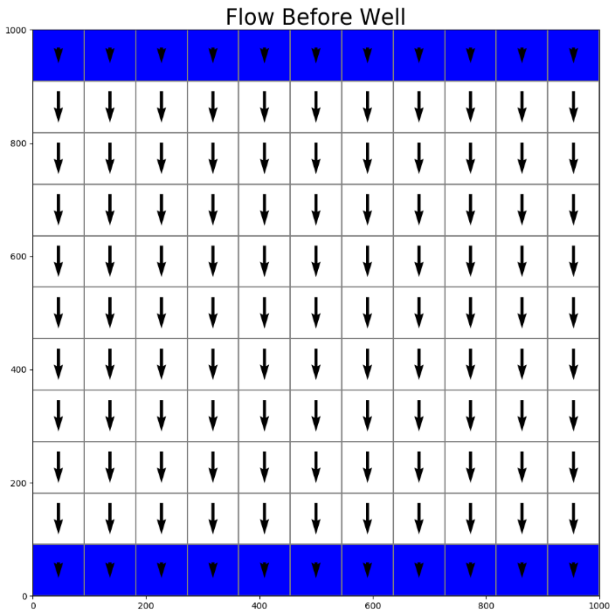
High Water Level

Low Water Level

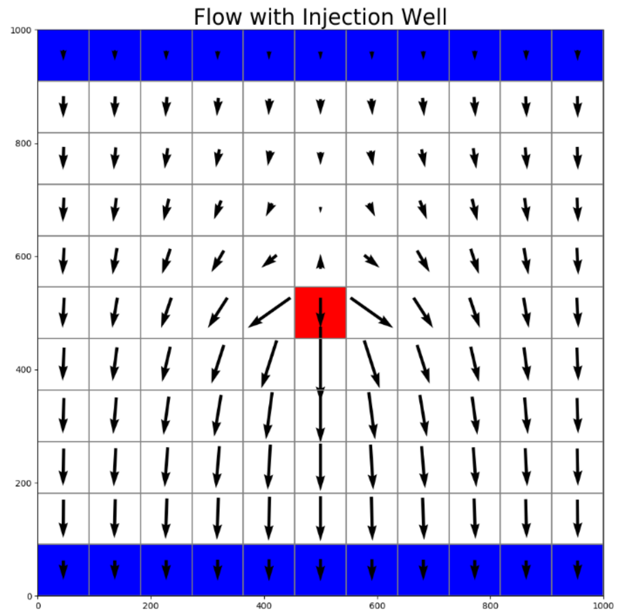
Example: 2-D homogeneous aquifer

Methodology: Calculate Groundwater Flow Vectors using MODFLOW

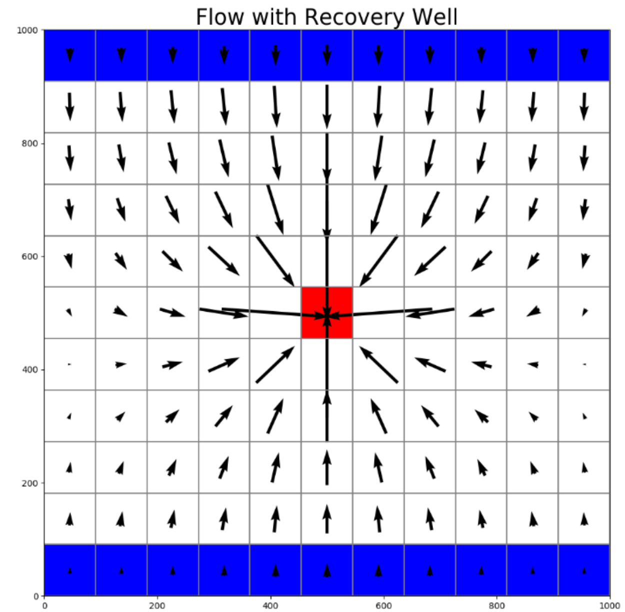
Ambient Flow Arrows



Flow Arrows During Injection



Flow Arrows During Recovery



→ Direction of Flow

Example: 2-D homogeneous aquifer

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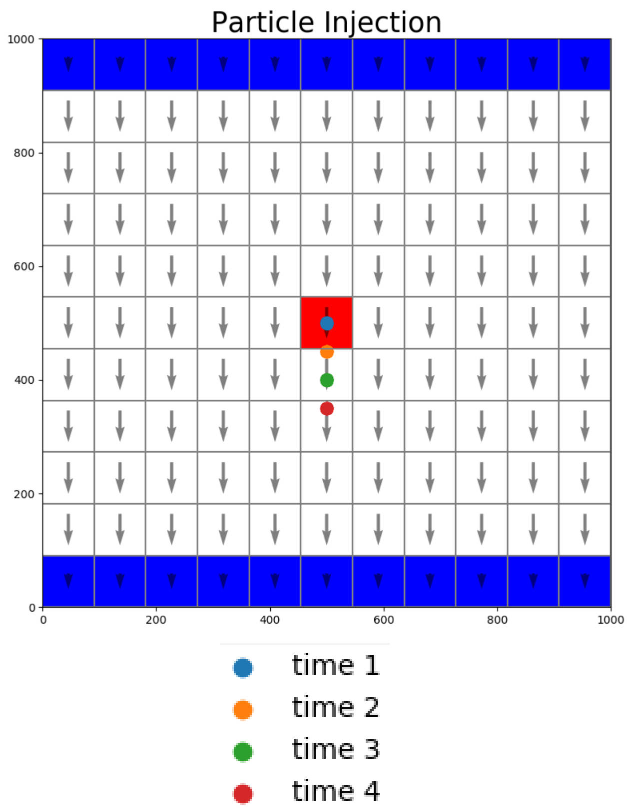
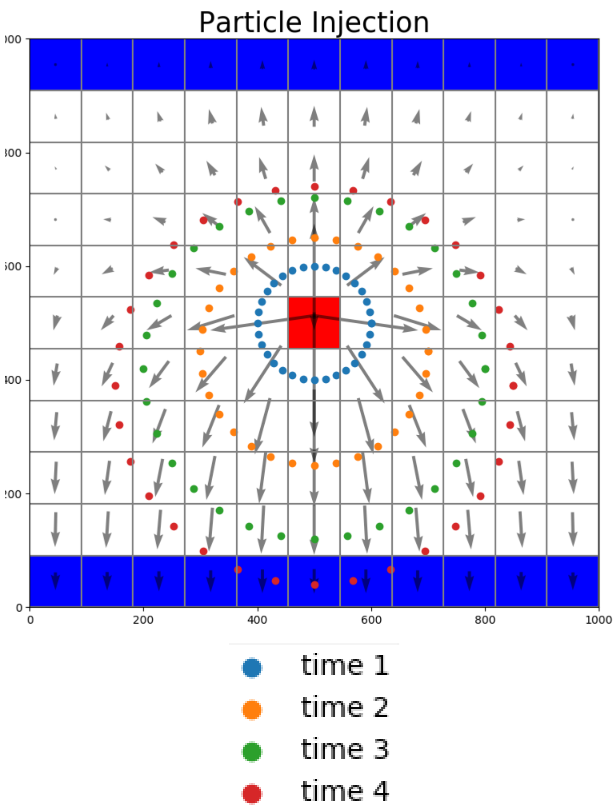
Methodology: Track Particles in Groundwater Flow Field using MODPATH

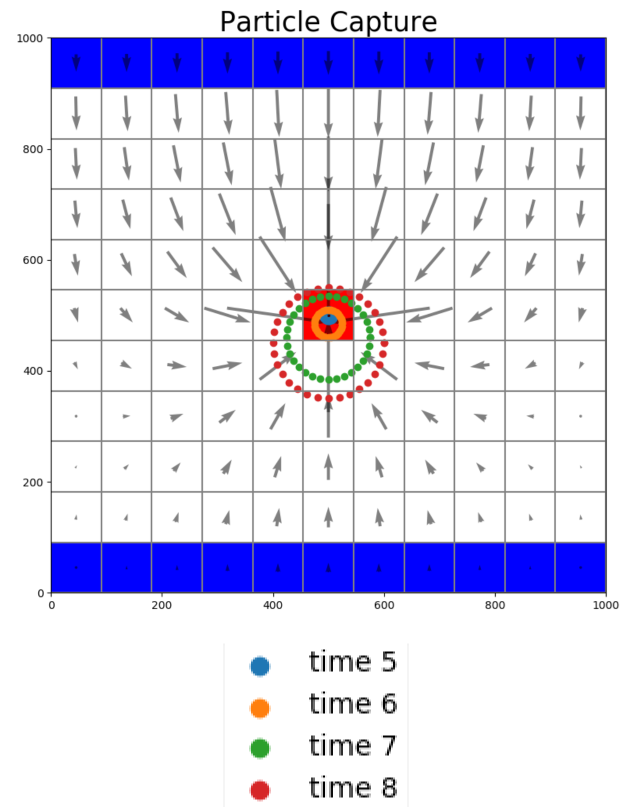
Ambient Particle Paths



Particle Paths During Injection

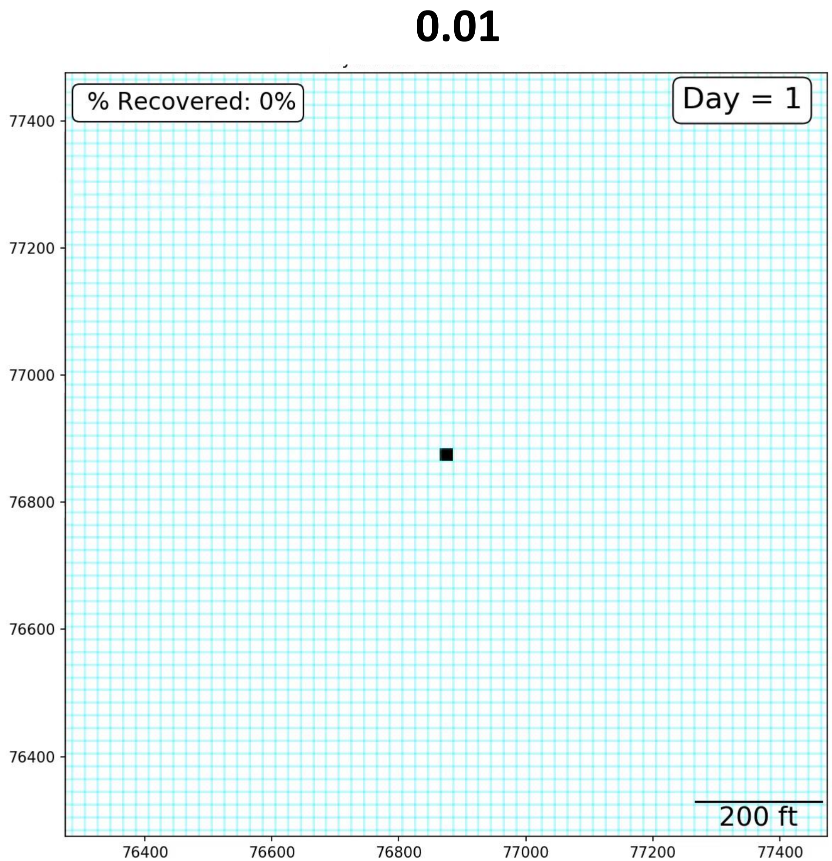


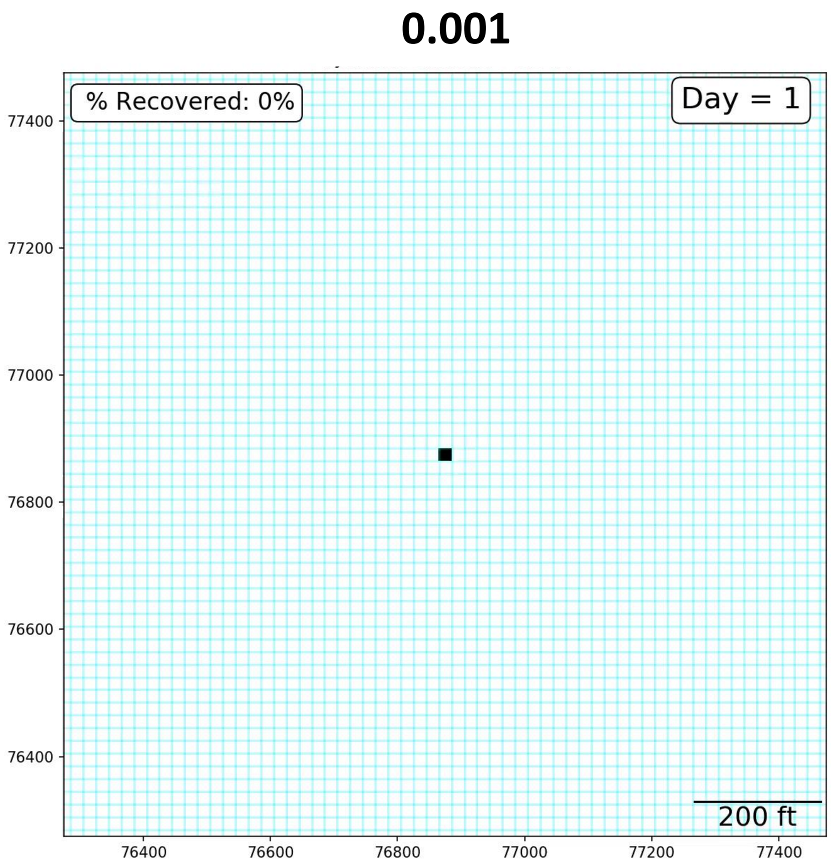
Particle Paths During Recovery



Example: 2-D homogeneous aquifer

Impact of Hydraulic Gradient on Recoverability





Targeted ASR Aquifer Zone

- **50 feet thick**
- **Hydraulic conductivity = 20 ft/day**

- **Inject water at 100 gpm for 11 months**
- **Extract water at 1100 gpm for 1 month**

Example: 2-D homogeneous aquifer

Model Comparison: Analytical versus Numerical

Baseline Aquifer Conditions

Parameter		Value	Units
Q_i	Injection rate	20,000	ft^3/day
Q_p	Pumping rate	220,000	ft^3/day
t_i	Injection time	330	days
t_d	Delay time	0	days
t_p	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
V_i	Injection Volume	6.60E+06	ft^3
Vp	Pumping Volume	6.60E+06	ft^3

Example: 2-D homogeneous aquifer

Model Comparison: Analytical with Numerical

Parameter		Value	Units
Q_i	Injection rate	20,000	ft^3/day
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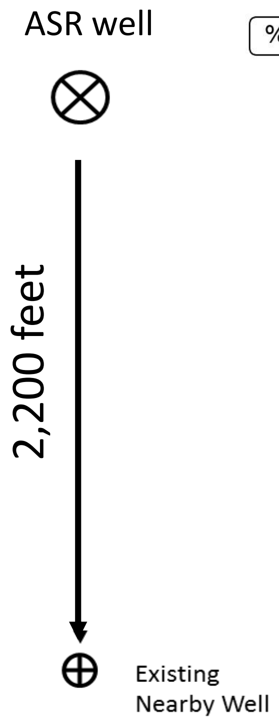
K	Hydraulic conductivity	20	ft/day
dh/dx	Regional hydraulic gradient	0.001	ft/ft
B	Thickness of aquifer	100	ft
V_i	Injection Volume	6.60E+06	ft^3
Vp	Pumping Volume	6.60E+06	ft^3

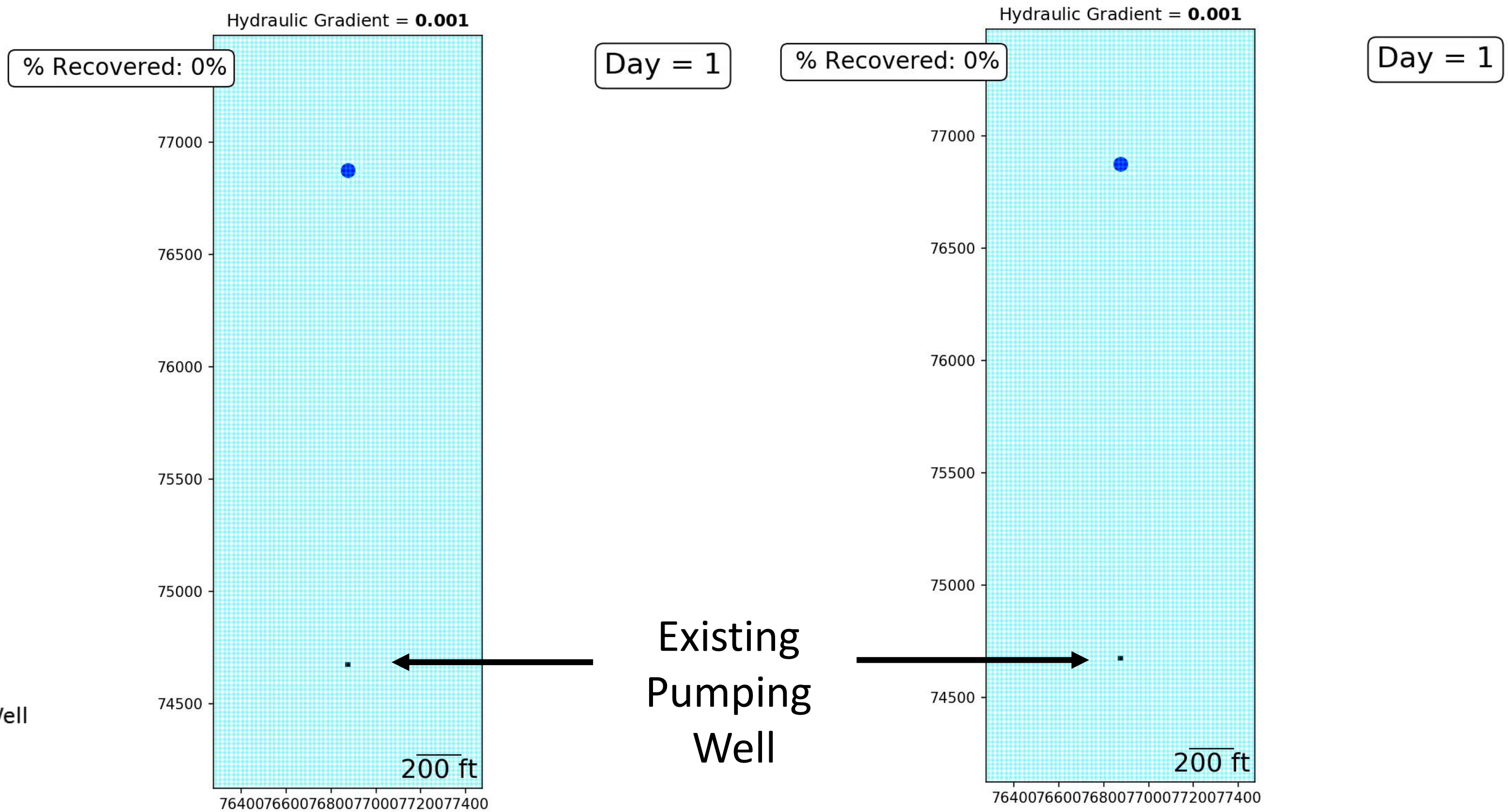
Example: 2-D homogeneous aquifer

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 ft^3	92.8%	93.0%
6.6E+06 ft^3	**96.0%**	**96.2%**
1.2E+07 ft^3	97.5%	97.8%
Storage Period		
No Delay	**96.0%**	**96.2%**
100 days	94.4%	94.6%
200 days	92.7%	92.9%

Impact of Pumping from Existing Nearby Well on Simulated Recoverability for Single ASR Well



Existing Well Pumping 100 gpm | **Existing Well Pumping 1100 gpm**



- **Inject water at 100 gpm for 11 months**
- **Extract water at 1100 gpm for 1 month**

Targeted ASR Aquifer Zone

- **50 feet thick**
- **Hydraulic conductivity = 20 ft/day**

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Predicted Recovery Efficiency for Single ASR Well (1-year cycle)

ASR well

No Nearby Well

Gradient	Single Well
0.01	85%
0.001	99%
0.0001	100%

ASR well

1100 ft

Existing Nearby Well

Gradient	Well 1100 ft down gradient		
	100 gpm	550 gpm	1100 gpm
0.01	76%	43%	26%
0.001	90%	52%	29%
0.0001	91%	53%	29%

ASR well

2200 ft

Existing Nearby Well

Gradient	Well 2200 ft down gradient		
	100 gpm	550 gpm	1100 gpm
0.01	81%	64%	47%
0.001	95%	76%	57%
0.0001	96%	77%	58%

ASR well

4400 ft

Existing Nearby Well

Gradient	Well 4400 ft down gradient		
	100 gpm	550 gpm	1100 gpm
0.01	83%	74%	64%
0.001	97%	87%	76%
0.0001	98%	89%	77%

Targeted ASR Aquifer Zone

- **50 feet thick**
- **Hydraulic conductivity = 20 ft/day**

- **Inject water at 100 gpm for 11 months**
- **Extract water at 1100 gpm for 1 month**
- **Calculate Recovery Efficiency after 24 months**

Example: 2-D homogeneous aquifer

Predicted Recovery Efficiency for Single ASR Well (10-year cycle)

ASR well

No Nearby Well

Gradient	Single Well
0.01	56%
0.001	93%
0.0001	96%

ASR well

1900 ft

Existing Nearby Well

Gradient	Well 1900 ft down gradient		
	100 gpm	1000 gpm	1900 gpm
0.01	45%	14%	7%
0.001	79%	19%	8%
0.0001	83%	19%	8%

ASR well

3800 ft

Existing Nearby Well

Gradient	Well 3800 ft down gradient		
	100 gpm	1000 gpm	1900 gpm
0.01	50%	26%	16%
0.001	86%	35%	22%
0.0001	90%	37%	22%

ASR well

7600 ft

Existing Nearby Well

Gradient	Well 7600 ft down gradient		
	100 gpm	1000 gpm	1900 gpm
0.01	54%	38%	30%
0.001	90%	36%	38%
0.0001	94%	60%	40%

Targeted ASR Aquifer Zone

- **50 feet thick**
- **Hydraulic conductivity = 20 ft/day**

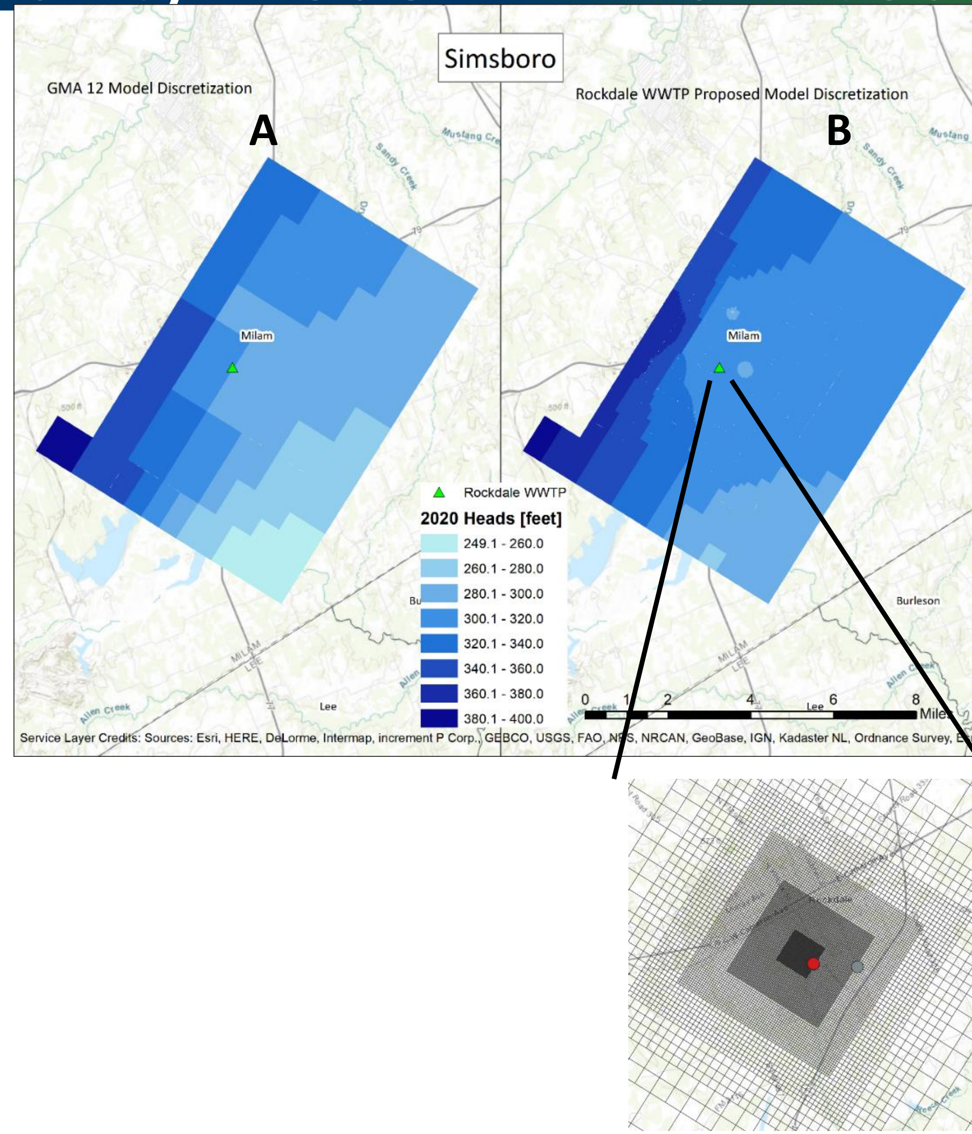
- **Inject water at 100 gpm for 9.5 years**
- **Extract water at 1900 gpm for 0.5 years**
- **Calculate Recovery Efficiency after 20 years**

Example: 2-D homogeneous aquifer

3-D Application: Refined Grid Spacing for Groundwater Availability Model in Milam County

- Water source is Rockdale Wastewater Treatment Plant
- Develop flow model from GMA 12 GAM

Month	Monthly Average	
	MGD	GPM
Jan	0.404	281
Feb	0.429	298
Mar	0.440	306
Apr	0.415	288
May	0.388	269
Jun	0.396	275
Jul	0.359	249
Aug	0.366	254
Sep	0.433	301
Average	0.403	280



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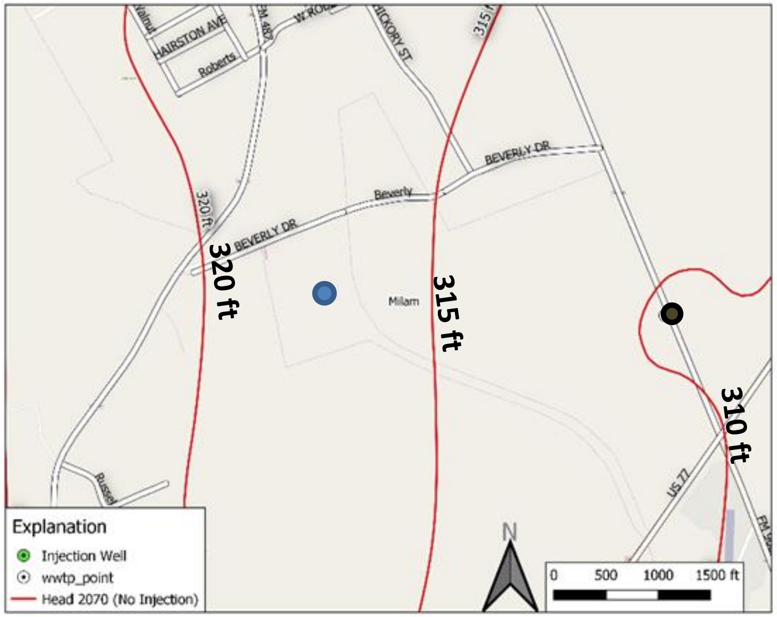
Groundwater Flow Conditions in Desired Future Condition (DFC) Simulation

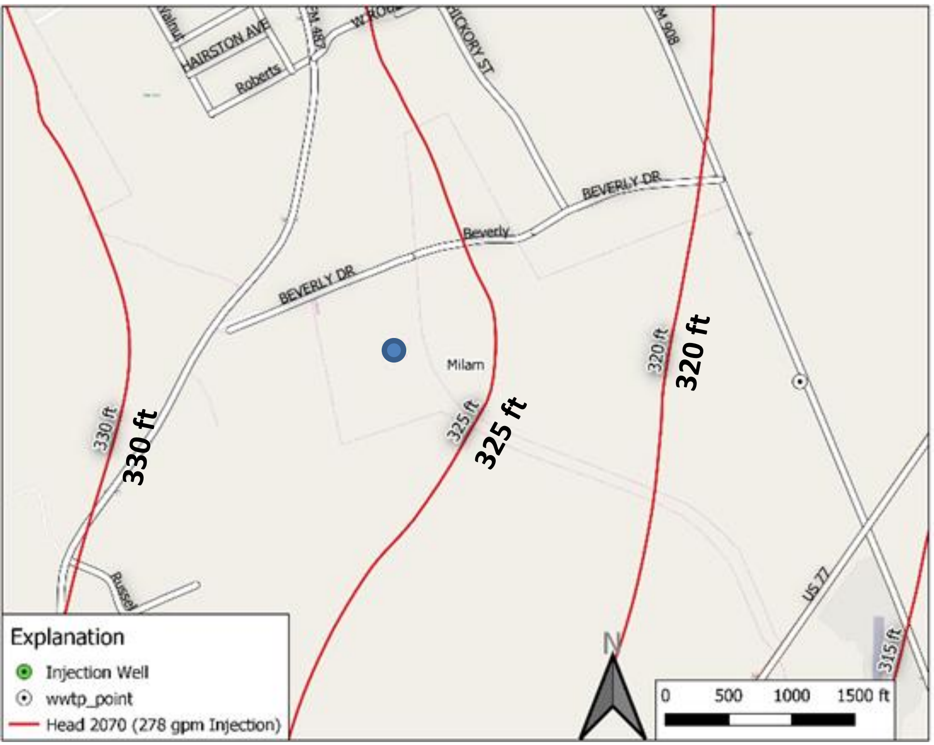
Hydraulic head contours for groundwater flow field



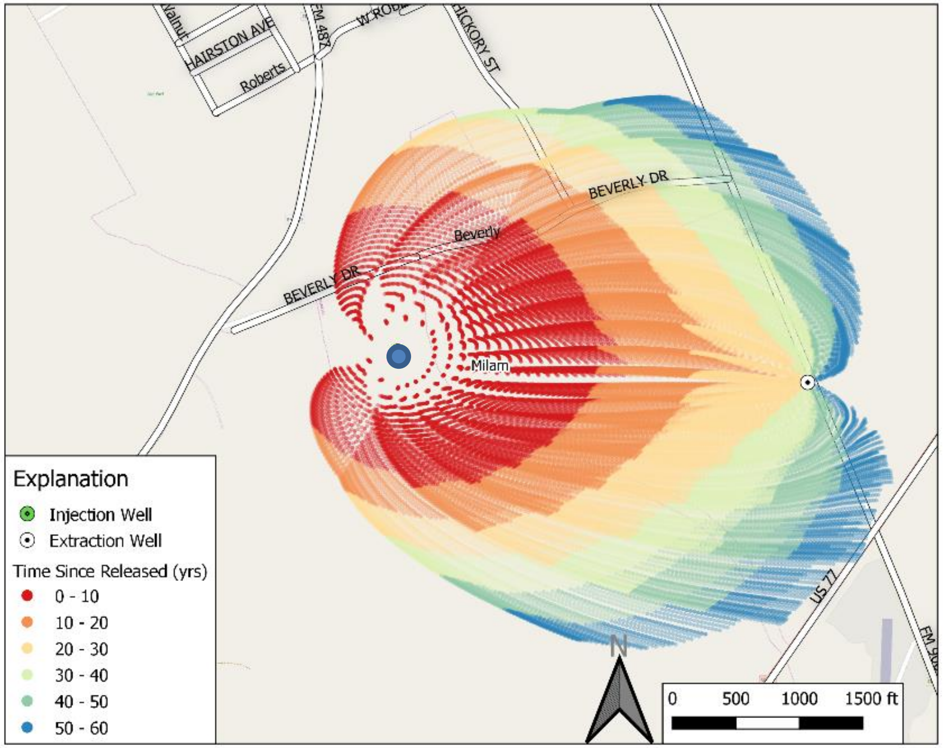
Travel time between WTTP and a nearby Pumping Well is about 50 years

Groundwater Flow Conditions in DFC Simulation with Enhanced Recharge at Injection at 277 gpm

Hydraulic head contours for groundwater flow field



Travel time between WTTP and a nearby pumping Well is 25 to 50 years



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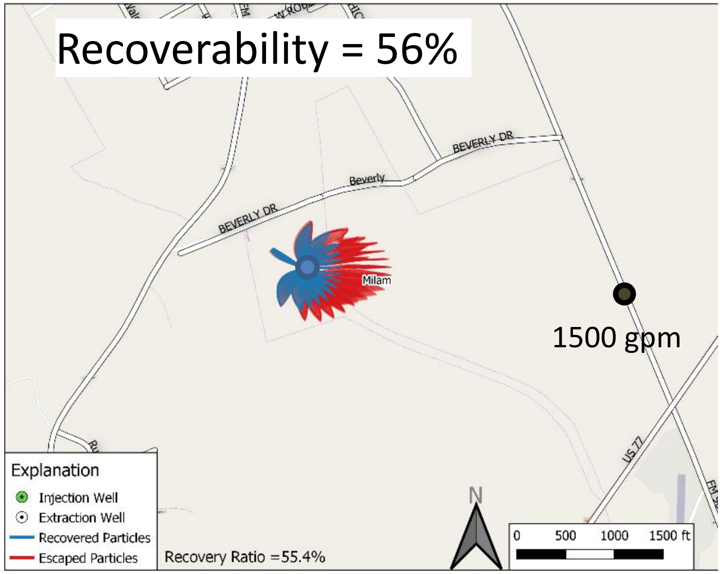
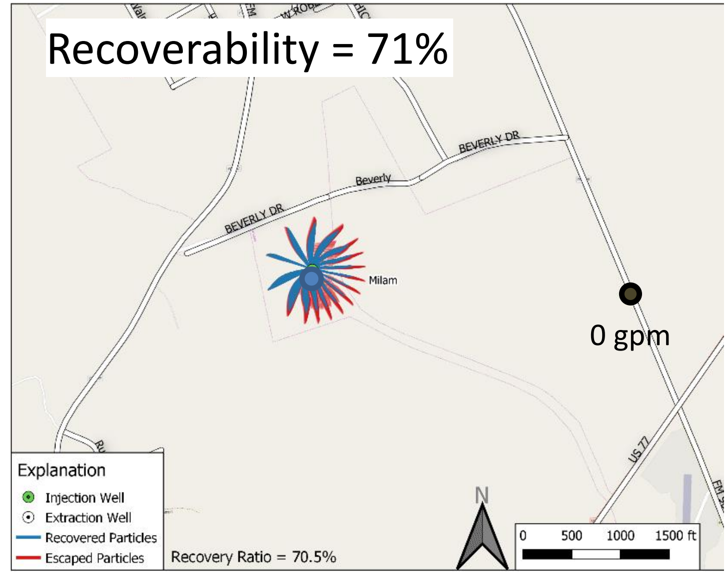
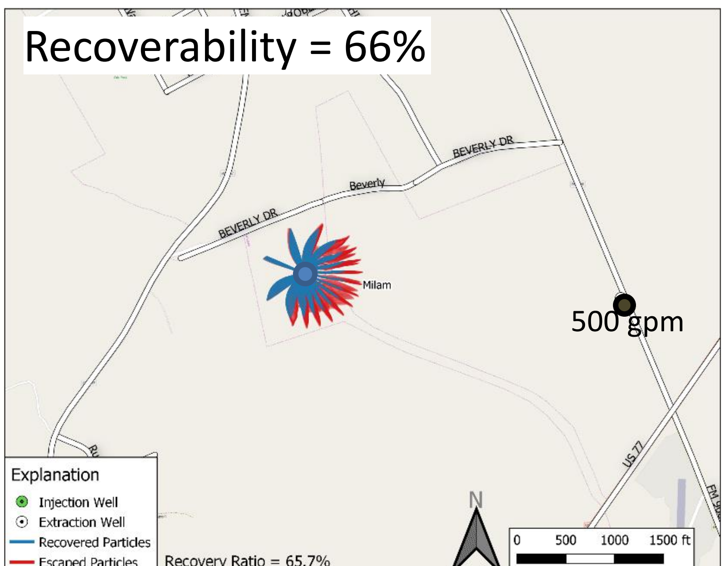
ASR Recoverability after 72 months







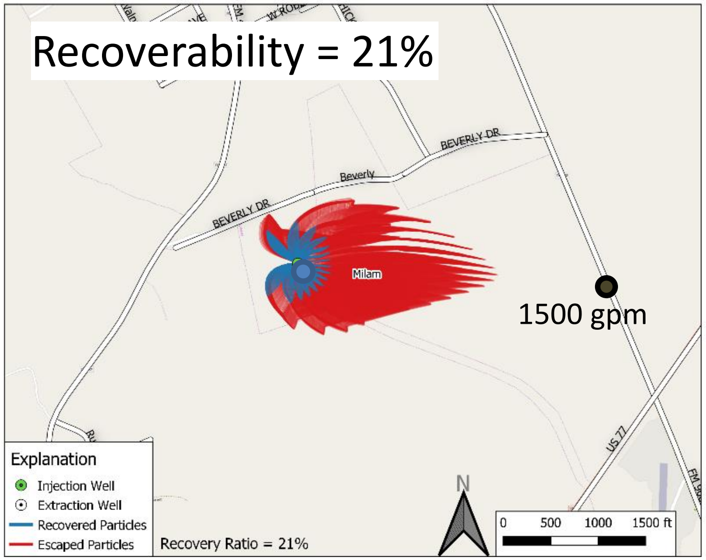
<u>ASR Injection/Pumping Schedule</u>

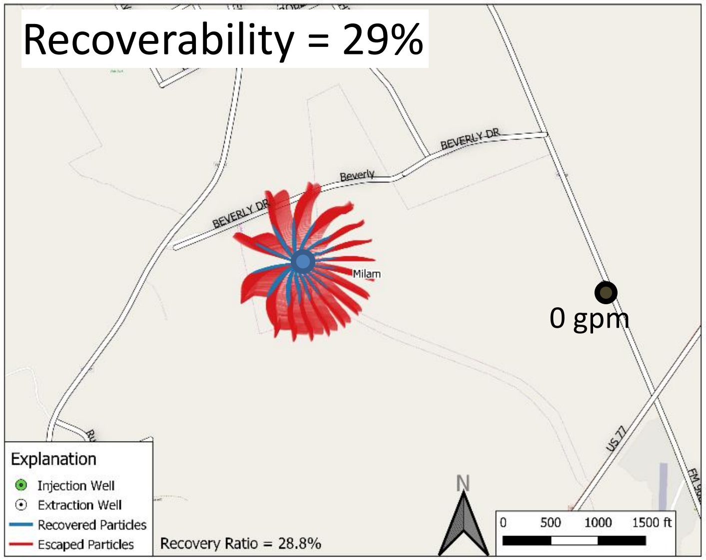
- Inject at 280 gpm for 32 months
- Extract at 2,240 gpm for 4 month

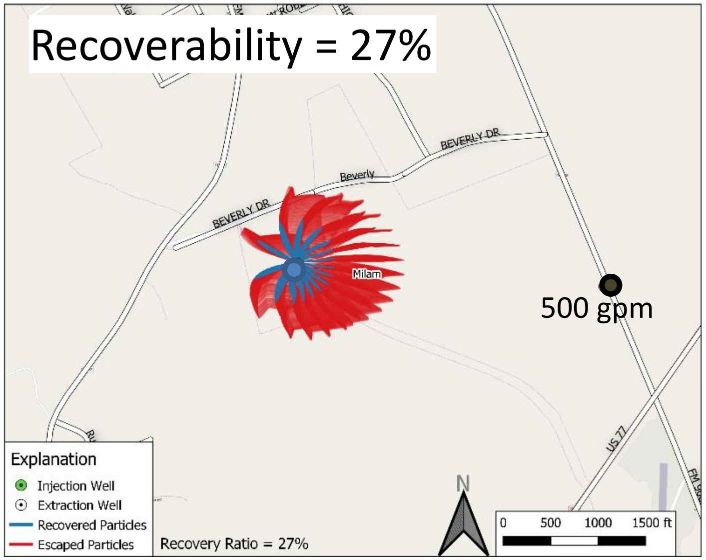
<u>Nearest Pumping Well</u>

- Vary from 1500, 500, and 0 gpm

ASR Recoverability after 144 months







ASR Injection/Pumping Schedule

- Inject at 280 gpm for 68 months
- Extract at 4,760 gpm for 4 month

Nearest Pumping Well

- Vary from 1500, 500, and 0 gpm

INTERA
GEOSCIENCE & ENGINEERING SOLUTIONS

Recoverability

- Importance
  - ASR application
  - GCD regulations
  - Impacts to existing nearby wells
  - Economics

- Factors affecting its Calculation
  - Hydraulic gradient
  - Hydraulic conductivity
  - Near pumping wells
  - Injection rate, pumping rate, and length of delays

Monitoring Groundwater Conditions

- Monthly pumping and injection amounts need to be reported (TWC §27.155)
- “Perform water quality testing annually on water to be injected into a geologic formation and water recovered from a geologic formation as part of the aquifer storage and recovery project” (TWC §27.156)

Potential GCD Roles/Responsibilities ??

Promotion of ASR Facilities

- Recharge credits
- Well spacing rules that provide greater protection to ASR wells
- Conjunctive permits that provide greater flexibility to ASR wells

Protection of Nearby Wells and Groundwater Resource

- Monitor
  - Groundwater quality
  - Water levels
  - Migration of injected water
- Estimate
  - Change in water levels
    (reduction in well production, subsidence??)
  - Migration of injected water offsite
    (change in water quality ??)

Questions ?

ASR Analytical Solution

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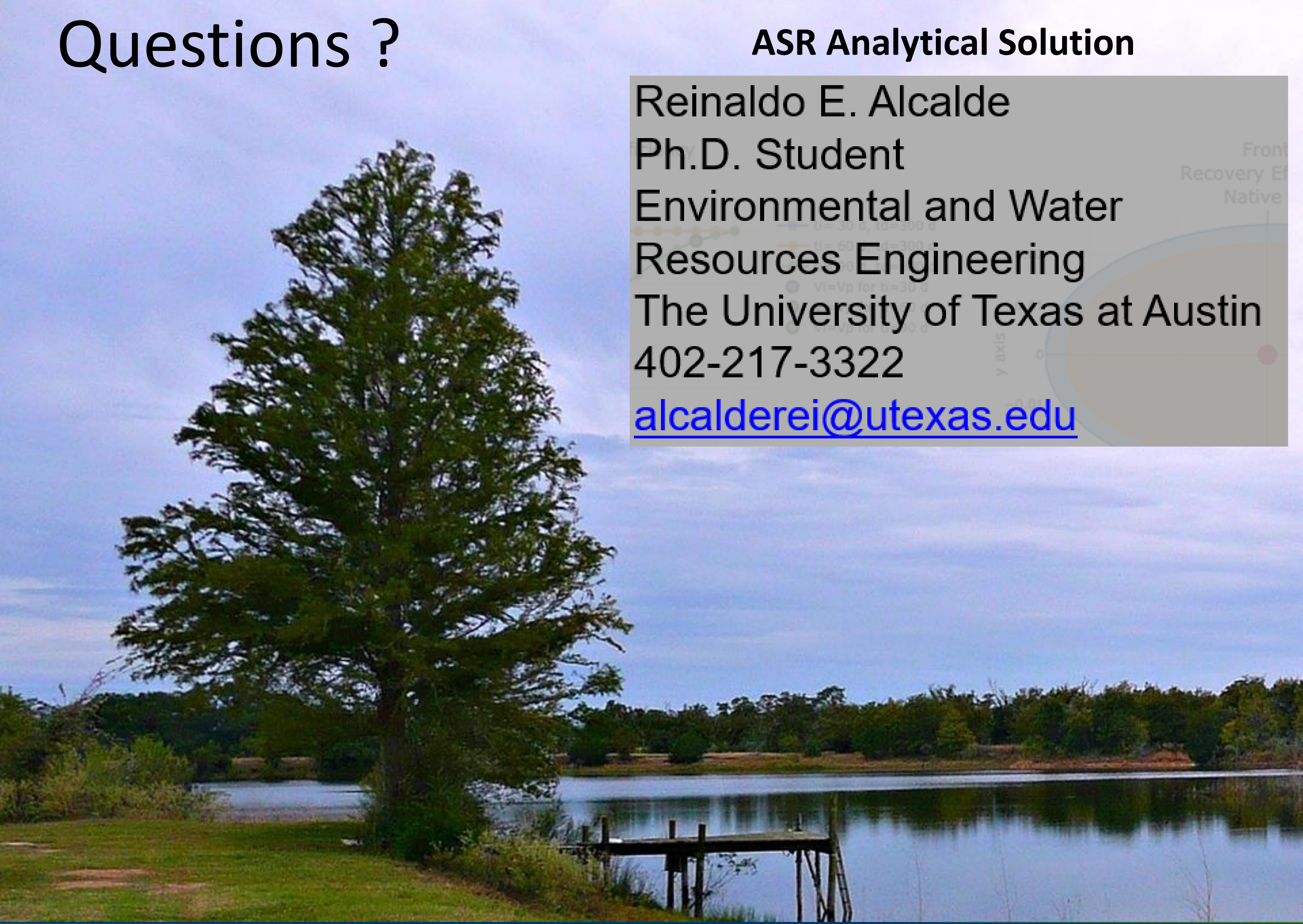

HB 655 84th Legislature : Bill Analysis

- TCEQ would be required to limit the amount of water that could be recovered by a project to the total amount that **was injected and further limit that amount to account for loss of native groundwater due to displacement.**

- If the project produced more water than the amount authorized for withdrawal by TCEQ, the project operator would be required to report the excess volume to the GCD. **A GCD's spacing, production, and permitting rules and fees would apply only to the withdrawals above the amount authorized.**

- Texas Commission on Environmental Quality (TCEQ) has exclusive jurisdiction over the regulation and permitting of ASR injection wells.