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

- ASR Well
- Injected Water
- GW Flow Path

Recovery of Groundwater

- ASR Well
- Pumped Water (injected water & native GW)
- GW Flow Path
Recoverability of Injected Water (RE)

\[
RE = \frac{V_r}{V_i} \times 100 \%
\]

\(V_i\) = 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

Recoverability = \(\frac{80}{100} \times 100\% = 80\%\)

Lost Injection volume = \(\frac{(100 - 80)}{100} \times 100\% = 20\%\)
Recovery of Native Groundwater (RNG)

\[ \text{RNG} = \frac{(V_p - V_r)}{V_p} \times 100\% \]

- \( V_i \) = injected volume of water
- \( V_r \) = recovered volume of injected water
- \( V_p \) = pumped volume

**Example**

\[ V_i = 100 \text{ acre-ft} \]
\[ V_r = 80 \text{ acre-ft} \]
\[ V_p = 95 \text{ acre-ft} \]

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

Recovered Injected Water = \( \frac{80}{95} \) \times 100 = 84.2\%
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.
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
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.
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

• 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

(modified from Maliva et al., 2006).
University of Texas Development of 2-D Analytical Model (Bear and Jacob; 1965)

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

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

**Recovery Efficiency**

- Recovery Efficiency vs. Pumping Time, days
  - ti= 30 d, td=300 d
  - ti= 60 d, td=300 d
  - ti= 90 d, td=300 d
  - Vi=Vp for ti=30 d
  - Vi=Vp for ti=60 d
  - Vi=Vp for ti=90 d

**Front Position:**
- Recovery Efficiency=72.22%
- Native Fraction=0%
University of Texas Development of 2-D Analytical Model (Bear and Jacob; 1965)

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

### Operational Parameters:
- Injection Rate, ft$^3$/day: 220000
- Pumping Rate, ft$^3$/day: 220000
- Time of Injection, day: 30, 60, 90
- Delay time, day: 300, 3000, 30000
- Time of Pumping, days: 5, 10, 15, 20, 25, 30, 35, 40, 45

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

#### Input Parameters:
- $Q_i$: injection rates
- $Q_p$: pumping rates
- $t_i$: injection time (*Multiple inputs supported*)
- $t_p$: pumping time (*Multiple inputs supported*)
- $t_d$: delay time (*Multiple inputs supported*)
- $B$: thickness of aquifer
- $n$: porosity in aquifer
- $K$: hydraulic conductivity
- $dh/dx$: regional hydraulic gradient

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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

Flow Before Well

Flow with Injection Well

Flow with Recovery Well

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

Example: 2-D homogeneous aquifer

Direction of Flow
Methodology: Track Particles in Groundwater Flow Field using MODPATH

Example: 2-D homogeneous aquifer
Impact of Hydraulic Gradient on Recoverability

Targeted ASR Aquifer Zone
- 50 feet thick
- Hydraulic conductivity = 20 ft/day

Example: 2-D homogeneous aquifer

- Inject water at 100 gpm for 11 months
- Extract water at 1100 gpm for 1 month
Baseline Aquifer Conditions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_i$ Injection rate</td>
<td>20,000</td>
<td>ft³/day</td>
</tr>
<tr>
<td>$Q_p$ Pumping rate</td>
<td>220,000</td>
<td>ft³/day</td>
</tr>
<tr>
<td>$t_i$ Injection time</td>
<td>330</td>
<td>days</td>
</tr>
<tr>
<td>$t_d$ Delay time</td>
<td>0</td>
<td>days</td>
</tr>
<tr>
<td>$t_p$ Pumping time</td>
<td>30</td>
<td>days</td>
</tr>
<tr>
<td>$n$ Porosity in aquifer</td>
<td>0.3</td>
<td>-</td>
</tr>
<tr>
<td>$K$ Hydraulic conductivity</td>
<td>20</td>
<td>ft/day</td>
</tr>
<tr>
<td>$dh/dx$ Regional hydraulic gradient</td>
<td>0.001</td>
<td>ft/ft</td>
</tr>
<tr>
<td>$B$ Thickness of aquifer</td>
<td>100</td>
<td>ft</td>
</tr>
<tr>
<td>$V_i$ Injection Volume</td>
<td>6.60E+06</td>
<td>ft³</td>
</tr>
<tr>
<td>$V_p$ Pumping Volume</td>
<td>6.60E+06</td>
<td>ft³</td>
</tr>
</tbody>
</table>

Example: 2-D homogeneous aquifer
Model Comparison: Analytical with Numerical

Example: 2-D homogeneous aquifer

<table>
<thead>
<tr>
<th>Sensitivity Parameter</th>
<th>Numerical Model</th>
<th>Analytical Model</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hydraulic Gradient</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.01</td>
<td>63.6%</td>
<td>63.6%</td>
</tr>
<tr>
<td>0.001</td>
<td>96.0%</td>
<td>96.2%</td>
</tr>
<tr>
<td>0.0001</td>
<td>99.5%</td>
<td>99.6%</td>
</tr>
<tr>
<td><strong>Thickness</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50 feet</td>
<td>97.0%</td>
<td>97.3%</td>
</tr>
<tr>
<td>100 feet</td>
<td>96.0%</td>
<td>96.2%</td>
</tr>
<tr>
<td>200 feet</td>
<td>94.3%</td>
<td>94.6%</td>
</tr>
<tr>
<td><strong>Hydraulic Conductivity</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.8 ft/day</td>
<td>98.5%</td>
<td>98.8</td>
</tr>
<tr>
<td>20 ft/day</td>
<td>96.0%</td>
<td>96.2%</td>
</tr>
<tr>
<td>60 ft/day</td>
<td>82.4</td>
<td>82.9</td>
</tr>
<tr>
<td><strong>Porosity</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30%</td>
<td>96.0%</td>
<td>96.2%</td>
</tr>
<tr>
<td>20%</td>
<td>95.1%</td>
<td>95.3%</td>
</tr>
<tr>
<td>15%</td>
<td>93.0%</td>
<td>93.3%</td>
</tr>
<tr>
<td><strong>Injected Volume</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.2E+06 ft³</td>
<td>92.8%</td>
<td>93.0%</td>
</tr>
<tr>
<td>6.6E+06 ft³</td>
<td>96.0%</td>
<td>96.2%</td>
</tr>
<tr>
<td>1.2E+07 ft³</td>
<td>97.5%</td>
<td>97.8%</td>
</tr>
<tr>
<td><strong>Storage Period</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No Delay</td>
<td>96.0%</td>
<td>96.2%</td>
</tr>
<tr>
<td>100 days</td>
<td>94.4%</td>
<td>94.6%</td>
</tr>
<tr>
<td>200 days</td>
<td>92.7%</td>
<td>92.9%</td>
</tr>
</tbody>
</table>
Impact of Pumping from Existing Nearby Well on Simulated Recoverability for Single ASR Well

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

<table>
<thead>
<tr>
<th>Gradient</th>
<th>Single Well</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>85%</td>
</tr>
<tr>
<td>0.001</td>
<td>99%</td>
</tr>
<tr>
<td>0.0001</td>
<td>100%</td>
</tr>
</tbody>
</table>

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)

<table>
<thead>
<tr>
<th>Gradient</th>
<th>Single Well</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>56%</td>
</tr>
<tr>
<td>0.001</td>
<td>93%</td>
</tr>
<tr>
<td>0.0001</td>
<td>96%</td>
</tr>
</tbody>
</table>

**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

<table>
<thead>
<tr>
<th>Month</th>
<th>Monthly Average MGD</th>
<th>GPM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>0.404</td>
<td>281</td>
</tr>
<tr>
<td>Feb</td>
<td>0.429</td>
<td>298</td>
</tr>
<tr>
<td>Mar</td>
<td>0.440</td>
<td>306</td>
</tr>
<tr>
<td>Apr</td>
<td>0.415</td>
<td>288</td>
</tr>
<tr>
<td>May</td>
<td>0.388</td>
<td>269</td>
</tr>
<tr>
<td>Jun</td>
<td>0.396</td>
<td>275</td>
</tr>
<tr>
<td>Jul</td>
<td>0.359</td>
<td>249</td>
</tr>
<tr>
<td>Aug</td>
<td>0.366</td>
<td>254</td>
</tr>
<tr>
<td>Sep</td>
<td>0.433</td>
<td>301</td>
</tr>
<tr>
<td>Average</td>
<td>0.403</td>
<td>280</td>
</tr>
</tbody>
</table>
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

Explanation
- Injection Well
- Extraction Well

Time Since Released (yrs)
- 0 - 10
- 10 - 20
- 20 - 30
- 30 - 40
- 40 - 50
- 50 - 60
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

Explanation
- Injection Well
- Extraction Well

Time Since Released (yrs)
- 0 - 10
- 10 - 20
- 20 - 30
- 30 - 40
- 40 - 50
- 50 - 60
ASR Recoverability after 72 months

Recoverability = 56%

Recoverability = 66%

Recoverability = 71%

ASR Injection/Pumping Schedule
- Inject at 280 gpm for 32 months
- Extract at 2,240 gpm for 4 months

Nearest Pumping Well
- Vary from 1500, 500, and 0 gpm
ASR Recoverability after 144 months

Recoverability = 21%

Recoverability = 29%

Recoverability = 27%

ASR Injection/Pumping Schedule

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

Nearest Pumping Well

- Vary from 1500, 500, and 0 gpm
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?

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ASR Analytical Solution
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.