Application of Risk Assessment Tools and Methodologies to Synthetic and Field Data

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Presentation Outline

• National Risk Assessment Partnership (NRAP) risk assessment tools and methodologies are being applied to data from field experiments and potential or active geologic storage projects

• Since there are no comprehensive field data sets where a large scale CO₂ leak has occurred, the partnership is also collecting and developing synthetic datasets for NRAP community use
Presentation Outline

• Field Applications
  – Groundwater Assessment Field Application (Diana Bacon, PNNL)
  – Containment Tools and Methodologies Field Demonstration (Liange Zheng, LBNL)
  – Induced Seismicity Tools and Methodologies Demonstration (Josh White, LLNL)
  – Strategic Monitoring Tools and Methodologies Demonstration (Catherine Yonkofski, PNNL)
  – Identify Field Site for Large Scale Leveraged Activities (Inci Demirkanli, PNNL)

• Synthetic Datasets
  – Development of Community Data Sets (Kelly Rose, NETL)
  – Kimberlina Site Data set for Testing of Monitoring Tools/Approaches (Quanlin Zhou, LBNL)
Groundwater Assessment Field Application

Diana Bacon¹, Randall A. Locke II², Elizabeth Keating³, Susan Carroll⁴, Abbas Iranmanesh², Kayyum Mansoor⁴, Bracken Wimmer², Liange Zheng⁵, ¹PNNL, ²U. Illinois, ISGS, ³LANL, ⁴LLNL, ⁵LBNL
## Groundwater Assessment Field Application

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Confined Alluvium ROM Parameters¹</th>
<th>IBDP Pre-Injection Observations²</th>
<th>Parameter vs. Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Non-adjustable</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial pH</td>
<td>7.6</td>
<td>7.31 (average)</td>
<td>Higher</td>
</tr>
<tr>
<td>pH No-Impact Threshold</td>
<td>6.625</td>
<td>6.81 (5th percentile)</td>
<td>Lower</td>
</tr>
<tr>
<td>Initial TDS</td>
<td>570 mg/L</td>
<td>1152 (average)</td>
<td>Lower</td>
</tr>
<tr>
<td>TDS No-Impact Threshold</td>
<td>1300 mg/L</td>
<td>1358 (95th percentile)</td>
<td>Similar</td>
</tr>
<tr>
<td>Sand fraction</td>
<td>0.35 – 0.65</td>
<td>--</td>
<td>Uncertain</td>
</tr>
<tr>
<td>Correlation length X</td>
<td>200 – 2,500 m</td>
<td>--</td>
<td>Uncertain</td>
</tr>
<tr>
<td>Correlation length Z</td>
<td>0.5 – 25 m</td>
<td>--</td>
<td>Uncertain</td>
</tr>
<tr>
<td>Permeability sand</td>
<td>$10^{-14} - 10^{-10}$ m²</td>
<td>$10^{-11.8} - 10^{-10.4}$ m²</td>
<td>Within range</td>
</tr>
<tr>
<td>Permeability clay</td>
<td>$10^{-18} - 10^{-15}$ m²</td>
<td>--</td>
<td>Uncertain</td>
</tr>
<tr>
<td>Goethite volume fraction</td>
<td>0 – 0.15</td>
<td>--</td>
<td>Uncertain</td>
</tr>
<tr>
<td>Illite volume fraction</td>
<td>0 – 0.2</td>
<td>--</td>
<td>Uncertain</td>
</tr>
<tr>
<td>Kaolinite volume fraction</td>
<td>0 – 0.15</td>
<td>--</td>
<td>Uncertain</td>
</tr>
<tr>
<td>Smectite volume fraction</td>
<td>0 – 0.3</td>
<td>--</td>
<td>Uncertain</td>
</tr>
<tr>
<td>Cation Exchange Capacity</td>
<td>0.1 – 40 meq/100 g</td>
<td>--</td>
<td>Uncertain</td>
</tr>
<tr>
<td><strong>Adjustable</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

¹ ROM Parameters
² IBDP Pre-Injection Observations
Groundwater Assessment Field Application

- Some non-adjustable parameters are significantly different than observations.
- Hydraulic parameters and source term magnitude are more sensitive than clay fraction or CEC.
- Constraining sand permeability reduced aquifer volume impacted by an order of magnitude.
- Constraining sand fraction and correlation lengths could reduce uncertainty.
Containment Tools and Methodologies Field Demonstration: Leakage Analog Site

Liange Zheng, Tom Daley, LBNL

Containment and Monitoring Institute (CaMI) Field Research Station

Phase I layout

Observation well(s)

CO₂ injectors

Surface monitoring technologies

Well-based monitoring technologies

CO₂

BGP

300 m

500 m
Containment Tools and Methodologies Field Demonstration:
Test modeling and monitoring methodologies

Geological model

Numerical mesh

Predict CO₂ plume
Containment Tools and Methodologies Field Demonstration: Monitoring at CaMI

**Continuous monitoring**
- Downhole pressure and temperature (injection well)
- Downhole pressure and temperature (observation wells)
- Electrical resistivity tomography, using 128 node CaMI equipment
- Well-based microseismic recording during injection phase, using permanent down-hole geophone array and optical fibre
- Surface-based microseismic recording during injection phase, using buried surface geophones
- Surface-based, broadband regional seismicity (year1); Bristol University

**Discrete monitoring – geophysics and well logging**
- 3C-3D surface seismic surveys using 500 CaMI nodes and fibre-based sensors
- Vertical seismic profiles – both permanent sensors and removable (Dave Eaton)
- Cross-well seismic surveys (LBNL)
- Cross-well electromagnetic surveys (LBNL)
- Surface-borehole electromagnetic surveys (LBNL)
- Surface-borehole electrical resistivity surveys (LBNL)
- Magnetometric resistivity surveys (INRS)
- Time-domain electromagnetic surveys (INRS)
- Pulsed neutron logs
- Borehole sonic logs
- Borehole induction logs

**Discrete monitoring - geochemistry**
- Atmospheric monitoring leakage program
- Groundwater sampling from domestic well
- Groundwater sampling from multi-level wells
- Soil gas (CO2 and CH4) monitoring with up to 24 soil gas probes
- Soil gas (CO2 and CH4) monitoring using 12 moveable soil gas flux measurements
- Surface casing vent flow monitoring
- Observation well fluid sampling and analysis
- Tracer studies including ‘doped’ CO2 with a trace of thermogenic methane
- Tracer studies including noble gases (collaboration with Edinburgh University, UK)
Strategic Monitoring Tools and Methodologies Demonstration

Catherine Yonkofski¹, Guzel Tartakovsky¹, Diana Bacon¹, Nik Huerta², Andy Wentworth², Joel Sminchak³, Glenn Larson³, Neeraj Gupta³
1. PNNL 2. NETL 3. BCO

BCO’s well integrity database (WID) is being used by the WLAT and DREAM tools to demonstrate design of practical monitoring strategies based on hypothetical leakage risk derived from the wellbore integrity indicator index (WBI).
DREAM results show the optimal pressure-based monitoring schemes based on

- Time to leak detection
- Marginal advantage of additional pressure sensors (right)
- Cost of system

Using WLAT output, we modeled hypothetical CO₂ and brine leakage into the deepest overlying aquifer.

DREAM Tool
Leakage Solution Space
Induced Seismicity Tools and Methodologies Demonstration

Kayla Kroll, Josh White LLNL

Oklahoma Application. Monitoring data and RSQSim simulation results analyzing the poroelastic deformation of the Arbuckle group [Kroll et al. 2017]
Induced Seismicity Tools and Methodologies Demonstration

Farnsworth Application.
Posterior probability distributions of elastic properties inferred from triaxial testing data [Burghardt et al. 2017].
Identify Field Site for Large Scale Leveraged Activities

Inci Demirkanli, Delphine Appriou, Signe White, PNNL

• A subset of FutureGen 2.0 project data was identified for supporting
  – Validation and testing activities; and
  – Compilation of a community dataset

• Data uploaded to EDX for larger NRAP community use included:
  – 2D seismic
  – Geophysical logs
  – Core analyses
  – Gravity and geodetic surveys
  – Borehole VSP
  – In-situ stress characterization
  – Hydrologic field test
  – Reservoir model
  – Leakage model
Use of NRAP-IAM-CS for Risk-Based AoR: FutureGen 2.0 Application

- Use of FutureGen 2.0 data for demonstrating a risk-based project Area of Review (AoR) delineation
  - Over-pressurized injection formations are challenging for delineating AoR, where the project may cause endangerment of USDWs
  - Current methods to calculate a critical pressure increase rely on the assumption that the injection zone is in hydrostatic equilibrium with respect to the USDW (Nicot et al., 2009; Birkholzer et al., 2011)
Use of NRAP-IAM-CS for Risk-Based AoR: Delineation Methodology

- Oldenburg et al. (2016):
  - Evaluation of the incremental increase in flow rate
  - Assume a hypothetical open borehole at varying distances from the injection well.
Development of Community Datasets
Jennifer DiGiulio¹, Kelly Rose¹, Bradley Gooch¹, Andrew Bean¹, Emily Cameron¹, Michael Sabbatino¹, Diana Bacon²
1. NETL 2. PNNL

NRAP Tool Developer Community Datasets Needs/Requests Survey

<table>
<thead>
<tr>
<th>Question</th>
<th>Number of Responses</th>
</tr>
</thead>
<tbody>
<tr>
<td>What is your name?</td>
<td>19</td>
</tr>
<tr>
<td>What is your affiliation?</td>
<td>19</td>
</tr>
<tr>
<td>What is your contact email?</td>
<td>19</td>
</tr>
<tr>
<td>Researcher Background?</td>
<td>19</td>
</tr>
<tr>
<td>Do you have an account on EDX?</td>
<td>19</td>
</tr>
<tr>
<td>Which specific NRAP Tasks are you affiliated with?</td>
<td>19</td>
</tr>
<tr>
<td>Which kind(s) of data and/or simulation results are you looking for to aide in your tool development?</td>
<td>19</td>
</tr>
<tr>
<td>Are there specific input/export data formats that are key to your validation and testing needs?</td>
<td>17</td>
</tr>
<tr>
<td>Are there field or synthetic datasets that you are currently using to develop NRAP tools?</td>
<td>10</td>
</tr>
<tr>
<td>Any other comments or suggestions?</td>
<td>5</td>
</tr>
</tbody>
</table>

In Progress

- Compile accessible data
- Identify utility of tools at each priority site
- Identify tools; identify and mitigate gaps
- Prepare interactive atlas in EDX GeoCube

Completed

- Design and distribute community datasets survey
- Synthesize results
- Develop preliminary data catalog

Upcoming Tasks

- Consider tools; identify and mitigate gaps

Accomplishments to Date

- Executed an 11-question survey to identify data needs of NRAP tools
  - Responses from 19 NRAP tool researchers spanning 6 of 7 tools
- Initiated development of US CCS data catalog for 18 sites on EDX
- Needs being cross-referenced against CCS sites to prioritize sites that meet NRAP tool needs
Data for NRAP Tools –

Building an NRAP Community Data Catalog

- Developing a catalog of CCS data for US sites
- Will help provide efficient access to authoritative, priority data for NRAP users & highlight data gaps

Catalog to Date:
- Initiated development in EDX
- Currently includes 18 US sites
- Kimberlina & Futuregen most complete
- Includes ~400 GB of data, 100’s of files, largely open-source
- Targeting desired datasets ID’s from survey

Desired Datasets

<table>
<thead>
<tr>
<th>Subsurface Structure</th>
<th>Geological framework</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fault surfaces and orientations</td>
<td></td>
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<tr>
<td>Petrophysical parameters</td>
<td></td>
</tr>
<tr>
<td>In-situ geophysical data</td>
<td></td>
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<tr>
<td>Pressure-temperature data</td>
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<thead>
<tr>
<th>Seismic</th>
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<tbody>
<tr>
<td>Seismic and microseismic data</td>
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<tr>
<td>Seismic velocity and Q structure</td>
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<td>Waveform data</td>
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</tbody>
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<thead>
<tr>
<th>Field Production Data</th>
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<tbody>
<tr>
<td>Injection volume and pressure histories</td>
</tr>
<tr>
<td>Operating GCS/EOR site data</td>
</tr>
</tbody>
</table>

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<thead>
<tr>
<th>Hydromechanical Characterization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Well logs</td>
</tr>
<tr>
<td>Porosity and permeability</td>
</tr>
<tr>
<td>In-situ stress data</td>
</tr>
<tr>
<td>Historical well log data</td>
</tr>
<tr>
<td>Elastic properties</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Electrical Properties</th>
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<tbody>
<tr>
<td>Conductivity, MT, SP, Permittivity data</td>
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<table>
<thead>
<tr>
<th>Geochemistry</th>
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<tbody>
<tr>
<td>Geochemical reaction data</td>
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<table>
<thead>
<tr>
<th>Simulation Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leakage simulation results</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Laboratory Experiments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental injection data</td>
</tr>
</tbody>
</table>

Reservoir Type

- Basalt Formations: 2
- Oil and Gas Reservoirs: 32
- Organic-Rich Shale: 1
- Saline Formations: 20
- Unmineable Coal Areas: 13

Tool | Tool Description | Number of Users*
--- | --- | ---
AIM | Aquifer Impact Model | 1
DREAM | Design for Risk Evaluation and Monitoring | 1
NRAP-JAM-CS | Integrated Assessment Model | 4
NSealR | Natural Seam ROM | 1
REV | Reservoir Evaluation and Visualization Tool | *
STSF | Short Term Seismic Forecasting | 4
WLAT | Wellbore Leakage Analysis Tool | 4

*11 of 19 survey participants were involved in tool development
Synthetic Data Set: Kimberlina V1.1

- Leakage from a wellbore into overlying aquifers
- Change in groundwater chemistry near wellbore

Susan Carroll, Kayyum Mansoor, LLNL

Leakage monitoring using multiple geophysical methods

<table>
<thead>
<tr>
<th>Geophysical Method</th>
<th>Signals</th>
<th>Lab</th>
</tr>
</thead>
<tbody>
<tr>
<td>MT and ERT</td>
<td>Gas phase and dissolved CO₂</td>
<td>LLNL</td>
</tr>
<tr>
<td>Pressure</td>
<td>Pressure plume</td>
<td>LLNL</td>
</tr>
<tr>
<td>Gravity</td>
<td>Gas phase CO₂</td>
<td>PNNL</td>
</tr>
<tr>
<td>Seismic</td>
<td>Gas phase CO₂</td>
<td>LANL</td>
</tr>
</tbody>
</table>
Kimberlina Site Data set v2.0 for Testing of Monitoring Tools/Approaches: Injection Scenarios

Quanlin Zhou, LBNL

CO$_2$ Plumes in Vedder Injection Reservoir

Pressure-Buildup Plumes in Vedder Injection Reservoir
Kimberlina Site Data set v2.0 for Testing of Monitoring Tools/Approaches: Fault Leakage Scenarios

Olcese Secondary Plume

Echegoin Secondary Plume
Accomplishments to Date:

Field Applications

- Demonstrated protocol for applying the Aquifer Impact Model to the Illinois Basin – Decatur Site
- Developed model to help plan the Containment and Monitoring Institute (CaMI) controlled leakage experiment
- Used field and laboratory data to better understand the relationship between rock elastic properties and induced seismicity
- Battelle’s well integrity database is being used with the Wellbore Leakage Analysis Tool (WLAT) and DREAM tools to demonstrate design of practical monitoring strategies
- Developed risk-based AOR method using the NRAP-IAM-CS integrated assessment model
Accomplishments to Date: Synthetic Datasets

- FutureGen 2.0 project data uploaded to EDX for use by NRAP community
- Surveyed NRAP tool developers to determine what data they need for testing the tools and what data they have to share
- Results being cross-referenced against CCS sites to prioritize sites that meet NRAP tool needs and identify data gaps
- Developed synthetic datasets for wellbore leakage at Kimberlina to be used for testing monitoring methodologies
- Distributed first synthetic datasets for fault leakage at Kimberlina for scientists to develop data readers for testing monitoring methods
Lessons Learned

– Field Applications
  • Current aquifer ROMs may not be flexible enough to apply to all sites, but a site-specific groundwater model may not have been developed for a potential storage site
  • Biggest obstacle in DREAM tool demonstration task was data generation. It took a significantly longer time to generate the example leakage simulations than to demonstrate the tool capabilities
  • The complex pore pressure history at the Farnsworth site make estimating the state of stress and risk of induced seismicity a bigger challenge than it would be in a greenfield

– Synthetic Datasets
  • User training for EDX is needed and was offered during this afternoon
Synergy Opportunities

- Application of NRAP tools by CarbonSAFE projects will help
  - Demonstrate how the tools can be applied at carbon storage sites
  - Identify ways in which the tools can be made more flexible and useful
- Synthetic datasets will be made available to the broader community
Project Summary

– Key Findings

• Aquifer Impact Model can be used to guide characterization by identifying sensitive parameters

• Using a typical pressure-based monitoring technology, DREAM results showed optimal configurations detecting hypothetical leaks in ~40% of scenarios. The rest did not exceed the user-defined detectable thresholds.

• At the Oklahoma site there are indications of permeability modification due to earthquakes.

• At the Farnsworth site even a few stress and pore pressure measurements could have a significant value by allowing an expanded operating pressure range

• Datasets for the other 43 CCS sites in North America have been cataloged on EDX for community access
Next Steps

- At the CaMI site, update CO₂ plume prediction, simulate the geochemical change at the injection formation, simulate hypothetical leakage of CO₂ to shallow aquifer
- Will submit journal article on results of DREAM field application
- Data analysis methods for identify permeability changes due to earthquakes will be enhanced using data from the Oklahoma site
- Identify 2-3 priority CCS sites and prepare detailed data catalogs for each
- Complete development and sharing of Kimberlina 2.0 synthetic dataset
Appendix

- These slides will not be discussed during the presentation, **but** are mandatory.
Benefit to the Program

• The motivating goal of NRAP is to develop science-based methodologies and tools for calculating risks at any CO$_2$ storage site while providing necessary scientific and technological advances to support that methodology. Phase II is focusing on management of risk associated with large-scale CO$_2$ storage, and with reducing associated uncertainties.

• Objectives of efforts under Phase II will focus on applying and extending that predictive capability to actively manage risks related to CO$_2$ storage to quantitatively assess improvements in environmental risk performance afforded by select mitigation strategies, and to reduce uncertainties in system performance through iterative conformance assessment and prediction improvement.
Project Overview
Goals and Objectives

- This task focuses on the validation of various components of the NRAP toolset, and the NRAP-IAM-CS. A primary goal of this task is to compare the predictive capability of the tools with data from real field observations.

- However, since field data are limited, and since there are no comprehensive field data sets where a large scale CO$_2$ leak has occurred, a synthetic data set based on simulated CO$_2$ storage with hypothetical leakage and stress effects at the Kimberlina site is being developed and used as a community dataset.
Organization

- **Field Applications**
  - Groundwater Assessment Field Application (Diana Bacon, PNNL)
  - Containment Tools and Methodologies Field Demonstration (Liang Zheng, LBNL)
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- **Synthetic Datasets**
  - Development of Community Data Sets (Kelly Rose, NETL)
  - Kimberlina Site Data set for Testing of Monitoring Tools/Approaches (Quanlin Zhou, LBNL)
## Task Milestones

<table>
<thead>
<tr>
<th>Milestone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Submit journal article on application of AIM to a large field demonstration project</td>
</tr>
<tr>
<td>Archive Kimberlina version 1 site reservoir, groundwater models, including metadata on domain size; parameters; and data set(s)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Date</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>3/17</td>
<td>Manuscript submitted to peer-review journal, and uploaded to NRAP EDX</td>
</tr>
<tr>
<td>3/17</td>
<td>Archived data uploaded to EDX</td>
</tr>
</tbody>
</table>
Bibliography


– Kroll, K. A. Cochran, E. S., and Murray, K. E., 2017. ”Poroelastic properties of the Arbuckle Group in Oklahoma derived from well fluid level response to the Mw5.8 Pawnee and Mw5.0 Cushing Earthquakes”, Seis. Res. Letters.