Lessons from Monetizing Leakage Risk for Monetizing Monitoring Costs

Jeffrey M. Bielicki, Ph.D.
IEAGHG 2nd Combined Meeting of Modeling and Monitoring Networks
Edinburgh Center for Carbon Innovation, University of Edinburgh
Edinburgh, Scotland | July 6, 2016
Work Relevant to **Modeling and Leakage Risk**

1. Characterizing leakage pathways and assessing their potential impact on caprock integrity;

2. Determining the effective permeability of a leakage pathway;

3. Investigating the outcomes of leakage into overlying formations, groundwater, the unsaturated zone, and to the atmosphere;

4. Remediating leakage by natural or engineered approaches;
Work Relevant to **Modeling and Leakage Risk**

5. Simulating horizontal and vertical fluid migration through stratigraphic sequences of sedimentary basins;

6. Identifying the economic costs of these physical processes, their social and regulatory drivers, and stakeholder financial liabilities;

7. Developing Measurement, Monitoring, Verification, and Assessment approaches to detect the movement, leakage, and impact of CO$_2$;
What is the Purpose of Monitoring?

ACQUIRE INFORMATION FOR:

**Verification of:**
- *Conformance*: The degree to which reservoir performance is consistent with expectations
- *Containment*: CO₂ is being contained within the target reservoir.
- *Environmental Impact*: the degree to which emplaced CO₂ or displaced brine is affecting, or has affected, environmental conditions.

For whom?
Prologue:
How do we locate geologic CO$_2$ injection sites among other subsurface activities?

Feature Presentation:
How can we monetize leakage risk for geologic CO$_2$ storage?

Monitoring and expected costs with secondary trapping.

Epilogue:
Some lessons from monetizing leakage risk for monitoring and verification.
Basin Scale Leakage Risk

Leakage Impact Valuation (LIV) method
Bielicki et al., (2014)

Leakage in Context of U.S. Policies
Bielicki et al., (2015)

The Leakage Risk Monetization Model (LRiMM)
Bielicki et al., (2016)
Michigan Sedimentary Basin

1. Natural Gas Production (9,756)
2. Oil Production (3,442)
3. Storage – Natural Gas (1,726)
4. Injection – Waste (727)
5. Injection – Enhanced Recovery (516)
6. Observation (490)
7. Oil or Gas – In Progress (54)
8. Mineral Wells (35)
9. Injection – UIC Class I (25)
10. Other (6)
11. Plugged (30,484)
12. Dry Hole (38)

Quaternary
Jurassic
Upper Pennsylvanian
Lower Pennsylvanian
Bayport-Michigan
Marshall
Devonian-Mississippian
Traverse-Dundee
Silurian-Devonian
Collingwood
Trenton-Black River
St. Peter
Prairie du Chein
Galesville
Eau Claire
Mt. Simon

candidate aquifers
Risk = 

Probability of an outcome 

× 

Impact of an outcome
Leakage Risk Monetization Model: LRiMM

leakage (CO$_2$ or brine) flowing through pathways and hydrostratigraphic units | 3D Geospatial Data

Probabilities | geophysical fluid flow simulations

Impacts | Leakage Impact Valuation Method
A. Specify Case Study

B. Develop Low- and High-Cost Storylines

C. Identify Stakeholders

D. Estimate Costs

**Leakage Impact Valuation method (LIV)**

A thorough **scenario-based** methodology estimate **financial** consequences across potential **outcomes** incurred by ten different **stakeholders**

*The Ohio State University - Energy Sustainability Research Laboratory*  
Bielicki et al. (2014)
<table>
<thead>
<tr>
<th>I. Specify Case Study</th>
<th>II. Develop Low- and High-Cost Storylines</th>
<th>III. Specify Mechanisms and Drivers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Identify Site Conditions</td>
<td>Geology</td>
<td></td>
</tr>
<tr>
<td>Injection formation</td>
<td>Injection formation</td>
<td></td>
</tr>
<tr>
<td>Site operating parameters</td>
<td>Site operating parameters</td>
<td></td>
</tr>
<tr>
<td>Types of subsurface activities nearby</td>
<td>Types of subsurface activities nearby</td>
<td></td>
</tr>
<tr>
<td>Cost Drivers</td>
<td>Technical</td>
<td>Legal</td>
</tr>
<tr>
<td>------------------------------------</td>
<td>-----------</td>
<td>-------</td>
</tr>
<tr>
<td>Legal Costs</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Labor Burden to Others</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Technical Remedies for Damages</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Business Disruption to Others</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Injection Interruption</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Find and Fix a Leak</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Environmental Remediation</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>
NOAK Costs

Injection Interruption: 3-98%
Find and Fix a Leak: 1%-36%
Environmental Remediation: 0-10%
Stakeholder Exposure

Injection Operators vs. Other Stakeholders

FOAK and NOAK costs differ

**Fig. 4.** Financial impacts incurred by CO₂ injection operators from FOAK projects (columns) to NOAK projects (black inset lines).

**Fig. 5.** Financial impacts imposed on others from a leaking geologic CO₂ storage from FOAK projects (columns) to NOAK projects (black inset lines, where only CO₂ emitters incur different costs).
Leakage Risk Monetization Model: LRIIMM

leakage \((\text{CO}_2 \text{ or brine})\) flowing through pathways and hydrostratigraphic units | 3D Geospatial Data

Probabilities | geophysical fluid flow simulations

Impacts | Leakage Impact Valuation Method
Probabilistic Risk Analysis with Critical Uncertainties

Bounding Analysis:
Well Leakage Permeability (m²): $10^{-10}, 10^{-12}, 10^{-14}, 10^{-16}$

Monte Carlo Simulation:
Mt. Simon:
Porosity: $\log N(0.13, 0.04)$

Permeability: $\kappa = \log N(2.25 \times 10^{-11}, 3.11 \times 10^{-13})$ m²

$\kappa = 5 \times 10^{18} \phi^{3.911}$
Secondary Trapping

Average Accumulation (tCO$_2$/yr)

Crystal Geyser

Mammoth Mountain

Natural Analogs
Leakage and Attenuation

Secondary Trapping:
CO$_2$ leaking reduces by 1-2 orders of magnitude per intervening stratigraphic layer

Leakage:
reduces pressure reduces AoR
Monetizing Leakage Risk

Economic Costs Weighted by Magnitude of Leakage

\[ W_{1,t} = \overline{h}_{CO_2,t} \quad \quad W_{2,t} = \frac{P_{i,t}}{P_h} \]

\[ I^0(W_{(.)}) = I^0_L + W_{(.)}(I^0_H - I^0_L) \]

Monetized Leakage Risk: \( MLR = \sum p_o x I_o / CO_2 \text{ injected} \)

\[ MLR_t = \frac{R_t}{r \cdot t} \]

\[ = \sum_{o=1}^{4} \left\{ W_{3,t} \cdot [p_{CO_2,t} \cdot I^0_t(W_{i,t}) + (1 - p_{CO_2,t}) \cdot p_{P_t,t} \cdot I^0_t(W_{2,t})] \right\} \]
Monetized Leakage Risk
(Location 1)

9.5 MtCO$_2$/yr
Monetized Leakage Risk
(Location 2)

9.5 MtCO$_2$/yr
Intervention Adjustment

\[ \text{IAML}_{t} = \frac{\text{IAR}_{t}}{r \cdot t} = \text{MLR}_{t} \cdot \prod_{\tau=1}^{t} [1 - q_{\tau-1}(L)] \]

Monetized Leakage Risk without intervention

Intervention based on detection of:
- 10,000 tCO₂
- 1,000 tCO₂
- 100 tCO₂

Year
Leakage Risk: Take Aways

MLR will vary over time
likely to be orders of magnitude below CO$_2$ storage costs.

Distribution of MLR
within sedimentary units varies by depth.
varies by primary or secondary leakage.
secondary trapping confines the majority of expected costs to the subsurface

Storage operators likely have adequate resources
substantial economic costs may be imposed on other stakeholders

Intervention and remediation
substantially reduces MLR.
Categories of Outcomes

Leakage:
1. Leakage Only

Leakage that
2. interferes with another subsurface activity
3. affects groundwater
4. escapes to the atmosphere

Monitoring and Verification:
• (Non)conformance
• (Non)containment
• Environmental Impact
• Economic Impact
• Others?
What is the Purpose of Monitoring and Verification?

ACQUIRE INFORMATION FOR:

Verification of:

• Conformance: The degree to which reservoir performance is consistent with expectations

• Containment: CO₂ is being contained within the target reservoir.

• Environmental Impact: the degree to which emplaced CO₂ or displaced brine is affecting, or has affected, environmental conditions.

• Economic Impact: the degree to which (non)conformance, (non)containment, or environmental impacts incur economic costs.
Value of Intervention

Area between MLR and IAMLR is a benefit to detection (and remediation)

Diminishing returns to detection limits
Categories of Stakeholders

Leakage:
1. Injection operator
2. Injection regulator
3. Activity operator
4. Activity regulator
5. Groundwater user
6. Groundwater regulator
7. CO₂ producer
8. Climate regulator
9. Surface owner/resident
10. Environmental / health regulator

Monitoring and Verification:
Anyone in the list that should be removed?

Anyone should be added?
- Future operators?
- Future researchers?
What is the Purpose of Monitoring and Verification?

ACQUIRE INFORMATION FOR:

Verification of:

- **Conformance**: The degree to which reservoir performance is consistent with expectations
- **Containment**: CO$_2$ is being contained within the target reservoir.
- **Environmental Impact**: the degree to which emplaced CO$_2$ or displaced brine is affecting, or has affected, environmental conditions.
- **Economic Impact**: the degree to which non/conformance, non/containment, or environmental impacts incur economic costs.

Informing (Assuring?) Stakeholders:

- Injection Operators, Regulators, General Public (surface owners, regional populace), …
- What is the value (cost) of a project that does (not) go forward due to (lack of) stakeholder acceptance?
- Is there a role for (un)coordinated citizen science?
What is the Purpose of Monitoring and Verification?

ACQUIRE INFORMATION FOR:

Verification of:
• Conformance: The degree to which reservoir performance is consistent with expectations.
• Containment: CO₂ is being contained within the target reservoir.
• Environmental Impact: the degree to which emplaced CO₂ or displaced brine is affecting, or has affected, environmental conditions.
• Economic Impact: the degree to which non/conformance, non/containment, or environmental impacts incur economic costs.

Informing (Assuring?) Stakeholders:
• Injection Operators, Regulators, General Public (surface owners, regional populace), …
• What is the value (cost) of a project that does (not) go forward due to (lack of) stakeholder acceptance?

Deriving Learning: value in the knowledge and its spillover to other applications
• Present operational decisions
• Research and modeling for future projects
• Regulatory evolution
Lessons and Questions

Identify full spectrum of outcomes and stakeholders.
- Conformance vs. Containment vs. Environmental impact vs. Economic impact vs. Stakeholder impact

What is the value of monitoring and verification beyond the economic costs?
- Projects with extensive experience with CO$_2$-EOR have generally not been monitored adequately.
- How much monitoring and verification and of what type are necessary to appease stakeholders? Before project? During operational phase? After active injection?

Monitoring and Verification are partly site-specific:
- Monitoring occurs at a site/project, may collect data that is sparse spatially and temporally, but there is…
- …Value in the feedback of information and knowledge for future operation, projects, and oversight.
Jeffrey M. Bielicki, Ph.D.

Assistant Professor\textsuperscript{1, 2, 3}
\textsuperscript{1}Department of Civil, Environmental, and Geodetic Engineering
\textsuperscript{2}John Glenn College of Public Affairs
\textsuperscript{3}Environmental Science Graduate Program
The Ohio State University
bielicki.2@osu.edu
References


