Optimal Monitoring for CO₂ Storage Projects
Stanford Center for Carbon Storage

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CCUS in IL Storage Corridor

- **Project Objective:** Approval for Class VI injection well permits at both sites
- **SCCS Objective:** Develop optimal pressure monitoring plans

- **Prairie State Generating Company**
  - Coal-fired Power Plant
  - 6 MTPA CO₂

- **One Earth Energy**
  - Ethanol Production
  - 0.450 MTPA CO₂
Subtask 7.4: Develop Monitoring Strategies

1. Develop pressure monitoring plan
2. CO\textsubscript{2} plume tracking through HM

- Led by the Illinois State Geological Survey (ISGS)
- Approximately 70 researchers from 14 institutions
Workflow Flowchart

**Determine Monitoring Well Locations**
- Establish Parameter Uncertainty & Simulate Prior Models
- Monitoring Optimization

**History Matching**
- Predict Observations
- Update Models
- Measure Observations
Cross-section of 3D “Base” Model

<table>
<thead>
<tr>
<th>Unit</th>
<th>Permeability (md)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eau Claire</td>
<td>0.10</td>
</tr>
<tr>
<td>Upper MS</td>
<td>7.43</td>
</tr>
<tr>
<td>Middle MS</td>
<td>2.30</td>
</tr>
<tr>
<td>Lower MS</td>
<td>35.00</td>
</tr>
<tr>
<td>LMS Ark.</td>
<td>84.00</td>
</tr>
<tr>
<td>Argenta</td>
<td>0.85</td>
</tr>
</tbody>
</table>

*Base permeability values treated as $\mu_{prior}$

*Fang Yang – University of Illinois Urbana-Champaign*
Radial Model Representation

Radial model allows the use of Gege Wen’s DNN simulator. Wen, Tang, & Benson (2021) showed that the surrogate model simulation time is less than 1 second.
Radial model allows the use of Gege Wen’s DNN simulator

- Wen, Tang, & Benson (2021)

Surrogate model simulation time: < 1 second
Introducing Uncertainty (1)

Distribution in Layer 4

- **Depth**
- **Radial Extent**
- **Perforations**
- **k (md)**

**Layer Permeability (md)**

- **Base Model**
- **Permeability Dist.**

 Frequency
Introducing Uncertainty (2)

![Graph showing distribution in Layer 5 with depth and radial extent dimensions, and a histogram of layer permeability frequencies.](image)
Simulation Results for Prior Models

- 1000 prior models generated and simulated
- All of these models are consistent with specified statistics
- Large variation in CO$_2$ saturations
Challenges Associated with Placing Sensors

- Best sensor locations found before any data collection
- Complicated, nested optimization problem
- Direct approach is to modify location, history match for many prior models, and repeat
Optimize Monitoring Well Locations (1)

Monitoring Optimization

\[ y_{\text{opt}} = \arg\min_y \left[ 1 - \frac{C_{Jd} (C_{dhd} + C_D)^{-1} C_{d} J}{\sigma_{JJ}^2} \right] \]

- Efficient optimization using a Bayesian approach (He et al. 2018; Sun & Durlofsky 2019)
- Analytical expression captures correlation between quantity of interest (J) and observations
- Utilize a **genetic algorithm** to minimize expected posterior uncertainty in J
Optimize Monitoring Well Locations (2)

Monitoring Optimization

$$y_{opt} = \arg\min_y \left[ 1 - \frac{C_{Jd_h}(C_{d_h}d_h + C_D)^{-1}C_{d_h}J}{\sigma_{JJ}^2} \right]$$

- $J$ is the fraction of the plume beyond $r_0$
- Acts as conformance limit
- At $r_0 = r(\text{cell 50}) = 490m$
Optimize Monitoring Well Locations (3)

Monitoring Optimization

\[ y_{\text{opt}} = \arg\min_y \left[ 1 - \frac{C_{\text{Jdh}}(C_{\text{dh}} + C_{D})^{-1}C_{\text{dh}}J}{\sigma_{JJ}^2} \right] \]

- Pressure input at \( y_{\text{opt}} \)
- Correlation between the observations and the quantity of interest \( J \)
- Expected uncertainty reduction w.r.t. observations
Optimize Monitoring Well Locations (3)

Monitoring Optimization

\[ y_{\text{opt}} = \arg\min_y \left[ 1 - \frac{C_{Jd} (C_{dh} + C_D)^{-1} C_{dhJ}}{\sigma_J^2} \right] \]

- Pressure input at \( y_{\text{opt}} \)
- Correlation between the observations and the quantity of interest \( J \)
- Expected uncertainty reduction w.r.t. observations

\[ y_{\text{opt}} = \begin{bmatrix} r_1 \\ Z_{11} \\ Z_{21} \\ r_2 \\ Z_{12} \\ Z_{22} \end{bmatrix} \]
Results for Optimal Monitoring Well Locations

- Conformance radius $r_0 = 50$ (490m)
- Background displays average pressure response over all prior models
- Sensor locations provide $d_{obs}$
Results for Optimal Monitoring Well Locations

- Conformance radius $r_0 = 50 \ (490\text{m})$
- Background displays average pressure response over all prior models
- Sensor locations provide $d_{obs}$
Actual pressure data from the aquifer will be used in practice

In this study, the true model is generated to be consistent with the prior

“True” model was not used in the optimization
History Matching: ES-MDA

- HM entails adjusting geomodel parameters to honor observations
- Preserve geological realism & manage computation demands
- $d_{obs}$ is provided from monitoring locations
- HM driven by mismatch of data observed and predicted

ES-MDA Algorithm

1. Define number of assimilation steps $N_a$ & coefficients $\alpha_i$, s.t. $\sum N_a i \alpha_i = 1$

2. For $i = 1 \ldots N_a$:
   2.1 Simulate ensemble
   2.2 Perturb obs: $d'_{obs} = d_{obs} + \sqrt{\alpha_i C_{1/2}}$
   2.3 Update model parameters: $m_f j + C_f MD(C_f DD - \alpha_j C_D) - 1 ((d'_{obs}, j - d_f j))$
History Matching: ES-MDA

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- Preserve geological realism & manage computation demands
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**ES-MDA Algorithm**

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2. For \(i = 1 \ldots N_a\):
   2.1 Simulate ensemble
   2.2 Perturb obs: \(d'_{\text{obs}} = d_{\text{obs}} + \sqrt{\alpha_i C_D^{1/2}} z_d\)
   2.3 Update model parameters: 
      \[
      m_f^j + C_{\text{MD}}^f (C_{DD}^f - \alpha_j C_D)^{-1} (d'_{\text{obs},j} - d_f^j)
      \]
Uncertainty Reduction for True Model 1

- **Red curve**: Prior distribution (CDF)
- **Blue curve**: Posterior (history matched) with optimally placed monitoring wells
- **Gray curves**: Posterior (history matched) with randomly placed monitoring wells

![Graph showing CO₂ Volume beyond r₀ = 50 with percentiles and curves.]
Uncertainty Reduction for True Model 2

- **Red curve**: Prior distribution (CDF)
- **Blue curve**: Posterior (history matched) with optimally placed monitoring wells
- **Gray curves**: Posterior (history matched) with randomly placed monitoring wells

2 Wells, 2 Sensors Each

- CO₂ Volume beyond \( r_0 = 50 \)
Conclusions & Future Work

Conclusions

- Developed workflow to optimally place monitoring wells
- Current implementation utilizes surrogate flow model (Wen et al., 2020), but framework is compatible with any simulator
- Demonstrated significant uncertainty reduction with CarbonSAFE base-case model using the overall workflow

Future Work

- Apply to more realistic 3D multi-well models provided by CarbonSAFE
- Test different HM & optimization methods
Acknowledgements

- Fang Yang for the base aquifer model
- Gege Wen for DNN CO$_2$ simulator
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