Optimal Monitoring for CO_2 Storage Projects

Stanford Center for Carbon Storage

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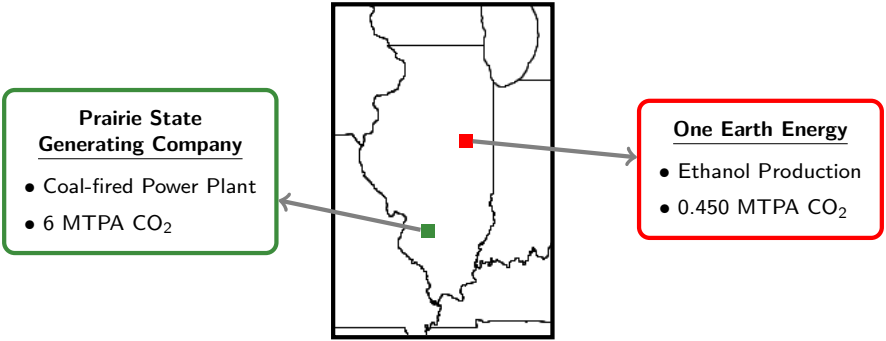
CCUS in IL Storage Corridor



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

Project Scope

- Task 1: Project Management
- Task 2: NEPA
- Task 3: Risk Assessment
- Task 4: Stakeholder Engagement
- Task 5: Site Characterization
- Task 6: Drilling and Well Testing
- Task 7: Storage Modeling
- Task 8: Class IV Permitting
- Task 9: Assess CO_2 Sources

Subtask 7.4:

Develop Monitoring Strategies

1. Develop pressure monitoring plan
2. CO_2 plume tracking through HM

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

Workflow Flowchart

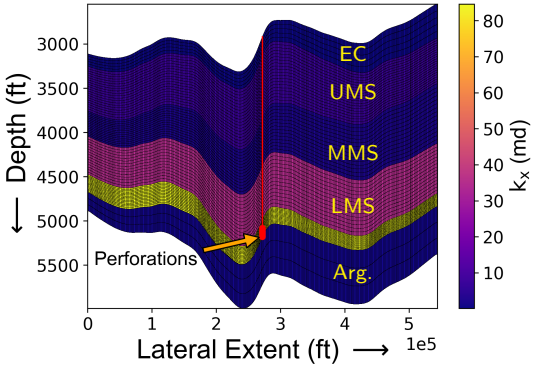
Determine Monitoring Well Locations

Establish Parameter Uncertainty & Simulate Prior Models → Monitoring Optimization

History Matching

Predict Observations → Measure Observations → Update Models → Predict Observations

Cross-section of 3D "Base" Model

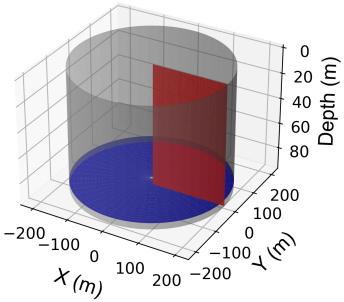


*Fang Yang – University of Illinois Urbana-Champaign

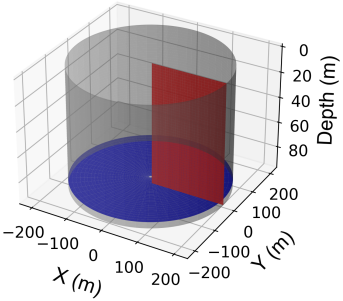
Unit (-)	**Permeability** (md)
Eau Claire	0.10
Upper MS	7.43
Middle MS	2.30
Lower MS	35.00
LMS Ark.	**84.00**
Argenta	0.85

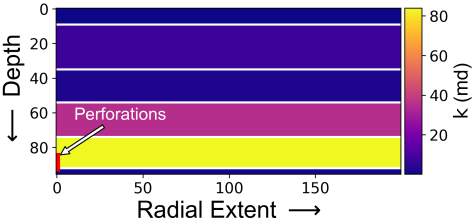
- Base permeability values treated as μ_{prior}

Radial Model Representation



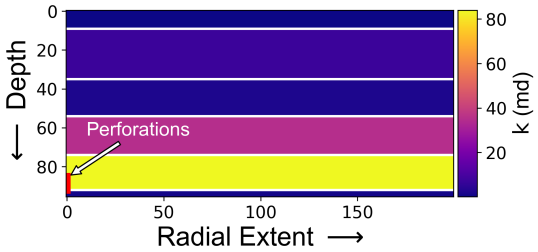
Radial Model Representation

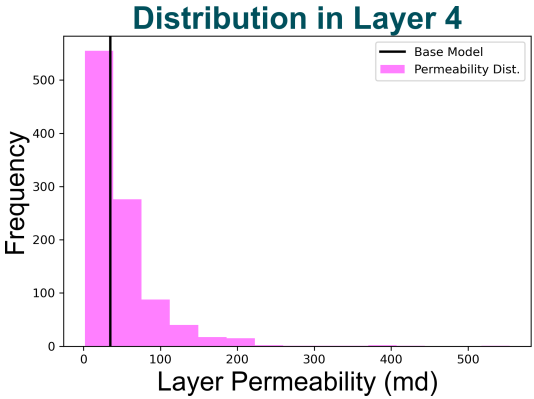




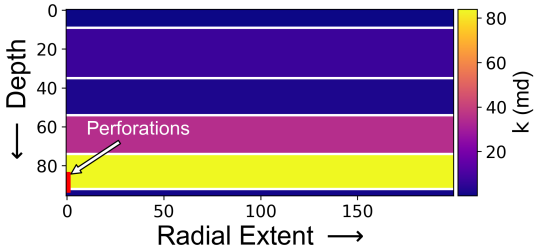
- Radial model allows the use of Gege Wen's DNN simulator
  - **Wen, Tang, & Benson (2021)**
- Surrogate model simulation time: < 1 second

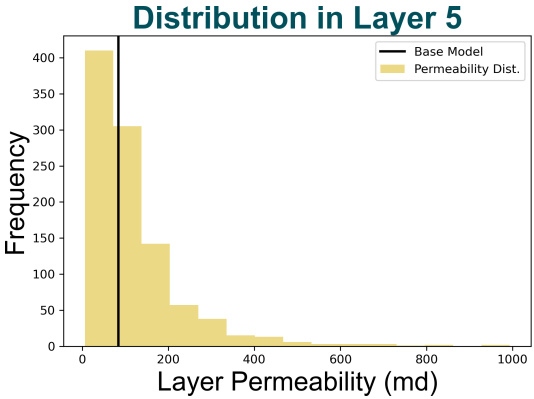
Introducing Uncertainty (1)



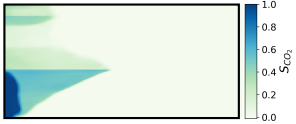


Introducing Uncertainty (2)





Simulation Results for Prior Models



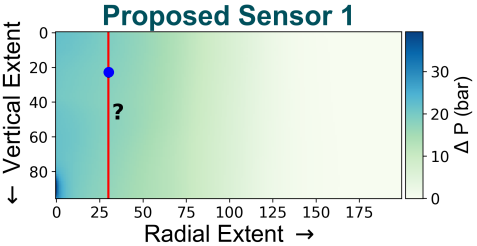
Prior Model 1

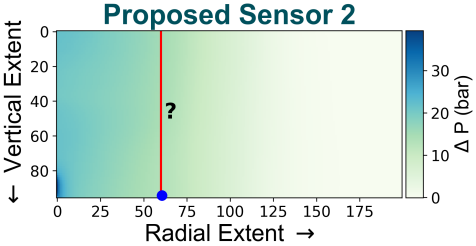
Prior Model 2

Prior Model 3

- 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

$$\mathbf{y}_{\text{opt}} = \underset{\mathbf{y}}{\text{argmin}} \left[1 - \frac{C_{Jd_h} \left(C_{d_h d_h} + C_D \right)^{-1} C_{d_h J}}{\sigma_{JJ}^2} \right]$$

- 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

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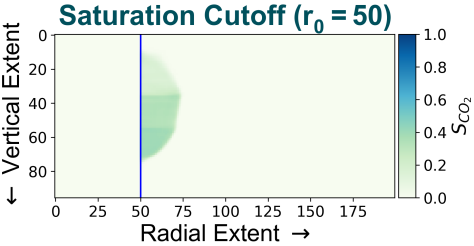

- J is the fraction of the plume beyond r_0
- Acts as **conformance** limit
- At $r_0 = r(\text{cell } 50) = 490\text{m}$

Optimize Monitoring Well Locations (3)

Monitoring Optimization

$$\mathbf{y}_{\text{opt}} = \underset{\mathbf{y}}{\text{argmin}} \left[1 - \frac{\mathbf{C}_{\mathbf{J}\mathbf{d}_\mathbf{h}} \left(\mathbf{C}_{\mathbf{d}_\mathbf{h}\mathbf{d}_\mathbf{h}} + \mathbf{C}_\mathbf{D} \right)^{-1} \mathbf{C}_{\mathbf{d}_\mathbf{h}\mathbf{J}}}{\sigma^2_{\text{JJ}}} \right]$$

- Pressure input at $\mathbf{y}_{\text{opt}}$
- Correlation between the observations and the quantity of interest J
- Expected uncertainty reduction w.r.t. observations

$$\mathbf{y}_{\text{opt}} = \begin{bmatrix} r_1 \\ z_{11} \\ z_{21} \\ r_2 \\ z_{12} \\ z_{22} \end{bmatrix}$$

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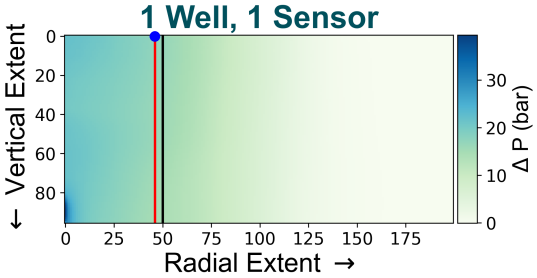
Results for Optimal Monitoring Well Locations



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

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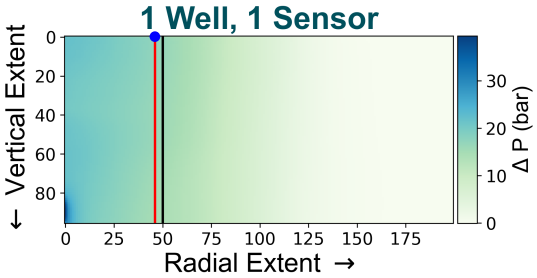

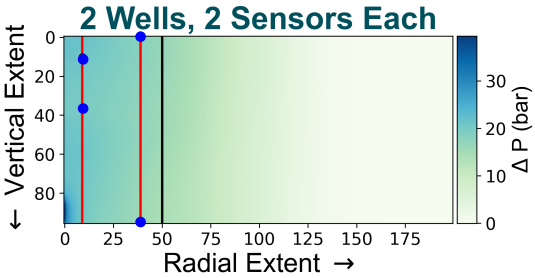

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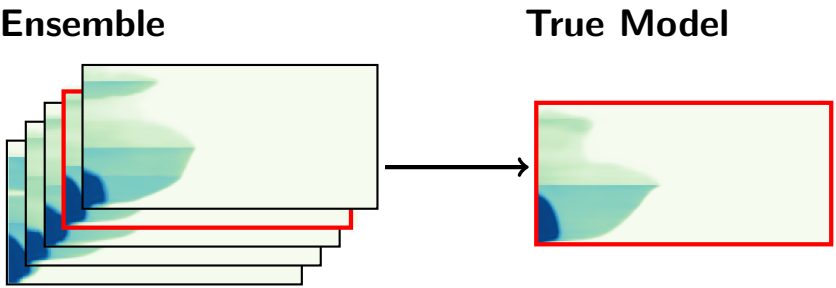
“True” Model



- 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

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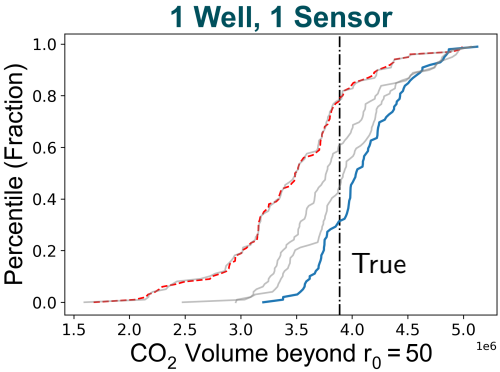
ES-MDA Algorithm

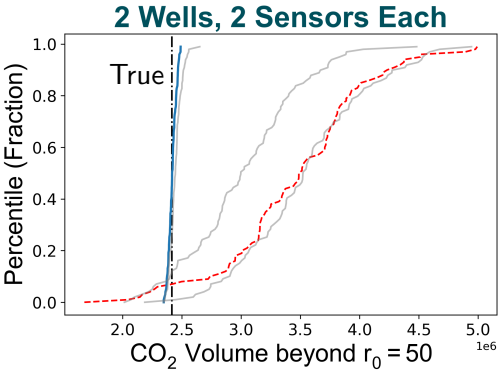
1. Define number of assimilation steps N_a & coefficients α_i, s.t. $\sum_i^{N_a} \frac{1}{\alpha_i} = 1$
2. For $\mathrm{i} = 1 \ldots \mathrm{N_a}$:
   - 2.1 Simulate ensemble
   - 2.2 Perturb obs: $\mathrm{d}'_{\mathrm{obs}} = \mathrm{d}_{\mathrm{obs}} + \sqrt{\alpha_i}\mathrm{C}_{\mathrm{D}}^{1/2}\mathrm{z}_{\mathrm{d}}$
   - 2.3 Update model parameters: $\mathrm{m}_{\mathrm{j}}^{\mathrm{f}} + \mathrm{C}_{\mathrm{MD}}^{\mathrm{f}}(\mathrm{C}_{\mathrm{DD}}^{\mathrm{f}} - \alpha_{\mathrm{j}}\mathrm{C}_{\mathrm{D}})^{-1}(\mathrm{d}'_{\mathrm{obs,j}} - \mathrm{d}_{\mathrm{j}}^{\mathrm{f}})$

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

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

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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