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1.1. Scale and Magnitude of GCS

World Oil Production in 2006: \(4.3 \times 10^9 \text{ m}^3\) (73.54 million barrel/day)

World CO\(_2\) Emissions in 2006: \(36.5 \times 10^9 \text{ m}^3\) (29.2 billion metric ton CO\(_2\)/year)

US Oil Consumption in 2006: \(1.2 \times 10^9 \text{ m}^3\) (7.55 billion barrels/year)

US CO\(_2\) Emissions in 2006: \(7.4 \times 10^9 \text{ m}^3\) (5.9 billion metric ton CO\(_2\)/year)

US Class II Brine Injection: \(2.8 \times 10^9 \text{ m}^3\) (2 billion gallons/day in 144,000 wells)

US Groundwater Extraction in 2000: \(117.0 \times 10^9 \text{ m}^3\) (84.5 billion gallons/day)

The Scale and Magnitude of GCS is unprecedented
1.2. DOE Regional Partnerships

Site Characterization (2003-2005)

Validation Phase (2006-2009)

Demonstration Phase (2008-2017)

Full-Scale Deployment (?-?)

with the goal to effectively mitigate climate change

Illinois Basin
1.3. Motivation and Objectives

(Birkholzer et al., IJGGC, 2009)

Mt Simon Storage Capacity: 27-109 Gt CO₂
Large Stationary CO₂ Emissions: ~300 Mt/Year
Average Updip Slope: 8 m/km
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2. Site Characterization

Site Characterization

- Oil and Gas Exploration and Production
  - Deep geo-boreholes for oil exploration
  - One order of magnitude in production rate/volume less than GCS
- Deep Waste Injection
  - 33 wells at 18 sites in the Illinois Basin, 18 of which are into Mt Simon
  - Injection rate of 1.2 million m³ in Illinois in 1984
- Natural Gas Storage (Analog)
- Groundwater Resources Development (Analog)
- Ongoing Geologic Carbon Sequestration

Objectives

- To determine basin hydrogeology
- To have analogs for multiscale GCS processes
- To understand potential discharge/leakage pathways
- To know the scale of the problems
2.1 Basin Stratigraphy

Top
- Maquoketa
- Eau Claire
- Ironton
- Coal

Middle
- St. Peter
- Ordovician

Bottom
- Petroleum Production
- Mt. Simon
- Precambrian Granite
2.2. Natural Gas Storage

<table>
<thead>
<tr>
<th>2006</th>
<th>USA</th>
<th>Illinois + Indiana</th>
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<tbody>
<tr>
<td># of Aquifer Storage Fields</td>
<td>44</td>
<td>30</td>
</tr>
<tr>
<td>Storage Capacity (10^9 m³, Standard T&amp;P)</td>
<td>38.4</td>
<td>27.3</td>
</tr>
<tr>
<td>Storage Capacity (10^9 m³, T=24°C, P=105 bar)</td>
<td>0.29</td>
<td>0.21</td>
</tr>
</tbody>
</table>
2.2. Natural Gas Storage (Cont.)

Manlove Natural Gas Storage Field

Herscher Natural Gas Storage Field

Secondary Seals

(Figures from Morse & Leetaru, MGSC, 2003)
2.3. Groundwater Development

(a) CO$_2$ Storage Rate vs. Pumping Rate

(Mandle and Kontis, 1992, Northern Midwest RASA)
3. Hydrogeology of the Illinois Basin

- **Basin Geology (Deep Formations)**
  - Mount Simon Sandstone → Storage Formation (4 Units and 24 Layers)
  - Eau Claire Formation → Caprock
  - Pre-Cambrian Granite → Baserock

- **Formation Properties (Porosity and Permeability)**
  - Vertical Variability at 0.15 m scale from deep wells
  - Spatial Variability Characterization

- **Pre-Injection Temperature/Salinity Conditions**
3.1. 3D GeoModel: Three Formations

(a) Mt Simon Thickness (m): 60 Boreholes

(b) Eau Claire Thickness (m): 98 Boreholes

Elevation (m)

Pre-Cambrian Granite

Mt Simon Sandstone

Overlying Formations

Site 10
Site 9
Site 8

Northing (km)

Easting (km)
3.1. 3D GeoModel: Four Mt Simon Units

Weaber-Horn #1 Well, with unit correlation with Hinton #7 Well in the Manlove Gas Storage Field
4. Basin-Scale Model Development

- A Hypothetical Storage Scenario for Full-Scale GCS Deployment
- 3D Mesh Generation
- Boundary and Initial Conditions
- TOUGH2/ECO2N (Pruess, 2005) Runs
  - Two-phase CO\(_2\)-brine flow at the plume scale
  - Single-phase brine flow at the basin scale
4.1. Hypothetical Storage Infrastructure and Scenario

- **Hypothetical Storage Infrastructure (Most Suitable, Core Injection Area):**
  - Sufficient Depth (1100 – 2500 m)
  - Sufficient Thickness (300 – 700 m for MS, and >90 m for Caprock)
  - No Known Large Faults
  - >32 km Away from Gas Storage Fields in Operation
  - 250 × 170 km = 24,000 km² in size

- **Hypothetical Storage Scenario (Full-Scale Deployment):**
  - 20 Injection Sites with Spacing: 27 km in Easting + 30 km in Northing
  - Injection Rate: 5 Mt CO₂/year per site over 50 years
  - 1/3 Large Stationary CO₂ Emissions

Top Mt Simon Elevation (m) Contour
4.2. 3D Mesh Generation

2D Mesh: 20,408 Columns, ~60 Model Layers (Maximum Δz=10 m)
3D Mesh: 1,254,000 Gridblocks, 3,725,000 Connections
5. Simulation Results

- CO₂ Plume Evolution and Secondary Seal Effects
- Pressure Buildup Propagation and Interference
- Basin-Scale Pressure Buildup and Brine Migration
- Environmental Impact on Groundwater Resources
5.1. CO₂ Plume Evolution (1)

- A typical gravity-override CO₂ sub-plume developed in the injection unit of high-K and high-porosity
- A pyramid-shaped sub-plume developed in the upper and middle units
- Preferential lateral flow occurring in high-K layers, with CO₂ accumulation
- A good correlation between CO₂ saturation and layer permeability and entry capillary pressure
The CO$_2$ plume never reaches the top of Mt Simon, because of the assumed stratified system and secondary seal effects.

After 150-year redistribution, most of the injected CO$_2$ is trapped as residual saturation (0.2~0.25). A small fraction CO$_2$ migrates in high-K layers along updip slopes.
5.1. CO₂ Plume Evolution (3)
5.1. CO$_2$ Plume Evolution (4): Analog

(Figures from Morse & Leetaru, MGSC, 2003)
5.2. Pressure Buildup Interference (1)

(a) Case A: 0.5 year

(b) Case A: 5 years
5.2. Pressure Buildup Interference (2)

No Caprock Geomechanical Damage is Expected
5.3. Basin-Scale Pressure Buildup and Brine Migration (1)

![Graphs showing pressure buildup and brine migration](image)

(a) Case A: 50 years

(b) Case A: 100 years

Cut-Off=0.01 bar
5.3. Basin-Scale Pressure Buildup and Brine Migration (2)

(a) Volume of displaced brine
(b) Volume of upward-migrated brine

<table>
<thead>
<tr>
<th>Time (years) Since Injection Starts</th>
<th>Volume of Resident Brine ($10^9$ m$^3$)</th>
<th>Volume of out-flowing brine</th>
<th>Volume of upward-migrated brine</th>
<th>Volume of stored brine by compressibilities</th>
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</thead>
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<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
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<td>5</td>
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<tr>
<td>100</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
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<tr>
<td>150</td>
<td>15</td>
<td>15</td>
<td>15</td>
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<tr>
<td>200</td>
<td>20</td>
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</table>

<table>
<thead>
<tr>
<th>Time (years) Since Injection Starts</th>
<th>Brine Upward-Migration Rate ($10^6$ m$^3$/year)</th>
<th>Total Rate</th>
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</thead>
<tbody>
<tr>
<td>50 years</td>
<td>0.95</td>
<td>0.95</td>
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<tr>
<td>200 years</td>
<td>2.1</td>
<td>2.1</td>
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</table>

<table>
<thead>
<tr>
<th>Far-Field</th>
<th>Near-Field</th>
<th>Core-Injection</th>
<th>Total</th>
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<tbody>
<tr>
<td>Upward Migration Rate at 50 years (10$^6$ m$^3$/y)</td>
<td>0.95</td>
<td>7.4</td>
<td>14.4</td>
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<tr>
<td>Upward Migration Rate at 200 years (10$^6$ m$^3$/y)</td>
<td>2.1</td>
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<tr>
<td>Volume at 50 years (x 10$^9$ m$^3$)</td>
<td>0.017</td>
<td>0.14</td>
<td>0.33</td>
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<tr>
<td>Volume at 200 years (x 10$^9$ m$^3$)</td>
<td>0.36</td>
<td>1.21</td>
<td>1.57</td>
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</tbody>
</table>
5.4. Environmental Impact of GCS

- GCS has no impact on freshwater in updip Mt. Simon: brine migration velocity in Mt. Simon in northern Illinois is on the order of 0.1 m/year.
- Upward brine migration is <0.008 m/year on the regional scale, although brine migration rate and volume is large.
- GCS-induced pressure buildup is less significant than pumping-induced drawdown in northern Illinois.
- If there is no significant salinity change in the worst pumping scenario in the 1980-1990s, it is believed that GCS will not impact groundwater beyond that scenario.
5. Summary and Conclusions

- An integrated model was developed to represent a *hypothetical full-scale deployment scenario of carbon sequestration* in the Illinois Basin.

- Simulated plume-scale behavior indicates favorable conditions for CO\(_2\) storage in Mt Simon:
  - High-K and high-\(\Phi\) Arkosic Unit provides *Excellent CO\(_2\) Injectivity* in lower Mt Simon,
  - Secondary seals *Significantly Retards upward CO\(_2\) migration,*
  - Thick, extensive Mt Simon provides *Large CO\(_2\) Storage Capacity,* and
  - Thick regional-scale Eau Claire seal ensures *Long-Term CO\(_2\) Containment* in the storage formation.

- Simulated basin-scale behavior indicates that
  - High hydraulic diffusivity helps reduce pressure buildup in the core injection area, thus *enhancing caprock geomechanical integrity,*
  - High regional caprock permeability allows for natural attenuation of pressure in the storage formation, thus *enhancing storage capacity of Mt Simon,*
  - Brine upward migration occurs in the core injection area, into a thick series of overlying saline aquifers and aquitards, at a maximum velocity of \(~8\) mm/year.
5. Summary and Conclusions (Cont.)

- Environmental Impact on Groundwater Resources
  - Environmental concerns of brine migration into the updip Mt Simon in northern Illinois and southern Wisconsin may not be an issue,
  - Moderate pressure buildup is obtained in northern Illinois, where upward brine migration might be a concern, if local seal imperfections exists,
  - Impact of GCS on shallow freshwater resources in northern Illinois may be less than that induced by heavy pumping from overlying freshwater aquifers.

- Further research is needed to couple a regional groundwater flow model with the integrated model for environmental impact assessment
Acknowledgment

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