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Limits of Simplification: Comparing 3D Reservoir Simulations and 1D Analytical Models for Pressure-Based AoR Assessment in Geological CO_2 Storage

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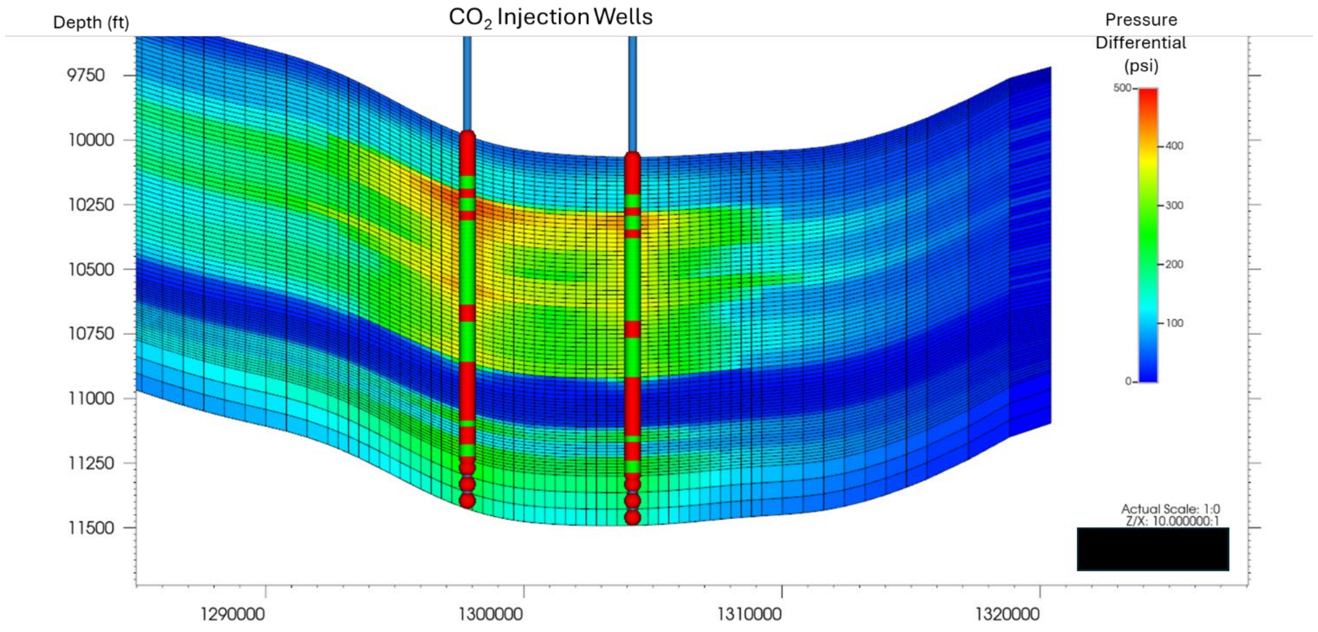
Motivation

- Area of Review (AoR) delineation is a fundamental component of Class VI permitting for geologic carbon dioxide (CO_2) storage projects.
- Reduced-order analytical methods are frequently applied to estimate pressure propagation and AoR extent.
- In regulatory practice, it is sometimes assumed that AoR estimates derived from reduced-order methods should be broadly comparable to those obtained from detailed numerical models.
- This study was conducted to evaluate that assumption.



Objectives

- Compare 1D analytical approximation of diffusivity equation proposed by Matthews and Russell (1967) with 3D dynamic reservoir simulations of 5 commercial-scale CO_2 storage project.
- Identify trends and key parameters affecting agreement or lack thereof between the methods.
- Determine appropriate usage of each model.

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Geological and Reservoir Setting

- The projects are selected to cover a wide range of potential storage settings.
- To ensure a fair comparison, reservoir properties and injection rates were harmonized across both methods.

CCS Project Number	1	2	3	4	5
Storage Formation Depth (ft)	10,000	5,000	4,300	2,900	7,100
Thickness (ft)	1,150	270	900	400	80
Rock Type	Sandstone	Sandstone	Carbonate	Sandstone	Sandstone
Depositional Settings	Fluvial	Fluvial to shallow marine	Shallow marine shelf	Shallow marine, tidal	Fluvial, deltaic
Avg. Porosity (fraction)	0.13	0.20	0.35	0.14	0.12
Avg. Permeability (mD)	51	98	213	29	28
Hydrostatic, Under or Over Pressure	Hydrostatic	Hydrostatic	Hydrostatic	Under Pressure	Hydrostatic
Initial Temperature (^{0}F)	233	104	120	91	183
Salinity (ppm)	200,000	300,000	132,000	123,600	90,000
Threshold Pressure (psia)	166	48	37	181	41
Caprock Type	Shale	Unspecified	Anhydrite	Shale	Shale
Caprock Thickness (ft)	300	Unspecified	808	~500	90
Boundary Condition	Open Boundary/Constant Pressure (Pore Volume multiplier of 1,000)	Open Boundary/Constant Pressure (Pore Volume multiplier of 1,000)	Open Boundary/Constant Pressure (Pore Volume multiplier of 1,000)	Infinite Acting Aquifer/Constant Pressure (Carter and Tracy ,1960)	Open Boundary/Constant Pressure (Variable Pore Volume multiplier with maximum value of 208)

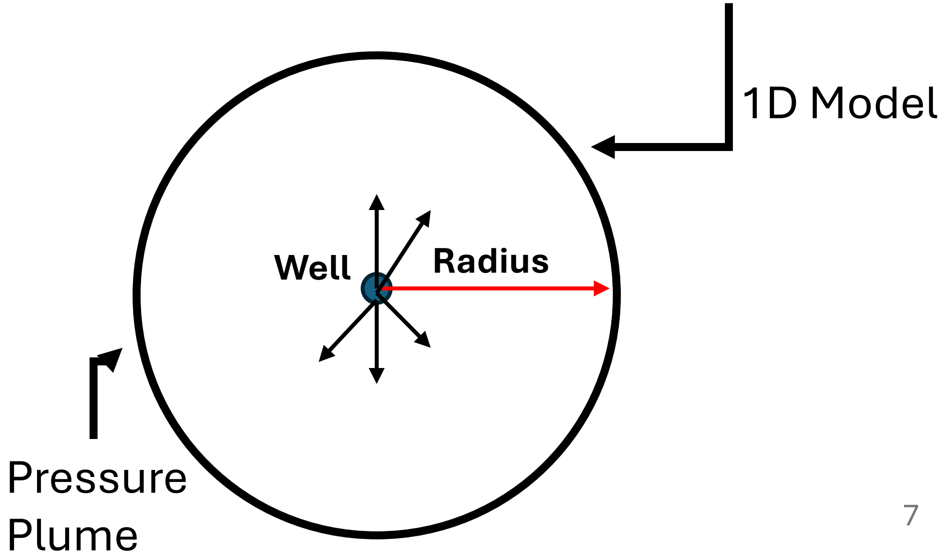
Modeling Approaches: 3D Compositional Model

- Simulations were performed using *CMG-GEM*, which is an equation of state fully compositional reservoir simulation software.
- The simulations accounted for multiphase fluid flow effects such as relative permeabilities and composite compressibility, and pressure communication within and between modeled formations.
- *GEM* has the capability to model all aspects of CO_2 storage and trapping, including residual gas trapping via relative permeability hysteresis, CO_2 dissolution into the aqueous phase, and mineral trapping

Modeling Approaches: Matthews and Russell (1967) Reduced Order Model (ROM)

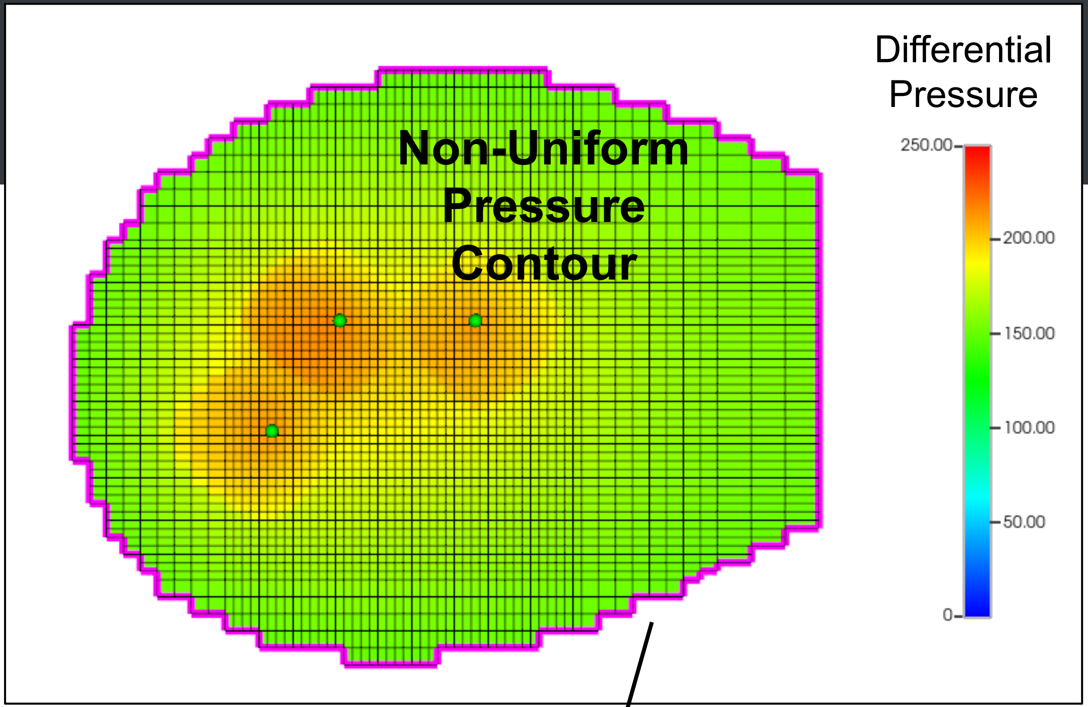
- Late-time logarithmic approximation (field units)
- Key assumptions:
  - Singe-phase, slightly compressible fluid behavior
  - Single-layer, 1D radial flow
  - Homogenous and isotropic reservoir properties
  - Infinite-acting reservoir
  - No pressure dissipation into adjacent formations
  - Idealized line-source well representation

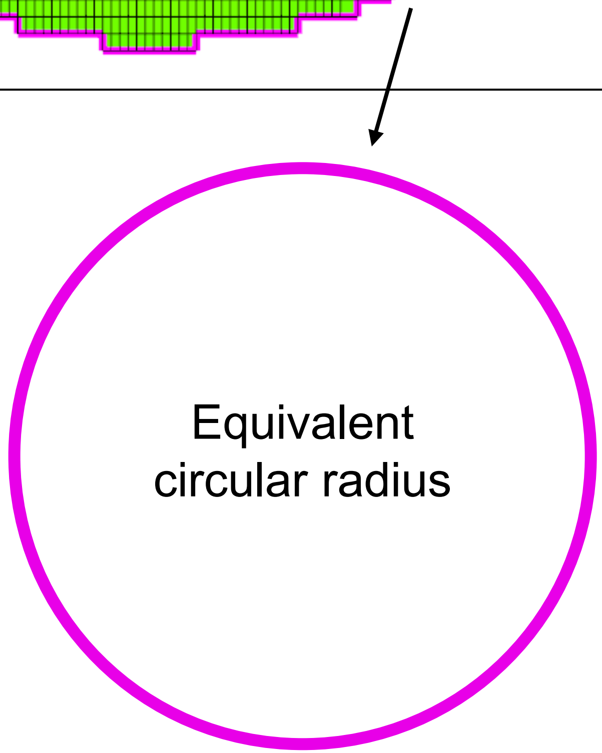
$$p(r,t) = p_i - \left(162.6\ \frac{q\ \mu}{k\ h}\right)\left[log\ \frac{k\ t}{\phi\ \mu\ c_t\ r^2} + 3.23\right]$$



Comparison Methodology

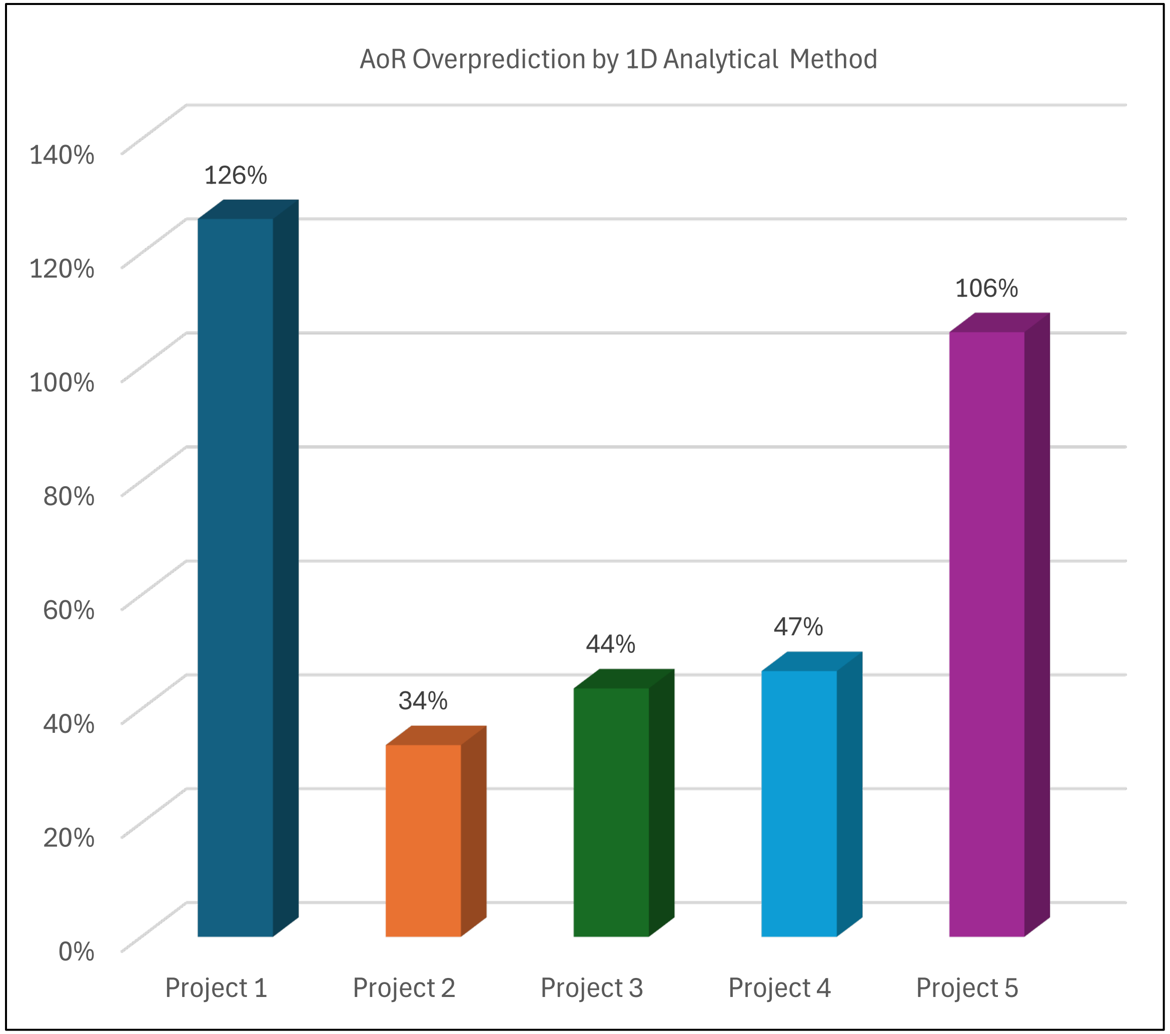
- The same regulatory threshold pressure increase and reservoir inputs were applied for both 1D and 3D AoR delineation, ensuring that observed discrepancies emerge solely from methodological differences, not input inconsistencies.
- Homogenized inputs, where possible.
- Circular AoR approximation from georeferenced plumes.





Results – Overprediction by 1D Analytical Model

- The 3D DRM shows the critical pressure contour is non-uniform due to heterogeneity, anisotropy, differences in completion strategy, and finite-domains.
- Even with only storage zone and caprock modeled, the 3D model allow vertical pressure dissipation.
- The analytical method therefore interprets the critical pressure contour as being a much larger area compared to 3D model.



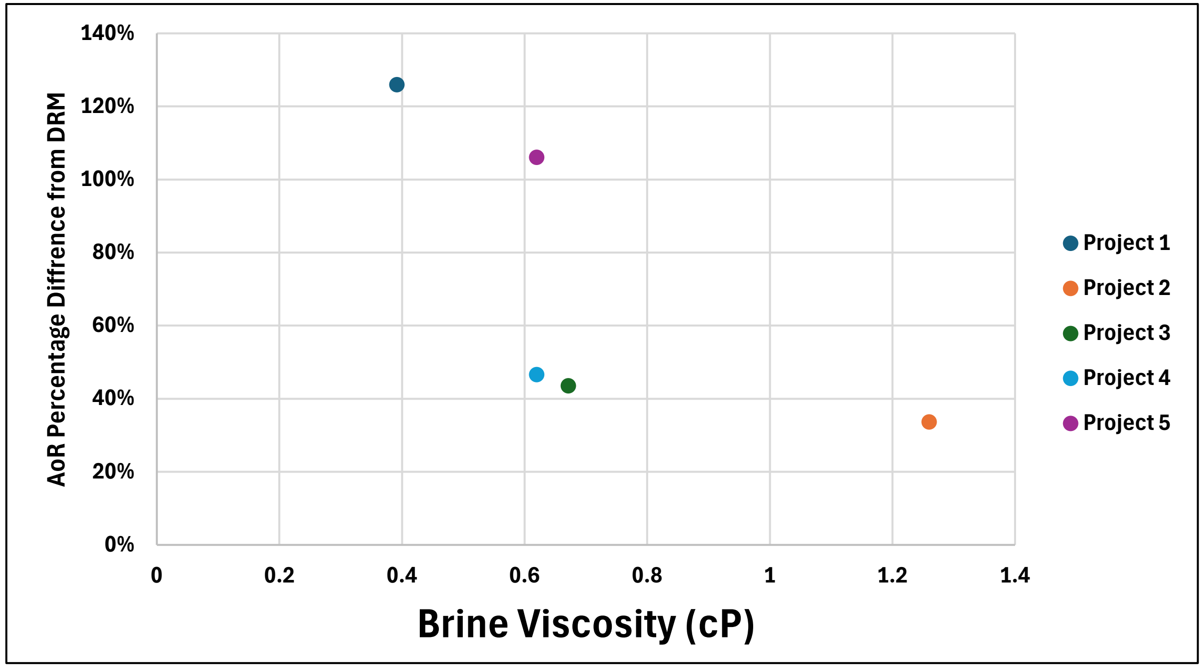
Results

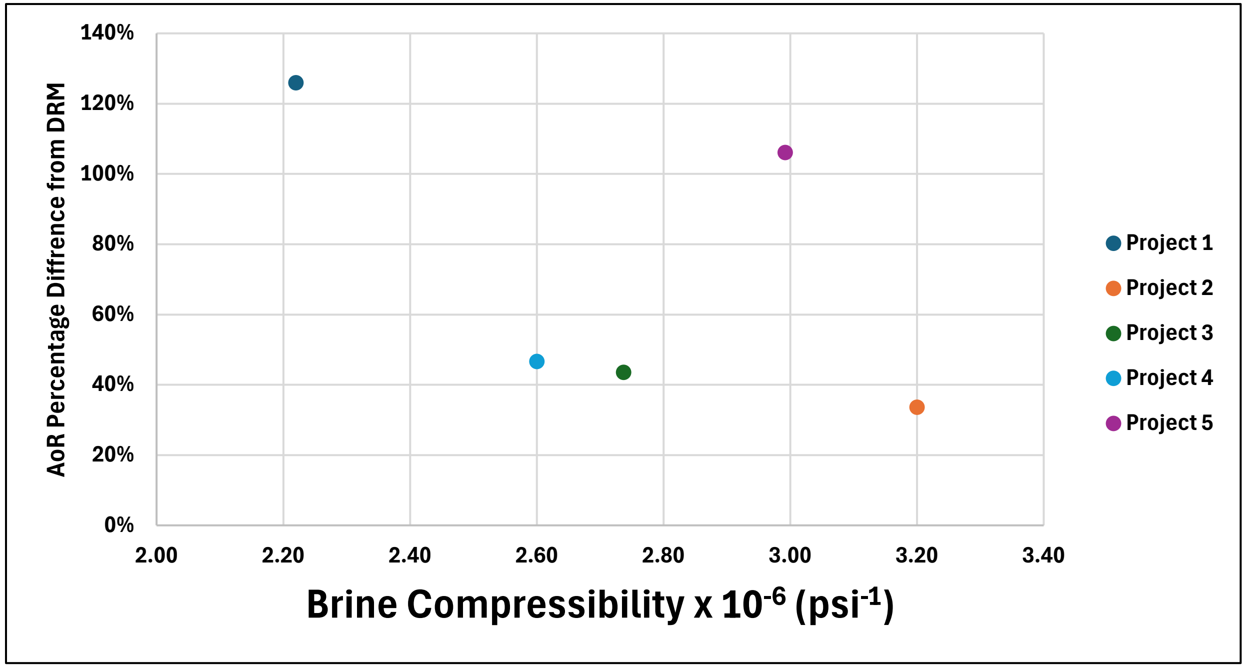
- 3D simulations capture transient near-wellbore pressure and vertical pressure redistribution.
- Variations in fluid compressibility and viscosity associated with evolving CO_2 saturation can influence AoR estimates derived from the M&R analytical formulation.
  - Sensitivity Study: ~75% AoR variation from fluid property variation
- Dynamic reservoir models (DRMs) capture variations in stratigraphy, formation thickness, petrophysical properties, and structural complexity within a three-dimensional (3D) framework

Results – Cross-Project Observations

- The modeling configuration employed simplifies the DRMs for easier comparison to M&R Method – therefore represents lower bound divergence between methods.
- No strong correlation was found between the CO_2 Mass Injection Rate or Threshold Pressure and the percentage difference in AoR.
- There is some indication that tighter reservoirs (those with lower storage zone permeabilities) have a larger variation in percentage difference in AoR.
- There is also an indication that as brine viscosity and compressibility increases, the difference between the two methods decreases. With the sample size taken, more research is required to confirm these indications.

Brine Properties Comparison





***Dataset is limited to 5 projects**

Limitations of M&R Method

- Oversimplified near-well geometry and line-source assumption
- Infinite-acting boundary assumption
- Logarithmic approximation breakdown (Cooper and Jacob, 1946)
- Inability to capture 3D flow mechanisms
- Systematic overprediction of pressure plume size

Conclusions

- Results from this study demonstrate that the one-dimensional (1D) M&R method consistently overestimates the AoR radius when compared to three-dimensional (3D) dynamic reservoir models (DRMs) - even when key input parameters are harmonized between the two approaches.
- These findings indicate that the M&R formulation is best suited for providing a conservative, screening-level approximation of AoR during early phases of project evaluation.
- A reduced AoR has important implications for project risk management, including decreased scope of Corrective Action, reduced monitoring and testing requirements, lower Financial Responsibility obligations, and potentially reduced land and pore-space acquisition needs.
- Accordingly, progression from reduced-order screening methods to DRM-based AoR delineation represents an important step in project maturation and risk reduction.

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