PS Limitations of Pressure-Based AoR Delineation Techniques under Pre-Injection Hydrostatic Equilibrium Conditions between Storage Zone and USDW

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Abstract

Pressure-based Area of Review (AoR) methods for CO_2 storage commonly rely on a single threshold pressure derived from hydrostatic equilibrium (EPA Method 2). While conservative, this approach may not adequately represent open-boundary systems where pressure dissipation and leakage behavior differ significantly. In this study, a 3D reservoir simulation model incorporating a representative leaky wellbore was used to evaluate pressure propagation and potential brine migration into the lowermost USDW. Results indicate that even when reservoir pressures exceed the Method 2 threshold, brine leakage remains negligible and does not lead to meaningful USDW impact under a no–net degradation criterion. These findings suggest that hydrostatic threshold-based AoR delineation can overestimate risk and extent in open systems. A physics-based, simulation-driven framework is proposed to better quantify leakage potential and support more realistic, site-specific AoR definitions.

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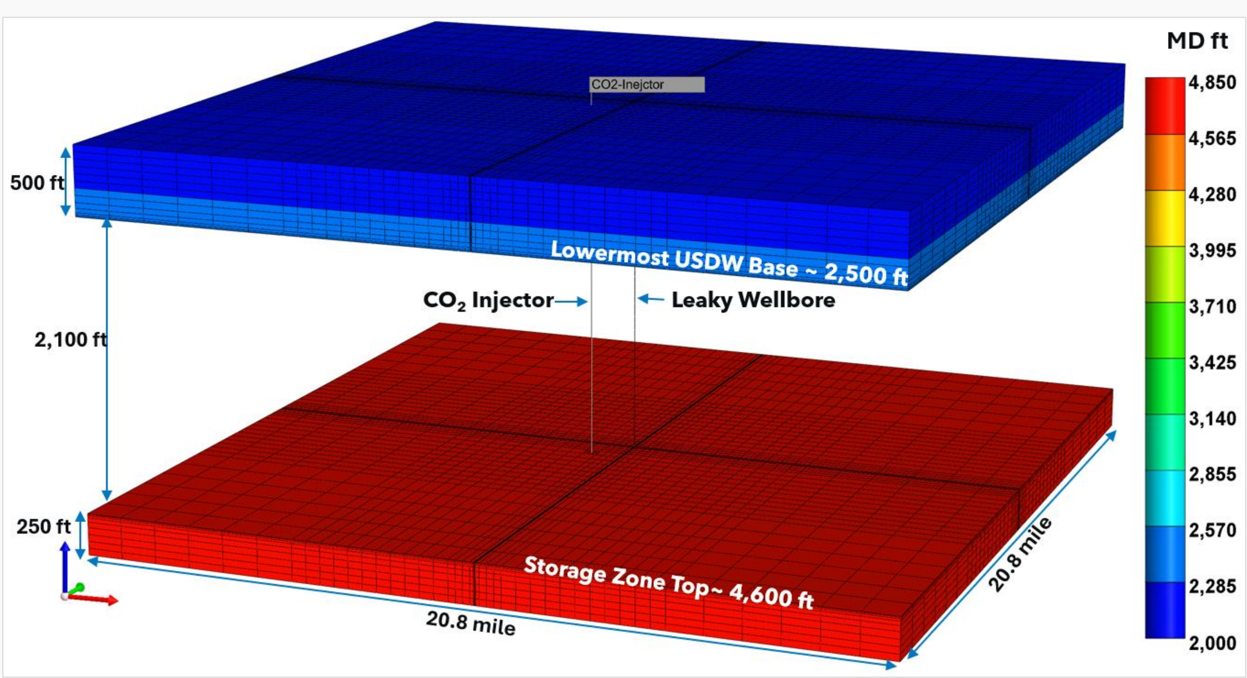
Introduction

Boundary conditions strongly influence pressure buildup and Area of Review (AoR) delineation in CO_2 storage projects. Current U.S. EPA guidance (Method 2) defines AoR using a single hydrostatic threshold pressure required to lift brine into the lowermost USDW. While straightforward, this approach may be overly conservative for open-boundary systems, where exceeding the threshold does not necessarily result in meaningful leakage. As a result, pressure-based AoR estimates may not accurately reflect actual subsurface impact. This study evaluates the limitations of the Method 2 framework and explores a simulation-based approach to better represent leakage behavior and AoR extent.

Methods

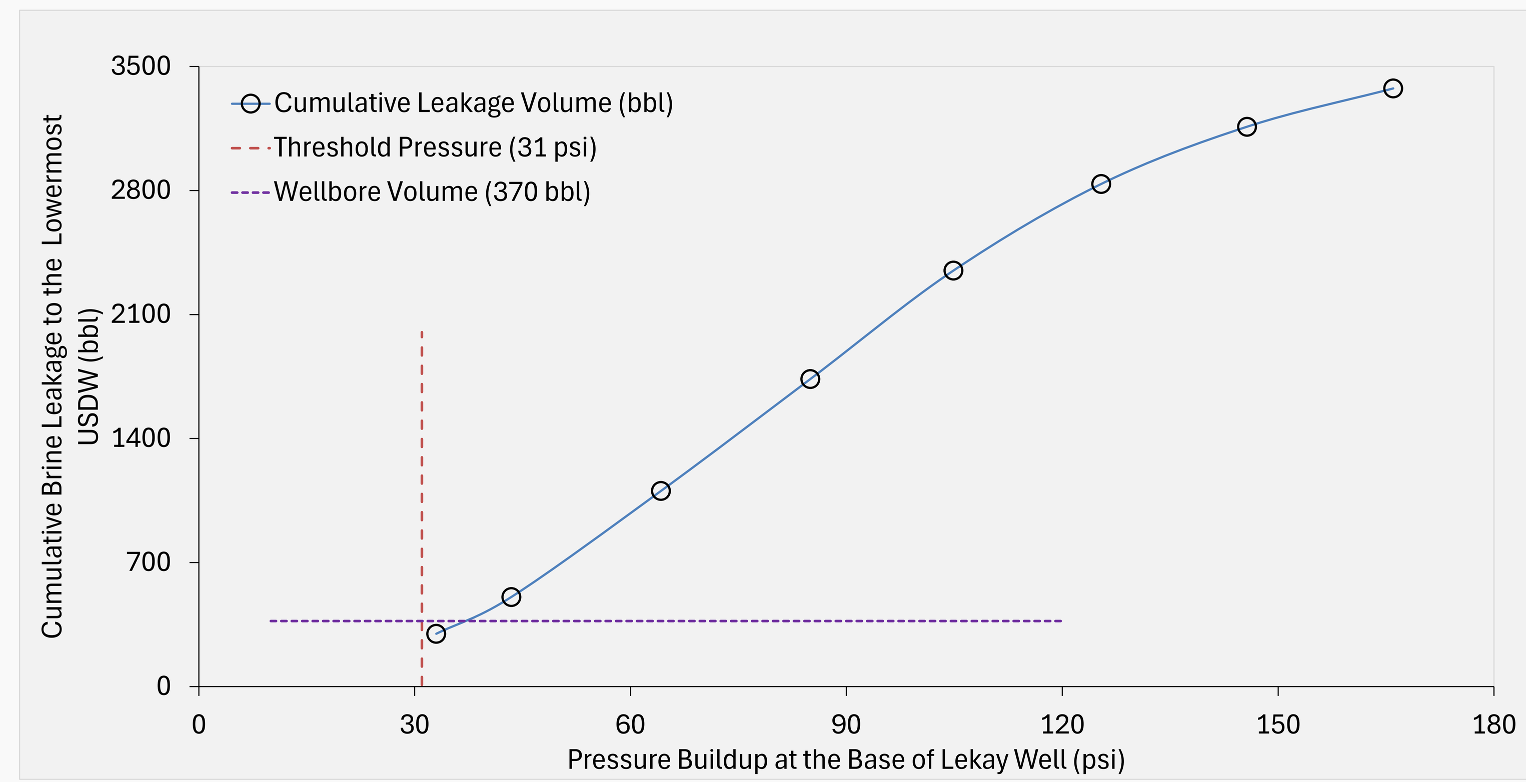
Conceptual model showing injector, leaky wellbore, and stratigraphic separation between storage zone and lowermost USDW



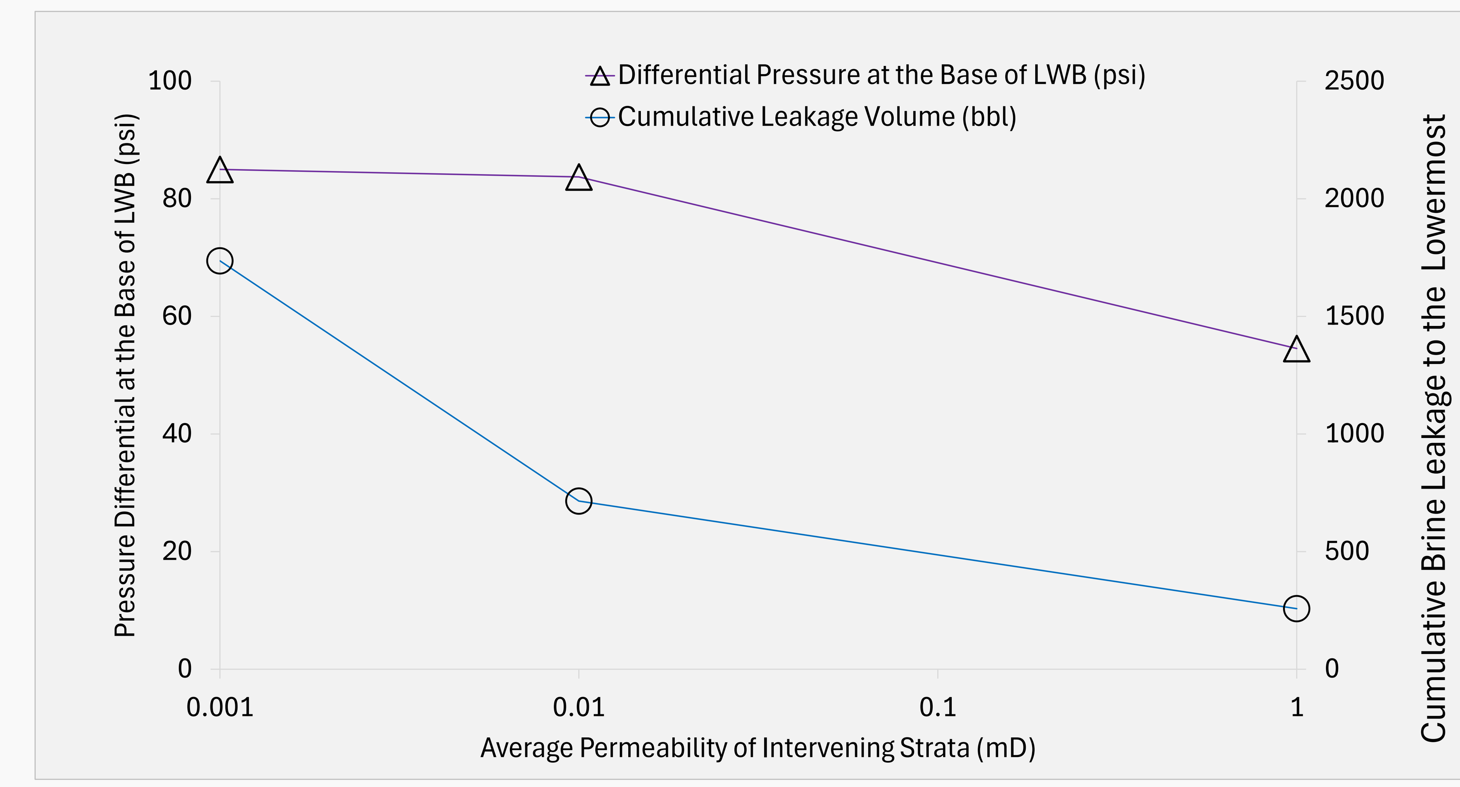
Scenario Matrix

Scenario Group	Primary Control Examined	Parameter Variation (Conceptual)	Case IDs	Results Subsection
Baseline pressure exceedance	Pressure above threshold	Incremental exceedance from near-threshold to several times threshold pressure	C01–C08	Baseline Pressure Exceedance Behavior
Thermal equilibration	Density evolution along leakage path	Thermal equilibration enabled vs. neglected	C09	Effect of Thermal Equilibration on Leakage
Intermediate stratigraphy (uniform)	Pressure dissipation capacity	Uniform intermediate permeability varied from very low to moderate	C10–C11	Influence of Intermediate Stratigraphy on Pressure Buildup
Intermediate stratigraphy (thief zone)	Localized high-permeability interval	Single high-permeability thief zone embedded within low-permeability strata	C12	Influence of Intermediate Stratigraphy on Pressure Buildup
Wellbore permeability	Leakage pathway transmissivity	Wellbore permeability varied over multiple orders of magnitude	C13–C15	Sensitivity to Wellbore Properties
Wellbore length	Vertical leakage path length	Leakage pathway length increased and decreased relative to reference case	C16–C17	Sensitivity to Wellbore Properties
Storage formation properties	System-level pressure response	Salinity, porosity, and permeability varied between 0.5× and 1.5× reference values	C18–C23	Sensitivity to Storage Formation Properties
AoR–leakage comparison	Pressure extent vs. volumetric impact	Normalized leakage volume compared to pressure-based AoR extent	All cases	Leakage Magnitude Relative to Pressure-Based AoR

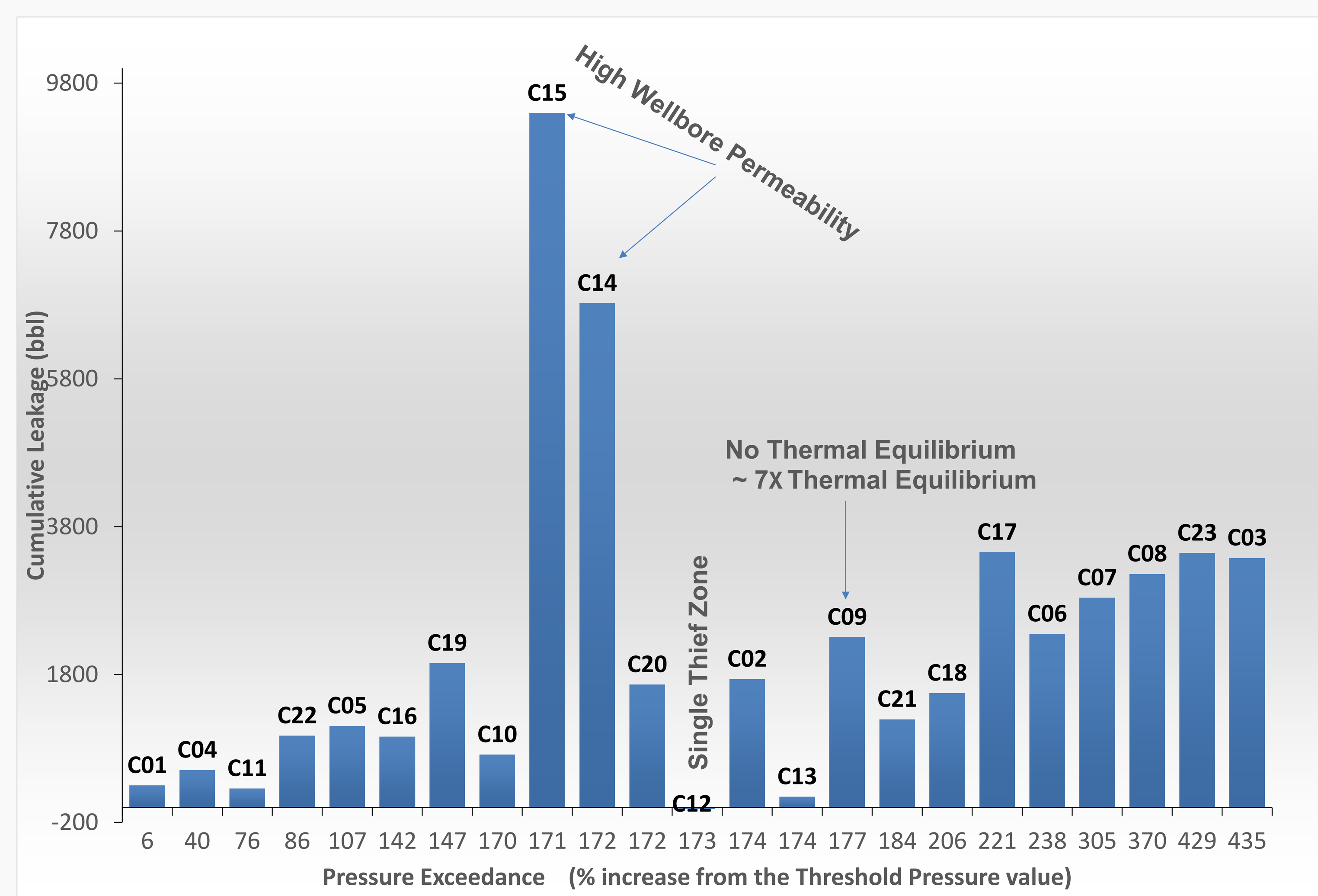
Results



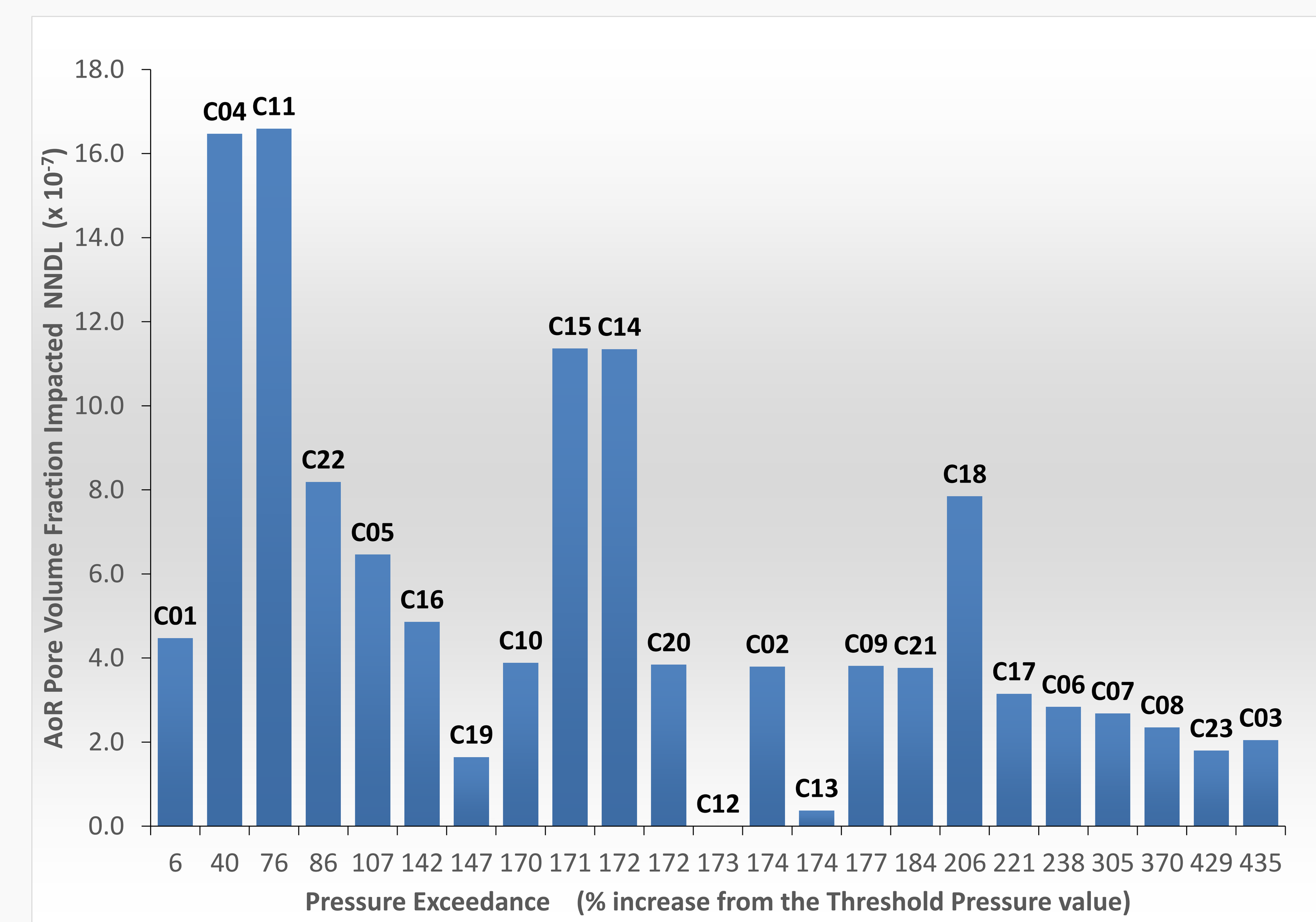
Relationship between cumulative leakage and pressure buildup is not linear.



Intervening strata have significant impact on leakage amount.



Wellbore permeability has significant impacts on cumulative leakage volume.



Across all scenarios, the USDW pore volume impacted by salinity changes above 420 NNDL remains below 0.0001% of the pressure-based AoR.

Conclusions

- Threshold pressure exceedance alone does not determine leakage magnitude, as leakage exhibits a non-linear behavior to increasing pressure buildup
- Leakage impacts are highly localized relative to pressure-based AoR extent. Across all scenarios, the USDW pore volume impacted by salinity changes remains below 0.0001% of the pressure-based AoR, demonstrating a clear decoupling between pressure propagation and volumetric leakage impact.
- Intermediate stratigraphy is the dominant control on leakage attenuation.
- Thermal equilibration significantly bounds leakage through density effects.
- Wellbore and storage formation properties act as secondary modifiers.

These findings suggest that **reliance on pressure-threshold exceedance alone** in open-boundary systems **may impose feasibility constraints that are disproportionate to physically meaningful leakage risk.**

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