Beyond the Caprock: Do Saline Aquifers Always Need a Permanent Seal?

Introduction

Saline aquifers offer vast CO_2 storage potential, but traditional site selection criteria mandate continuous, impermeable caprocks. However, composite confining systems[1] – featuring stacked sequences of discontinuous low-permeability barriers – may provide effective containment through capillary pressure heterogeneity and distributed trapping mechanisms, even when primary seals fail. This study quantifies CO_2 leakage probability to groundwater systems and to surface, migration timescales, and trapping efficiency when primary caprock integrity fails from the onset of injection, while demonstrating the role of rock and fluid properties, the importance of barriers in the overburden, and varying injection rates and patterns on migration, trapping and CO_2 storage security.

Methodology

We employed tNavigator to construct 2D and 3D models of a 1000 meters deep saline aquifer-to-surface system with compromised primary seal. The model consists of a 100-meter thick fully water saturated reservoir, and a 900 meters thick overburden section. Injection happens through a single vertical well, into the bottom 50 meters of the reservoir section. The compositional model is initialized using a hydrostatic pressure gradient, an initial reservoir temperature of 40 C and the CO2STORE option to account for dissolution. Further, the model is split into vertical section to assess the extent of the vertical migration, considering the presence of potable water, the depth of water tables and the median depth of U.S. water wells, based on data by the U.S. Geological Survey. [2]

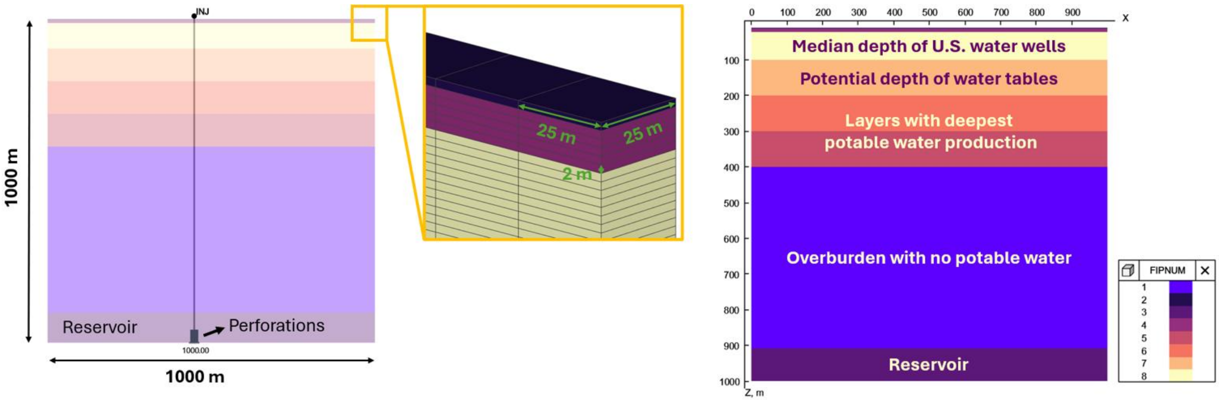

Figure 1. *Model geometry (left) and model segmentation (right)*

To evaluate the risk of CO_2 leakage into groundwater or the atmosphere, we use deterministic sensitivity analysis across various geological scenarios, focusing on overburden heterogeneity (permeability anisotropy, barriers, and capillarity), injection patterns and rates, and in-place fluid properties, specifically salinity.

Results of deterministic sensitivity analysis

1. Overburden Heterogeneity

To start off, we wanted to see what would happen if we injected CO_2 into a homogeneous model, fully saturated with water, with uniform porosity and uniform permeability, and a NaCl concentration of 10 mol% in the brine. The injection period is 2 years, injecting a total of 0.2 reservoir pore volume of supercritical CO_2, followed by a 98-year observation period. Figure 2. shows (from left to right) the permeability field – with a compromised seal around the wellbore, the gas saturation after 100 years, and the distribution of the CO_2 trapping mechanisms over time.

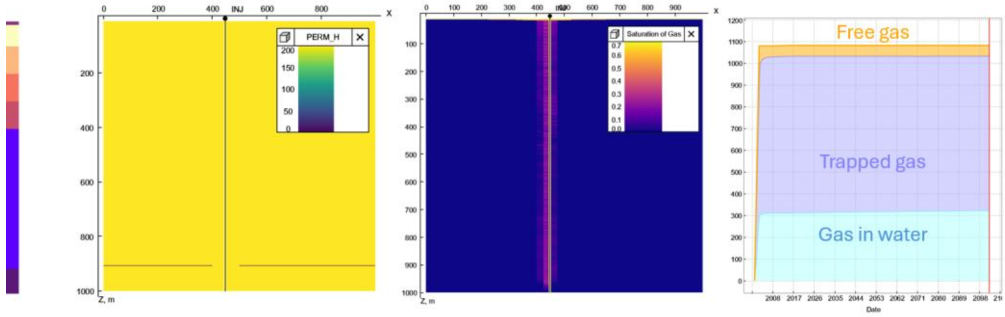

Figure 2. *Permeability field (left), CO_2 saturation after 100 years (center), distribution of trapping mechanisms (right)*

Considering this very pessimistic and geologically unrealistic setup, the results show that over our simulation period 12% of the injected gas escapes to the surface. On one hand, CO_2 escaping to the surface is not what we would ideally like. On the other hand, it is a promising start that even under these conditions, 88% of the injected gas is trapped in the subsurface, underlining the effectiveness of the geological storage process.

In the next steps (Figure 3.) we wanted to make these models more realistic. First, we introduce a 200 meter long, non-permeable barrier in the overburden section (left), while keeping the permeability field unchanged. Second, we introduce heterogeneity not by a barrier, but by simply reducing the vertical permeability, using a permeability anisotropy value – kv/kh of 0.1 (right).

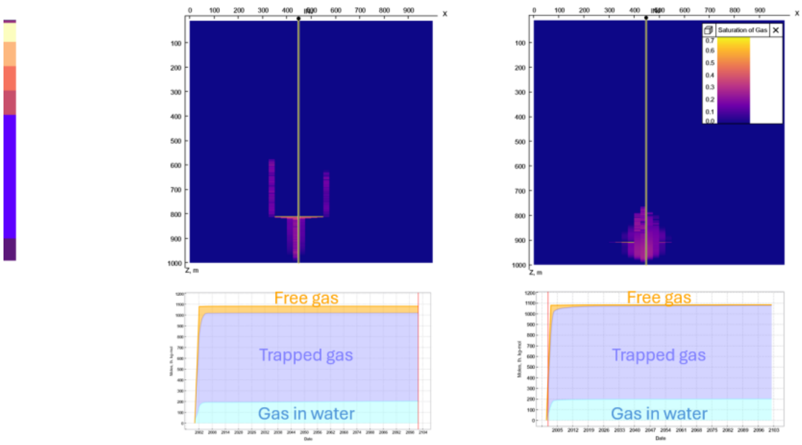

Figure 3. *CO_2 saturation after 100 years with barrier in overburden (left) and kv/kh of 0.1 (right)*

These slight variations in the overburden section disrupt vertical CO_2 flow enough to prevent surface leakage and protect deep potable water layers. With most CO_2 already dissolved or trapped by capillary forces, further migration is expected to be minimal.

For further analysis, we proceed with using the model with a kv/kh of 0.1. Now, we are introducing further complexities to the overburden section e.g. a simple high-permeability fault system and a more realistic 3-facies (sand, silt and shale) overburden – shown on Figure 4., with each facies having their own porosity-permeability relationships as well as their own relative permeability curves[3].

Focusing on the heterogenous overburden, our model demonstrates that the discontinuous barriers are effective at preventing the vertical movement of the gas and causing the plume to be more laterally dispersed. Over a period of 100 years, CO_2 migrated less than 200 meters in the vertical direction.

We can conclude that heterogeneity is important and could be effective in preventing gas migration to the surface and into the groundwater systems, if a continuous seal is not present.

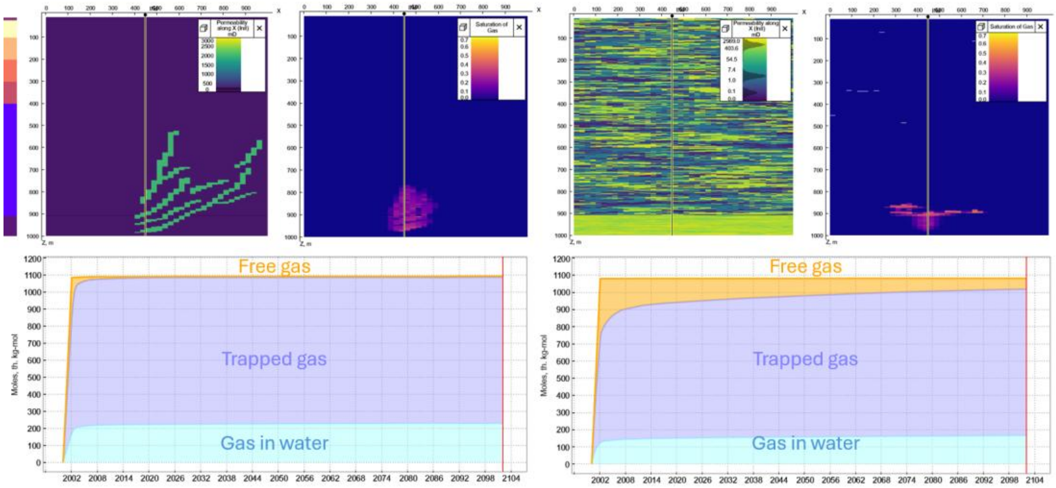

Figure 4. *CO_2 saturation after 100 years for **s**imple, high permeability fault system (left) and heterogeneous overburden with three facies (right) Legend scale: Permeability: 0 – 3000 mD, Gas saturation 0 – 0.7.*

2. Injection rate and patterns

Our simulations show that CO_2 injection rates and patterns (constant vs. intermittent) dictate the dominant fluid flow forces. Figure 5. displays CO_2 saturation after 100 years for three cases, each involving the injection of 0.2 reservoir pore volumes of supercritical CO_2 via different injection regimes. The first picture shows the case when the injection was carried out at a high rate (0.02 reservoir PV/year), but in an intermittent manner over 20 years. The second picture depicts a constant, but lower injection rate (0.01 reservoir PV/year) case over 20 years. The third picture shows a high injection rate (0.02 reservoir PV/year) case – just like in the first case, but with constant injection over 10 years.

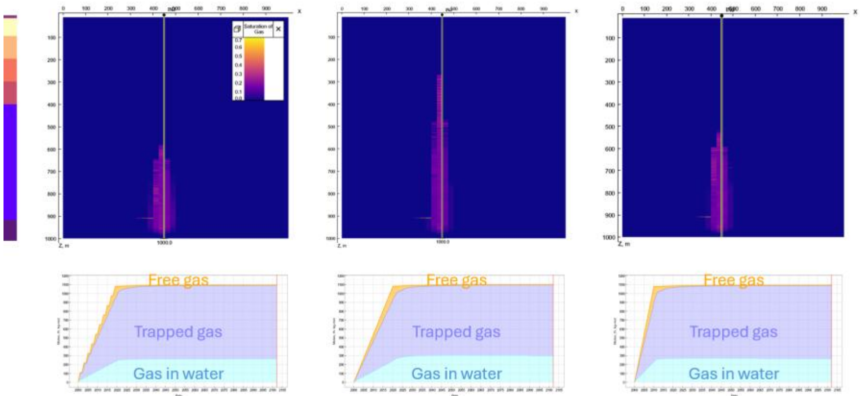

Figure 5. *CO_2 saturation after 100 years for intermittent injection at high rate (left), constant injection at low rate (center), constant injection at high rate(right). Legend scale: 0 – 0.7*

At low injection rates, gravity-driven buoyancy causes rapid vertical migration and minimal lateral spread. Conversely, high injection rates promote lateral movement, increasing contact with the rock matrix and brine to enhance dissolution and capillary trapping. Utilizing intermittent high-rate injection further reduces vertical migration by allowing CO_2 to stabilize between cycles. In our unrealistic, homogeneous model with a permeability anisotropy of 0.1, only the continuous low-rate scenario resulted in CO_2 reaching the "deepest potable water" layers within 100 years, with approximately 2% of the total mass injected migrating to that depth.

3. Salt concentration

Salinity significantly influences CO_2 migration by dictating gas solubility. In high-salinity water, dissolved ions compete for water molecules, reducing CO_2 dissolution compared to fresh water [4]. This reduction in solubility increases the volume of free CO_2, directly affecting plume size and behavior. Figure 6. illustrates this relationship using three identical models with a permeability anisotropy (kv/kh) of 0.1, isolating water composition as the primary driver of varying migration patterns. Models featuring 1, 10, and 20 mol% NaCl in the brine show that CO_2 plume dimensions expand both laterally and vertically as salinity rises. Because higher salinity reduces gas dissolution, the resulting larger plume increases the probability of vertical migration. Consequently, accurate fluid modeling is essential for evaluating the containment potential of discontinuous barriers. Notably, even when the brine contains 20 mol% dissolved NaCl, the plume remains far below potable water layers.

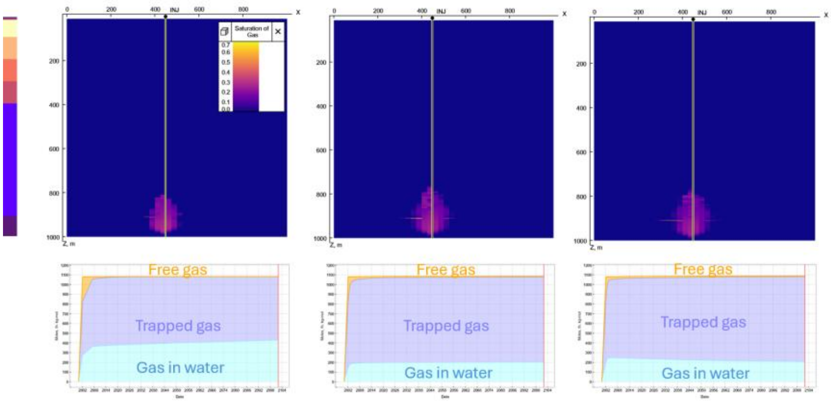

Figure 6. *CO_2 saturation after 100 years for 1 mol% NaCl concentration in brine (left) 10 mol% NaCl concentration (center) and 20 mol% NaCl concentration (right). Legend scale: 0 – 0.7*

Conclusions

Results demonstrate that composite confining systems effectively contain CO_2 despite seals being discontinuous. These findings challenge conventional assumptions that continuous, impermeable caprocks are essential for secure CO_2 storage, showing that a heterogeneous overburden can provide effective containment through multiple trapping mechanisms and heterogeneity-driven flow retardation. Free gas migration to surface appears unlikely under realistic geological scenarios. Net storage benefits across most of the cases investigated are undeniable. This work expands viable storage capacity by validating sites with discontinuous seals, provides risk-assessment frameworks for regulatory evaluation, and may enhance public acceptance by quantifying leakage resilience under worst-case scenarios.

References

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