Introduction

Predicting the long-term migration and final state of the plume of CO_2 plume during the early stages of storage projects is highly complex due to significant uncertainty in the subsurface environment. Managing these uncertainties is essential for assessing the potential risks of CO_2 leakage beyond the storage complex and determining whether a site is suitable for long-term storage. Traditional modeling methods often fail to adequately capture these uncertainties, which may lead to overly optimistic or unnecessarily pessimistic conclusions, because uncertainties are guesstimated, rather than properly quantified. This could lead to good storage sites being abandoned, for no scientific good reason. And with negative financial implications.

Method and Theory

Regulatory frameworks will require a comprehensive evaluation of potential risks and uncertainties to guide decision-making. Ensemble modeling offers a robust tool for addressing these uncertainties, as it incorporates a range of possible scenarios from the start, rather than relying on a single baseline model with adjustments over time. This method, widely used to improve predictions in reservoir engineering (Emerick and Reynolds, 2013), can also be applied to CO_2 storage assessments. Traditional reservoir simulators are commonly used to predict CO_2 plume migration and explore various trapping scenarios. However, they face challenges in running multiple "what-if" scenarios due to high computational demands, limiting the number of scenarios that can be tested. Moreover, the resolution and physics applied in these simulations can restrict accuracy, often resulting in poor matches with observed CO_2 plumes (Singh et al., 2010; Cavanagh, 2013).

This paper describes an ensemble-based approach to modeling that generates multiple subsurface realizations, each capturing different uncertainty aspects of the reservoir, seal, and other geological features. By generating multiple equi-probable scenarios of the model, we capture a wide range of flow properties variations, such as porosity and permeability, within the static model. To effectively explore a broader range of plume migration scenarios in the early stages of CO_2 storage investigations, a simulator capable of quickly processing plume migration is essential. In this study, we employ a modified invasion percolation simulator, which provides faster results for CO_2 migration using more applicable flow physics that accurately capture long-term plume migration and has demonstrated superior performance in representing CO_2 plume distribution compared to traditional reservoir simulators. (Singh et al., 2010).

Approach and Results

Thirty distinct model realizations were generated, each representing different combinations of geological properties, including variations in capillary threshold pressure, porosity, and permeability. A series of dynamic simulations were conducted to evaluate the potential outcomes of CO_2 injection, and these were used to determine how different levels of uncertainty align with real-world plume observations.

Our results for a single base case model shows that, while providing a reasonable initial estimate (Figure1) of plume behavior, it fails to capture certain key features of the observed CO_2 distribution, especially in selected layers. By exploring the scenarios through modeling across an ensemble of models (Figure 2), we discovered that 33% of the scenarios were distinctly different from the baseline result and hence demonstrated a different plume migration pattern that needed to be understood. This distinct difference indeed matched the observed data, proving the importance of addressing a span of alternatives in the early planning phase and accounting for factors such as lateral variations in shale layers and different capillary pressure thresholds. These findings highlight the sensitivity of predictions to subsurface uncertainties and emphasize the importance of considering a wide range of scenarios, even in sites with relatively well known geology and low levels of heterogeneity. With only a 33% match, a P50 scenario would not have picked up the observed distribution. If there had been an abandoned well in this area or a direct leak path out of the storage complex, a 33% chance of predicting a plume in such an “surprising” location is too high for the industry. We need to ensure we consider the tail members of the migration distribution to deal with potential leaks before they become a reality.

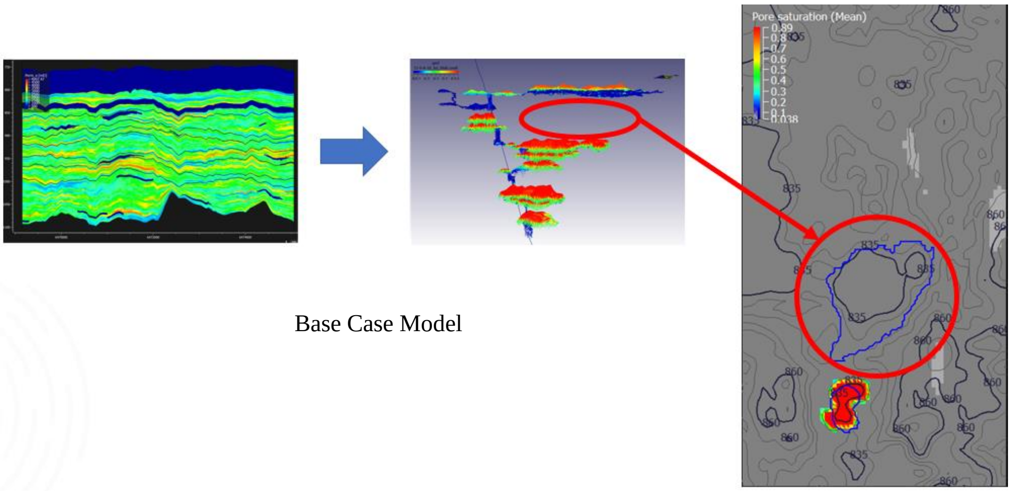

***Figure 1**. Base case model; 3D view of the simulated plume distribution Layer 8 - CO_2 Saturation Map; plume wasn't detected in one of the closures in layer 8; blue polygon is the observed plume boundary from the 4D seismic.*

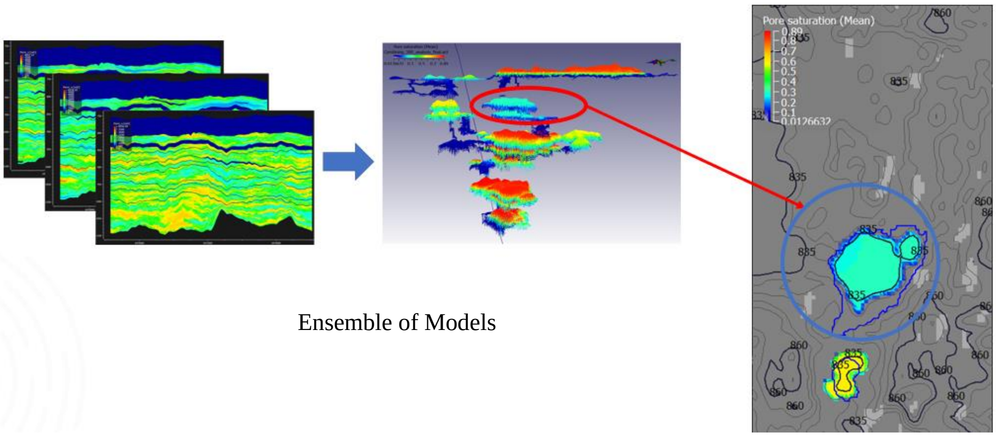

***Figure 2** Ensemble of models; a 3D view of the simulated plume distribution highlighting probability of plume migration; Layer 8 - CO_2 Saturation Map; blue polygon is the observed plume boundary from 4D seismic.*

Conclusions

By utilizing an ensemble modeling approach from the beginning of a CO_2 storage project, operators can gain a clearer understanding of the uncertainties involved and improve the identification of low-risk storage sites. The integration of rapid modified invasion percolation simulations allows for the efficient generation of diverse plume migration scenarios, supporting the development of effective monitoring and verification strategies. This approach also facilitates regulatory compliance, ensuring that the risks of CO_2 storage are thoroughly assessed and managed. Regulators can use these methods to guide safe and effective CCS implementation, which is critical for achieving decarbonization goals.

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