Subsurface Insights

Accelerating carbon storage readiness through innovative reconnaissance methodologies

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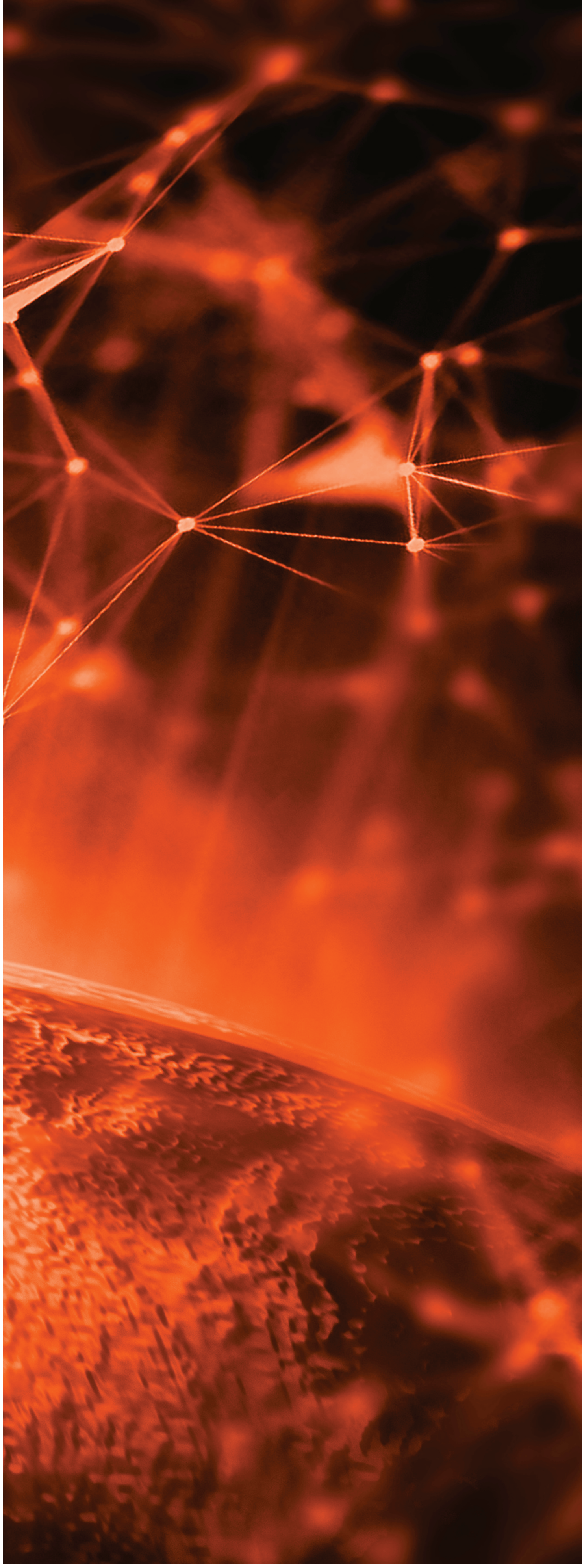


INTRODUCTION

As global decarbonization efforts accelerate, Carbon Capture and Storage (CCS) is recognized as a pivotal technology in mitigating greenhouse gas emissions. However, the success of CCS projects hinges on the ability to accurately and efficiently identify and evaluate the geological formations at specific locations for long-term CO_2 storage — an endeavor that remains technically complex, uncertain, and resource-intensive.

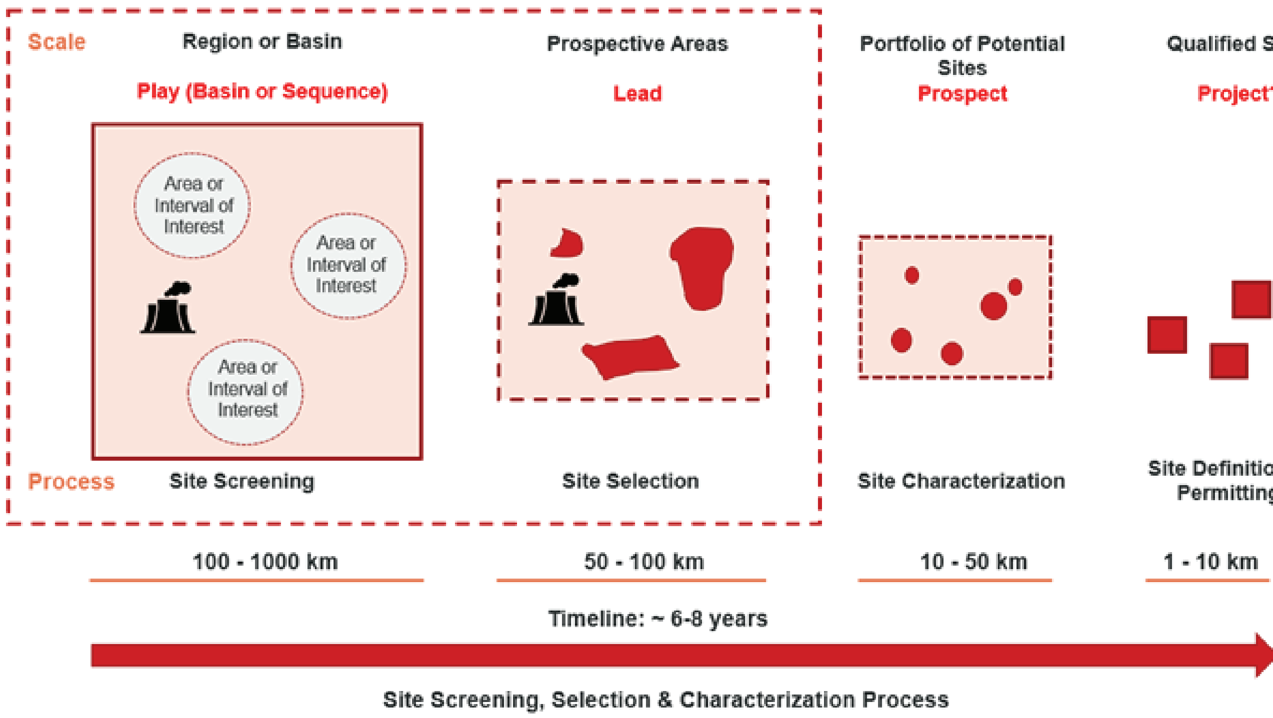


Figure 1: CCS site evaluation workflow (Adapted from NETL Best Practices, 2017). The red dashed box outlines the scope discussed in this article.

Figure 1 shows the CCS site evaluation workflow which typically begins with regional-scale screening to identify high-potential storage fairways that may hold future potential for storage locations. These are identified based on key geological criteria such as reservoir-seal pairs, pressure-temperature conditions for supercritical CO_2, and other key factors (Uren et al. 2025; Smith et al. 2023; Uren et al. 2024). These fairways serve as the foundation for more detailed investigations aimed at selecting prospective storage sites. The subsequent step involves identifying and ranking specific leads located within these fairways based on their feasibility for advancement to candidate storage sites. The lead assessment stage is critical for de-risking projects, as the insights gained support the selection of optimal sites and help focus subsequent detailed site characterization efforts. Advancing to site characterization requires high-resolution full-scale 3D modeling, including seismic interpretation, petrophysical analysis, and geostatistical modeling — processes that are both time-consuming and costly, so should only be undertaken on high-graded leads.

Traditional approaches, which often rely on multiple fit-for-purpose analytical models or oversimplified subsurface models, tend to overlook critical geological heterogeneities and risk factors. This lack of resolution contributes to a slow, iterative project maturation process, and impedes timely progress from feasibility to execution, which increases the overall cost for a CCS project. Moreover, the absence of risk quantification techniques and limited capacity for dynamic simulation in early-stage workflows hinders the identification of effective storage concepts with adequate capacity and long-term containment potential for the target injection volume.

To overcome these challenges, a more integrated and dynamic workflow is needed — one that enables rapid transition from fairway scale screening to lead ranking, supports early-stage risk assessment in high-resolution geological models that encompass regional scale insights, and integrate dynamic simulation aspects from the earliest stages of project development with faster turnaround times. This article introduces a novel approach to CO_2 storage site reconnaissance for saline aquifers, powered by Permedia® CO_2, a DecisionSpace® 365 CO_2 Storage Solution, designed to streamline early-stage CCS evaluation and accelerate decision-making.

A NEW RECONNAISSANCE PARADIGM WITH PERMEDIA® CO_2 SOFTWARE

To effectively overcome these challenges associated with early-stage CO_2 storage evaluation, it is essential to implement a high-fidelity risk assessment process at the beginning of the project lifecycle. Permedia CO_2 software, part of DecisionSpace® 365 CO_2 Storage Solution, offers a robust suite of tools and workflows purpose-built for CO_2 storage reconnaissance and feasibility assessment (***Figure 2***). These tools allow users to develop fit-for-purpose regional scale models, support high-resolution models for simulating long-term plume migration and pressure evolution, and facilitate dynamic risk assessment. By integrating these capabilities within a single, unified environment, Permedia CO_2 software supports technically rigorous, data-driven decision-making during the critical early phases of storage site selection, as outlined in the key capabilities below:

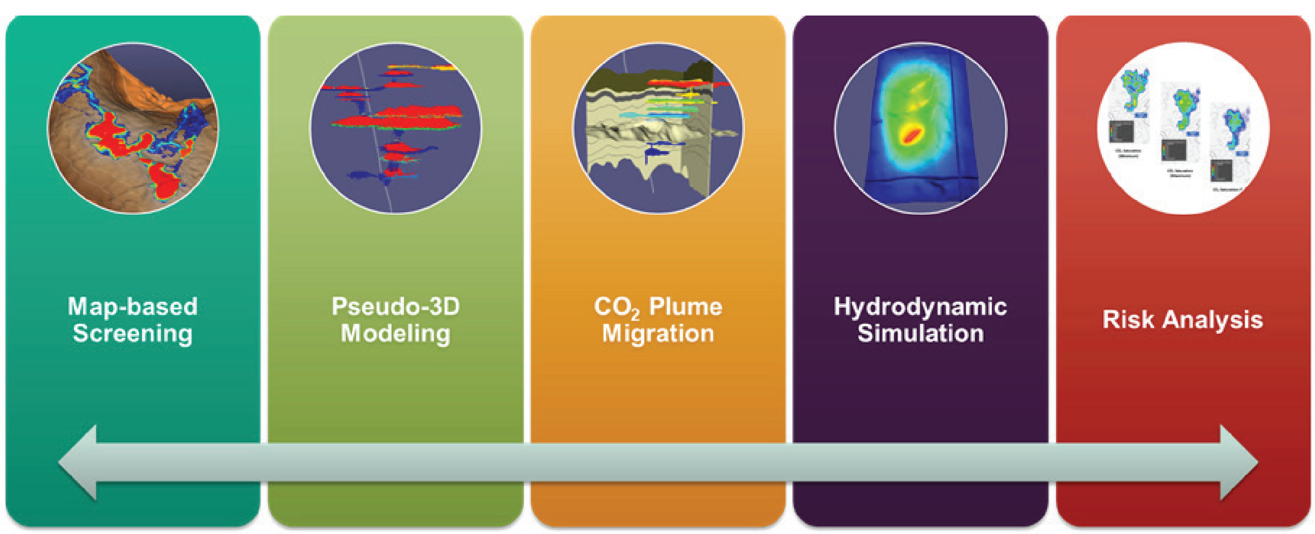


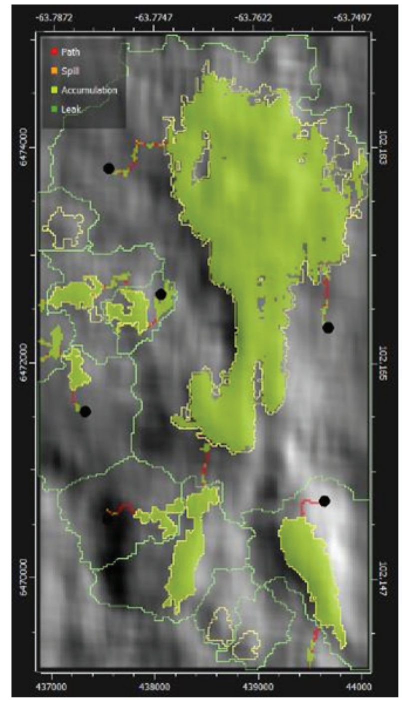
Figure 2: Permedia CO_2 software offers a range of tools for early risk identification and reducing turn-around time in site feasibility study.

1. Streamlining the transition from regional mapping to site selection with map-based tools: While early investment in fairway and lead identification can reduce the burden on the costly and time-consuming site characterization phase, a major challenge remains in translating broad-scale mapping into detailed, actionable sites. Key uncertainties — such as trap presence and connectivity, spill-point locations, well placement effects, leakage risks, and cap-rock sensitivity — must be addressed early to reduce risk and move confidently toward site selection. To address these challenges, Permedia software offers a suite of tools designed to extract insights from regional scale geological maps, enabling a more agile, streamlined, and rapid assessment process for lead identification/ranking.

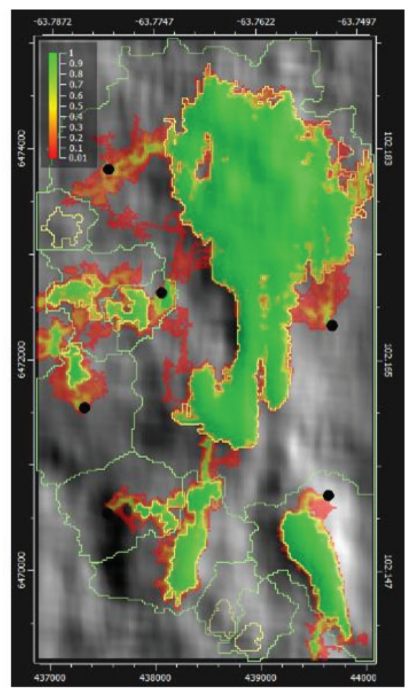
Fill-spill and closure-fetch analyses can be applied to identify potential traps, associated spill-points and possible leakage pathways, evaluate the impact of well placement on migration-trapping (***Figure 3a***) as well as to assess cap-rock sensitivity to CO_2 column height etc. At a basic level, the workflow utilizes depth map inputs but can be significantly enhanced by integrating additional data such as capillary threshold pressure (Pth) maps and potential barriers to flow (e.g., fault polygons), enabling a more detailed evaluation of trap viability and connectivity.

Key uncertainty at this scale — such as depth conversion errors from velocity modeling — can be addressed and quantified through multiple realizations (***Figure 3b***). Critical properties like interfacial tension (IFT), brine density, and CO_2 density can be adjusted to reflect varying storage conditions.

This integrated approach helps project teams to de-risk early-stage screening for potential leads by resolving key technical uncertainties mentioned above and supports more confident advancement from lead identification to site feasibility assessment.



(a)



(b)

Figure 3: Map-based assessment workflow applied to a depth map of the Sleipner storage site, North Sea. Black dots indicate proposed injection locations. **(a)** Fill-spill analysis results showing potential traps and spill-point locations. **(b)** Impact of depth conversion uncertainty on trap stability and spill trajectories; green areas indicate stable accumulations, while red areas denote instability.

2. Pseudo-3D approach for early reconnaissance prior to 3D geological model: While map-based workflows are still effective for early-stage lead identification, evaluating storage capacity and containment feasibility typically requires constructing a 3D geological model. At early stages, building a full-scale 3D geological model in saline basins is challenging due to limited subsurface data availability. With typically only a few maps and seismic data available, extracting meaningful insights to assess key project risks early remains a significant challenge. As a result, there is a strong need for approaches that can approximate plume migration behavior in 3D context using the data at hand — prior to committing to a comprehensive 3D model.

Permedia CO_2 software offers a robust suite of workflows to bridge this gap through a pseudo-3D modeling approach. This method leverages a combination of map-based inputs to define lateral resolution, while seismic attributes can be used to infer vertical geological heterogeneity. Although not a substitute for comprehensive 3D geological modeling, this approach provides early insights into CO_2 migration and trapping mechanisms, helping to identify potential risk areas (e.g. seal breaching or spilling areas) and prioritize focus during the early stage of site feasibility assessment (***Figure 4***).

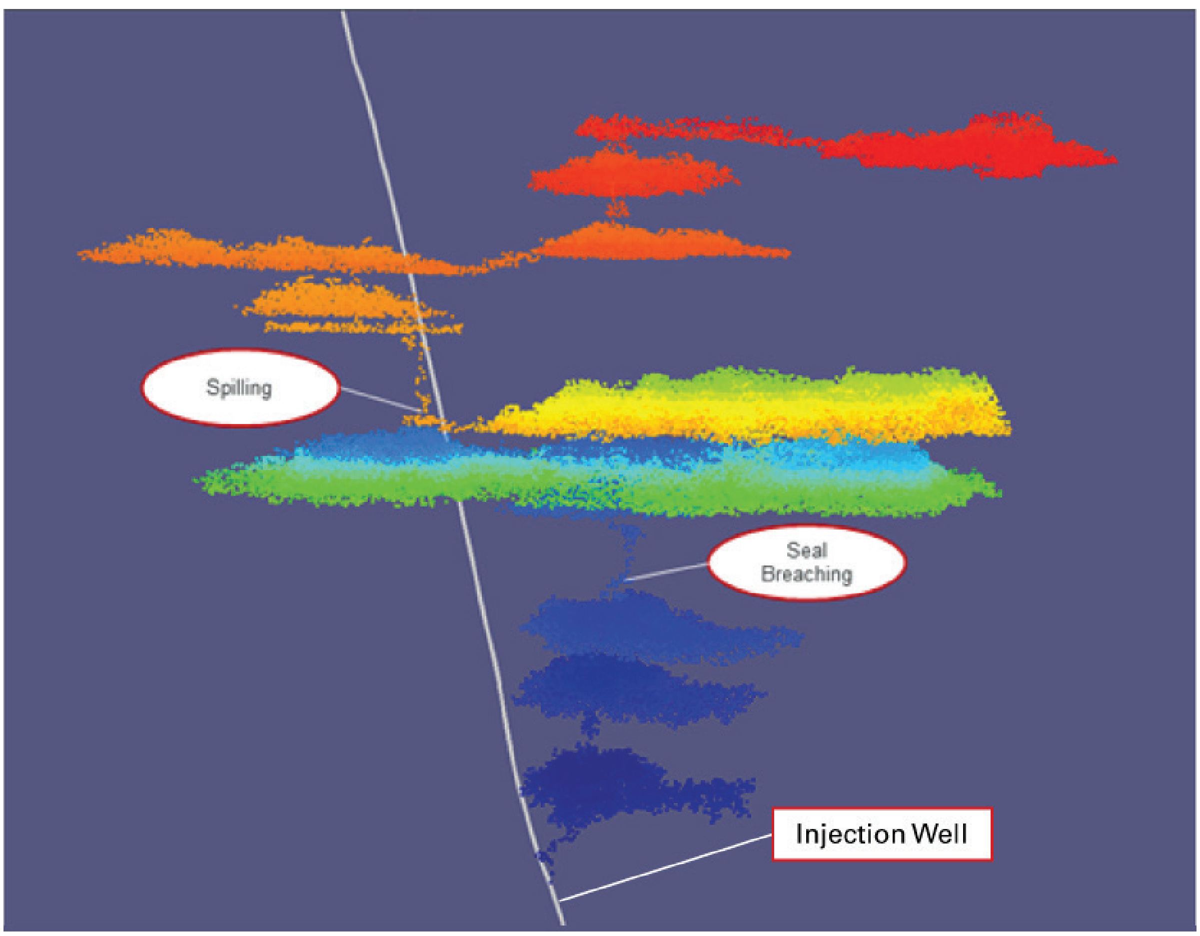


Figure 4: The pseudo-3D modeling workflow using the Static Migration tool generates plume distribution in a 3D context from limited information such as a few maps and seismic attributes, highlighting critical risk areas such as seal breaches and spill points. These results offer valuable guidance for subsequent detailed 3D modeling.

3. CO_2 migration modeling to predict long-term plume behavior: Understanding the long-term behavior of the CO_2 plume is vital for site feasibility assessment, as it guides the selection of the Storage Complex and Area of Review — both crucial for regulatory approval and project viability. Traditional Darcy-based reservoir simulators, originally developed for hydrocarbon production, are now being applied to model CO_2 migration as well. While these simulators effectively capture viscous-dominated flow near the wellbore region, extensive research shows that beyond this region, plume movement is primarily controlled by buoyancy and capillary forces due to very low flow rates. This distinction significantly affects the evaluation of storage performance and containment risk.

To overcome this limitation, Permedia CO_2 software employs a modified invasion percolation approach that models fluid flow primarily governed by buoyancy and capillary forces. The invasion percolation approach is valid for CO_2 storage modeling because at low flow rates, the viscosity contributions to flow are negligible, and viscous-dominated (Darcy flow) approximation breaks down in favor of capillary-dominated forces (Cavanagh and Ringrose, 2011). This approach provides a superior alternative to Darcy-based methods for simulating CO_2 plume migration from the near-wellbore region to the far-field. This method predicts CO_2 movement more accurately under capillary-dominated conditions common throughout much of the storage domain, resulting in more realistic predictions of plume migration and trapping that reflect long-term containment potential. It enables fast, reliable simulation of plume dynamics, and supports better decision-making in the early stages of project development — without requiring complex full-physics based models. This approach has been validated in major industrial CCS projects, such as the Sleipner Project (***Figure 5***).

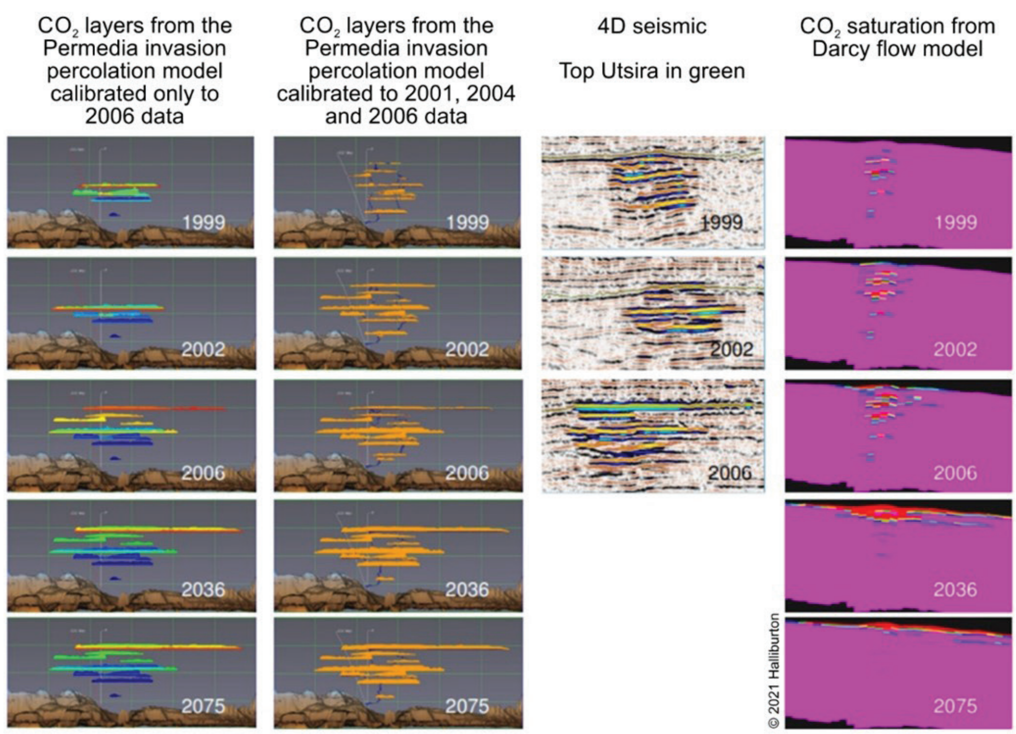


Figure 5: Reservoir simulations of the plume dynamics at the Sleipner CO_2 storage site. Darcy-based reservoir simulator predicted continued vertical movement of CO_2 for decades after injection ceased and is not accurate when compared with the CO_2 distribution observed in 4D seismic data. Permedia CO_2 was able to model the plume distribution more accurately and provided a close match to the observed seismic distribution. (Images from Lippard et al. 2008).

While this approach does not fully replace Darcy-based simulators — which remain effective for modeling CO_2 behavior near the wellbore region, invasion percolation offers rapid insights into the long-term plume state. By integrating invasion percolation flow physics in early-stage assessments and complementing it with Darcy-based simulations at later stages during site-characterization, operators can reduce uncertainty, streamline the permitting process, and enhance confidence in long-term storage integrity.

4. Preserving data fidelity while representing geological heterogeneity: One of the foremost challenges in CO_2 storage is accurately modeling the geological heterogeneity of the subsurface. Traditional reservoir simulators often rely on upscaled models to reduce computational load, thereby losing important geological details. This oversimplification can obscure key migration pathways, trap mechanisms, or leakage risks, ultimately affecting containment predictions. Permedia CO_2 addresses this limitation by supporting high-resolution geological models without the need for upscaling. This capability enables accurate representation of how small-scale heterogeneities impact CO_2 migration and trapping mechanisms, which are critical in capillary-dominated flow regimes. Capillary threshold pressure contrasts due to small-scale heterogeneities can affect the flow path of invading CO_2, resulting in back filling and accumulation beneath the capillary barriers. Therefore, it is important to account for small-scale heterogeneities that can affect flow paths within a capillary-dominated regime, to enable realistic CO_2 plume migration modeling (***Figure 6***).

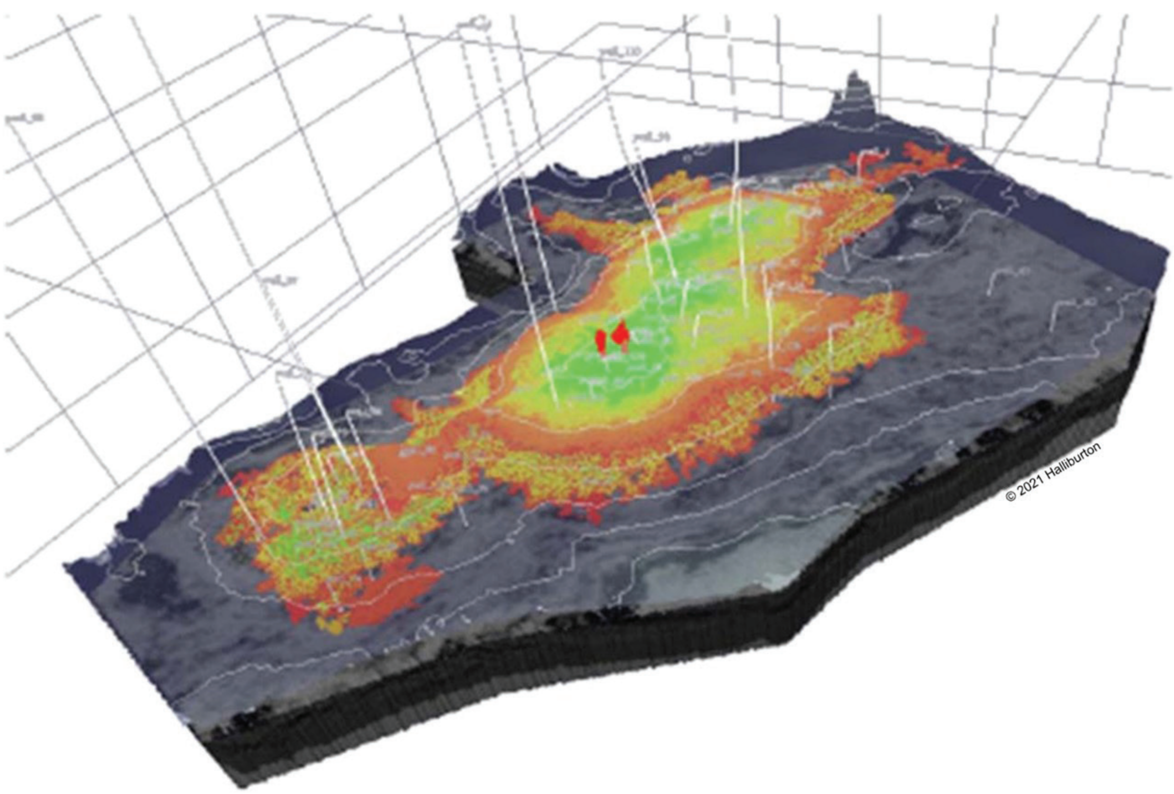


Figure 6: Evaluation of CO_2 storage capacity and leakage mechanisms in a giant oilfield, modeled using Permedia software. The heterogeneity of the giant oil field can be picked out in the layered saturation of the model (Bunney and Cawley, 2007).

5. Predicting pressure evolution using geologically realistic boundaries: Pressure build-up in deep saline formations can severely limit CO_2 storage capacity and increase the risk of caprock failure and leakage risks, often underestimated by traditional closed-system reservoir simulations. Although open-system models better represent pressure dissipation at regional scales, conventional reservoir simulators typically lack this capability to incorporate geologically realistic boundary conditions needed for accurate early-stage risk assessment.

Permedia software addresses this limitation through its CO_2 Flow simulator, which is a high-resolution, single-phase (e.g., brine) hydrodynamic simulator specifically developed to address the limitations of conventional reservoir simulators in CO_2 storage applications. Unlike traditional simulators that often impose zero-flow closed boundary conditions, CO_2 Flow incorporates geologically realistic, open-boundary conditions to accurately represent pressure dissipation at regional scales (***Figure 7***).

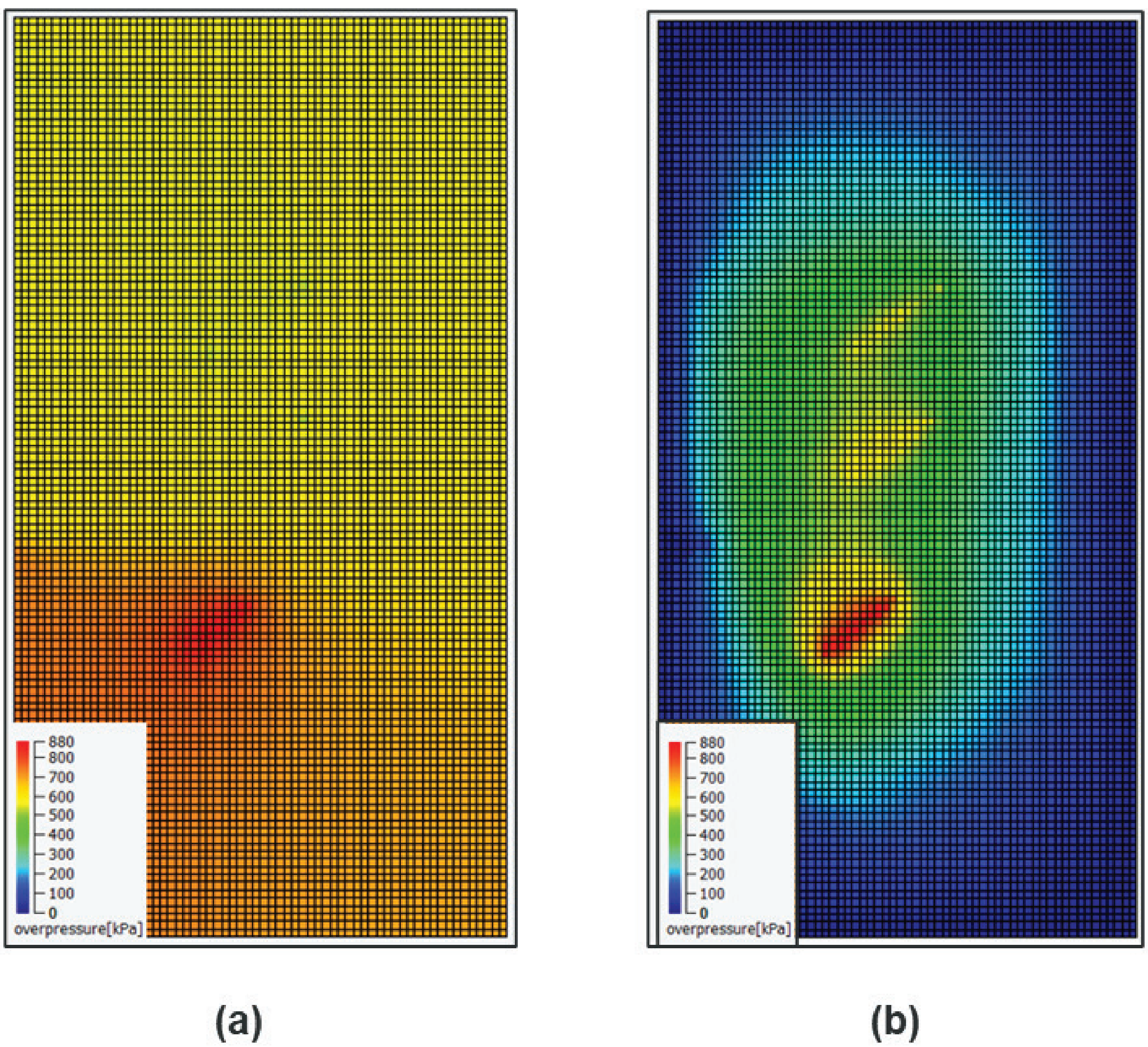


Figure 7: CO_2 Flow pressure simulation, **(a)** Closed system model showing highly pressurized compartment, **(b)** Open system model showing pressure dissipating into basin.

This capability is essential during the early stages of CO_2 storage project feasibility study, enabling rapid and reliable assessments of storage capacity and associated risks, including caprock integrity and potential leakage due to over-pressurization. CO_2 Flow is also effective in regions where CO_2 injection intersects with oil and gas operations, where subsurface pressure dynamics are inherently complex.

By simulating an open system that better reflects geological reality, CO_2 Flow significantly reduces uncertainties in pressure forecasting and storage capacity estimation. Its advanced modeling framework also facilitates proactive water abstraction strategies to mitigate pressure buildup, thereby enhancing the safety and long-term reliability of CO_2 storage operations.

6. Overcoming PVT modeling challenges using the CO_2 dashboard: In saline basins, early-stage CO_2 storage assessments are often hindered by the lack of comprehensive Pressure-Volume-Temperature (PVT) data. The core challenge is how to effectively utilize minimal information to generate reliable model predictions and evaluate their influence on CO_2 migration and pressure build-up.

Permedia software offers a CO_2-specific equation-of-state and PVT wizard, known as the CO_2 Dashboard, designed to initialize simulations using minimal input data such as pressure, temperature, and salinity — ideal for addressing challenges in saline basins with limited PVT information. CO_2 Dashboard can be used to initialize model conditions, including gas and brine phase density, compressibility, viscosity, solubility, and interfacial tension. The wizard has been validated against several published works (Cavanagh and Ringrose, 2011; Cavanagh and Rostron, 2013; Lippard et al. 2008) containing both theoretical and experimental data. Initial model conditions for these key properties can be automatically transferred from the Dashboard to the CO_2 specific simulators within the application, e.g. CO_2 Migration, CO_2 Flow Simulators.

7. Enabling early-stage risk assessment: Risk assessment is central to CCS project development. As regulatory oversight intensifies and investor scrutiny grows, there is increasing demand for these projects to demonstrate long-term safety and viability from the early stages. Risk mitigation requires tools that quickly evaluate multiple scenarios — rather than relying on a single scenario — to address uncertainties in subsurface flow parameters. There is a critical need for solutions that deliver fast, reliable insights into CO_2 plume migration and pressure dissipation, empowering confident, informed decisions during site feasibility studies.

To fulfill the need for a risk assessment tool tailored to early-stage evaluations, Permedia CO_2 software supports early-stage risk mitigation efforts by enabling rapid evaluation of both plume migration and pressure dissipation at regional scale. It can simulate multiple scenarios by incorporating uncertainties associated with key flow parameters, generating probabilistic scenario outputs within minutes rather than days (***Figure 8***). This fast-turnaround capability provides timely insights into long-term CO_2 plume behavior and pressure evolution, which are critical for reducing uncertainty and supporting confident, data-informed decision-making during site feasibility assessments. By reducing turnaround time, it directly lowers costs and accelerates decision-making without compromising on quality.

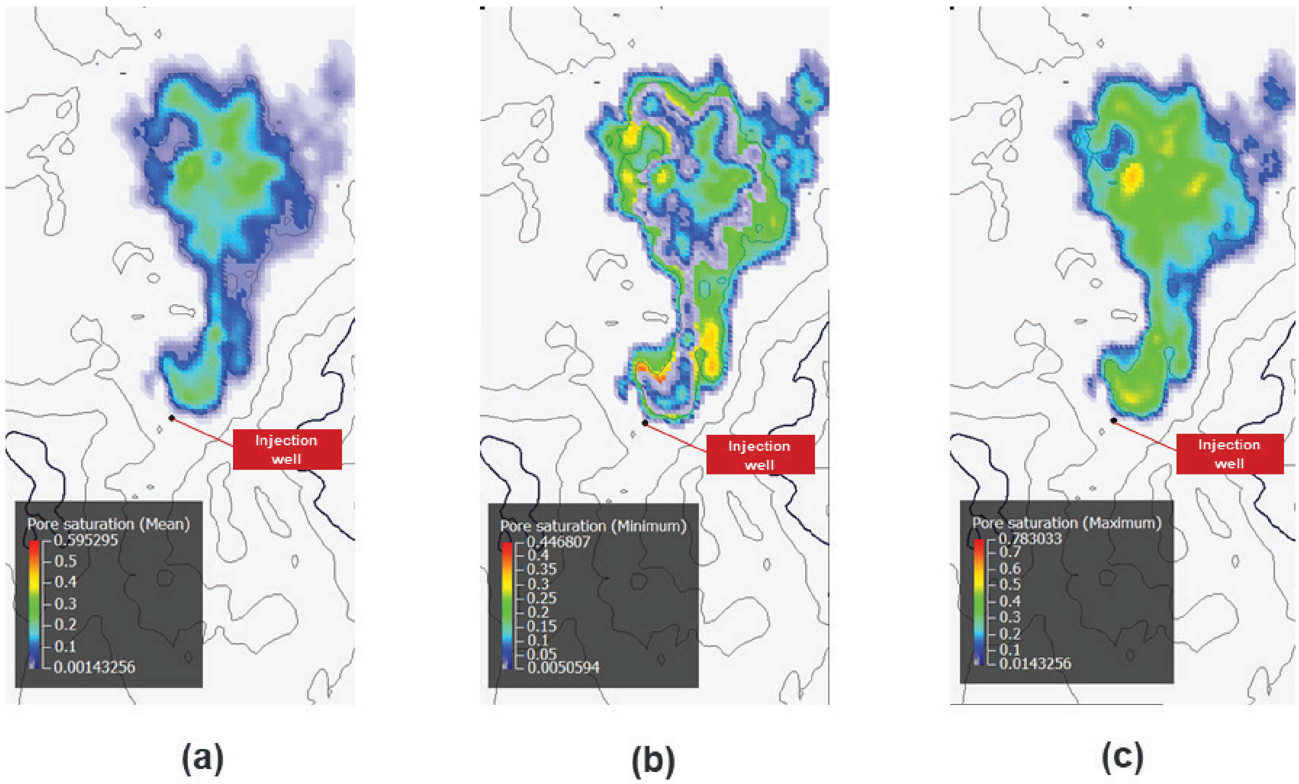


Figure 8: Probabilistic plume distribution maps illustrating the impact of uncertainties in critical flow parameters such as capillary threshold pressure (Pth) and critical gas saturation (Scr); **(a)** Mean CO_2 saturation map, **(b)** Minimum CO_2 saturation map, **(c)** Maximum CO_2 saturation map.

CONCLUSION

Permedia CO_2 software delivers exceptional value to stakeholders involved in CCS projects by transforming early-stage reconnaissance into a fast, data-driven, and risk-aware process — saving both time and cost. It accelerates site selection by integrating regional screening data with high-resolution modeling, enabling rapid assessment of storage capacity and containment potential over geological timescales. This early insight reduces costly delays by supporting quick, reduced-physics-based feasibility evaluations and allowing geoscientists to identify risks and rank sites before advancing to detailed site characterization. With flexible workflows and seamless integration into the DecisionSpace® 365 platform, Permedia CO_2 supports dynamic model updates to maintain an evergreen state throughout the monitoring phase, ensuring models remain accurate and compliant.

As CO_2 storage becomes a cornerstone of global decarbonization efforts, there is a pressing need for tools that combine scientific precision with operational efficiency. Permedia CO_2 software meets this need by offering a cost-effective, advanced tool for early-stage storage feasibility assessments. In a landscape where climate urgency meets technical and financial constraints, embracing novel reconnaissance methodologies like those enabled by Permedia CO_2 is essential to accelerate progress while optimizing resources and reducing overall project expenditure.

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