Risk Screening and Leakage Modelling: A Holistic Approach to Managing Legacy Wellbores for Offshore Carbon Capture and Storage

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Crown Estate Scotland
Oighreachd a' Chrùin Alba

Context: Scotland's offshore CCS potential

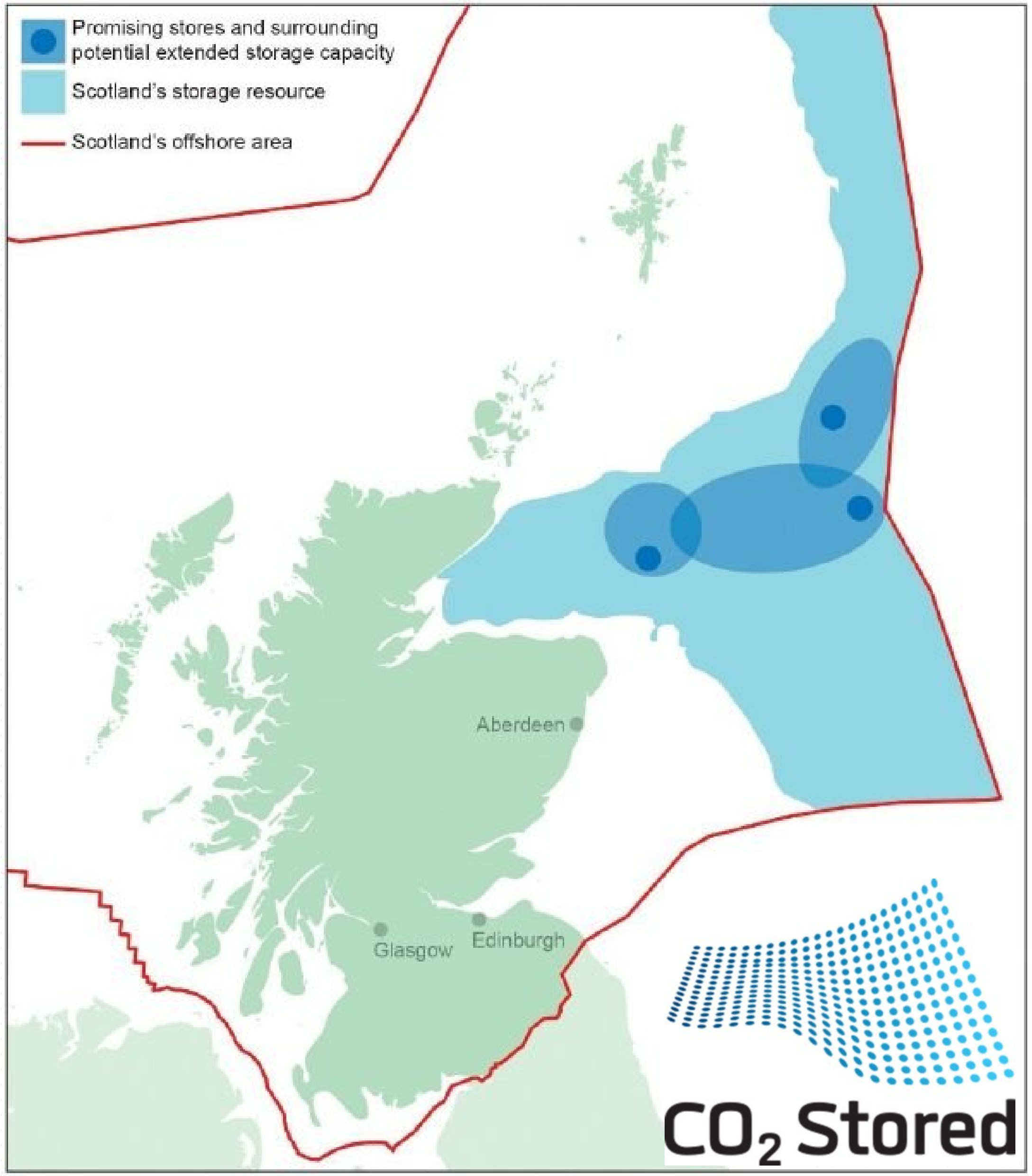
53 thousand million tonnes theoretical capacity storage around Scotland

2/3 of UK storage capacity

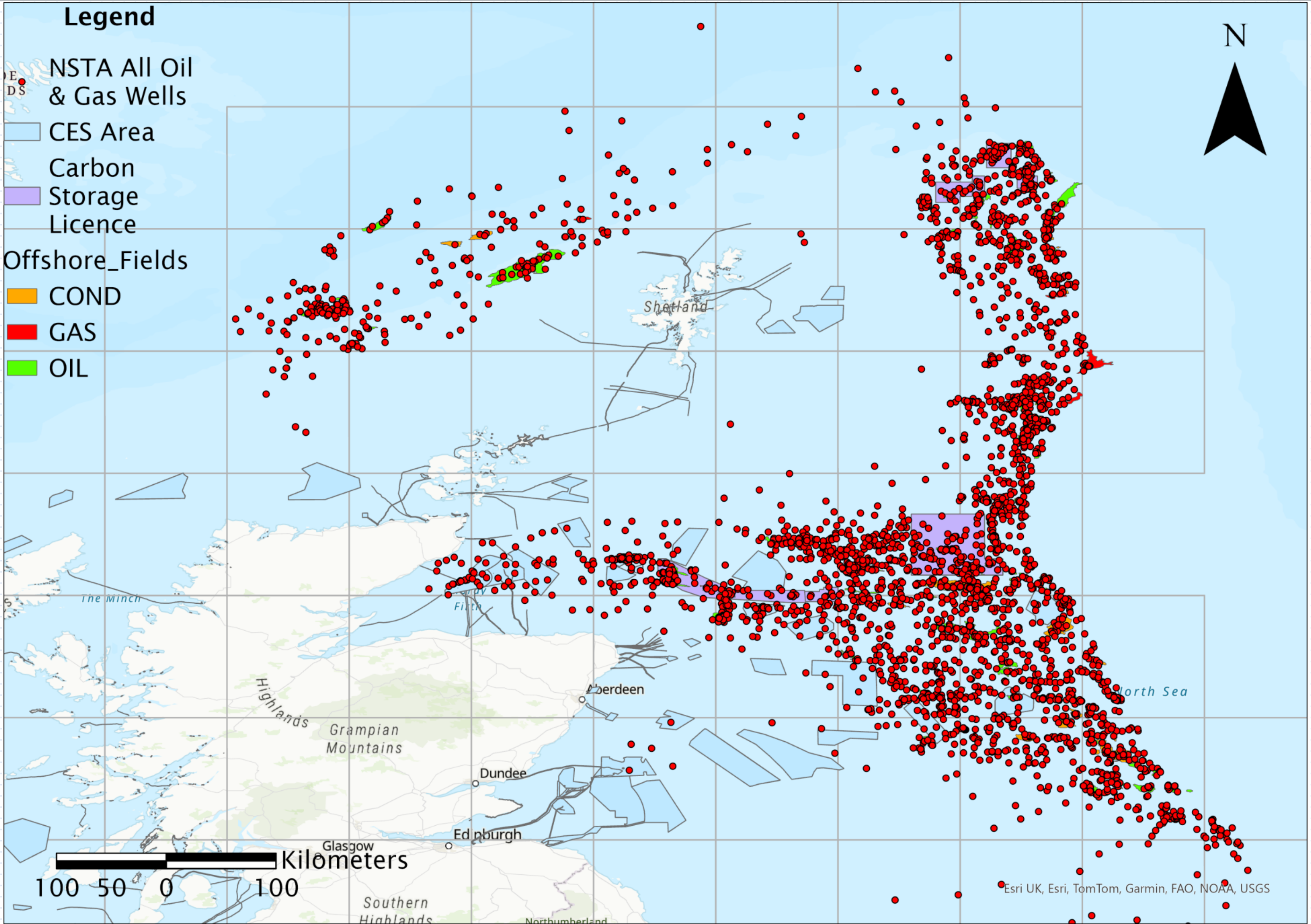
3 of Scotland's most promising stores could provide...

345 million tonnes of practical storage capacity

BGS (2023)

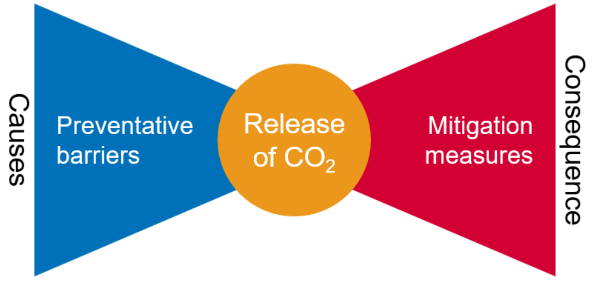


Context: Scotland's offshore domain



Existing approaches to managing legacy well risk

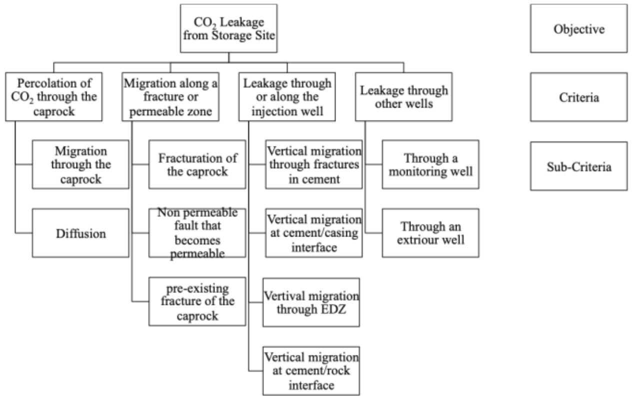
Bow-tie diagrams



Risktec (2025)

useful for conceptualising barriers and failure chains

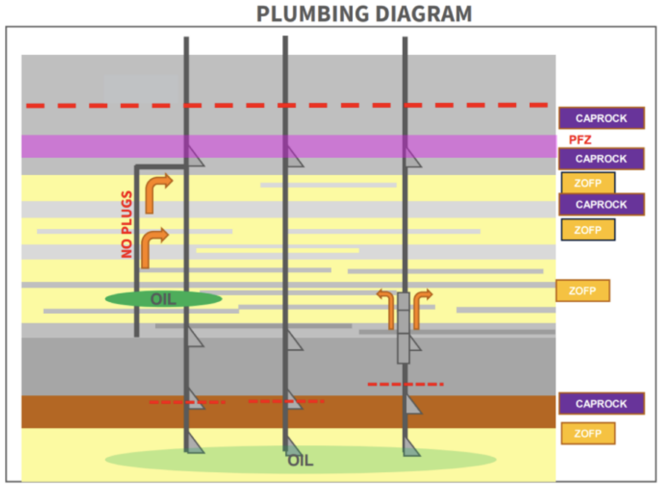
Probabilistic event trees



Oraee-Mirzamani et al (2013)

formal but data-hungry and uncertain for legacy wells

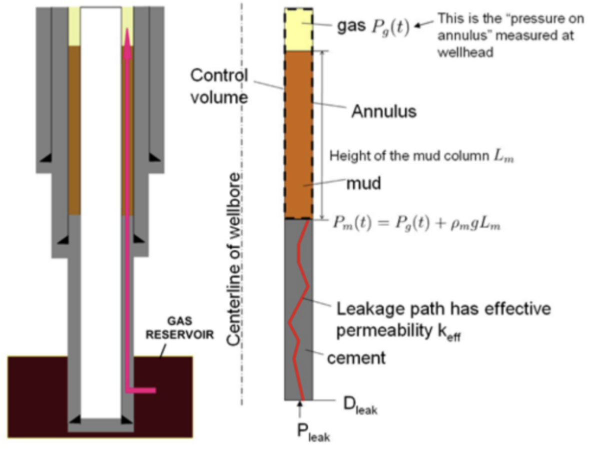
Plumbing diagrams



NSTA (2024)

quick but often rely on incomplete or outdated or incomplete records

Leakage modelling

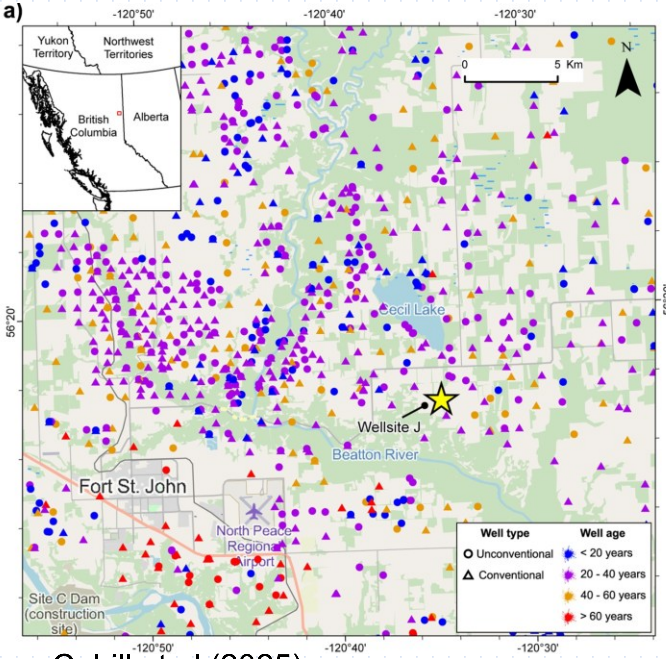


Tao et al (2010)

high fidelity but slow and expensive; suitable for single sites

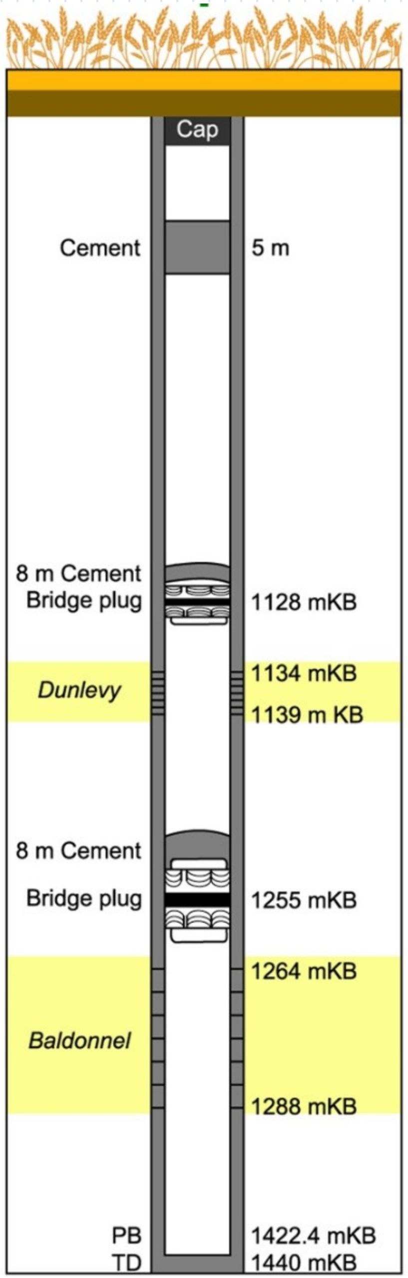
These methods are valuable at the site or well scale, but not across entire domains with thousands of legacy wells

Sometimes even the “best” wells leak

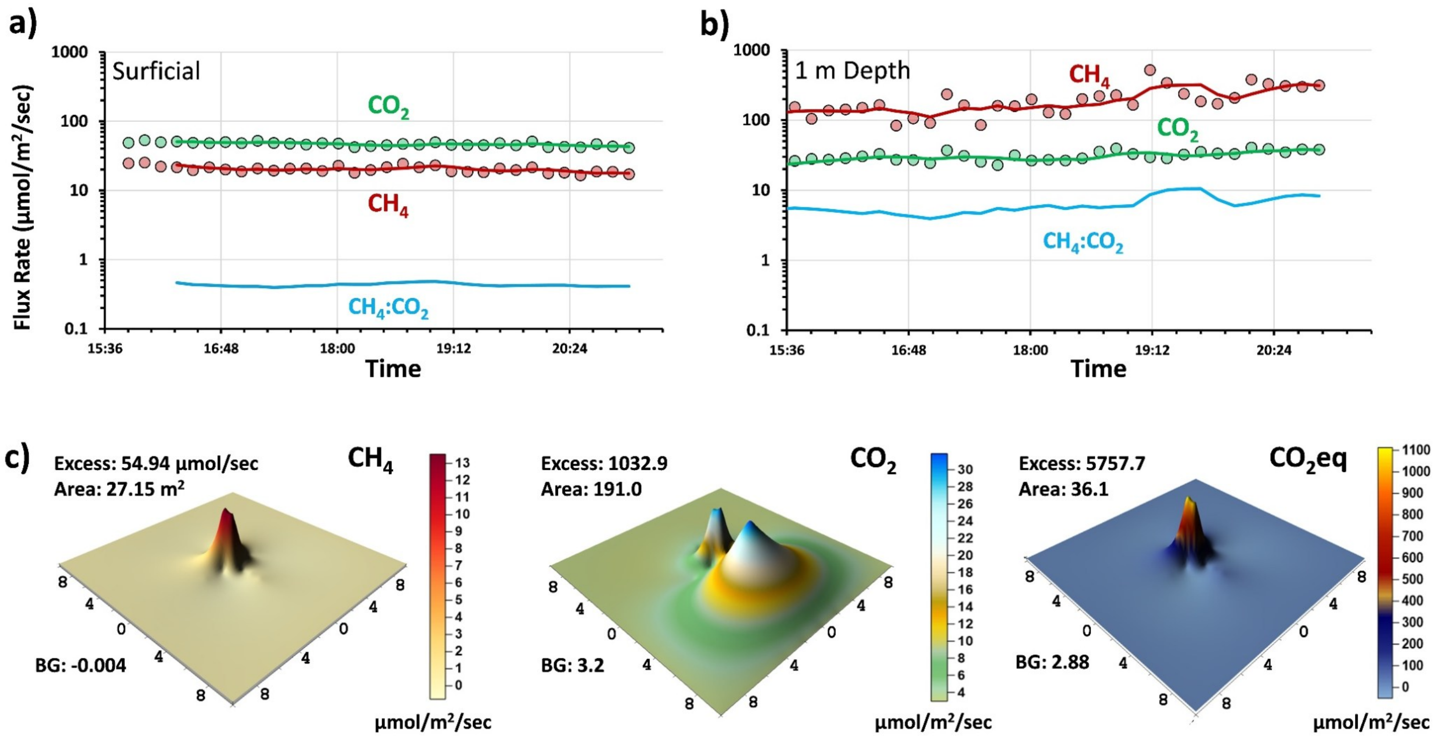


Cahill et al (2025)

- Drilled 2008, subsequently abandoned
- Adequate plugs and cement
- P&A compliant with regulations



However… Persistent methane leakage observed



If a compliant onshore well can leak, what does that mean for thousands of ageing offshore wells where direct inspection is extremely challenging?

Scalable approaches

International Journal of Greenhouse Gas Control 114 (2022) 103560

Contents lists available at ScienceDirect

International Journal of Greenhouse Gas Control

journal homepage: www.elsevier.com/locate/ijggc

ELSEVIER

Check for updates

Prioritizing stewardship of decommissioned onshore oil and gas wells in the

Data in Brief 37 (2021) 107165

Contents lists available at ScienceDirect

Data in Brief

Key research question: Which wells truly warrant attention, and how can we prioritise them across an entire offshore domain?

International Journal of Greenhouse Gas Control

journal homepage: www.elsevier.com/locate/ijggc

ELSEVIER

SINTEF Industry, Applied Geoscience Group, P. O. Box 4763 Torgarden, 7465 Trondheim, Norway

Check for updates

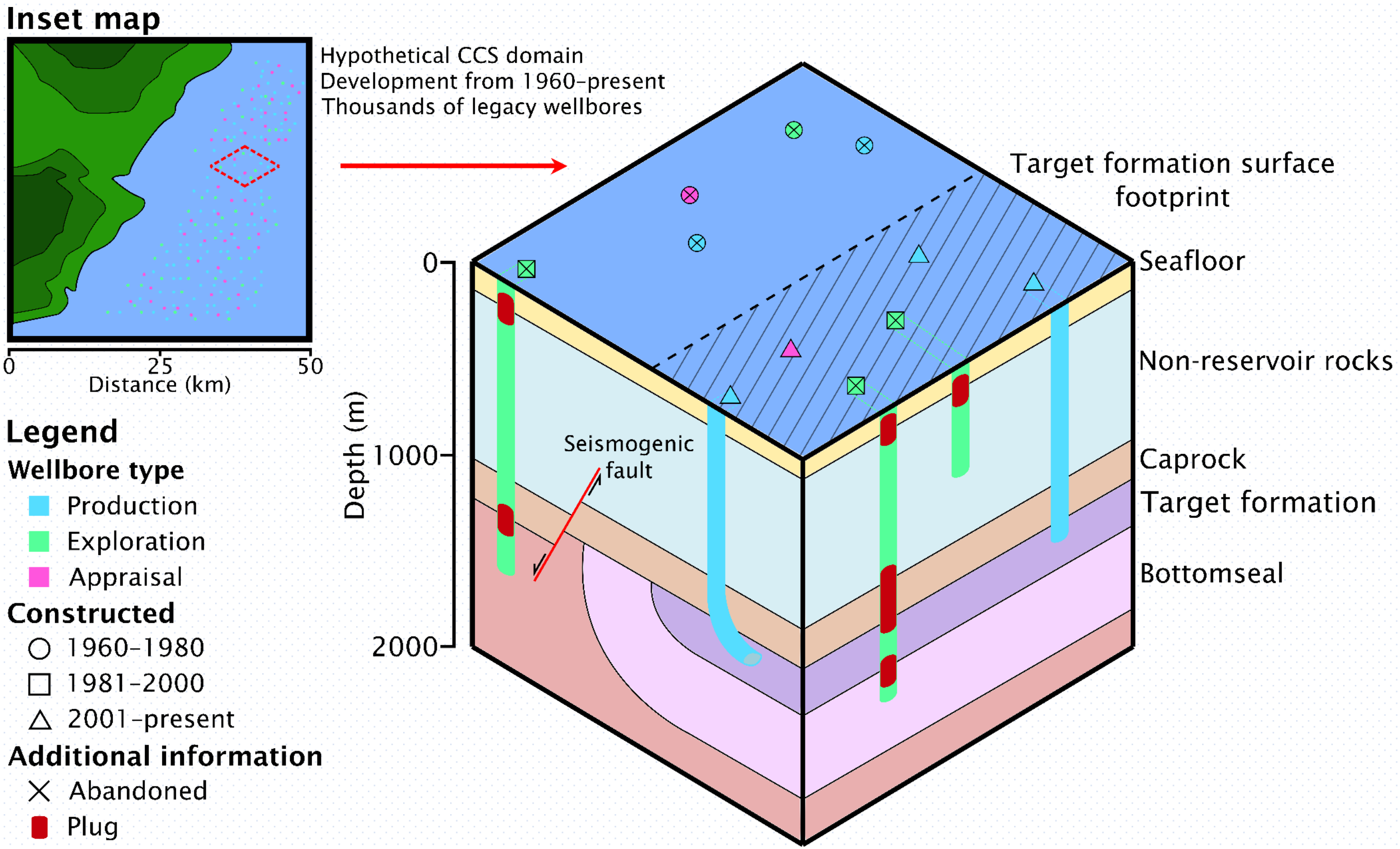
Qualitative risk assessment of legacy wells based on publicly available data for class VI well permit applications—Illinois basin case study

Nachiket Arbad *, Marshall Watson, Lloyd Heinze, Hossein Emadi

Bob L. Herd Department of Petroleum Engineering, Texas Tech University, Lubbock, TX, United States

Our approach

Multi-Criteria Decision Analysis (MCDA) of compounding risk factors using expert weighting + readily available regional datasets



Key to identify: Which wells have the right (or wrong) set of risk factors?

Methodological overview

Distance to significantly seismogenic fault

Depth of wellbore

Wellbore density within geologic formation

Geospatial

Time to failure of components

Well design and construction regulations

Temporal

Extent of data and historical records

Operational challenges during drilling

Wellbore configuration

Wellbore operational status

Wellbore intent

Engineering

Expert elicitation

Removal of irrelevant criteria

Refinement of scoring approach

Weighting of remaining criteria

Validation of methodology

Input (Wellbore Data)

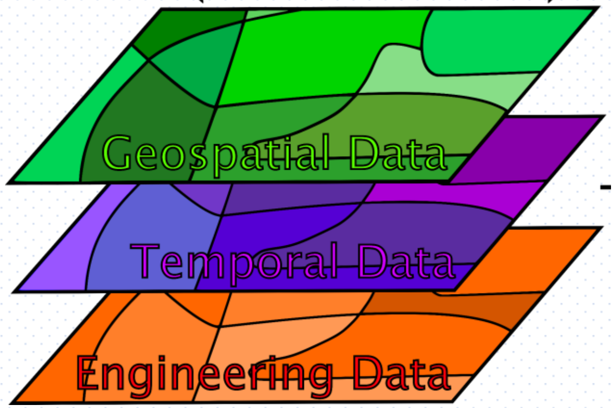


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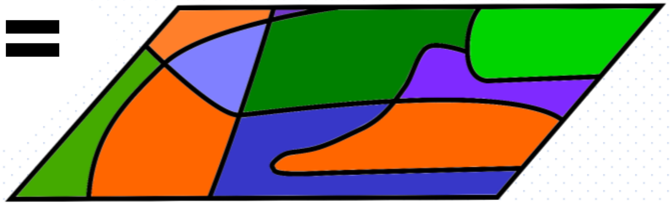
Table 3
Determined weighting for legacy well factors of consideration based on expert survey.

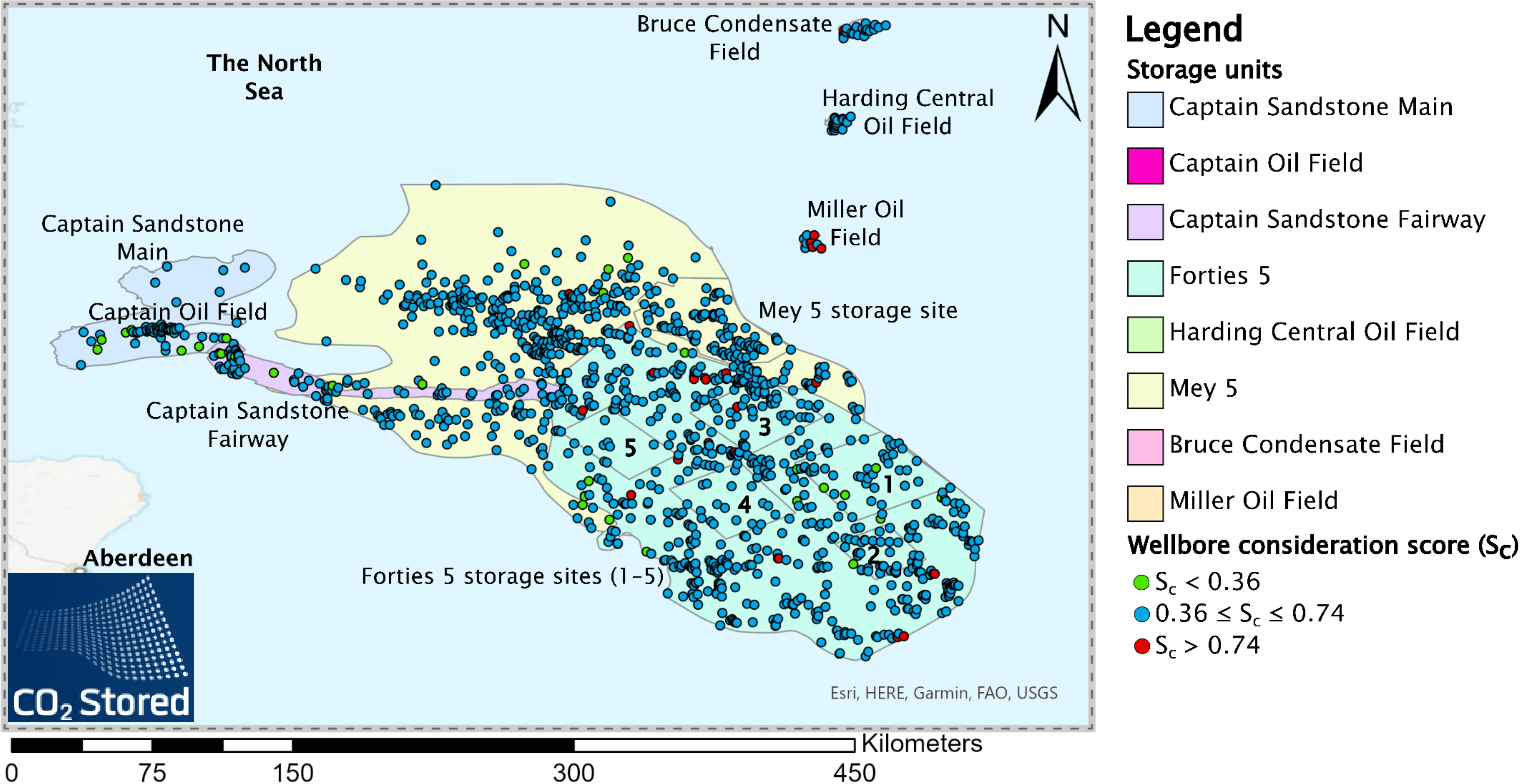
Factor of consideration	Weight
Wellbore configuration	0.133
Well Design and Construction Regulations	0.128
Extent of data and historical records	0.11[illegible]
Time to failure of components	0.107
Wellbore operational status	0.107
Wellbore intent	0.101
Distance to significantly seismogenic fault	0.093
Depth of wellbore	0.081
Wellbore density within geologic formation	0.078
Abnormal rate of penetration whilst drilling	0.055

=

Output (Consideration Score)



Distribution of consideration score



Nine of the Scottish Sea's most promising CO_2 storage units as identified in Kirk et al. (2023) with wellbore intersections coloured by their computed MCDA consideration score.

Contrasting storage risk profiles

Captain Fairway vs. **Miller Field**

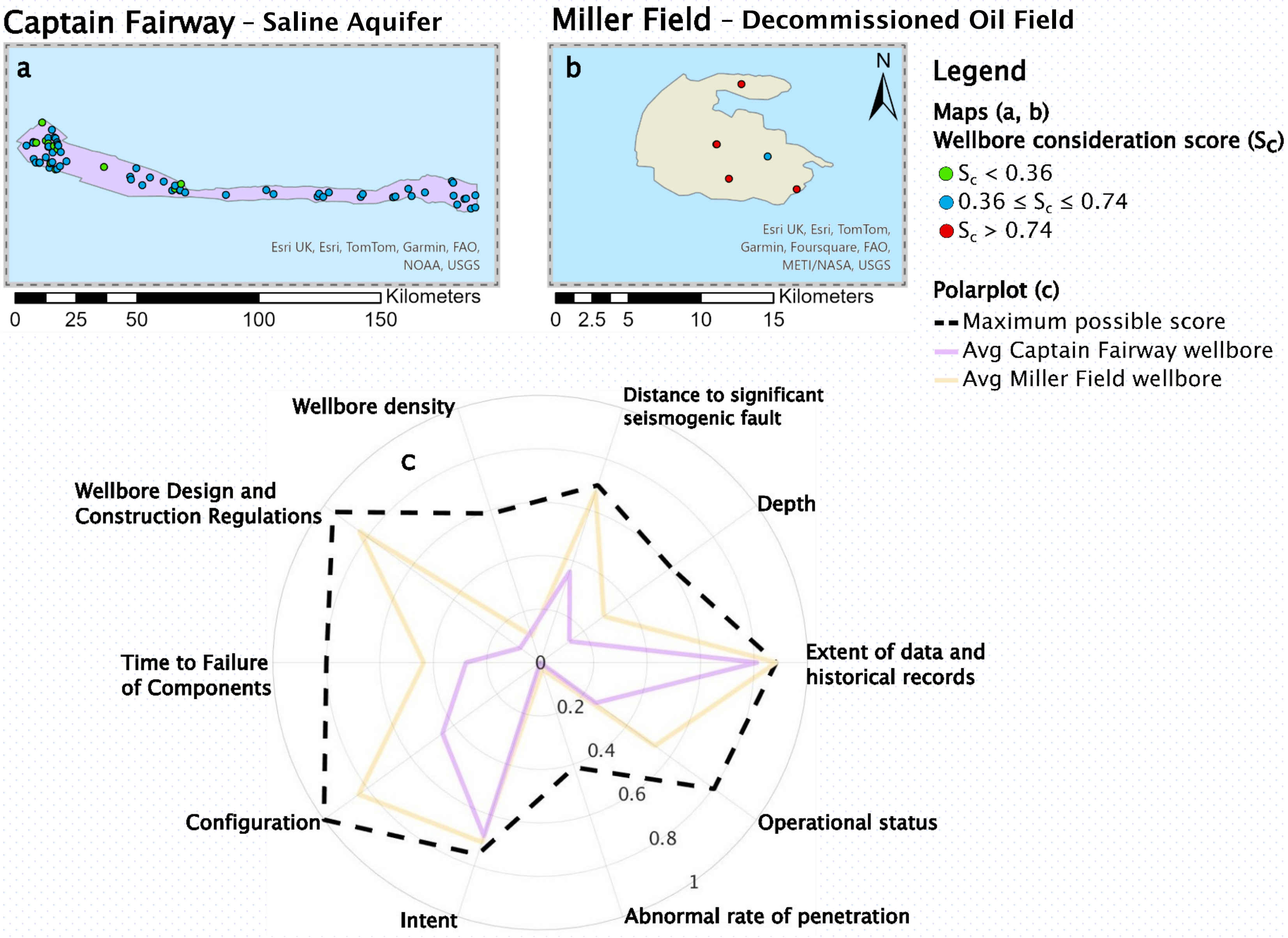
Wellbore density & consideration score:

Captain: 137 intersections (134 penetrating), lower average score (0.48), cumulative (64.03).

Miller: 43 intersections (31 penetrating), higher average score (0.71), cumulative (22.01).

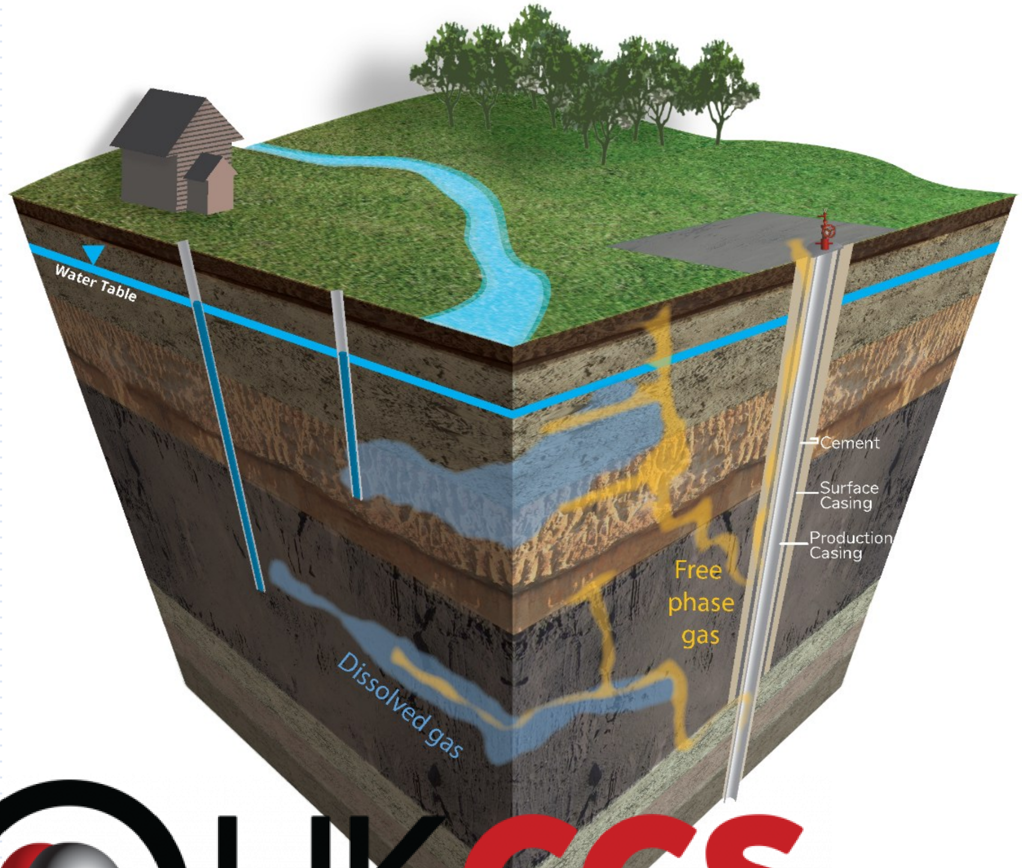
Risk concentration vs. risk aggregation: Choice between managing fewer high-risk wells (Miller) or a larger number of lower-risk wells (Captain).

Both sites are viable CCS reservoirs but require different risk management strategies.



From risk scores to physical leakage – Q-WellRATE

A Practical Physics-Based Model for Rapid Assessment of CO_2 Leakage from Legacy Wells



UKCCS RESEARCH COMMUNITY

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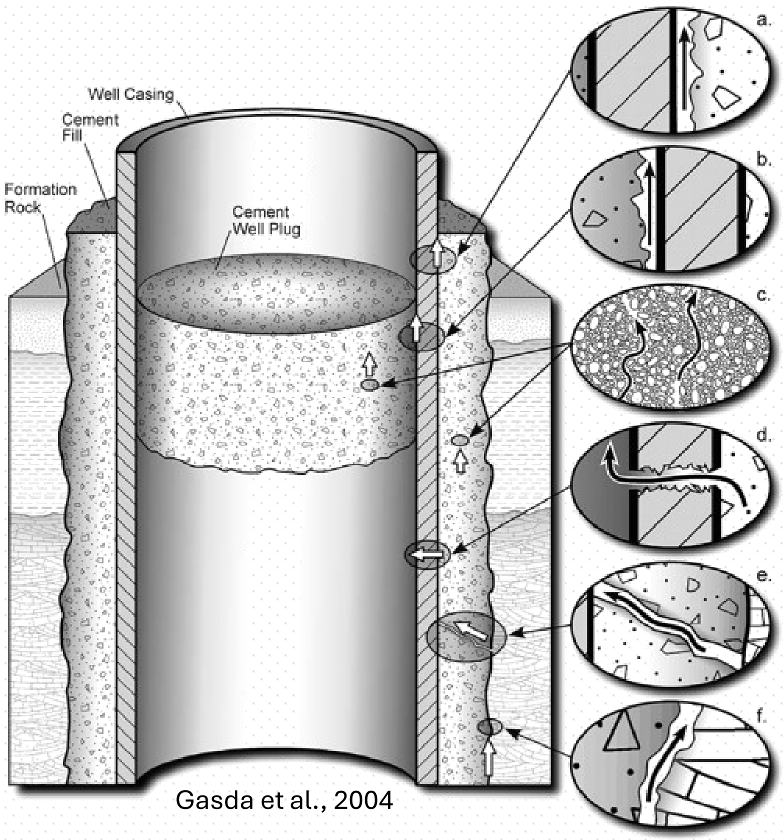
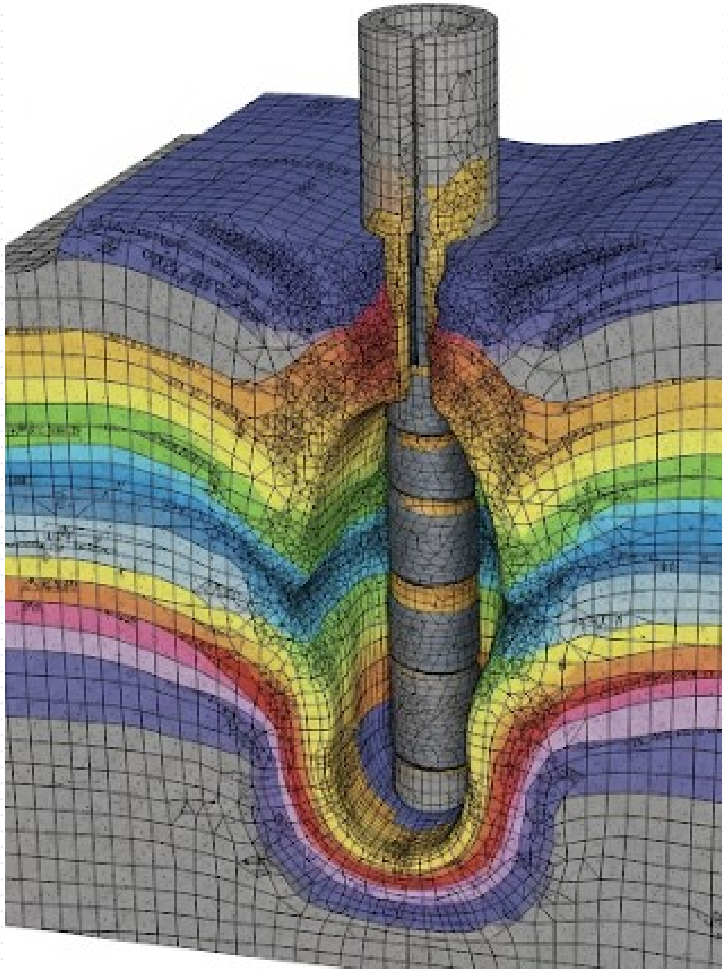
Benjamin Pullen
Model implementation and application

The complexity of wellbore leakage, and why we need a simpler way

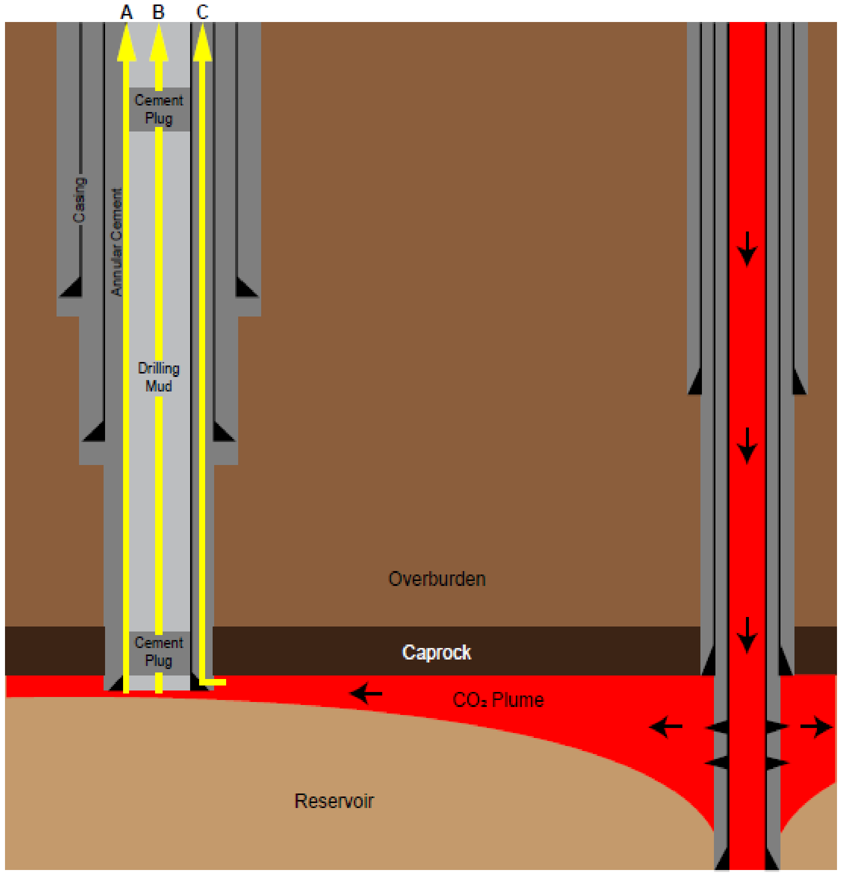


Gasda et al., 2004

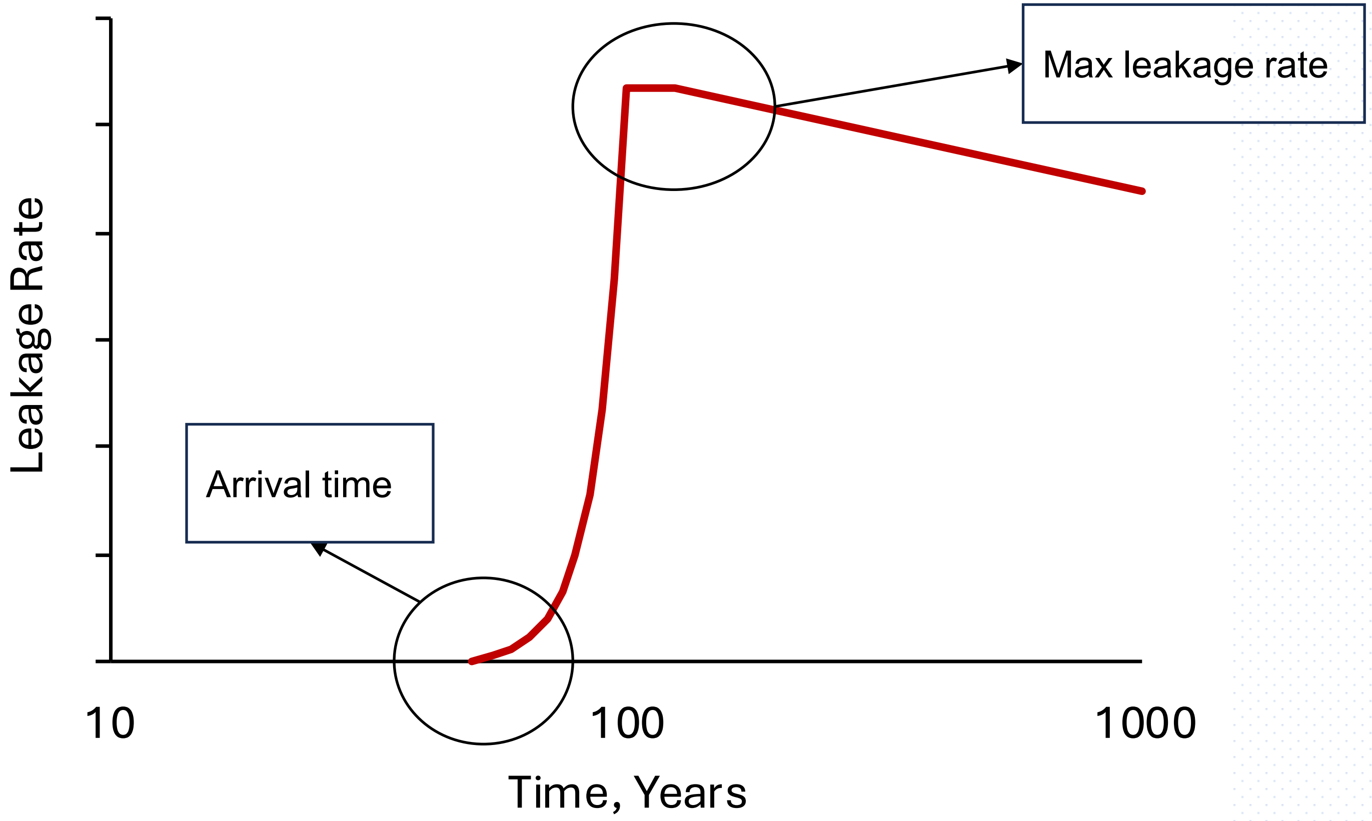


A fully coupled THMC problem, but data gaps and computational cost make fine-scale simulation impractical for early risk screening

For early risk screening, max flux matters most



Many unknowns!



We focus on estimating maximum leakage flux, a risk-conservative indicator for screening and site ranking.

Building on prior simplified leakage models

Estimating CO_2 Fluxes Along Leaky Wellbores

Qing Tao, Dean A. Checkai, Nicolas J. Huerta, and **Steven L. Bryant,** University of Texas at Austin

Summary

Large-scale geological storage of carbon dioxide (CO_2) is likely to bring CO_2 plumes into contact with a large number of existing wellbores. The flux of CO_2 along a leaking wellbore requires a model of fluid properties and of transport along the leakage pathway. Knowing the range of effective permeability of faulty cement is essential for estimating the risk of CO_2 leakage. The central premise of this paper is that the leakage pathway in wells that exhibit sustained casing pressure (SCP) is analogous to the rate-limiting part of the leakage pathway in any wellbore that CO_2 might encounter. Thus, field observations of SCP can be used to estimate transport properties of a CO_2-leakage pathway. Uncertainty in the estimate can be reduced by accounting for constraints from well-construction geometry and from physical considerations. We then describe a simple CO_2-leakage model. The model accounts for variation in CO_2 properties along the leakage path and allows the path to terminate in an unconfined (constant-pressure) exit. The latter assumption provides a worst-case leakage flux.

By use of pathway permeabilities consistent with observations in SCP wells, we obtain a range of CO_2 fluxes for the cases of

layers, and encounter existing wellbores (Fig. 1). Wellbores that no longer provide proper zonal isolation establish a primary pathway for a buoyant CO_2-rich phase to escape from the intended storage formation. They provide a relatively direct path to shallower subsurface formations and to the surface. The hazard of CO_2 leakage along wellbores will depend on the rate of leakage. Predicting the rate of leakage in turn requires a model of fluid properties and of transport along the leakage pathway. Leakage rates through the cement matrix are likely to be smaller than naturally occurring background fluxes because the permeability of intact cement is on the order of a few microdarcies. Leakage large enough to be a concern is most likely to occur along a defect (fracture, microannulus, or gas channel) in the steel/cement/Earth system (Watson and Bachu 2008; Crow et al. 2010). This type of discrete leakage pathway is a conduit or series of conduits with a specific geometry (e.g., aperture, diameter, cross-sectional area).

Models to quantify CO_2-leakage rates through abandoned wells have been introduced in past work (Pruess 2004; Nordbotten et al. 2005; Celia et al. 2006). But a key question that is not well addressed is a reasonable approach to estimate the conductivity of the wellbore leakage pathway. This lack of knowledge on wellbore permeability can be addressed by use of the SCP model. The

Leakage Calculator for Plugged-and-Abandoned Wells

Fatemeh Moeinikia, University of Stavanger and International Research Institute of Stavanger; **Eric P. Ford, Hans Petter Lohne, Øystein Arild,** and **Mohammad Mansouri Majoumerd,** International Research Institute of Stavanger; and **Kjell Kåre Fjelde,** University of Stavanger

Summary

The current practice on the Norwegian Continental Shelf (NCS) when designing solutions for permanent plug and abandonment (P&A) complies with *NORSOK Standard D-010* (2013). This is a prescriptive approach to P&A, as opposed to a "fit-for-purpose" risk-based approach. A risk-based approach means that any given P&A solution is expressed in terms of the leakage risk, which can be formulated in terms of the following quantities: the probability that the (permanent) barrier system will fail in a given time period, and the corresponding consequence in terms of leakage to the environment.

As part of building a leakage-risk model for permanently plugged-and-abandoned wells, a simple leakage-rate calculator has been developed for quick evaluation of the leakage potential from a given (permanent) well-barrier solution. This tool is developed to serve the second aspect of the risk-based approach: the consequence in terms of leakage rate to the environment. The leakage potential from the well can then be quantitatively assessed, taking into account different leakage pathways including leakage through bulk cement, through cement cracks, and through microannuli along cement interfaces.

In the paper, we will provide models to estimate leakage rate for each leakage pathway and show how to integrate them in the leakage calculator to obtain a description of leakage flow from the reservoir through failed barriers to the environment. The information and input parameters needed to achieve this will be discussed, and uncertain parameters will be treated probabilistically, thus allowing for expressing uncertainty in the leakage-rate estimate. Results from the leakage calculator will be demonstrated on a synthetic case, showing variants of a permanently plugged-and-abandoned well.

Environ. Sci. Technol. **2008**, *42*, 7280–7286

Development of a Hybrid Process and System Model for the Assessment of Wellbore Leakage at a Geologic CO_2 Sequestration Site

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Sequestration of CO_2 in geologic reservoirs is one of the promising technologies currently being explored to mitigate anthropogenic CO_2 emissions. Large-scale deployment of geologic sequestration will require seals with a cumulative area amounting to hundreds of square kilometers per year and will require a large number of sequestration sites. We are developing a system-level model, CO_2-PENS, that will predict the overall performance of sequestration systems while taking

"wedges" that can be used to limit atmospheric concentrations of CO_2. One of these options includes the capture and geologic sequestration of CO_2. Since fossil fuels are expected to make up a large component of the world's energy supply in the near future, geologic sequestration of CO_2 will likely need to play a role in reducing CO_2 emissions into the atmosphere (2). The technology for injecting CO_2 into deep geological formations already exists and has been applied for enhanced oil recovery and acid gas disposal (3). However, for geologic sequestration to become a viable option, sites must be assessed to determine if they can store much larger amounts of CO_2 over much greater periods of time.

Factors such as leakage need to be considered in any comprehensive study of a sequestration site. Because free-phase CO_2 is less dense than formation water, the potential for upward leakage in a geologic reservoir is enhanced due to CO_2 buoyancy (3). Leakage may occur through geological features, such as fractures and faults. Existing wells at sequestration sites also have the potential for leakage, since they often penetrate deep into the formation (3). Assessment of long-term viability of CO_2 storage is a complex function of CO_2—reservoir interactions, leakage pathways, and risks. It requires integrating theory, field observation, experiment, and simulation over a wide range of spatial and temporal scales, all of which involve substantial uncertainties. Existing risk and performance assessment models for geologic sequestration often rely on simplified analytical models for simulating processes and have been designed for a specific site (1, 4). A detailed model that incorporates all of the underlying physical, chemical, and geological processes is not computationally feasible. Instead, a methodology is required that abstracts these processes into a manageable, system-level model that is robust enough to apply to a wide variety of potential sequestration sites (1).

and many more models and approaches available in the literature…

We adopt the simplified Darcy-based approach but extend it to account for non-isothermal CO_2 behaviour, a key control often ignored.

Modelling philosophy: reliability over complexity

Model assumptions

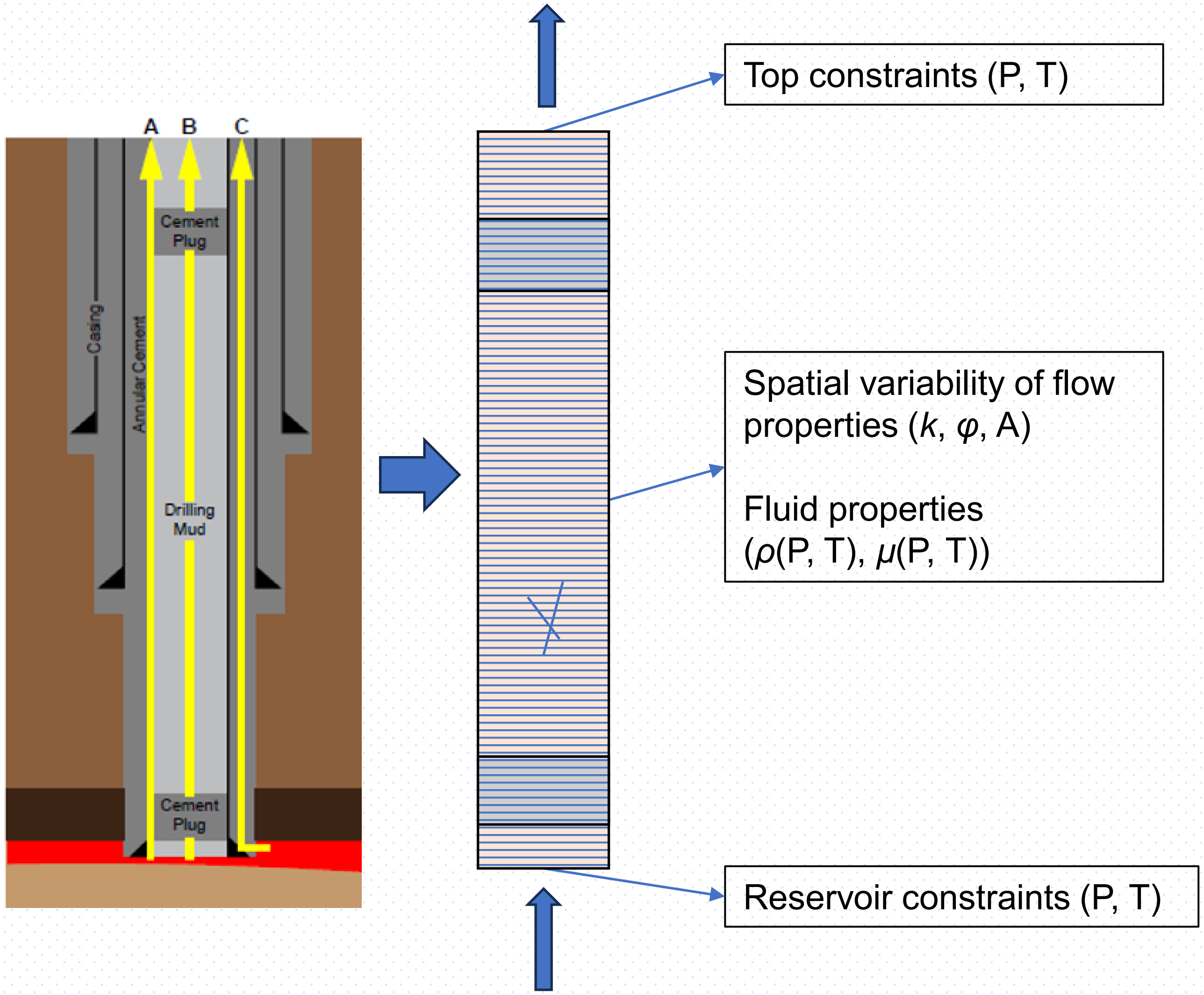
- Steady-state, single-phase Darcy flow: represents worst-case flux
- Multiphase behaviour captured through effective properties

Model inputs

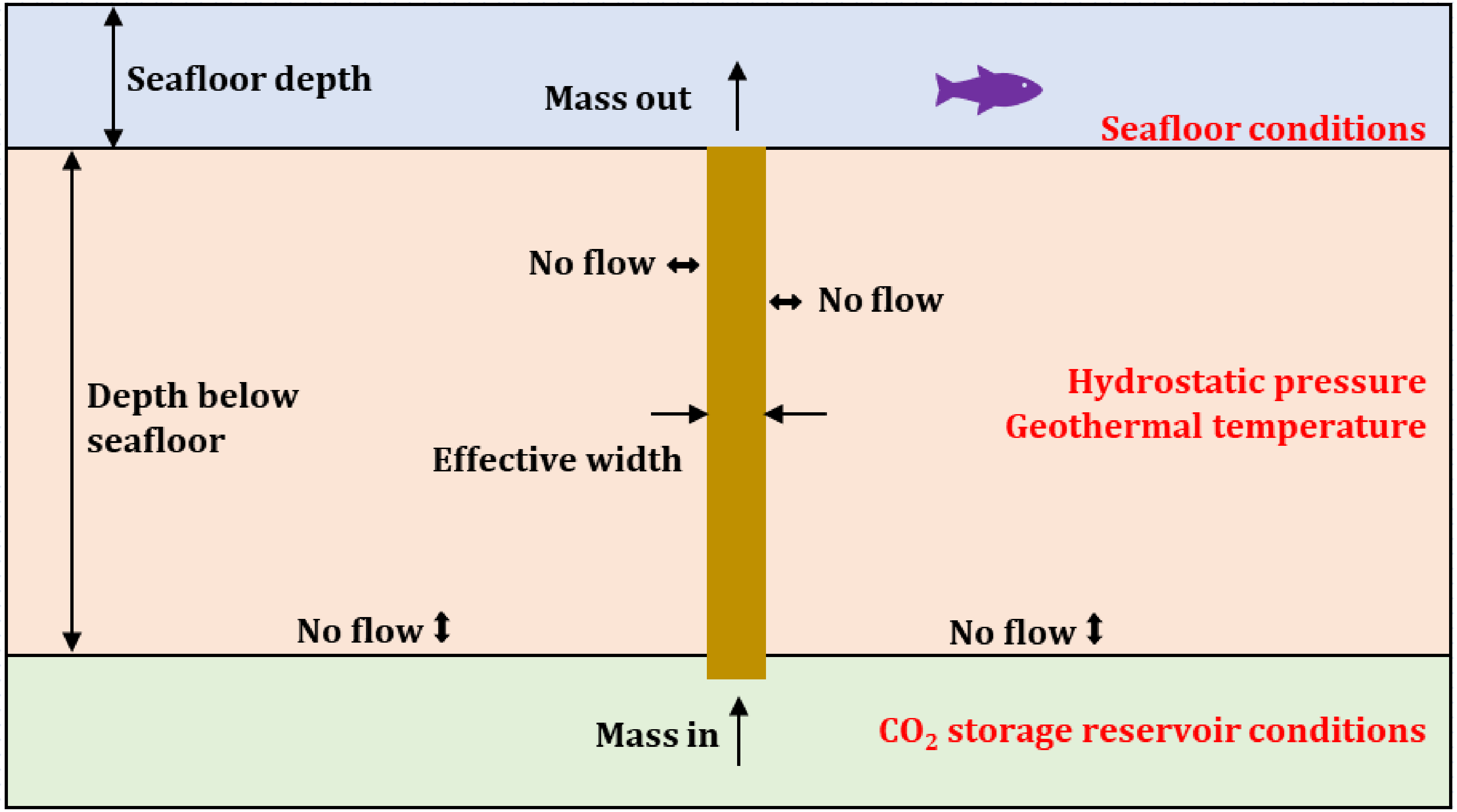
- Effective wellbore permeability (from SCP/SCVF correlations)
- Well geometry and cement-plug configuration
- Rock–fluid properties, pressure–temperature profiles, reservoir boundary conditions

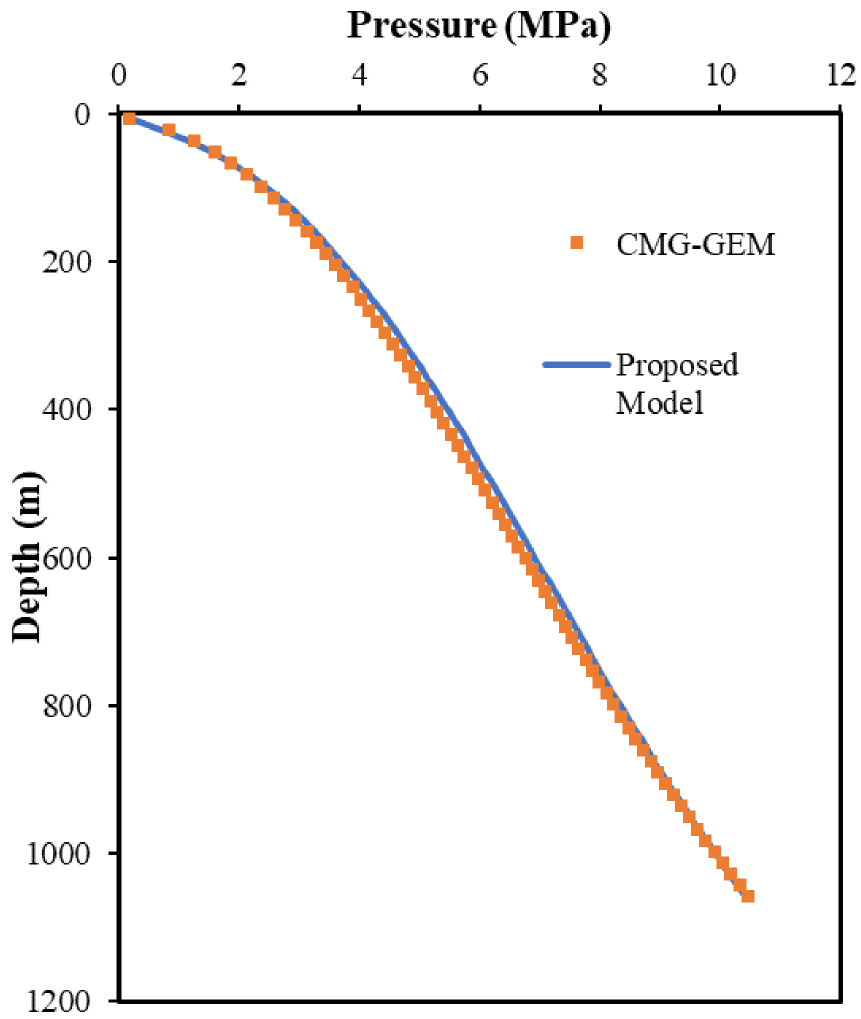
Model features

- Simulates leakage via bulk or annular cement and fractures
- Allows depth-variable cement properties
- Handles multiple gases (CO_2, CH_4, H_2, H_2O)



Fast, accurate, and ready for screening studies





- Validation: CMG (10 min) vs Q-WellRATE (0.1 s)
- Example: 100 nD cement leads to flux of 0.16 kg CO_2 yr^{-1} ≈ 1,300 km car journey
- Can we detect this flux? Motivates coupling with monitoring & impact models

Key takeaways

- The Scottish North Sea has immense CCS potential, but its thousands of legacy wells make containment assurance complex.
- Fast, scalable screening is essential to manage risk across a domain shared by many users.
- Our MCDA framework uses expert-weighted criteria to rank and prioritise wells for attention.
- Q-WellRATE links those rankings to physics-based leakage estimates, enabling rapid, realistic risk screening.
- Together, these tools offer a practical, transparent foundation for large-scale CCS risk management, complementing detailed site-specific studies.

Many thanks for listening ☺
Questions?

Thank you again to sponsors and colleagues

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