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A computationally efficient numerical model to understand potential CO_2 leakage risk within gigatonne scale geologic storage

Iman R. Kivi[1,2,3], Roman Y. Makhnenko[4], Curtis M. Oldenburg[5], Jonny Rutqvist[5], and Victor Vilarrasa[3]
[1]Institute of Environmental Assessment and Water Research, Spanish National Research Council (IDAEA-CSIC), Barcelona, Spain
[2]Associated Unit: Hydrogeology Group (UPC-CSIC), Barcelona, Spain
[3]Global Change Research Group (GCRG), IMEDEA, CSIC-UIB, Esporles, Spain
[4]Department of Civil & Environmental Engineering, University of Illinois at Urbana-Champaign, Urbana, Illinois, USA
[5]Energy Geosciences Division, Lawrence Berkeley National Laboratory, CA, USA

The majority of available climate change mitigation pathways, targeting net-zero CO_2 emissions by 2050, rely heavily on the permanent storage of CO_2 in deep geologic formations at the gigatonne scale. The spatial and temporal scales of interest to geologic carbon storage (GCS) raise concerns about CO_2 leakage to shallow sediments or back into the atmosphere. The assessment of CO_2 storage performance is subject to huge computational costs of numerically simulating CO_2 migration across geologic layers at the basin scale and is therefore restricted in practice to multi-century periods. Here, we present a computationally affordable and yet physically sound model to understand the likelihood of CO_2 leakage over geologic time scales (millions of years) (Kivi et al., 2022). The model accounts for vertical two-phase flow and transport of CO_2 and brine in a multi-layered system, comprising a sequence of aquifers and sealing rocks from the crystalline basement up to the surface (a total thickness of 1600 m), representative of a sedimentary basin. We argue that the model is capable of capturing the dynamics of CO_2 leakage during basin-wide storage because the lateral advancement of CO_2 plume injected from a dense grid of wellbores transforms into buoyant vertical rise within a short period after shut-in. A critical step in the proposed model is its initialization, which should reproduce the average CO_2 saturation column and pressure profiles. We initialize the model by injecting CO_2 at a constant overpressure into an upper lateral portion of the target aquifer while the bottom boundary is permeable to brine, resembling brine displacement by CO_2 plume or leakage at basin margins. The optimum model setting can be achieved by adjusting the brine leakage parameter through calibration. We solve the governing equations using the finite element code CODE_BRIGHT. Discretizing the model with 7,100 quadrilateral elements and using an adaptive time-stepping scheme, the CPU time for the simulation of CO_2 containment in the subsurface for 1 million years is around 140 hours on a Xeon CPU of speed 2.5 GHz. The obtained results suggest that the upward CO_2 flow in free phase is strongly hindered by the sequence of caprocks even if they are pervasively fractured. CO_2 leakage towards the surface is governed by the intrinsically slow molecular diffusion process, featuring aqueous CO_2 transport rates as low as 1 meter per several thousand years. The model shows that GCS in multi-layered geologic settings is extremely unlikely to be associated with leakage, implying that GCS is a secure carbon removal technology.

Reference

Kivi, I. R., Makhnenko, R. Y., Oldenburg, C. M., Rutqvist, J., & Vilarrasa, V. (2022). Multi-layered systems for permanent geologic storage of CO_2 at the gigatonne scale. *Geophysical Research Letters*, 49, e2022GL100443. https://doi.org/10.1029/2022GL100443