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An examination of geologic carbon sequestration policies in the context of leakage potential

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ABSTRACT

Carbon dioxide (CO_2) injected into geologic reservoirs for long-term sequestration, or the brine it displaces, may leak through natural or manmade pathways. Using a leakage estimation model, we simulated fluid leakage from a storage reservoir and its migration into overlying formations. The results are discussed in the context of policies that seek to assure long-term sequestration and protect groundwater. This work is based on a case study of CO_2 injection into the Mt. Simon sandstone in the Michigan sedimentary basin, for which we constructed a simplified hydrologic representation of the geologic formations. The simulation results show that (1) CO_2 leakage can reach an aquifer containing potable water, but numerous intervening stratigraphic traps limit the rate to be orders of magnitude less than the rate of leakage from the storage reservoir; (2) U.S. Department of Energy guidelines for storage permanence allow for more leakage from larger injection projects than for smaller ones; (3) well leakage permeability is the most important variable in determining leakage processes and substantial leakage requires that numerous wells leaking with the anomalously high permeability of 10^{-10} m^2; and (4) leakage can reduce the U.S. Environmental Protection Agency's Area of Review.

1. Introduction

Meeting goals for limiting future climate change entails the deployment of a broad portfolio of technologies that reduce the carbon dioxide (CO_2) emissions intensity of the energy used to power economies (GEA, 2012). Analyses often favor expanded deployment of renewable energy technologies combined with CO_2 capture and storage (CCS) (GEA, 2012; Pacala and Socolow, 2004). CCS is a process whereby CO_2 is captured from large stationary point sources (e.g., coal-fired power plants, ethanol refineries, and cement manufacturers), compressed, and transported by pipeline to locations where that CO_2 is injected deep into the subsurface for isolation from the atmosphere (IPCC, 2005). These subsurface storage options include depleted oil and gas reservoirs, unmineable coal seams, and deep saline aquifers (NETL, 2012); basalt formations may also offer storage potential (Matter et al., 2007). In the United States and Canada, the lower-bound estimate for CO_2 storage capacity is 2102 $GtCO_2$ in saline formations, compared to 226 $GtCO_2$ in oil and gas reservoirs, and 56 $GtCO_2$ in unmineable coal seams (NETL, 2012). In some formations, injecting CO_2 can create value by enhancing oil recovery (NETL, 2010), producing methane from gas reservoirs and coalbeds (Mazzotti et al., 2009), or generating electricity using geothermal resources (Buscheck et al., 2013, 2012; Randolph and Saar, 2011). As a consequence of the possibility to couple geologic CO_2 injection with the production of a marketable commodity, CCS has been re-branded CCUS, where "U" refers to the "Utilization" of CO_2. Future deployment of CCS or CCUS to make a substantial contribution to mitigating climate change will necessarily involve deep saline aquifers within sedimentary basins because they offer an enormous potential onshore storage capacity.

The viability of CCS as an effective climate mitigation technology depends on its reliability in terms of secure, long-term containment of CO_2. Under the high-pressure conditions in the deep subsurface, CO_2 will be a supercritical fluid—dense like a liquid but buoyant relative to the resident brine. Also, pressure increases in storage reservoirs will occur because CO_2 will be injected into formations that already contain fluids (Birkholzer et al., 2009; Strandli and Benson, 2013), and this increase in pore pressure may mobilize the resident brine. Therefore, containment

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of the CO_2 within a particular stratigraphic formation relies upon the integrity of an impervious caprock overlying the permeable and porous storage reservoir. Leakage from storage reservoirs is possible if CO_2 or displaced brine encounters locations where caprock integrity is compromised. These potential leakage pathways include geologic faults and transmissive fracture systems (Jordan et al., 2011; Rutqvist, 2012; Zeidouni, 2012), poorly or improperly plugged wells, poorly-cemented existing wells and wellbores (e.g., Birkholzer et al., 2011; Tao et al., 2012; Watson and Bachu, 2007), altered well cement (e.g., Carey, 2013; Kutchko et al., 2007), the boundary between this cement and the well casing or host rock (e.g., Carey et al., 2010; Newell and Carey, 2013), or geochemically-altered fractures (e.g., Deng et al., 2013; Ellis et al., 2013, 2011; Fitts and Peters, 2013). Leakage may incur costs to a variety of stakeholders (Bielicki et al., 2014; Pollak et al., 2013), but moderate amounts of leakage may be tolerated from the perspective of climate mitigation (Hepple and Benson, 2004; Van der Zwaan and Smekens, 2009) and cost effectiveness (Ha-Duong and Keith, 2003; Van der Zwaan and Gerlagh, 2009). Leakage through leakage pathways could also relieve some pressure (Cihan et al., 2013) and thus, reduce a driving force for upward migration of non-native fluids and the potential for inducing seismicity. Helpful pressure relief could also be provided by distant out-of zone brine migration or by diffuse flow of brine though the confining layer, but the loss of CO_2 may limit the success of the project in part as a result of oversight and regulation by relevant agencies.

Oversight that allows some leakage can have benefits over those that prohibit leakage. For example, some degree of leakage can have performance benefits by reducing pressure, and operators can continue to accrue knowledge of how the reservoir behaviors despite, and because of, this leakage. The opaque and heterogeneous nature of the subsurface means that operators, regulators, the public, and other stakeholders can have at best probabilistic expectations of the security of a given geologic CO_2 storage project. Agencies in the United States and elsewhere are seeking to limit leakage of injected and mobilized fluids, and some of their guidance and oversight incorporates the potential for some leakage, despite their different perspectives. For example, the European Union Directive on the Geological Storage of Carbon Dioxide does not allow permits for reservoirs that have a significant risk of leakage (European Union, 2009). In the United States, the Department of Energy (U.S. DOE) focuses on storage performance and has set a climate mitigation goal for CO_2 storage of 99% storage permanence. That is, leaked CO_2 would be limited to at most 1% of the amount of CO_2 injected into a reservoir. The United States Environmental Protection Agency (U.S. EPA) focuses on environmental and human health and is charged with protecting potable groundwater resources under the Safe Drinking Water Act (SDWA). In the United States, an underground source of drinking water (USDW) is defined as an aquifer with less than 10,000 ppm total dissolved solids (TDS). For CO_2 or brine to contaminate a USDW, these fluids must encounter vertical leakage pathways and flow, due to natural buoyancy or a pressure drive, through numerous intervening sedimentary units before reaching a USDW aquifer. Subsequent deterioration of water quality may result from the brine salinity or from the direct or indirect mobilization or release of toxic metals, trace elements, and normally occurring radioactive materials (NORMs) (Atchley et al., 2013; Humez et al., 2011; Keating et al., 2013, 2010; Lemieux, 2011; Lions et al., 2014; Little and Jackson, 2010; Yang et al., 2014a,b). The U.S. EPA Underground Injection Control (UIC) program Class VI rule includes Above Zone Monitoring Intervals (AZMI), where the formations above the intended storage reservoir are monitored for leakage. If leakage is detected, leakage pathways could be repaired to reduce or stop leakage. If an impact of leakage is detected in a USDW, the injection site will violate the SDWA and be out of compliance with the UIC Class VI regulations that govern CO_2 injection for storage.

The Class VI rule (U.S. Federal Register, 2010), requires that an Area of Review (AoR) be delineated as “the region surrounding the proposed well where USDWs may be endangered by the injection activity [40CFR 146.84]” (U.S. EPA, 2013). The AoR is thus, the geographic area within which leakage could reach a USDW aquifer, and has been defined as either the area where the brine pressure is sufficiently elevated to drive fluid upward and into a shallow USDW aquifer, or the areal extent of the CO_2 plume, and is delineated by whichever is larger (U.S. Federal Register, 2010). In contrast to the Class I rules for hazardous waste injection and the Class II rules for injecting waste from oil and gas production, which stipulate that assessments of the potential for leakage must be made at specific radial distances from the injection well (at least Class I = 3.2 km and Class II = 0.8 km), the Class VI rule requires a site-specific assessment. This rule requires that injection operators establish the AoR based on approved modeling of fluid flows [40CFR 146.84(a)] (which have provided good fits of the extent of the CO_2 plume in demonstration injections (Hovorka et al., 2006)), identify and characterize potential leakage pathways within the AoR [40CFR 146.84(c)], conduct appropriate corrective action on artificial penetrations within the AoR through which leakage might reach a USDW [40CFR 146.84(d)], and reassess this AoR and the penetrations over time [40CFR 146.84(d and e)] (U.S. EPA, 2013). The AoR can cover a large area within the basin (Birkholzer and Zhou, 2009), and some have called for a tiered definition of the AoR based on the potential leakage of CO_2 or of brine (Birkholzer et al., 2014).

Our previous work has examined how the regulatory discretion regarding this corrective action may influence the costs of leakage (Bielicki et al., 2014). Here we used very large injection rates in a consistent manner to examine the geophysical controls on leakage and the implications for policies governing geologic CO_2 storage in the United States, with specific attention to the U.S. DOE storage permanence goal and the U.S. EPA Class VI rule. The U.S. DOE goal allows for some leakage, and we investigated scenarios of CO_2 leakage that exceed the goal and if the approach of a constant rate may have unintended consequences of allowing more CO_2 to leak from operations with higher injection rates. The U.S. EPA Class VI rule is examined in regard to the effect on the AoR as well as the potential of leakage to reach a USDW. Finally, we discuss the extent to which the U.S. DOE goal and the U.S. EPA rule are self consistent or at odds with each other by examining the extent to which allowed leaked CO_2 from the storage reservoir leads to disallowed contamination of potable groundwater aquifers. The layered structure of sedimentary basins means that leaked CO_2 disperses horizontally as well as vertically through the stratigraphic sequence and does not necessarily end up contaminating a USDW.

The total amount of leakage and the extent to which fluids migrate horizontally (defining the AoR) and vertically (defining the threat to a USDW) depend on numerous interacting parameters, including geophysical characteristics (e.g., leakage pathway permeability, unit permeability, and unit porosity), siting choices (e.g., proximity to leakage pathways, depth and thickness of CO_2 storage reservoir), and operational decisions (e.g., injection rate). In this work, we simulated leakage from a storage formation into overlying aquifers by running a semi-analytical leakage model. Our case study is a hypothetical geologic CO_2 storage project in a realistic target reservoir in the Michigan sedimentary basin, with very large injection rates to encourage substantial leakage rates. We constructed a three-dimensional model of the hydrostratigraphic units of the Michigan sedimentary basin based largely on the characterization by the United States Geologic Survey (USGS) (Lampe, 2009), and focused specifically on the aquifers in Western Michigan. We examined three main sources of uncertainty and variability: the