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A risk map methodology to assess the spatial and temporal distribution of leakage into groundwater from Geologic Carbon Storage

Erica R. Siirila-Woodburn*, Abdullah Cihan, Jens T. Birkholzer

Energy Geosciences Division, Lawrence Berkeley National Laboratory, 1 Cyclotron Road, M.S. 74R-316C, Berkeley, CA 94704, USA

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ABSTRACT

The risks to potable aquifers due to brine leakage through plugged and abandoned (P&A) wells is highly uncertain and a potentially significant contributor to the risk profile in Geologic Carbon Storage (GCS). This uncertainty stems from the unknown location of wells and the large variance of P&A wellbore permeability, making the spatial assessment of P&A brine leakage risk challenging. A new methodology is presented to generate "risk maps", or spatial distributions of brine leakage risk to groundwater resources as defined with no-impact or Maximum Contaminant Level (MCL) thresholds. The methodology utilizes probability theory, thereby avoiding the use of computationally expensive Monte Carlo simulations while maintaining flexibility in modeling techniques. These maps provide quantitative probabilities of risk as a function of time to inform site selection and monitoring during and post-injection, conducive to the US EPA's permitting of class-VI wells and the so-called "area of review", AoR. As a demonstration of the methodology, a numerical model of a hypothetical fully-coupled system spanning from the injection reservoir to the USDW is used to assess the evolution of brine leakage through P&A wells. Risk maps of CO_2 leakage can also be generated with this methodology for a comprehensive assessment of GCS leakage risk.

1. Introduction

Geologic Carbon Storage (GCS) may be a viable option to aid in mitigating climate change, and is frequently included in projections to reduce global CO_2 emissions. The intergovernmental panel on climate change (IPCC) most recently planned that cost-effective fossil fuel power generation without the use of GCS will be entirely phased out by 2100 (IPCC, 2014). Although the emission reductions projected from GCS-inclusive strategies could be as high as 30% by 2050 (IEA, 2009), questions related to the safety of overlying drinking water aquifers still need addressing given that potential leakage of CO_2 and/or brine from deep geologic storage formations into groundwater resources may adversely affect water quality (Little and Jackson, 2010; Siirila et al., 2012; Navarre-Sitchler et al., 2013; Varadharajan et al.., 2013; Carroll et al., 2014, 2016; Zhong et al., 2014; Zheng et al., 2015; Bacon et al., 2016; Keating et al., 2016; Xiao et al., 2016).

As part of the protection of these freshwater resources, the US EPA has implemented permitting regulations for class-VI wells used to inject CO_2 into deep storage formations. These regulations include the need to delineate a so called "area of review" (AoR), formally defined as the region surrounding the geologic sequestration site where underground sources of drinking water (USDWs) may be endangered by the injection activity (US EPA, 2013). Guidelines state that the AoR should encompass 1) the maximum extent of the CO_2 plume and 2) the pressure front of sufficient magnitude required to force fluids from the injection zone into the formation matrix of the USDW over the lifetime of the project, the latter of which is typically larger in extent than the former for industrial-scale injections (Bandilla et al., 2012; Birkholzer et al., 2014).

Assuming hydrostatic conditions, a worst-case brine leakage scenario is used in class-VI well permitting to determine the extent of the differential pressure front covering an area within which differential pressures exceed a critical differential pressure sufficient in magnitude to force fluids from the injection zone into the USDW via an open-wellbore conceptual model. The calculated critical differential pressure for open conduit flow from the injection zone upwards towards the USDW is a function of temperature and salinity variations (Birkholzer et al., 2011), and thus in an injection

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* Corresponding author.
E-mail address: ERWoodburn@lbl.gov (E.R. Siirila-Woodburn).

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reservoir with relatively low-salinity brine, even small pressure increases at several kilometers distance from the injection location may result in USDW leakage via a potential open-wellbore. The AoR calculated using the proposed method by the US EPA's class-VI regulation (US EPA, 2013) is arguably over-conservative, as open-wellbores are an extreme risk scenario, and may not be a representative characterization of more likely wellbore leakage risks such as leakage in and around the damage zones of plugged and abandoned wells (Celia et al., 2004). As pointed out by Birkholzer et al. (2014), the presence of thief zones (i.e. brine-bearing intermediate layers between the USDW and the injection reservoir) can prevent brine leakage into the USDW by laterally mitigating the vertical flow of brine through and around the wellbore casing. Also, the inherent assumption of a hydrostatic equilibrium between the injection reservoir and the USDW in the US EPA's suggested method of the critical pressure calculation may not be valid in some reservoir systems (US EPA, 2013, p. 42; Oldenburg et al., 2016), requiring the development of more general and robust methods for AoR delineation.

Birkholzer et al. (2014) presented an alternative, tiered AoR methodology which differentiates GCS leakage risks by constituent (CO_2 or displaced brine from the injection reservoir) and the type of leakage pathway (plugged and abandoned or open wellbores). They proposed a three-tier AoR system to differentiate these types of risks. The first tier of AoR is defined by the spatial extent over which the CO_2 plume exists, and CO_2 leakage could occur. Similarly, a second tier of AoR is defined by the spatial extent over which the pressure front is sufficiently large enough to result in brine leakage into the USDW via open-boreholes (i.e. the proposed method in the US EPA's class-VI regulation). Finally, a third tier of AoR is defined as the intermediate area between Tier 1 and 2 where brine leakage could occur via plugged and abandoned (P&A) wellbores. The spatial extent of Tier 2 AoR can be estimated via simple analytical and semi-analytical equations and some knowledge of the initial fluid pressure in the USDW and injection zone, density and temperature variations, and depth between the USDW and injection reservoir (see US EPA, 2013; Nicot et al., 2008; Birkholzer et al., 2011). As shown in Fig. 1a, estimating the spatial extents of AoR Tiers 1 and 2 is fairly straightforward (provided that reliable predictions of future CO_2 migration and reservoir pressurization are available) whereas a risk-driven methodology to determine the spatial extent of the Tier 3 AoR has yet to be developed.

Here we present a methodology that appropriately differentiates the risks related to geologic carbon storage while providing an approach to quantify the spatial extents of brine leakage risk through P&A wells. This approach also considers the substantial uncertainty due to varying wellbore hydraulic properties along the leakage pathway. Because the area where brine leakage through P&A wells could occur is likely expansive in spatial extent, the presented methodology incorporates a way to determine how risk evolves as a function of lag distance from the injection well, thus the term "risk maps." It also integrates time as a dimension in the methodology, allowing for risk assessors and other stakeholders to determine not only the spatial but also the temporal evolution of risk. The concept of spatially distributed risk has been applied in a number of different disciplines such as the spread of invasive species (e.g. Hulme, 2009; Venette et al., 2010), the spread of diseases (e.g. Moffett et al., 2007; Boender et al., 2007), and for natural hazards (e.g. Gaull et al., 1990; Douglas, 2007). The presented method of generating risk maps is flexible in techniques used (numerical versus analytical) and is computationally very efficient, stemming from probability theory rather than computationally expensive Monte Carlo simulations. While advances in quasi-Monte Carlo and Latin Hypercube Sampling have recently been made in the realm of CO_2 storage to greatly reduce computational demands in some applications (e.g. Hou et al., 2016; Pawar et al., 2016), the computational efficiency of our approach allows for higher fidelity models and more complexity to be integrated into the risk assessment framework. Lastly, although we present the probabilistic methodology applied to the assessment of brine leakage via P&A wells, the same set of steps in the risk map procedure may be used to assess both CO_2 leakage and brine leakage via open-borehole wells. It may also be applied to assess leakage where reservoir conditions prior to injection are not in equilibrium.

2. Construction of risk maps: methodology

Fig. 1b shows the conceptual model used to generate risk maps for brine leakage via P&A wells. CO_2 is injected beneath a deep, low permeability caprock layer into an injection reservoir which leaky wells may penetrate. In the region between Tier 1 and Tier 2 AoR, the two greatest sources of uncertainty are assumed to be the unknown location of the leaky well and the leaky well's permeability, which can range over several orders of magnitudes. The first step in the calculation of a risk map used to define Tier 3 AoR is to determine leakage at a discrete number of lag distances between Tiers 1 and 2. In Fig. 1b, this is shown as example leaky wells labeled W_1, W_2, and W_3. These can be thought of as the "sampled" leaky well locations, where the calculations are performed. While this method can be applied for complex anisotropic and heterogeneous systems, if the assumption of homogeneous, isotropic layers is made (i.e. that the USDW, thief and caprock zones, and injection reservoir do not contain significant heterogeneity below the strata-scale) then calculations only need to be performed along one direction, where the leaky well location increases as a function of distance from the injection well. With these assumptions, a radial extrapolation can then be performed in the x-y plane. In the example shown in Fig. 1b, leakage at well W_1 is equivalent to leakage at well W_4. Then, leakage at well W_5 can be interpolated from wells W_1 and W_2. As described below, leakage amounts at the discrete leaky well locations (e.g. W_1, W_2, W_3 in Fig. 1) are used to quantify the uncertainty of P&A leakage as a function of distance from the injection well. Note that the topic of well interference where multiple wells may be leaking simultaneously is not considered here, and is the topic of future work.

2.1. Simulations

As shown in Fig. 2, the first step of the risk map methodology begins with the calculation of brine leakage through P&A wells as a function of time and at increasing distances away from the injection. This can be solved numerically, or if density differences are neglected, with analytical methods. Once discrete lag locations are selected, brine leakage is calculated over a range of effective well permeabilities, where the permeability of the well does not vary in the vertical direction. Unlike computationally expensive Monte Carlo simulations that would randomly sample hundreds or more of effective well permeabilities for each location, the risk map methodology only requires data for a small and discrete number of effective well permeability values for each location. For example, a typical risk map calculation with simple homogenous and isotropic layers would only require on the order of tens of leaky well locations and tens of permeability values, typically with less than 100 total simulations. As further described in Section 2.3, a probabilistic theory approach other than Monte Carlo simulations is used here to alleviate the need for additional computations in this step.

From Step 1, a number of output metrics can be compared. To assess the risk to potable drinking water resources, two practical parameters for analysis are the volume and the area of groundwater impacted by leaky wells. For sake of terminology, hereafter we will refer to the volume or area of impacted water as the "parameter of