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Risk-based area of review estimation in overpressured reservoirs to support injection well storage facility permit requirements for CO_2 storage projects

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Abstract

In the United States, the U.S. Environmental Protection Agency (EPA) regulates the construction, operation, permitting, and closure of injection wells used to place fluids underground for storage. In 2018, EPA approved an application from the state of North Dakota to implement an Underground Injection Control Program for Class VI (CO_2 storage) injection wells located in most areas within the state. The primary regulatory permit for a storage project in North Dakota is the storage facility permit, a major technical component of which is the delineation of the area of review (AOR). The AOR is defined as the region surrounding the storage project where underground sources of drinking water (USDWs) may be endangered by the injection activity. In North Dakota, and elsewhere around the United States, some storage reservoirs are already overpressured relative to overlying aquifers and thus subject to potential vertical formation fluid migration from the storage reservoir to the lowermost USDW, even prior to implementing the planned storage project. Consequently, applying AOR delineation methods that assume hydrostatic equilibrium to these geological situations essentially results in an infinite AOR, which makes regulatory compliance infeasible. This paper summarizes the regulatory environment in North Dakota, briefly illustrates the authors' published risk-based approach to AOR delineation in overpressured reservoirs, and provides a case study example from the Project Tundra commercial CO_2 capture and storage project that was recently permitted in North Dakota, USA.

Keywords: CO_2 storage; area of review; risk-based approach; North Dakota; USA; overpressure

1. Introduction

In the United States, the U.S. Environmental Protection Agency (EPA) regulates the construction, operation, permitting, and closure of injection wells used to place fluids underground for storage. The federal regulations for the Underground Injection Control (UIC) Program are found in Title 40 of the Code of Federal Regulations (CFR) (https://www.ecfr.gov/current/title-40). The Safe Drinking Water Act (SDWA) establishes requirements and provisions for the UIC Program [1]. Regulations for carbon capture and storage (CCS) fall under the Class VI Rule of the UIC Program – Wells Used for Geologic Sequestration of CO_2. The Class VI Rule requirements are designed

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to protect underground sources of drinking water (USDWs). On April 24, 2018, EPA approved an application from the state of North Dakota under the SDWA to implement a UIC Program for Class VI injection wells located within the state, except within "Indian lands." Therefore, in the state of North Dakota, Class VI injection wells and the associated storage facility permit for the storage project are managed under the North Dakota Century Code (NDCC) (Chapter 38-22, Carbon Dioxide Underground Storage) and the North Dakota Administrative Code (NDAC) (Chapter 43-05-01, Geologic Storage of Carbon Dioxide).

In North Dakota, a CO_2 storage project (hereafter "storage project") comprises a storage facility (an area on the ground surface, defined by the operator and/or regulatory agency, which is occupied by CO_2 injection facilities and where storage activities, including monitoring, take place) and a storage complex (a subsurface geologic system comprising a storage unit and primary and possibly secondary seal(s), which extend laterally to the defined limits of the CO_2 storage operation or operations). The primary regulatory permit for a storage project in North Dakota is the storage facility permit, a major technical component of which is the delineation of the area of review (AOR). The AOR is defined as the region surrounding the storage project where USDWs may be endangered by the injection activity (40 CFR 146.84 and NDAC Section 43-05-01-05.1, Area of Review and Corrective Action).

EPA guidance [2] for delineation of the AOR includes several computational methods for estimating the pressure buildup in the storage reservoir in response to CO_2 injection and the resultant areal extent of pressure buildup above a "critical pressure" that could potentially drive higher-salinity formation fluids up an open conduit, from the storage reservoir to the lowermost USDW. The methods described by EPA for estimating the AOR under the Class VI Rule were developed assuming that the storage reservoirs would be in hydrostatic equilibrium with overlying aquifers. However, in the state of North Dakota, and elsewhere around the United States, some storage reservoirs are already overpressured relative to overlying aquifers and thus subject to potential vertical formation fluid migration from the storage reservoir to the lowermost USDW, even prior to implementing the planned storage project. Consequently, applying the assumed-equilibrium methods of EPA to these geological situations essentially results in an infinite AOR, which makes regulatory compliance infeasible.

The mere presence of a permeable pathway between saline fluids and a USDW is not sufficient to pose a risk of contamination to the USDW. Thus, leakage of brine is a concern for drinking water resources only if the pressure increase due to injection is large enough to drive brine from the injection formation to the elevation of the lowermost USDW. In the approach presented in [3], "risk-based" refers to quantifying the potential impacts to the USDW resulting from the flow of brine from the storage reservoir to the USDW under different input assumptions, accounting for the site-specific properties of the storage reservoir, leaky wellbore, and aquifer. This risk-based approach contrasts with the default EPA assumptions, which presume that all locations at which the reservoir pressure is greater than the critical pressure pose a potential leakage risk and must therefore be included in the AOR. The remainder of this paper summarizes the risk-based approach to AOR delineation of [3] and provides a case study example from a commercial CO_2 capture and storage project that was recently permitted in the state of North Dakota, USA.

2. Methods

After knowledge of an overpressured condition is established (e.g., using EPA methods [2]), the workflow developed for delineating AOR in overpressured CO_2 storage reservoirs consists of four parts. First, the potential leakage from the reservoir to the lowest USDW is estimated for a hypothetical leaky wellbore under an ensemble of pressure scenarios within a simplified geologic model, including one case where no CO_2 is injected (noninjection case or base case). Second, the relationship between change in reservoir pressure and incremental leakage (i.e., leakage relative to the noninjection case) is derived using a semianalytical model to develop a pressure leakage curve. Third, the reservoir pressure map from compositional simulation of CO_2 injection is used with the pressure leakage curve to develop a map of estimated leakage along hypothetical leaky wells across the simulation area. Fourth, the maximum amount of leakage allowed into the USDW over the course of the project is used as a threshold to delineate the AOR on the estimated leakage map. These four steps are summarized below and detailed in [3] for an example 180,000-tonne-per-year CO_2 injection scenario described therein. Table 1 shows the stratigraphy of the example scenario.

Table 1. Example scenario stratigraphy [3].

Hydrostratigraphic Unit	Depth, m	Thickness, m
Overlying Units		473
Aquifer 3 – USDW	473	88
Aquitard 2	562	900
Aquifer 2 – Thief Zone	1462	142
Aquitard 1	1604	334
Aquifer 1 – Storage Reservoir	1938	96

Part (1). To estimate potential brine leakage rates caused by injection of CO_2, the software tool ASLMA (Analytical Solution for Leakage in Multilayered Aquifers) is used to establish preinjection non-hydrostatic-equilibrium conditions among two or more aquifers [4–7]. Following the computational framework established by [6,7], a distinction is made between vertical fluid migration along a hypothetical leaky well connecting the storage reservoir and the lowest USDW that would occur from an overpressured reservoir under a baseline scenario with no CO_2 injection (noninjection case) versus other cases with CO_2 injection. Potential leakage rates from the baseline scenario are subtracted from potential leakage rates from a scenario under which CO_2 injection is occurring to derive the incremental leakage solely attributable to the increased pressure buildup from CO_2 injection.

Part (2). An ensemble of ASLMA model cases is run for a given CO_2 injection scenario. For each injection case, the hypothetical leaky wellbore is placed a different distance from the injection well, which results in a pair of values for each case: cumulative pressure buildup in the storage reservoir and cumulative incremental leakage into overlying aquifers. These results are plotted (Fig. 1a) to derive an experimental curve that shows the relationship between pressure buildup in the storage reservoir and incremental leakage. Fig. 1b shows two curves, which reflect the effect of an intermediary saline aquifer between the storage reservoir and USDW. This intermediary saline aquifer is designated as a "thief zone" because vertically migrating fluid is lost to this aquifer, thereby lowering the vertical hydraulic head gradient with increasing vertical location in a leaky wellbore and thereby decreasing, or nearly eliminating, vertical fluid migration above this aquifer to the USDW. By analogy, the thief zone phenomenon was described by Nordbotten et al.[8] as an "elevator model," where an elevator on the ground floor is full of people, some of whom get off at various floors as the elevator moves up, with the end result that only very few people ride all the way to the top floor.

Part (3). Although the ASLMA model is effective at estimating flow along a leaky wellbore, the semianalytical solution assumes a homogeneous and isotropic storage reservoir such that the overall pressure field generated by CO_2 injection into a single well will be radially symmetrical and will not reflect the heterogeneity of the reservoir. Compositional reservoir simulation of a more complex geocellular model is performed as best practice for CO_2 storage projects to predict the distribution of CO_2 and pressure in the subsurface over the life of the project. To estimate the amount of potential leakage more accurately at a given location (assuming a leaky wellbore or other leakage pathway exists), the derived curve(s) generated in the previous step are mapped onto the cumulative pressure buildup from the compositional simulation (Fig. 2) to produce one or more potential leakage maps (Fig. 3).

Part (4). The map(s) produced in the previous step show the amount of leakage that could occur within the study area if a leakage pathway existed. In contrast to the simpler methods of EPA [2], which for an overpressured reservoir would delineate an AOR over the entire project extent (model area), the result of this risk-based approach produces a map of potential leakage that more accurately reflects the true incremental leakage risk, given the planned CO_2 injection scenario, storage complex, and wellbore properties (Fig. 3). An AOR can be delineated by applying a threshold to the map of potential leakage values.

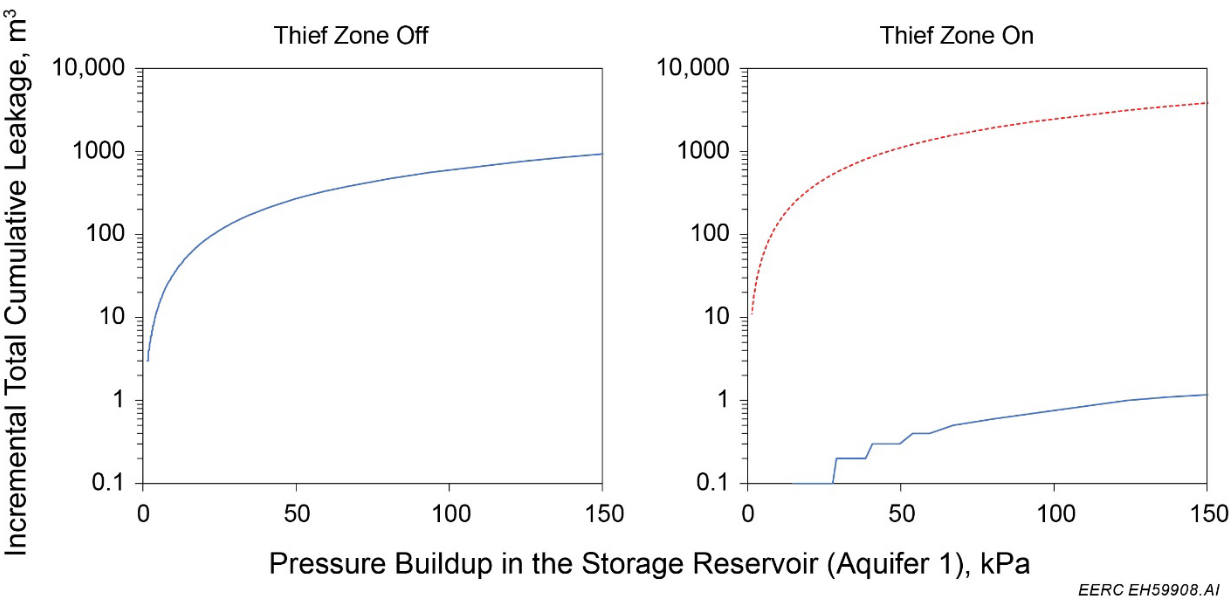

Fig. 1. An example showing the relationship between pressure buildup in the storage reservoir (x-axis, kPa) and incremental total cumulative leakage (y-axis, m^3) for Aquifer 3 (USDW, blue line) and Aquifer 2 (thief zone, red dashed line, right-hand panel only). The left-hand panel shows the scenario where the leaky wellbore is closed to Aquifer 2, and the right-hand panel shows the scenario where the leaky wellbore is open to Aquifer 2 (from Burton-Kelly et al. [3]).

2.1 Sensitivity

The delineated AOR using the above method is sensitive to several model parameters related to the geology and hydrogeology of the storage complex, which are generally obtained through routine site characterization activities during storage project development. In addition, the delineated AOR is sensitive to three important user-defined parameters: the effective permeability of the hypothetical leakage pathway, the presence or absence of a potential thief zone between the storage reservoir and the lowest USDW, and the potential leakage threshold used to delineate the AOR.

Fig. 3 shows the effect of a range of different leaky wellbore permeabilities on the potential leakage map. In accordance with Darcy's law, as permeability along a hypothetical leakage pathway is increased, so is flow along that pathway. According to data from Cary [9], shown in Fig. 4, permeability values used for the maps in Fig. 3 (approximately 10^{-16} to 10^{-8} m^2) are many orders of magnitude higher than the most likely permeability values of outside casing completion failures or degradation of the annulus (approximately 10^{-24} to 10^{-16} m^2). Consequently, Fig. 3a–3c represent higher-than-likely (conservative) potential leakage maps.

A porous and permeable geologic interval between the CO_2 storage reservoir and the lowest USDW (e.g., Table 1, Aquifer 2) may act as a thief zone for reservoir fluid migrating along a leakage pathway if the vertical leakage pathway is hydraulically connected to the interval and the interval is in hydrostatic equilibrium or underpressured relative to the storage reservoir during injection [5,8,10,11]. A thief zone can reduce the amount of storage reservoir fluid that reaches the lowest USDW and attenuate the size of the AOR. For the example scenario, Fig. 1a shows leakage into the USDW when no thief zone is present, and Fig. 1b shows leakage into the USDW and the thief zone when it is present. At 100 kPa buildup over the injection period, the presence of a thief zone in this scenario reduces flow into the USDW from ~500 m^3 (thief zone off) to <1 m^3 (thief zone on) — a 100% reduction in the incremental leakage.

The final step of the risk-based AOR delineation is to draw a boundary around the potential leakage map using a potential leakage threshold. While a no-impact threshold would be the most conservative AOR delineation (i.e., the boundary beyond which the potential leakage is zero), alternative thresholds have been presented in the literature [12,13]. The degree of impact a certain volume of reservoir fluid will have on a selected USDW is dependent

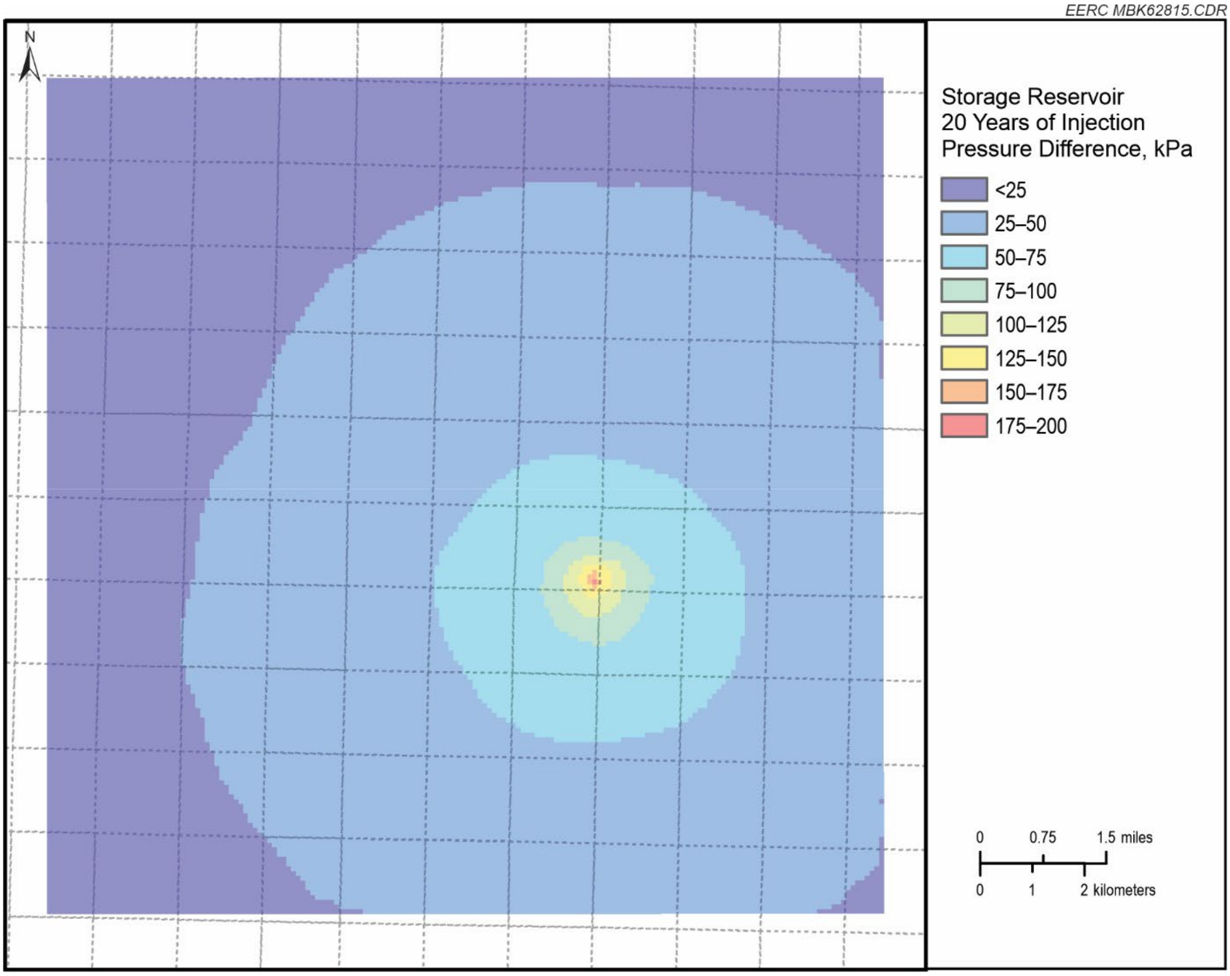

Figure 2. For the scenario in Burton-Kelly et al. [3], the average pressure increase within the storage reservoir at the end of a simulated 20-year CO_2 injection operation. Grid is 1.6-km Public Land Survey System sections.

on site-specific data including the chemistry of each fluid involved, recharge rate of the USDW, potential leakage rate out of the reservoir, volume of the USDW, number of water wells and annual drawdown, and other factors. As with the other user-defined parameters discussed, data can be used to guide conversations with regulators and stakeholders when defining a site-appropriate threshold to use for delineating the risk-based AOR.

3. Application to a commercial storage project

The risk-based approach described in Burton-Kelly et al. [3] was used to delineate the AOR for the "Tundra Secure Geologic Storage" (Project Tundra) North Dakota [USA] CO_2 Storage Facility Permit Application submitted in September 2021 [14]. The storage facility permit was approved by the North Dakota Industrial Commission in January 2022 for up to 4 million tonnes annually [15].

Fig. 5 shows the stratigraphy of the Project Tundra storage facility, which includes the Fox Hills Formation (lowest USDW), Inyan Kara Formation (potential thief zone), and Broom Creek and Deadwood Formation target storage reservoirs. Because the Deadwood Formation is sufficiently underpressured relative to the Fox Hills, EPA methods [2] were applied to delineate the AOR for this storage reservoir. On the other hand, the Broom Creek Formation is overpressured relative to the Fox Hills, requiring the use of the risk-based method summarized here to delineate its AOR.

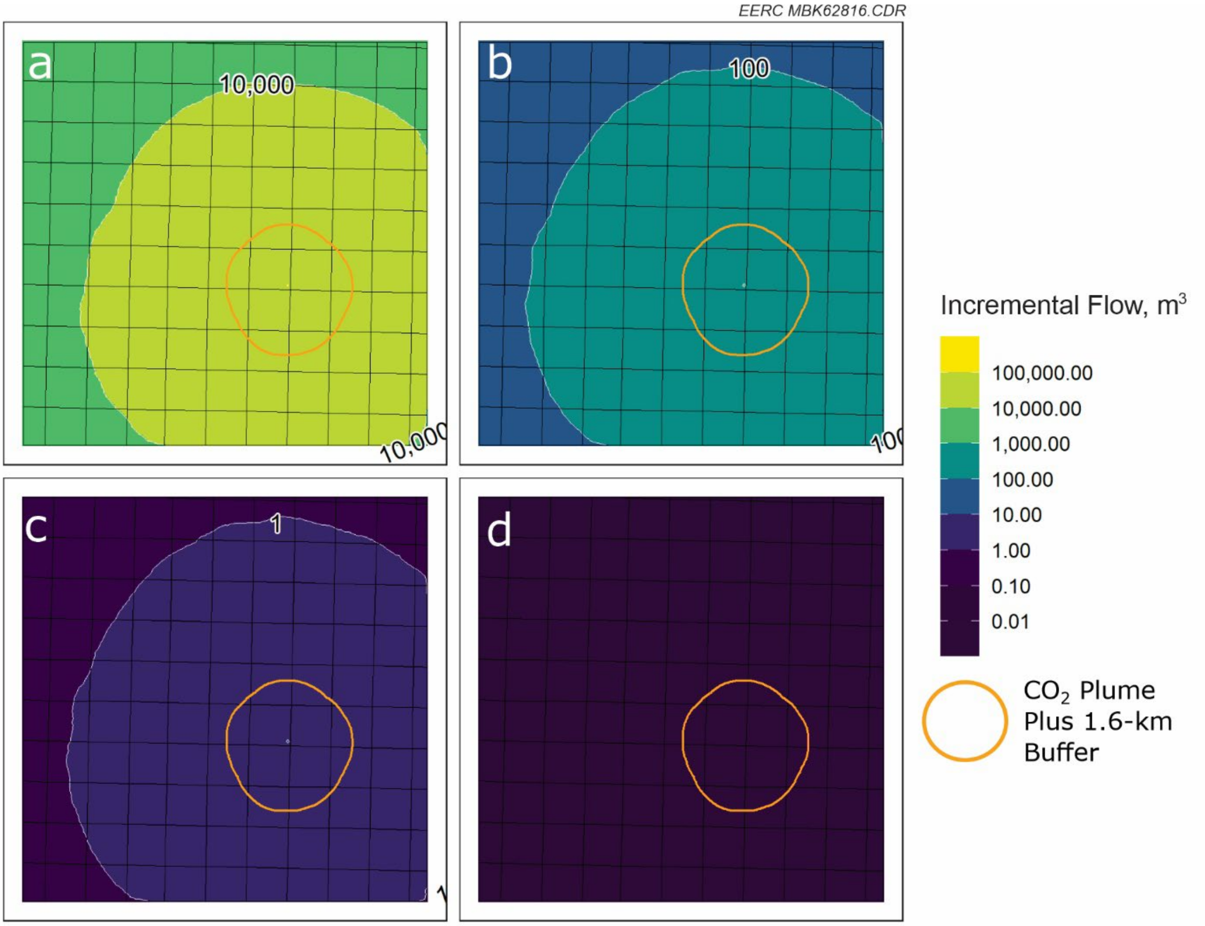

Fig. 3. Example maps from the scenario described in Burton-Kelly et al. [3] showing the response of potential leakage from reservoir to USDW along hypothetical wellbores with different effective permeabilities: a) 10^{-8} m^2 (pseudo-open conduit); b) 10^{-10} m^2 [3]; c) 10^{-12} m^2 [9], high-end); d) 10^{-16} m^2 [9], Alberta). Grid is 1.6 km Public Land Survey System sections.

The Broom Creek Formation is estimated to be overpressured relative to the Fox Hills Formation across the area covered by the Project Tundra compositional simulation model (~1500 km^2); i.e., the AOR using EPA methods would be at least that extensive, essentially "infinite." Oil and gas development is uncommon in this area, so only 12 legacy oil and gas wells penetrate the reservoir within the model extent (Fig. 7).

A complete description of the risk-based AOR method application and parameters used for Project Tundra is included in the storage facility permit application [14]; key supporting data are shown in Figs. 6, 7, and 8. This scenario used a hypothetical leaky wellbore permeability value of 10^{-16} m^2, assumed no thief zone access by the hypothetical leaky wellbore, and used a potential leakage threshold of 1 m^3 to delineate the AOR. Because the area where estimated leakage volume over the injection period below 1 m^3 is smaller than the storage facility area (at minimum, the area of the stabilized CO_2 plume plus a small buffer) (Fig. 8), a regulatory buffer of 1.6 km was added to the storage facility area to delineate the AOR.

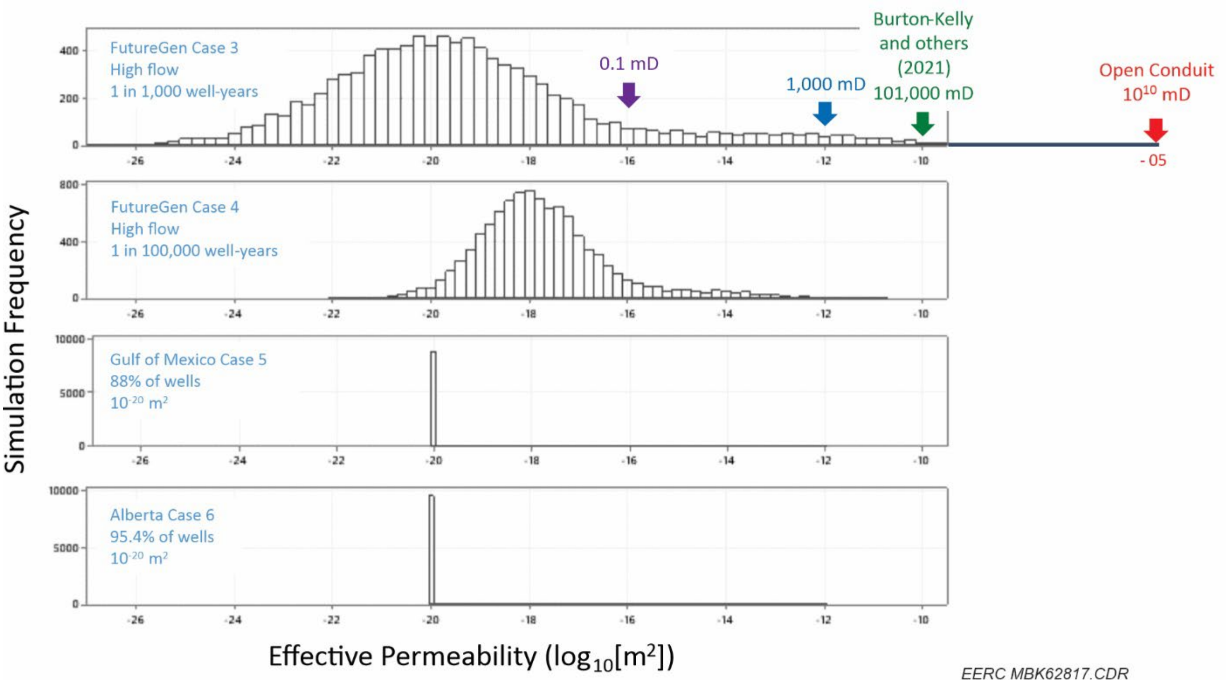

Fig. 4. Histograms describing the expected frequency of leaky wellbore effective permeabilities under different scenarios shown in Fig. 3. Constructed from data presented by Carey [9] (modified from North Dakota Industrial Commission [14]).

Four safety factors are given in the storage facility permit application [14] to illustrate that the leakage potential described by this method is a conservatively high estimate:

- The hypothetical leaky wellbore permeability (10^{-16} m^2) used to estimate leakage is orders of magnitude higher (more conservative) than known and estimated values in the literature (approximately 10^{-24} to 10^{-16} m^2).
- The potential leakage maps assume no communication between the hypothetical leaky wellbore and the potential thief zone (Inyan Kara Formation).
- Relatively few legacy oil and gas wells (the most probable potential leakage pathways) are present in the Project Tundra area.
- Because of the continued overpressured nature of the Broom Creek, it is unlikely that vertical leakage pathways out of the reservoir exist. Stated differently, the presence of an overpressured system is evidence of good sealing formations with no leakage; otherwise, the system would have equilibrated over millions of years and would not be overpressured [7].

The risk-based AOR used in the storage facility permit application [14] extends only 1.6 km beyond the area projected by the stabilized CO_2 plume (storage facility area) and contains only three legacy oil and gas wells. Therefore, the risk-based method reduced the AOR from at least 1500 km^2 to 160 km^2 for the storage project and allowed for a more tractable AOR and associated monitoring, reporting, and verification (MRV) plan.

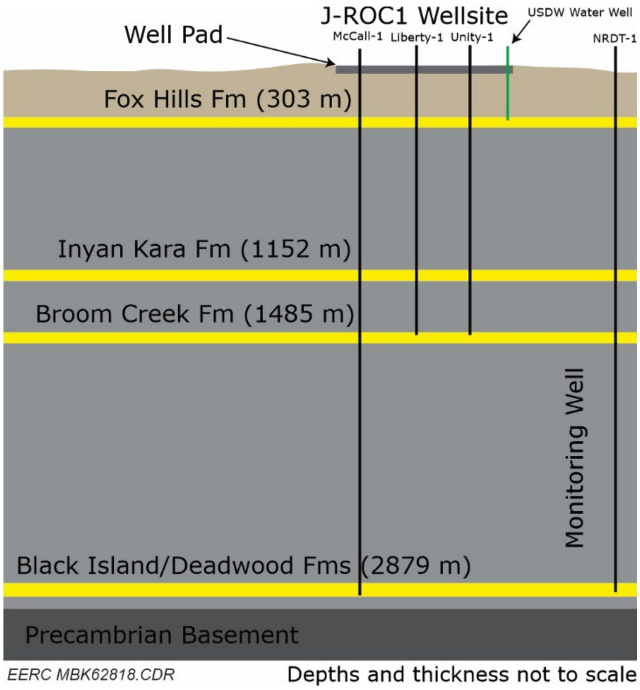

Fig. 5. Monitoring schematic (not to scale) includes the location of the Broom Creek injectors (Liberty-1 [J-ROC1, North Dakota Industrial Commission File No. 37672] and Unity-1 [proposed]), the Deadwood injector (McCall-1 [proposed]), and the monitoring well NRDT-1 (proposed) (modified from North Dakota Industrial Commission [14]).

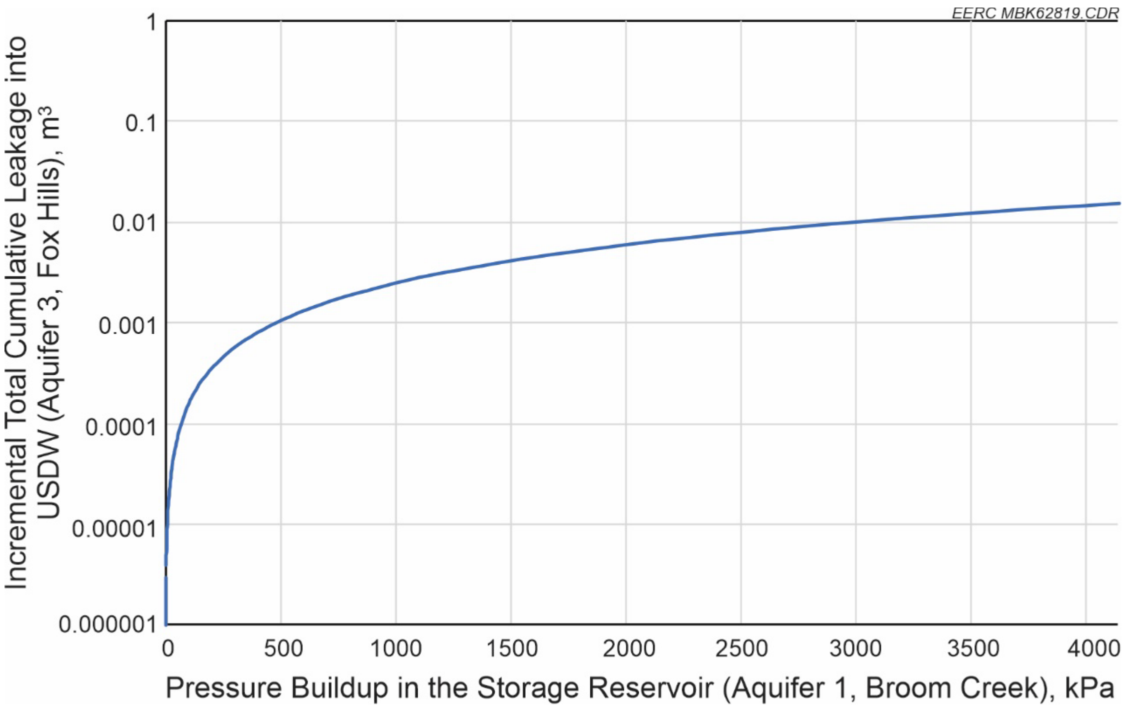

Fig. 6. For the Project Tundra scenario [14], the relationship between pressure buildup (x-axis, psi) in the storage reservoir (Broom Creek) and incremental total cumulative leakage (y-axis, m3) for the USDW (Fox Hills). In this scenario, the leaky wellbore is closed to the potential thief zone (Inyan Kara) (modified from North Dakota Industrial Commission [14]).

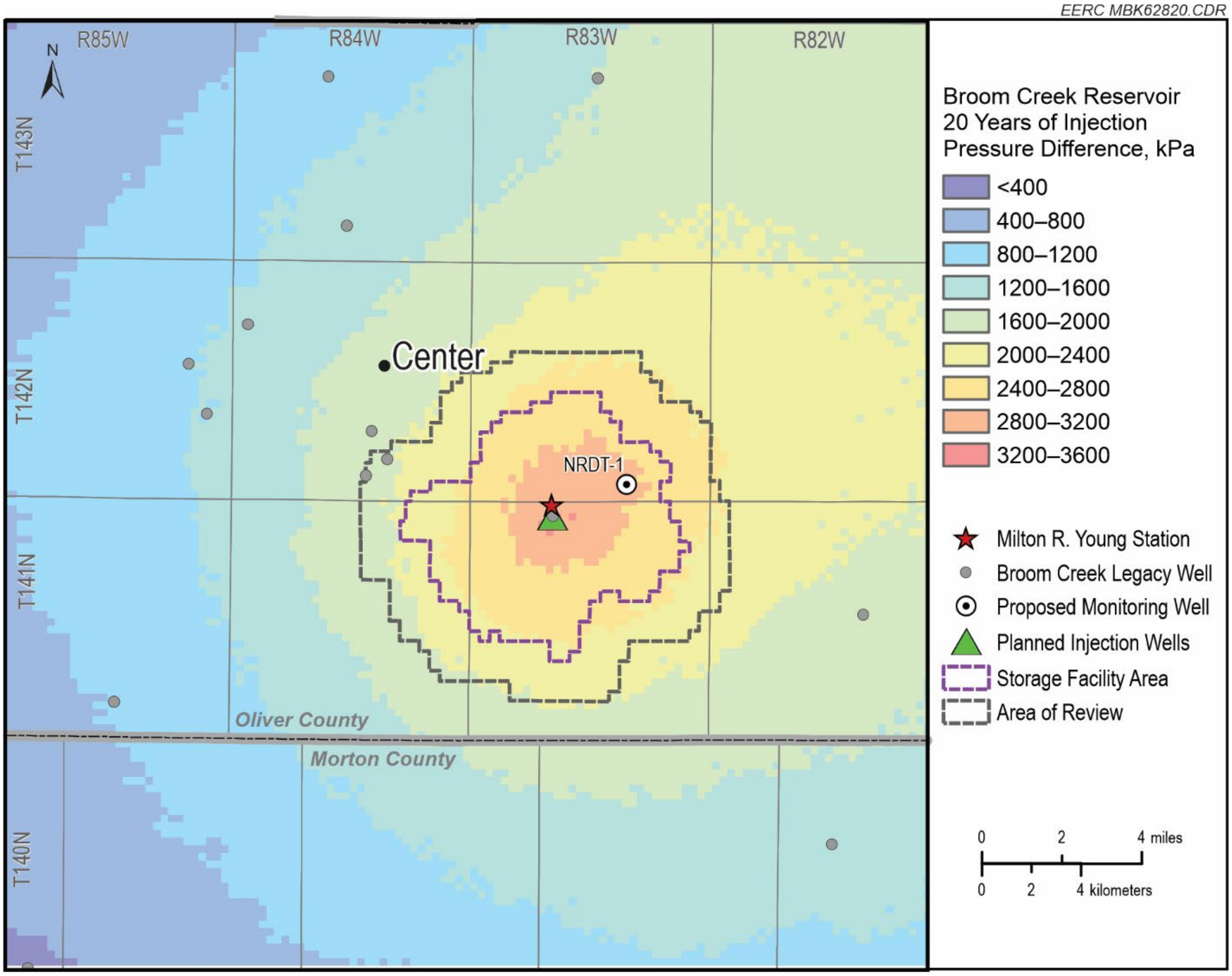

Fig. 7. For the Project Tundra scenario [14], the average pressure increase within the Broom Creek Formation at the end of a simulated 20-year CO_2 injection operation (modified from North Dakota Industrial Commission [14]).

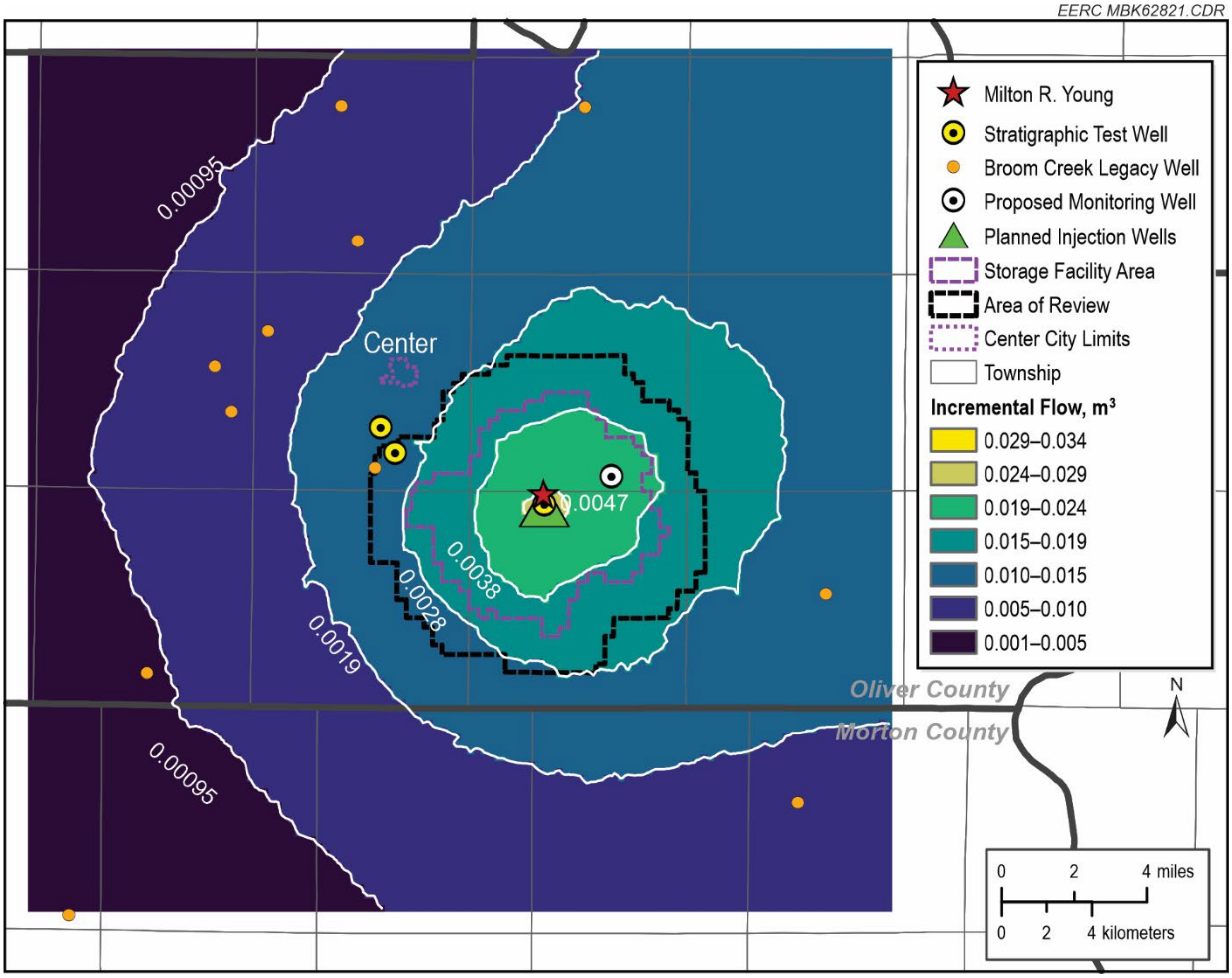

Fig. 8. From the Project Tundra scenario [14], an incremental leakage map at the end of 20 years of CO_2 injection for the scenario where the leaky wellbore is closed to Aquifer 2 (thief zone). The dotted black polygon denotes the approximate areal extent of the CO_2 plume in the storage reservoir (storage facility area) plus a 1.6-kilometer buffer at the end of 20 years of CO_2 injection as determined using a compositional simulator and the site-specific geologic model (modified from North Dakota Industrial Commission [14]).

4. Discussion and conclusions

This paper summarizes the regulatory requirements for delineating an AOR in North Dakota, USA, challenges with using established AOR delineation methods and a solution using a previously published risk-based AOR delineation method [3], and briefly describes the successful application of the risk-based method to a commercial storage facility permit [14].

Although the risk-based method has user-defined parameters, these parameters were conservatively applied at the Project Tundra site. Although a potential thief zone (Inyan Kara Formation) exists, no connection between the thief zone and potential leakage pathways was included in the final model. At other sites with larger CO_2 injection rates or higher relative overpressure in the reservoir, the assumption of a thief zone, if present, could be used to reduce the size of the AOR. At Project Tundra, the entire Broom Creek is overpressured relative to the Fox Hills, but AORs delineated at other, underpressured sites using the EPA methods, may still be quite large. The risk-based approach has not yet been applied to a site that has a reservoir in hydrostatic equilibrium with, or is underpressured relative to, the lowest USDW, but similar methods (potential leakage map, threshold, and thief zone considerations) could be applied to reduce the size of the AOR—again, in discussion with regulators and stakeholders.

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