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Assessment of the Area of Review and Leakage Impact for Site 7 using the NRAP-IAM-CCS Tool, Northern Michigan Basin-CarbonSAFE Phase 1 Pre-Feasibility Study

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Executive Summary

U.S. Environmental Protection Agency's (EPA's) Class VI regulations require owners or operators of carbon storage projects to determine an Area of Review (AoR) representative of project risk to underground sources of drinking water (USDWs). The AoR is an estimate of the project footprint and is used to develop monitoring plans to ensure protection of USDWs. In this syudy, the NRAP-IAM-CS software tool was applied to estimate the AoR and the leakage potential of legacy wells located within the AoR to impact groundwater quality at a carbon storage screening site for the NMB-CS, Phase 1 project. The NRAP-IAM-CS is a science-based toolset developed by the U.S. Department of Energy for quantitative risk assessment of geologic sequestration of carbon dioxide (CO_2) (Pawar et al., 2016). The toolset adopts a stochastic approach in which predictions include site uncertainties using storage reservoir, leakage scenario, and shallow groundwater impact reduced order models (ROMs).

Risk-based analysis done using the NRAP-IAM-CS yielded an AoR that was comparable to estimates defined by the critical pressure needed move fluid from the reservoir to the overlying USDW through an open wellbore. The risk-based AoR was slightly smaller than that based on the critical pressure (234 km^2 compared to 269 km^2), because small fluxes did not impact groundwater quality. Leakage from two legacy wells located within the AoR should not impact groundwater quality over the 30-year injection period. Legacy Well 1 penetrates the simulated CO_2 plume and would require a permeability of 5×10^{-12} m^2 (~5 Darcy) to impact groundwater quality after about 20 years of injection. Legacy Well 2 falls outside of the CO_2 plume footprint, where reservoir pressures are too small to generate large enough leakage flux to change groundwater quality even with well permeabilities as high as 5×10^{-11} m^2 (~50 Darcy).

This work represents one of the first applications of the NRAP toolset for the screening of potential CO_2 storage sites. The toolset provides a risk-based method of evaluating the AoR and the impact of CO_2 or brine leakage through legacy wells. The following recommendations will strengthen the use of probabilistic assessments for site selection and permitting of Class VI CO_2 injection wells.

- The AoR calculations would be more robust if the toolset sampled pressures and CO_2 saturations from many horizontal planes within the reservoir. This is particularly important for stacked storage reservoirs where geologic heterogeneity will control pressure and CO_2 gas saturations. A ROM specific to the site reservoir would further improve a probabilistic assessment of the AoR.
- USDW ROMs need to be calibrated against the high leakage fluxes generated from open wellbores. All USDW ROMs were calculated for cemented wellbores, which assumes leakage is controlled by the permeability of a damaged cemented zone within the well's casing-borehole annulus; this results in a much lower leakage rate than the rate for a hypothetical open (uncemented) well.
- The NRAP-IAM-CS currently has one option for a UDSW ROM, the unconfined carbonate aquifer ROM, which simulates CO_2 leaks to the aquifer and to the atmosphere. NRAP is updating the toolset with a confined alluvium aquifer in which all CO_2 leaked will stay within the aquifer system.

- Any AoR and groundwater impact assessments should be made over the injection and post-injection periods. This is important for AoR assessments to demonstrate that the CO_2 plume has stabilized and that the reservoir pressures have returned to pre-injection levels. Post-injection assessments of CO_2 leakage are important because buoyancy will continue to move the CO_2 along leakage pathways. Conclusions in this study were based only on the injection period.

1.0 Introduction

U.S. Environmental Protection Agency's (EPA's) Class VI regulations require owners or operators of carbon storage projects to determine an Area of Review (AoR) representative of project risk to underground sources of drinking water (USDWs). The AoR is an estimate of the region potentially impacted by the CO_2 injection and is used to develop monitoring plans to ensure protection of USDWs. Estimates of the AoR need to account for the physical and chemical properties of all phases of the injected carbon dioxide stream, are based on available site characterization, monitoring, and operational data, and are to be made with computational models (40 CFR 146.84). Permitting also requires an understanding of the leakage risks from leakage pathways, such as wells and/or faults connecting the storage reservoir with any overlying underground sources of drinking water (USDWs). Environmental Protection Agency's (EPA) Class VI Rule requires groundwater geochemistry monitoring above the lowermost confining zone overlying the storage reservoir to detect changes in aqueous geochemistry resulting from fluid leakage out of the injection zone [40CFR 146.90(d)] (U.S. Environmental Protection Agency, 2012).

The NRAP-IAM-CS is a science-based toolset developed by the U.S. Department of Energy (DOE) for quantitative risk assessment of geologic sequestration of carbon dioxide (CO_2) (Pawar et al., 2016). The toolset adopts a stochastic approach in which predictions address uncertainties in storage reservoirs, leakage scenarios, and shallow groundwater impacts. It is derived from detailed physics and chemistry simulation results that are used to train more computationally efficient models, referred to here as reduced-order models (ROMs), for each component of the system. These tools can be used to help regulators and operators define the AoR and better understand the expected sizes and longevity of changes in water quality caused by CO_2 and brine leakage from a storage reservoir into drinking water aquifers.

The EPA defines the AoR as the maximum extent of the separate-phase CO_2 plume or the pressure front over the lifetime of the project as measured by numerical model simulations. Generally, the maximum pressure front defines the AoR because it is larger than the supercritical CO_2 plume. The AoR is often delineated by the area within which the maximum pressure buildup is above that needed to move the reservoir fluids through an open wellbore (U.S. EPA, 2013). This approach is conservative and assumes that any leakage will impact USDW quality regardless of the magnitude and duration of the leak.

Wells are considered to be high-risk pathways for fluid leakage from geologic CO_2 storage reservoirs because breaches in this engineered system have the potential to connect the reservoir to drinking water resources and the atmosphere. Well integrity is often difficult to measure due to a lack of well data such as permeability of the annular material between the outermost well casing and the borehole wall, a potential avenue for upward fluid migration. For such cases, the NRAP-IAM-CS can be used to evaluate the probability of CO_2 and brine leakage and its impact on drinking water quality from known well locations using default permeability distributions based on oil and gas wells in the Alberta and Gulf Coast basins and the greenfield FutureGen Site.

1.1.1 Organization

This section discusses the use of the NRAP-IAM-CS model to estimate the Area of Review (AoR) and the impact of leakage through legacy wells to overlying drinking waters for Site 7, one of two example St.

Peter Sandstone saline reservoir storage sites evaluated as part of the Michigan, CarbonSafe Phase 1 project[a]. The section is organized into the following sections:

- Section 1.1.2 presents a risk-based AoR calculated using the NRAP-IAM-CS tool based on leakage impacts to groundwater quality in a shallow drinking water aquifer overlying the storage reservoir from hypothetical open (uncemented) wells.
- Section 1.1.3 presents an AoR calculated using the U.S. EPA critical pressure method;
- Section 1.1.4 presents an assessment of leakage impacts to groundwater quality in a shallow drinking water aquifer overlying the storage reservoir from known legacy wells in the AoR calculated using the NRAP-IAM-CS tool.

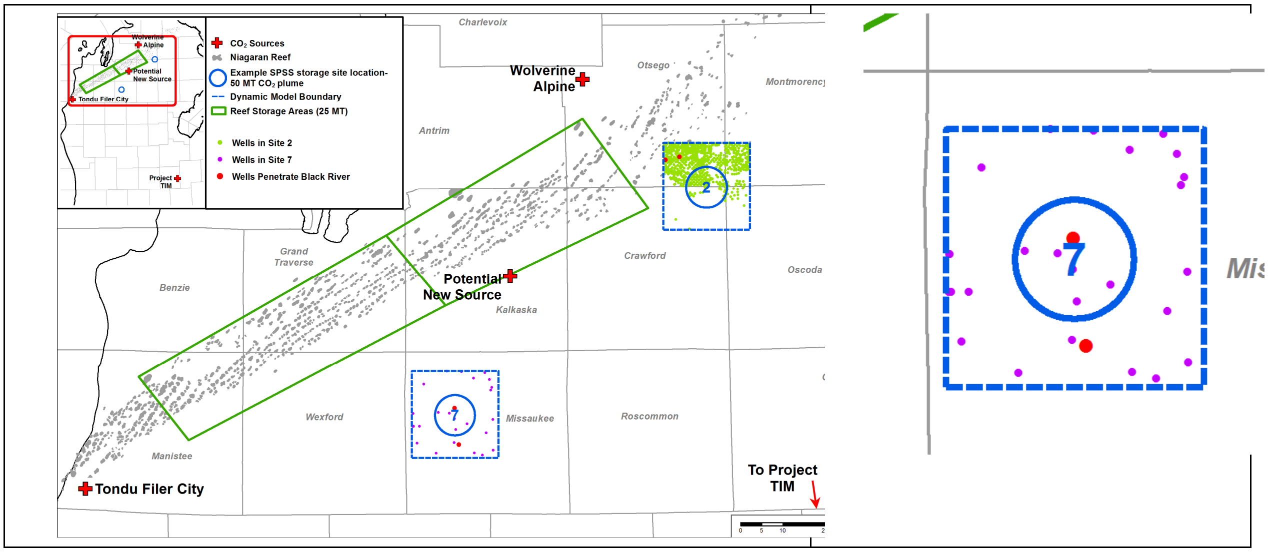

Figure 1. Location of Sites 2 and 7, two St. Peter Sandstone (saline reservoir) CO_2 storage site locations considered in the Michigan, CarbonSafe Phase 1 project, the Niagaran reefs proposed for associated storage (each group of reefs within a green rectangle has a storage capacity of 25 MMT). Only Site 7 is evaluated in the AoR analysis in this section. Dashed blue line indicates extent of CMG-GEM reservoir model area; solid blue circles indicate approximate extent of modeled 50 MMT CO_2 plume in the St. Peter Sandstone. Two legacy wells that penetrate the St. Peter Sandstone are present in the Site 7 model area and are shown as solid red circles in the Site 7 box (enlarged in the righthand image). Purple circles are wells that do not reach the St. Peter Sandstone.

1.1.2 Risk-Based Approach for Determining the Area of Review (AoR)

The risk-based AoR calculated using the NRAP-IAM-CS is the area where CO_2 or brine leakage from a hypothetical open (i.e., uncemented) well connecting the storage reservoir to the shallow drinking water aquifer would cause drinking water quality to change outside "no-net degradation" thresholds. The "no-net-degradation" thresholds are pH = 6.5 and total dissolved solids (TDS) = 500 ppm. The boundaries of the AoR were calculated by calculating pH and TDS in the shallow drinking water aquifer at hypothetical open wells located at increasing distances to the east, west, north, and south of the injection wells until no impact to the aquifer was observed. CO_2 or brine leakage at a location beyond the AoR boundary is possible, but the leaked mass is too small to cause pH or TDS to change outside their threshold values

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[a] Site 2 was not considered because the simulation results for that site could not be converted to the format needed for the NRAP-IAM-CS.

1.1.2.1 Description of NRAP-IAM-CS and Assumptions

The NRAP-IAM-CS is an integrated system model developed by the U.S. Department of Energy for use in performance and quantitative risk assessment of geologic sequestration of carbon dioxide (CO_2) (Pawar et al., 2016). The model components include a primary CO_2 injection reservoir, potential leakage pathways, and receptors such as shallow aquifers. The model is designed to perform probabilistic simulations related to the long-term fate of a CO_2 sequestration operation. A stochastic framework at the system level allows NRAP-IAM-CS to be used to explore complex interactions among large numbers of uncertain variables and helps evaluate the likely performance of potential sequestration sites. The model samples values for each uncertain parameter from probability distributions, leading to estimates of global uncertainty that accumulate as the coupled processes interact during a simulation. NRAP-IAM-CS is designed to link together many different processes (e.g., subsurface injection of CO_2, CO_2 migration, leakage, and shallow aquifer impacts) required in the analysis of long-term CO_2 storage in geologic reservoirs. The underlying processes can be simulated using reduced-order models (ROMs) developed for the components in the IAM. Details of the NRAP-IAM-CS are provided in the manual (Stauffer, et al., 2016). The risk-based AoR for Site 7 was calculated using spatial and temporal distributions of CO_2 saturations and pressures within the storage reservoir from a multi-phase numerical reservoir flow simulator (Computer Modeling Group-Generalized Equation of State Model [CMG-GEM] that was used to predict CO_2 plume boundaries as input to a site-specific open wellbore ROM and a shallow groundwater ROM developed with NRAP-IAM-CS (Figure 2).

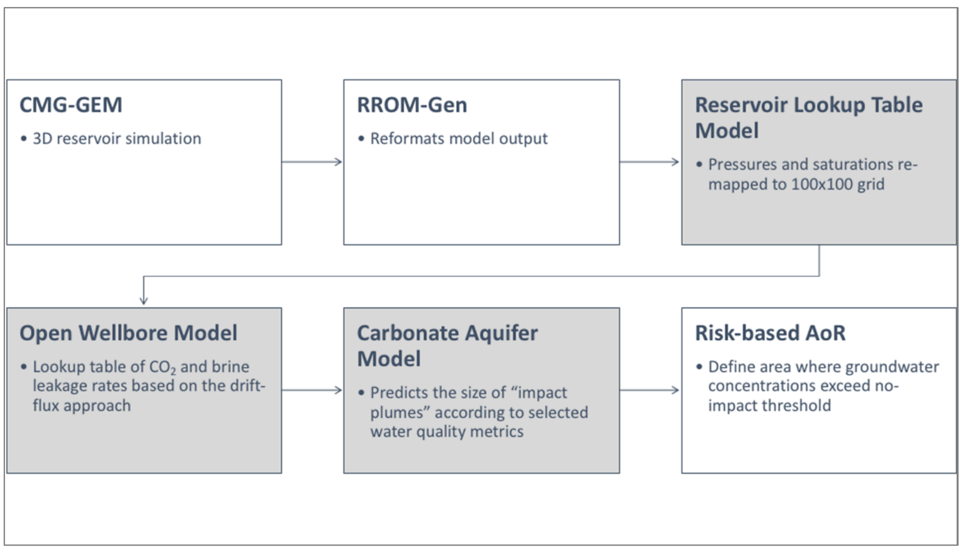

Figure 2. *Components of the risk-based AoR approach for Site 7 (grey components are part of the NRAP-IAM-CS system model).*

The ***open wellbore model*** is a multiphase and non-isothermal model that couples wellbore and reservoir flow of CO_2 and variable salinity brine to calculate CO_2 and brine leakage rates into a shallow underground source of drinking water (USDW) aquifer and to the atmosphere (Pan et al., 2011). The model allows for the phase transition of CO_2 from supercritical phase to gaseous phase and accompanying

Joule-Thompson cooling and exsolution of CO_2 from the brine phase. The model simulates CO_2 and/or brine leakage from the storage reservoir using inputs of pressure and CO_2 saturations from the RROM-GEN generated look-up tables. The CO_2 and brine fluxes from the open wellbore ROM used to calculate groundwater impacts are qualitative, because leakage rates from the open wellbore ROM may exceed the range of values to which the carbonate aquifer ROM was calibrated (Table 1). Additional parameters needed for the wellbore leakage and aquifer impact calculations are shown in Table 2.

It is very important to note that ***open wellbore model*** assumes that the wellbore is completely open – meaning that the annular space outside the casing is completely devoid of cement or other material. The assumption of a completely open borehole that penetrates the storage reservoir and connects it to the shallow drinking water aquifer can lead to unrealistically high leakage rates (flux of brine and CO_2) and aquifer impacts (resulting from chemical constituent concentrations in the shallow drinking water aquifer). However, this assumption is consistent with EPA's guidance for calculating the Area of Review.

The ***unconfined carbonate aquifer ROM*** predicts the volume of impacted groundwater in a shallow drinking water from CO_2 and brine leaks using nine water quality parameters (Keating et al., 2016a). The unconfined carbonate aquifer ROM is the only USDW ROM available in NRAP-IAM-CS. NRAP is currently adding a confined alluvium aquifer ROM. In this analysis two of the nine parameters (pH and total dissolved solids [TDS]) were used. pH and TDS plume volumes below the no-impact threshold were assumed to be consistent with EPA guidelines for no-net degradation. More information on how the threshold values were determined can be found in Last et al (2016). Adjustable model input parameters, including permeability mean, variance, correlation length and anisotropy, aquifer thickness and horizontal hydraulic gradient were based on site characterization data where possible.

Table 1. *Carbonate Aquifer ROM wellbore leakage parameter maximum values*

Parameter	Maximum Value	Unit
CO_2 leak rate	500	gram/s
Brine leak rate	75	gram/s
Cumulative CO_2 mass leaked	500	kTon
Cumulative Brine mass leaked	100	kTon

Table 2: *NRAP-IAM-CS Input Parameters for Site 7*

	Site 7 – Model Layer 253	
Parameter	**Reservoir**	**USDW**
Surface Elevation (m)	381	381
Initial Pressure (MPa)	32.57	2.96
Elevation of Top (m)	-2777.34 3032	76.2
Temperature (◦C)	65 (Footnote a)	15.56
Mean Permeability (m^2)	4.8×10^{-5} (Footnote a)	9.8692×10^{-15}
Mean Porosity (fraction)	0.018 (Footnote a)	0.1
Thickness (m)	Footnote a	304
Salinity (ppm)	200,000	0

a. These parameters are incorporated in the 3-D CMG GEM reservoir model.

For the reservoir component, the Reservoir Reduced-Order Model – Generator (RROM-Gen) (King, 2016) was used to create NRAP-IAM-CS reservoir ROM look-up tables from the 3D reservoir simulations performed with the CMG GEM code. Simulated CO_2 saturations and pressures for Site 7 for 30-years of CO_2 injection and a total injection of 50 MMT CO_2 were converted to a format acceptable to the NRAP-IAM-CS. The tool defines a new (100 x 100 cells) grid based on user input options, then uses piecewise bi-linear interpolation to convert the reservoir data from the original grid to the new grid. The gridded results are then written to specified file format reservoir lookup tables. Only one horizontal plane (layer) is extracted from the reservoir simulation results for use in the NRAP-IAM-CS calculations. For this application, reservoir pressures and CO_2 saturations for all nodes in Layer 253 of the Site 7 GEM model at yearly time steps from 0 to 30 years were used. This layer was selected because it had the highest pressure (gradient) and largest CO_2 plume. The top of the reservoir is defined at an elevation of -2,777.34 m (9,112 ft), corresponding to a depth of 3,158.34 m (10,362 ft). Interpolated pressures and CO_2 saturations are shown at years 0 and 30 in Figures 3-6.

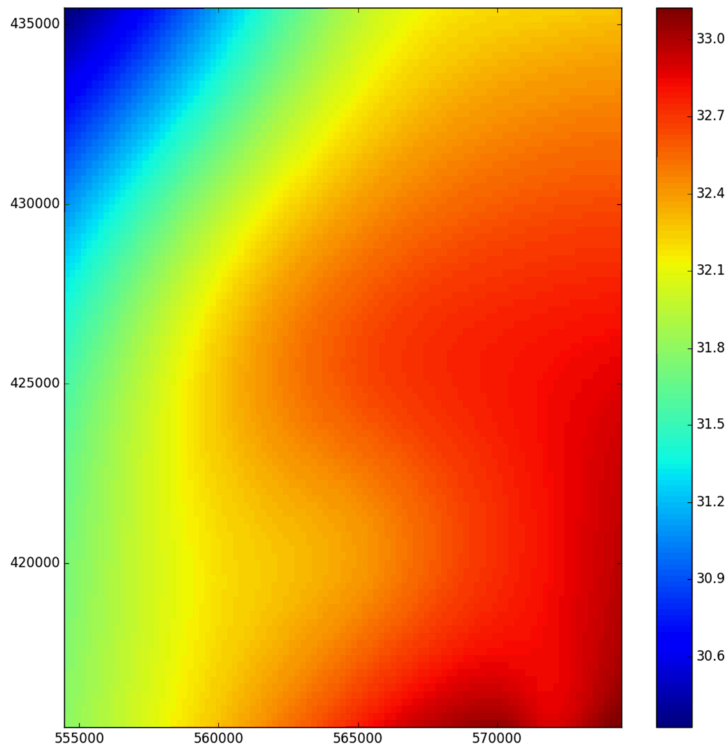

Figure 3. *Pressure distribution in MPa for CGM-GEM model layer 253 at time 0 years interpolated to a 100x100 grid. The grid has units of meters.*

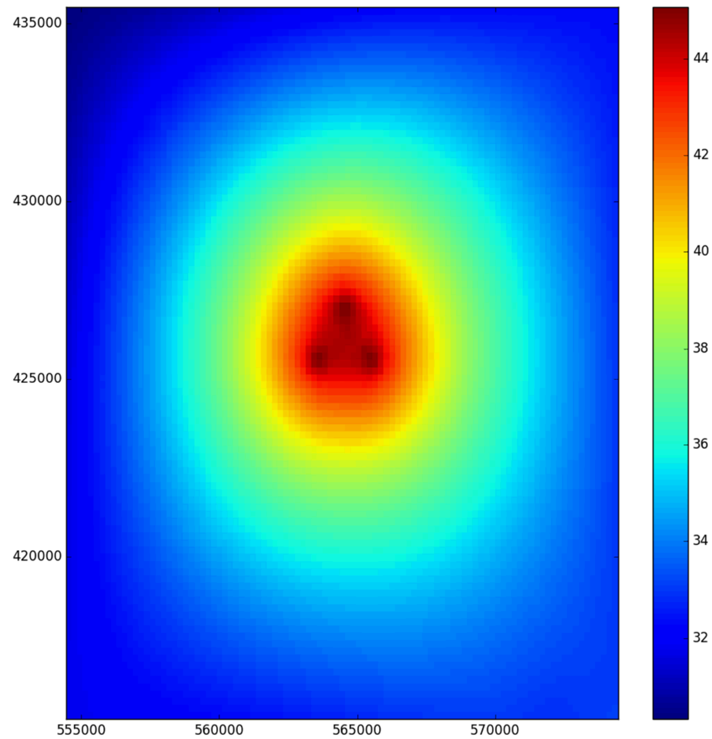

Figure 4. *Pressure distribution in MPa for CGM-GEM model layer 253 at time 30 years interpolated to a 100x100 grid (the three injection well locations can be seen in the center of grid). The grid has units of meters.*

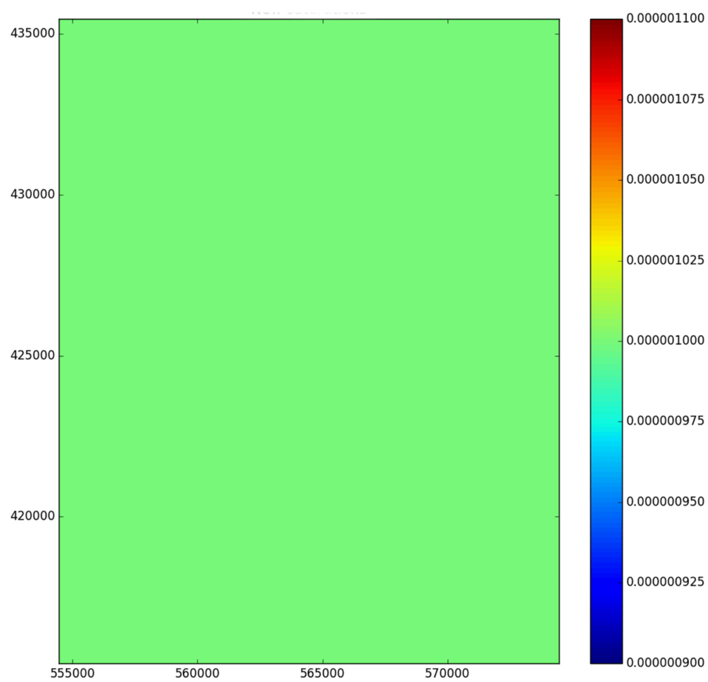

Figure 5. *CO_2 gas saturation distribution for CMG-GEM model layer 253 at time 0 years interpolated to a 100x100 grid. The grid has units of meters.*

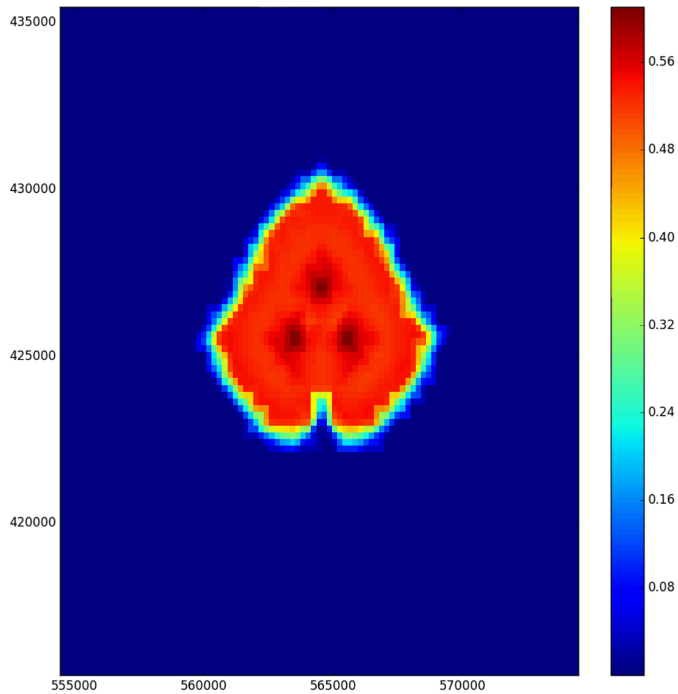

Figure 6. *CO_2 gas saturation distribution for CMG-GEM model layer 253 at time 30 years interpolated to a 100x100 grid. The grid has units of meters.*

1.1.2.2 Risk-Based AoR Results

Figure 7 shows the locations of the hypothetical wells used to estimate the AoR. The modeled reservoir pressure and CO_2 saturation vs. time for each of the four hypothetical well locations are shown in Figures 8 and 9. These values were used to calculate the CO_2 and brine leakage fluxes with time at each location. Wells 1, 2, and 3 are located within the CO_2 plume and Well 4 is located outside of the CO_2 plume but within the pressure front. Pressure buildup varies from approximately 11.9 MPa (1,726 psi) at the center of the injection area to about 1.8 MPa (261 psi) at Well 4.

CO_2 leakage to the USDW occurs at Wells 1, 2 and 3 and changes the shallow groundwater pH to below pH 6.5 (Figures 10, 11). Impacts to groundwater are used only to define the AoR; a full quantitative analysis would require updating the groundwater ROMs to handle large fluxes created by flow through an open wellbore. Qualitatively, the magnitude of the impact to groundwater decreases with distance from the injection center; and, the timing of the onset of impact increases in time with distance. There is no impact on groundwater pH at location 4 because the well is located outside the CO_2 plume. In contrast to CO_2 leakage, brine leakage to the USDW occurs at all four hypothetical well locations resulting in impacts to groundwater at all locations, although the magnitude of impact decreases with increasing distance from the center of injection (Figure 12, 13).

The ellipse in Figure 14 defines the risk-based AoR for Site 7. Table 3 specifies the boundary points for the AoR and Figure 15 and 16 show the brine flux during the 30-year CO_2 injection period. The estimated AoR has a radius from 8,295 m (27,215 ft) to 9,205 m (30,200 ft), corresponding to an area of 234 km^2 (90 mi^2).

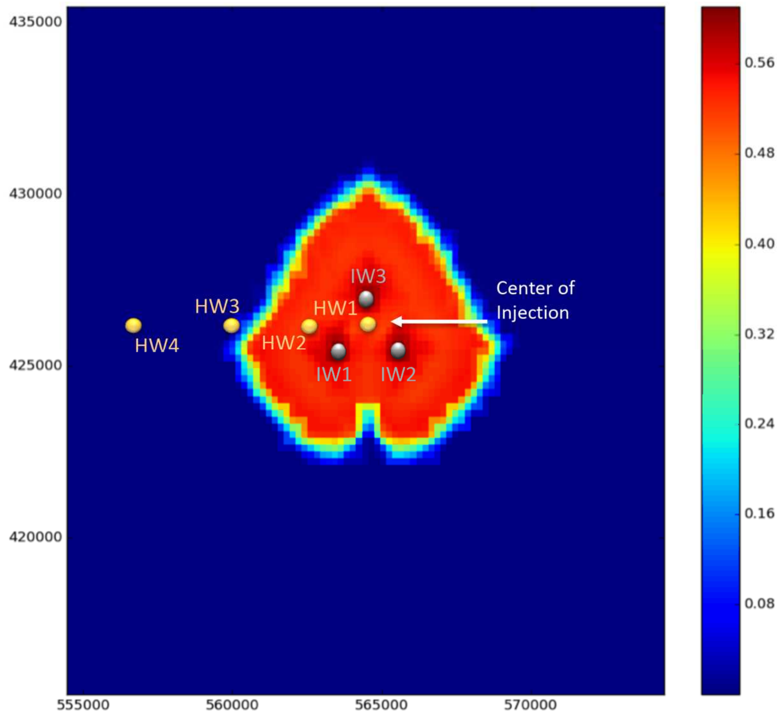

Figure 7. *Locations of hypothetical wells superimposed on the CO_2 saturation contour plot for year 30. The grid has units of meters.*

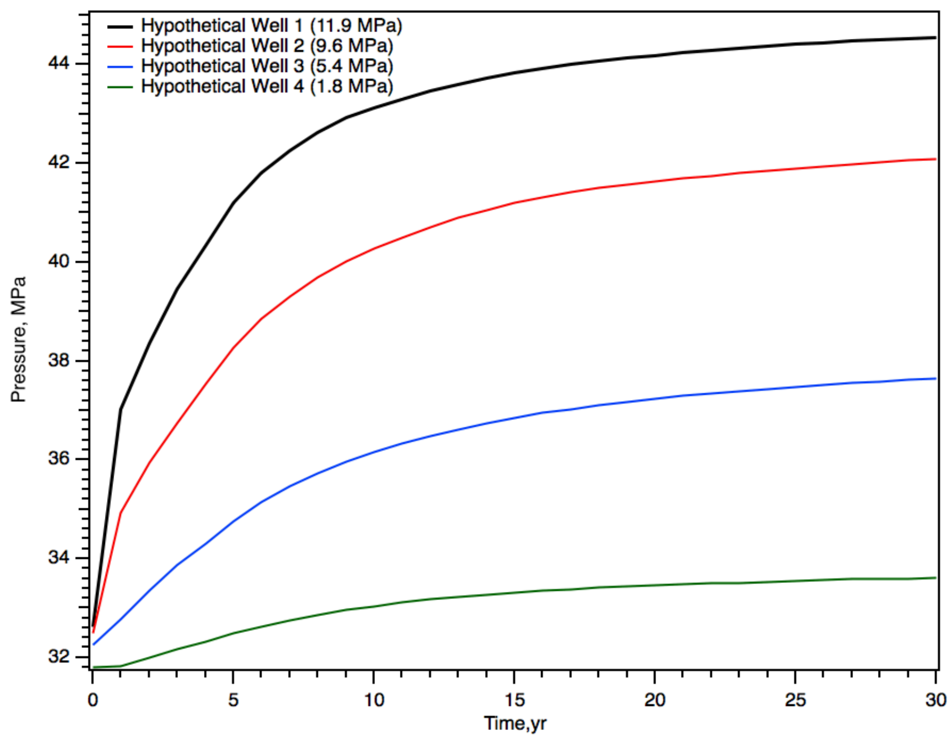

Figure 8. *Pressure vs. time at each hypothetical well location. The maximum pressure difference is shown in parenthesis for each well.*

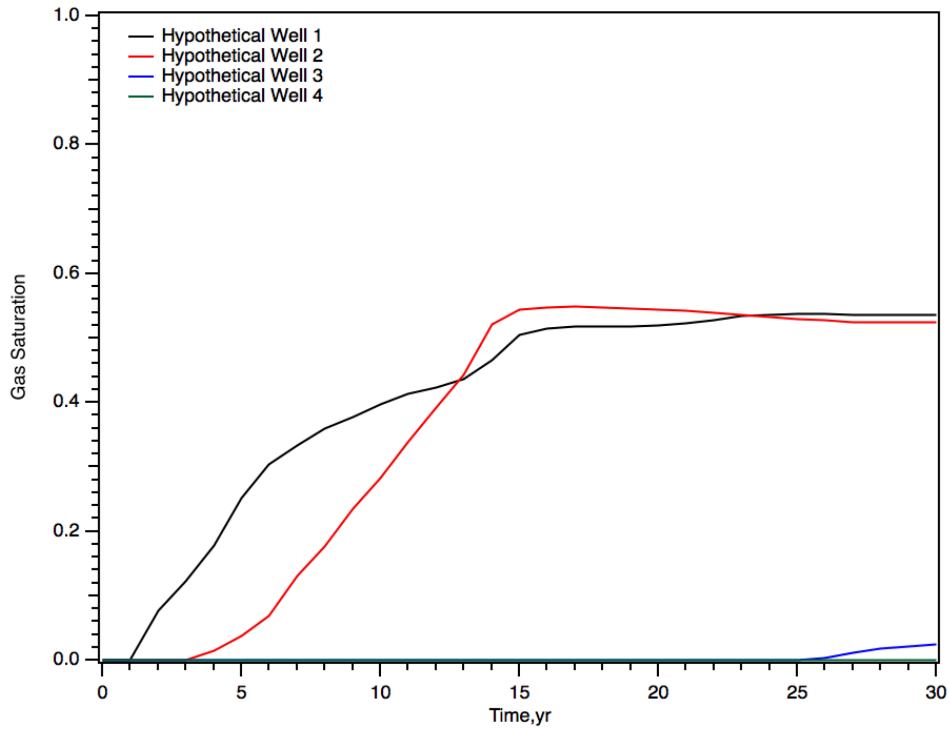

Figure 9. *CO_2 saturation vs. time at each hypothetical well location*

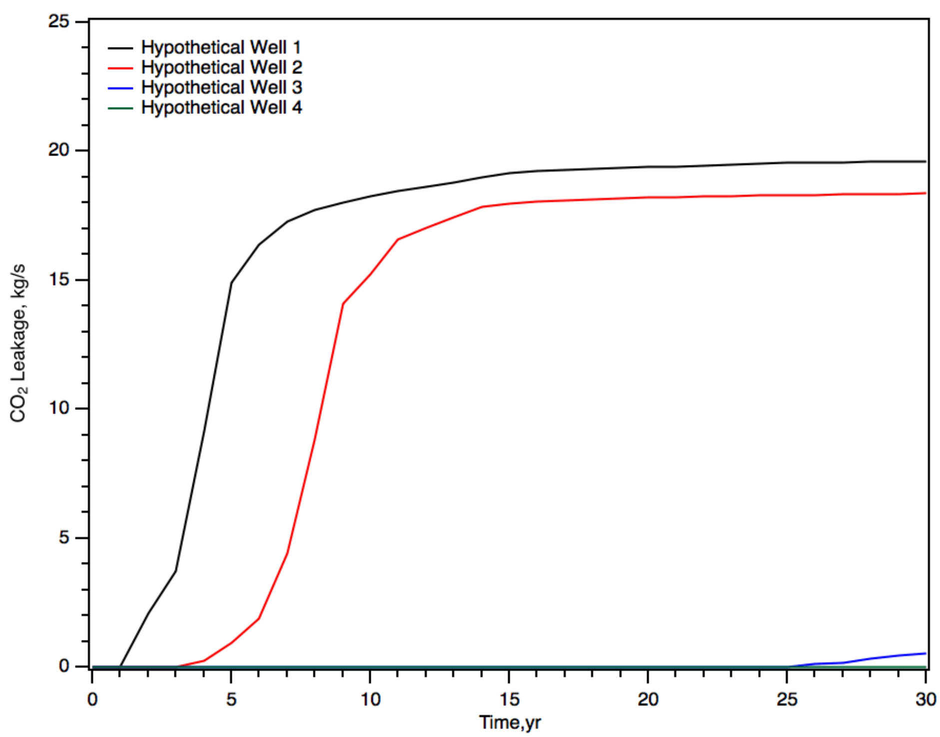

Figure 10. *CO_2 leakage rates over time at hypothetical well locations within (wells 1, 2, and 3) and outside (well 4) the CO_2 plume footprint*

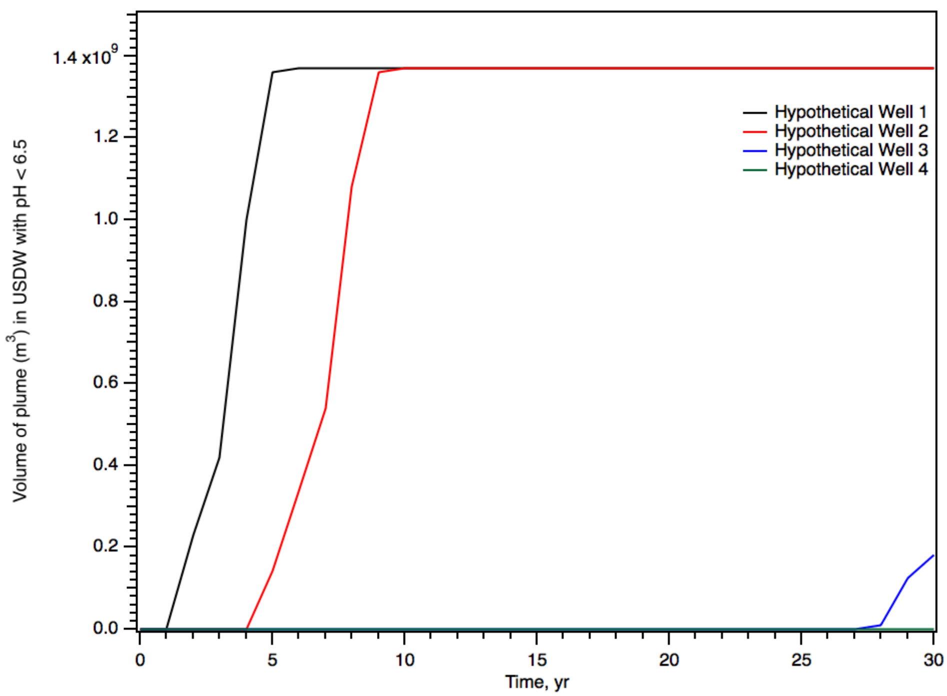

Figure 11. *Impact to the USDW in terms of pH changes at hypothetical well locations within (wells 1, 2, and 3) and outside (well 4) the* CO_2 *plume footprint*

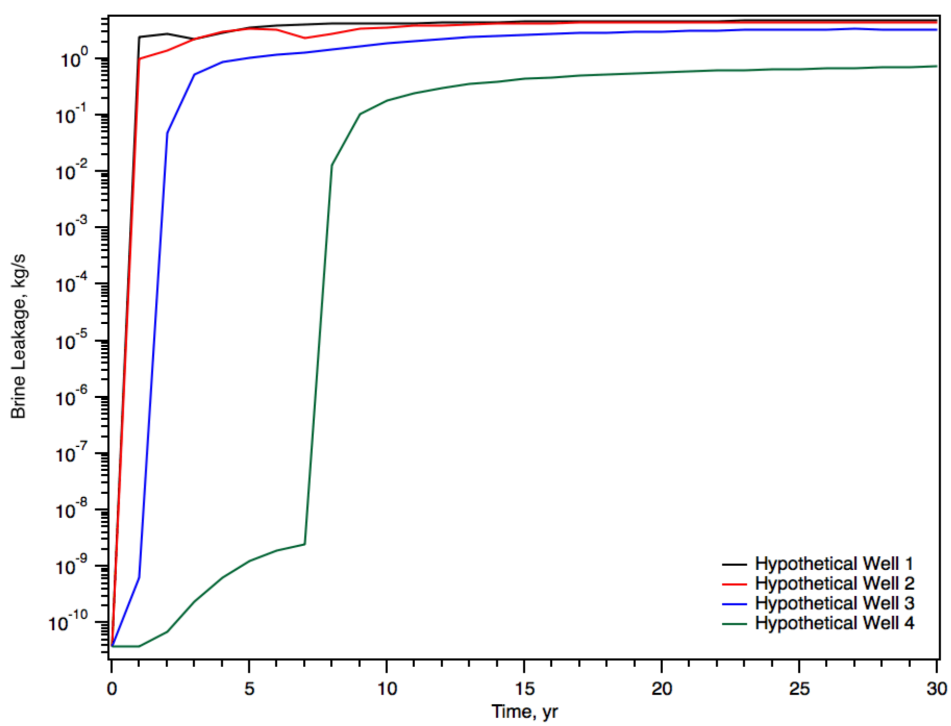

Figure 12. *Brine leakage rates over time at hypothetical well locations within (wells 1, 2, and 3) and outside (well 4) the* CO_2 *plume footprint*

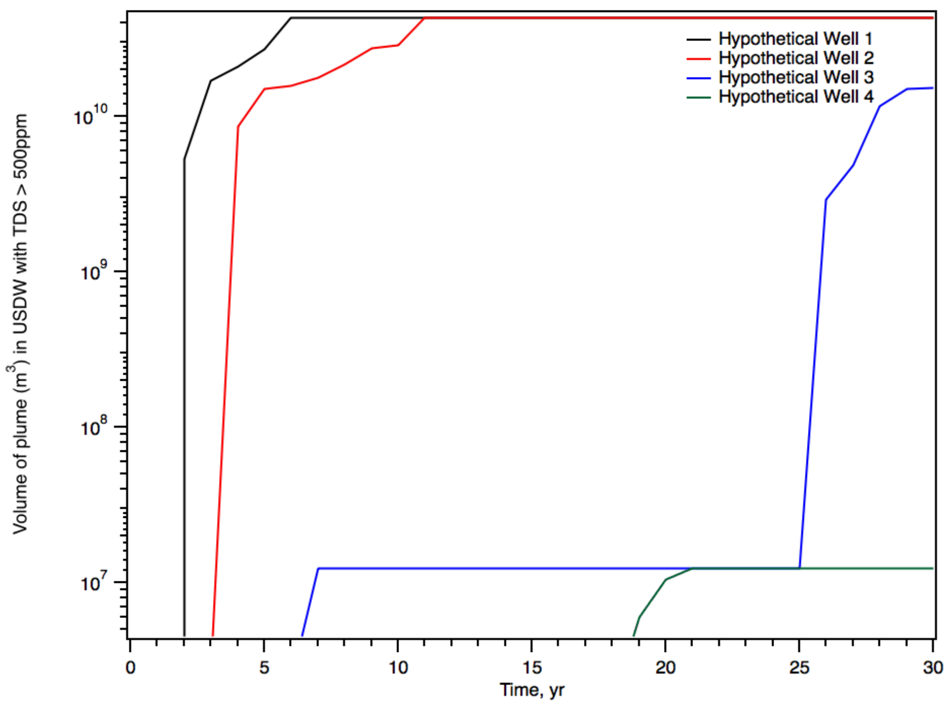

Figure 13. *Impact to the USDW in terms of TDS at hypothetical well locations within (wells 1, 2, and 3) and outside (well 4) the CO_2 plume footprint*

Table 3. *Locations of hypothetical wells defining the boundary of the risk-based AoR*

AoR Boundary Points			Distance from Center of Injection Well Field
	x(m)	**y(m)**	**m**
North	564461	434500	8295
East	573000	426205	8539
South	564461	417000	9205
West	556000	426205	8461

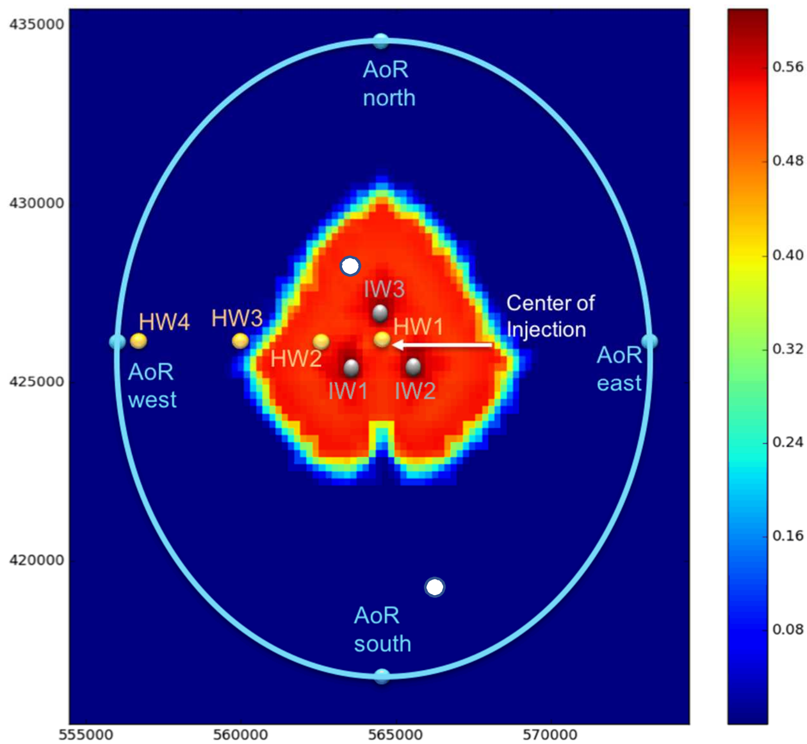

Figure 14. *Area of Review as determined by the area inside which there is impact to the USDW from CO_2 or brine leakage. Approximate locations of the legacy wells (white circles) showing their penetration of the CO_2 plume (Well 1) and the pressure plume to the south of the CO_2 plume (Well 2). CO_2 plume is shown with colored contours of CO_2 saturation. The grid has units of meters.*

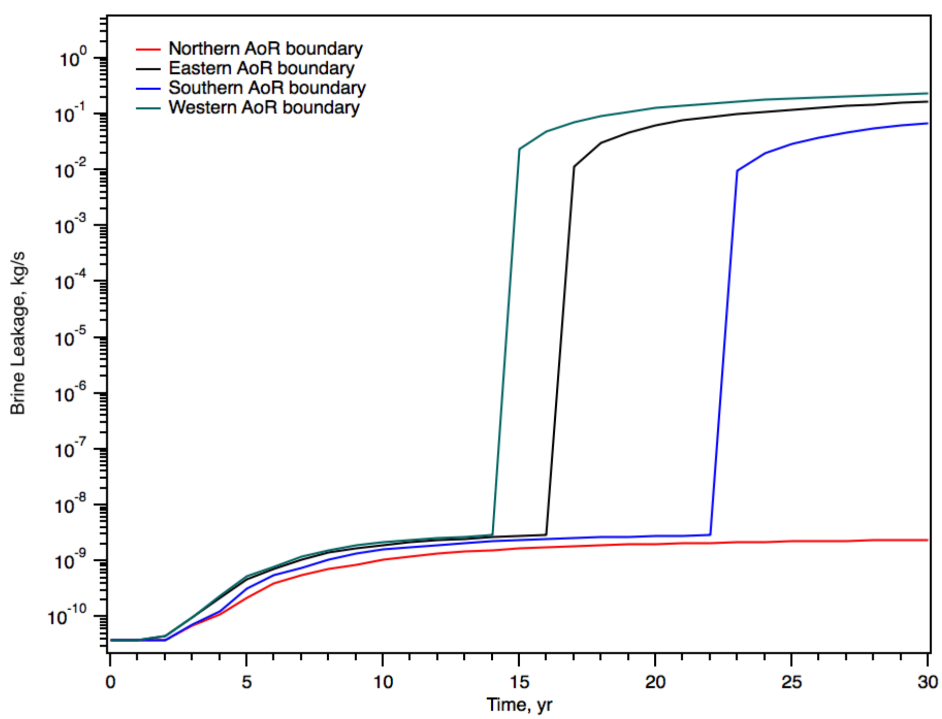

Figure 15. *Brine leakage at points representing the northern, eastern, southern, and western limits of the Area of Review as determined by estimated zero risk to the USDW*

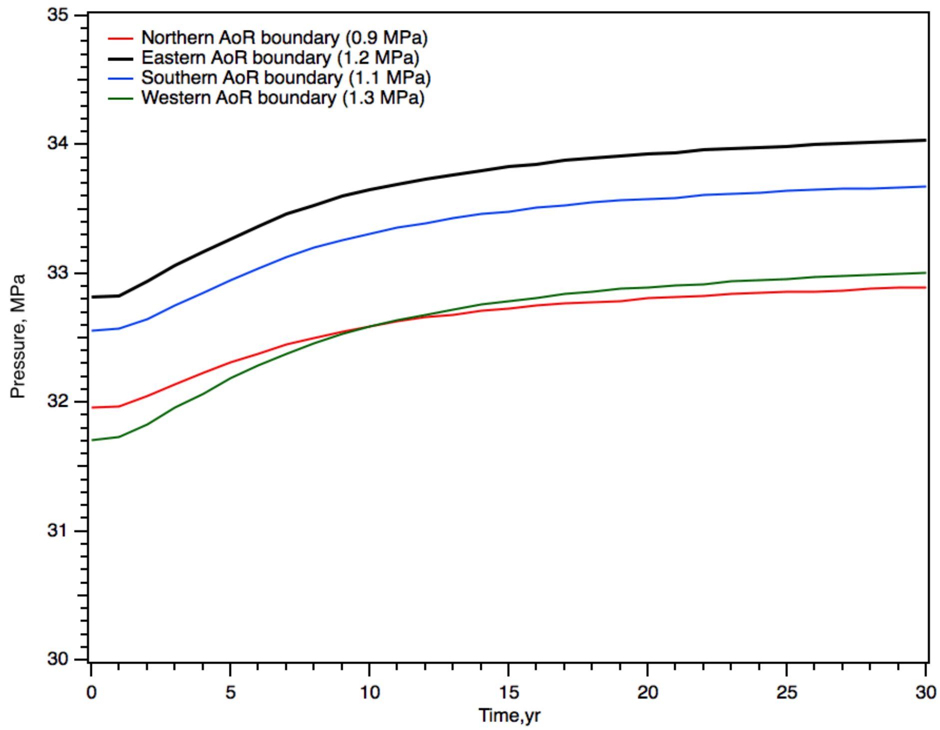

Figure 16. *Pressure vs. time at points representing the northern, eastern, southern, and western limits of the Area of Review as determined by estimated zero risk to the USDW. Maximum pressure buildup is indicated in parenthesis for each location.*

1.1.3 Critical Pressure Based AoR

Currently, the EPA provides guidance to operators of CO_2 storage sites for approaches to determining the critical pressure that should be used to define the pressure front that is considered in the AoR delineation (U.S. EPA, 2012). Comparison of the risk-based and critical pressure approaches yielded very similar AoR, with the risk-based AoR being equal to 234 km^2 and the critical pressure AoR being equal to 269 km^2. The approach taken to determine a critical pressure AoR for Site 7 is discussed below.

The critical pressure corresponds to the critical (minimal) pressure needed to move fluids from the reservoir into a USDW through a hypothetical open conduit, such as an uncemented well (U.S. EPA, 2012). The first step is to use a method that is applicable to reservoirs that are hydrostatic or underpressurized prior to the injection of CO_2 (Birkholzer et al., 2011). This method assumes that the density of the fluid in the wellbore is uniform and equal to the density in the injection zone. Equation 1 can be used to calculate the necessary increase in pressure in the reservoir to equalize the hydraulic head between the injection zone and the USDW.

$$\Delta P_{if} = P_u + \rho_i g \cdot (z_u - z_i) - P_i \qquad \text{Equation 1}$$

where:

P_u is the initial pressure in the USDW (Pa= $kg{\cdot}m^{-1}{\cdot}s^{-2}$),
ρ_i is the density of the injection zone fluid (kg/m^3),
g is the acceleration of gravity (m/s^2),
z_u is the depth to the base of the lowermost USDW (m),
z_i is the depth to the top of the injection zone (m), and
P_i is the initial pressure in the injection zone (Pa)

A positive value of $\Delta P_{i,f}$ (Equation 1) corresponds to an injection reservoir that is under-pressurized relative to the USDW (i.e., a downward hydraulic gradient exists between the USDW and the injection zone). The reservoir overpressure would need to increase to values equal to or above $\Delta P_{i,f}$ to move reservoir fluid into the drinking water aquifer. A $\Delta P_{i,f}$ value of zero corresponds to the hydrostatic case. A negative value of $\Delta P_{i,f}$ indicates an over-pressurized injection zone where reservoir brine has the potential to migrate to the drinking water aquifer prior to any CO_2 injection.

Using Equation 1 and the parameters in Table 4, a critical pressure of -1.013 MPa (-147 psi) was calculated for site 7. The negative critical pressure indicates that the reservoir is over-pressurized relative to the USDW. Some over-pressurization within the injection zone may be allowable without causing sustained fluid leakage, owing to the density differential between the fluids in the injection zone and USDW. In such cases, a second method, shown in Equation 2, can be used to estimate the pressure needed to displace the existing fluid in the borehole and create leakage into the USDW. Equation 2 assumes that below the calculated "threshold" pressure, no leakage into the USDW will occur (Nicot et al, 2009). Using Equation 2, a threshold pressure of 1.749 MPa (254 psi) was calculated for site 7. Because the value of ΔP_c using Equation 2 is greater than the value of $\Delta P_{i,f}$ using Equation 1, the difference in magnitude between the two may be used as an estimate of the allowable pressure increase, subject to the assumptions used to derive Equation 2 (see Nicot et al, 2009). This results in an allowable pressure increase of 0.736 MPa (107 psi), (1.749 MPa - 1.013 MPa) which can be used to define the AoR (Figure 17)[b].

$$\Delta P_c = \frac{1}{2} \cdot g \cdot \xi \cdot (z_u - z_i)^2$$

Equation 2

where:

g is the acceleration of gravity (m/s^2),
z_u is the depth to the base of the lowermost USDW (m),
z_i is the depth to the top of the injection zone (m),
ρ_i is the fluid density in the injection zone (kg/m^3),
ρ_u is the fluid density in the USDW (kg/m^3), and
$\xi = \frac{\rho_i - \rho_u}{z_u - z_i}$ (kg/m^2)

Table 4. *Inputs for Critical Pressure and Threshold Pressure Calculation (Equations 1 and 2)*

Input Parameter	Value
Depth to top of injection zone (m)	3,158
Depth at base of the lowermost USDW (m)	609
Initial Pressure in Injection Zone (MPa)	32.572
Initial Pressure at the base of the lowermost USDW (MPa)	2.964
Fluid Density in the Injection Zone (kg/m^3)	1,144
Fluid Density in the USDW (kg/m^3)	1,004
Critical Pressure from Equation 1 (MPa)	-1.013
Threshold Pressure Increase from Equation 2 (MPa)	1.749

[b] Because the injection reservoir is over pressurized relative to the shallow drinking water aquifer, neither the critical pressure from Equations 1 or 2 can be used to define the AoR. In this case, the allowable pressure increase (this is the term EPA uses) is used to delineate the AoR. The allowable pressure increase is the difference between the two critical pressures calculated with Equations 1 and 2. This likely would need to be negotiated with EPA. Figure 17 uses the allowable pressure of 0.736 MPa (107 psi) to define the AoR.

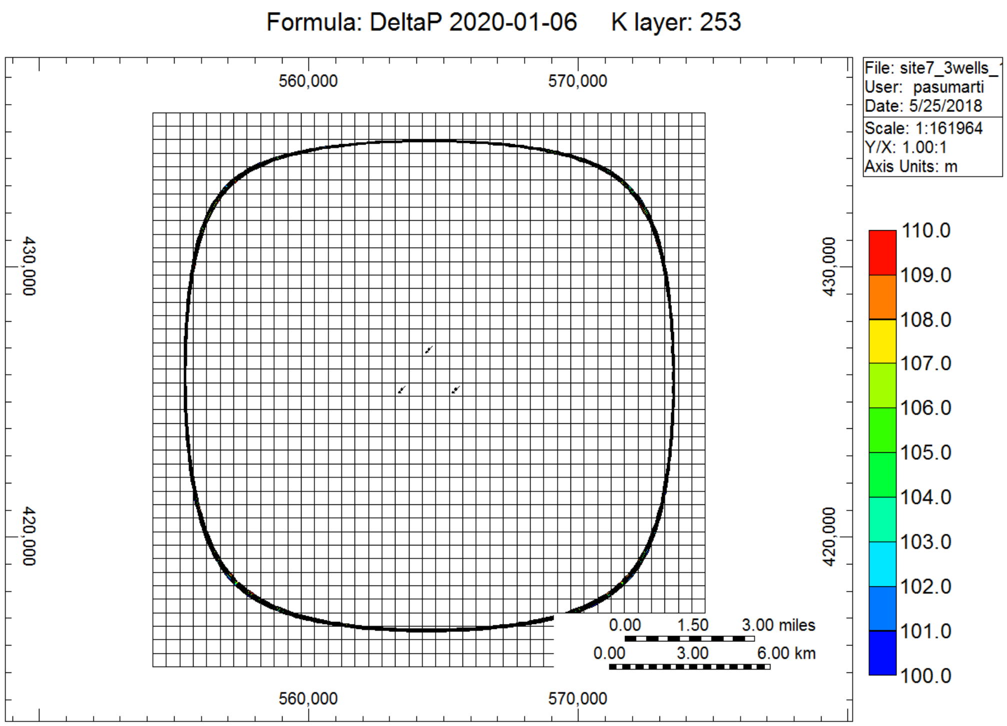

Figure 17. *Area of Review as determined by the critical pressure calculated using the analytical approaches (0.736 MPa [107 psi]); Area =269 km² (104 mi²).*

1.1.4 Assessment of Leakage Impacts from Known Legacy Well Locations

The NRAP-IAM-CS was also used to evaluate the probability and impacts of CO_2 and brine leakage from known well locations at Site 7. Groundwater impacts through cemented wellbores and known well locations were calculated using the same approach used to calculate the risk-based AoR; however, the open wellbore assumption was replaced with permeability data representative of cemented wellbores (Figure 2). There are a limited number of oil and gas wells around Site 7 and only two legacy wells were identified that were drilled to depths below the caprock (Figure 1). In this analysis, only the two legacy wells that fall within the AoR and are likely to penetrate the CO_2 storage reservoir are considered. Table 5 lists the location of the two legacy wells and Figure 14 shows their location relative to the CO_2 and pressure plumes. One well is clearly within the CO_2 plume where CO_2 saturations are about 50%. The other well is to the south of the CO_2 plume close to the southern edge of the estimated area of review, where CO_2 saturations are low.

Table 5. *Locations of the Site 7 legacy wells*

	API Number	Latitude	Longitude	X - meters	Y - meters
Legacy Well 1	21113397250000	-85.1899	44.39144	564360.44	426977.23
Legacy Well 2	21113386820000	-85.1787	44.31443	565341.13	418432.1

A probabilistic assessment for known well locations was conducted using predefined permeability distributions that are included in the NRAP-IAM-CS. These are described below:

- The Alberta model – a uniform distribution with permeability between 10^{-12} to 10^{-13}m^2 for 0.2% of the wells, 10^{-14} to 10^{-17}m^2 for 4.4 % of the wells, and 10^{-20}m^2 for 95.4% of the wells.
- The Gulf of Mexico model – a uniform distribution with permeability between 10^{-12} to 10^{-13}m^2 for 0.6% of the wells, 10^{-14} to 10^{-17}m^2 for 11.4 % of the wells, and 10^{-20}m^2 for 88% of the wells.

- The FutureGen Low models – assumes a log normal distribution, where 10% of the wells are assumed to have of permeability of 10^{-15} to $10^{-17}m^2$ and 90% of the wells have a much lower permeability of $10^{-20}m^{-2}$ for low rates of failure.
- The FutureGen High model – assumes a log normal distribution, where 10% of the wells have a permeability of 10^{-13} to $10^{-15}m^2$ and 90% of the wells a much lower permeability of 10^{-18} to $10^{-20}m^2$.

The number of realizations was limited to 3000. Each realization calculated the mass of CO_2 and brine leaked to the USDW, as well as the impact that leakage would have on shallow groundwater quality. The probabilistic calculations using the default permeability distributions showed minimal leakage, with most realizations yielding no leakage and no impact to the groundwater. *Overall, the analysis suggests no risk to the overlying aquifer from CO_2 or brine leakage through these two legacy wells.*

Because the probabilistic assessment using the default permeability distributions yielded no leakage from the two legacy wells for Site 7, the NRAP-IAM-CS was used to estimate the permeability each well would need to have to cause an unacceptable impact to groundwater quality. The leakage profiles are different for the two legacy wells reflecting their locations relative to the CO_2 plume in the storage reservoir. Figure 18 shows the mass of CO_2 and brine leaked into the shallow groundwater assuming fixed well permeabilities for Legacy Well 1, which is located within the CO_2 plume. Modeling results indicate that leakage from Legacy Well 1 may change the groundwater below the pH 6.5 threshold if the well permeability is 5×10^{-12} m^2 or higher[c]. Figure 19 indicates that impacted volumes would be delayed for 10 to 20 years and would exceed 200,000 to 700,000 cubic meters after 30 years. CO_2 leakage from a legacy well with permeabilities between 5×10^{-13} m^2 and 5×10^{-18} m^2 does not impact groundwater and no leakage occurs at permeability of 5×10^{-19} m^2 and below[d]. These estimates may under predict the magnitude of impact (i.e., change in pH) because NRAP-IAM-CS uses an open (i.e., unconfined) aquifer to estimate leakage, allowing a large fraction of the CO_2 to move to the vadose zone and out to the atmosphere, rather than into the shallow groundwater where it could alter the pH. If a confined aquifer is used to represent the shallow groundwater, then the volume of impacted water would be greater. Brine leakage from Legacy Well 1 does not impact the shallow groundwater above the total dissolved solids (TDS) threshold.

Legacy Well 2 is south of the CO_2 plume. As expected, the NRAP-IAM-CS predicts only brine leakage at this location. The amount of brine leaked does not impact the shallow groundwater above the total dissolved solids (TDS) threshold. Results of the fixed permeability analysis of Legacy Well 1 and 2 supports the null outcome of probabilistic analysis using the default well permeability distributions provided with the NRAP-IAM-CS. Although two of the four distributions include permeabilities as high as 10^{-12} m^2, these higher values make up a small fraction of the sampled permeabilities. Permeabilities sampled by the FutureGen models are all below 10^{-12} m^2 and leakage would not be expected.

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[c] Approximately 5 Darcy

[d] Approximately 500 to 0.05 millidarcy

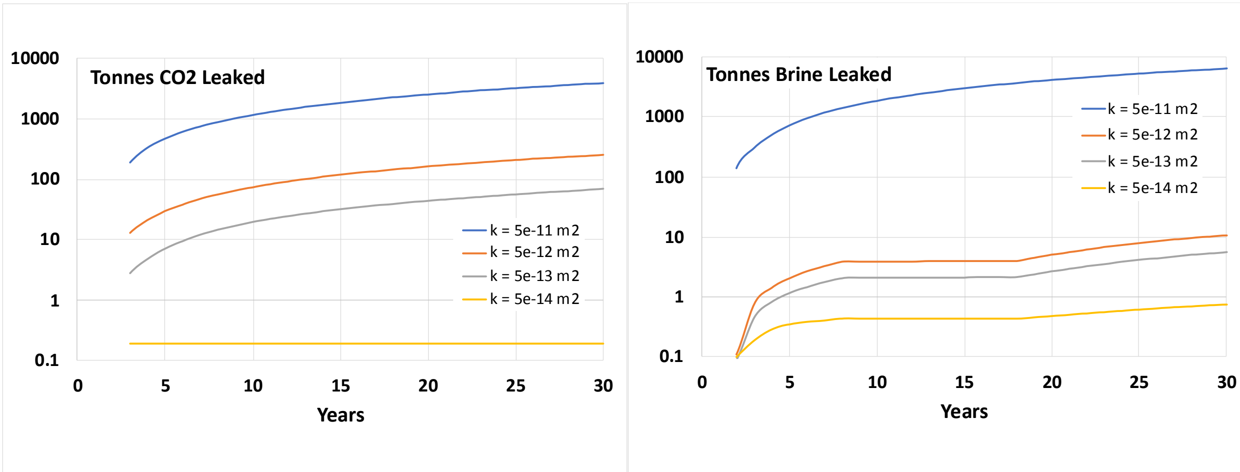

Figure 18. *Mass of CO_2 (left) and brine (right) leaked estimated to leak into a shallow groundwater from Legacy Well 1 for four values of wellbore permeability.*

Figure 19. *Shallow groundwaters are estimated to impact groundwater because leaking CO_2 will change the pH above the threshold if the permeability of Legacy Well 1 is 5 x 10^{-12} m^2 (~5 Darcy) or higher.*

1.1.5 Summary and Conclusions

The NRAP-IAM-CS was used to estimate the AoR and the impact of leakage from legacy wells located within the AoR at a representative carbon storage site for the Michigan CarbonSAFE, Phase 1 project. The risk-based analysis yielded an AoR of 234 km^2 (90 mi^2), which is slightly smaller in size to the AoR defined using the critical pressure approach (269 km^2, 104 mi^2) because small fluxes did not impact groundwater quality.

Leakage from two legacy wells located within the AoR should not adversely impact groundwater quality over the 30-year injection period. Legacy Well 1 penetrates the simulated CO_2 plume and would require permeability of 5 x 10^{-12} m^2 or 5 Darcy to impact groundwater quality after about 20 years of injection. Legacy Well 2 falls outside of the CO_2 plume, where reservoir pressures are too small to generate large enough leaks to change groundwater quality even with well permeabilities as high as 5 x 10^{-11} m^2 or 50 Darcy.

1.1.6 Recommendations

The NRAP-IAM-CS toolset was released in 2017. The strength of the toolset is the ability to perform probabilistic assessments that account for the uncertainty of the storage complex. This work represents some of the first applications of the tools to potential CO_2 storage sites. The following recommendations to the toolset could advance its use for the determination of probabilistic assessments of risk-based AoR and leakage from legacy wells on quality to USDWs.

- The AoR calculations would be more robust if the toolset could sample pressures and CO_2 saturations from many 2D planes within the reservoir. This is particularly important for stacked storage reservoirs where stratigraphic heterogeneity will control pressure and CO_2 gas saturations. A ROM specific to the site reservoir would further improve a probabilistic assessment of the AoR.
- USDW ROMs need to be calibrated against the high leakage fluxes generated from open wellbores. All USDW ROMs were calculated for cemented wellbores, where leakage is controlled by the permeability of damage zones within the completed wells.
- The NRAP-IAM-CS currently has one option for a UDSW ROM, the unconfined carbonate aquifer, where CO_2 leaks to aquifer and to the atmosphere. NRAP is updating the toolset with a confined alluvium aquifer in which all CO_2 leaked stays within the aquifer system.
- Any AoR and groundwater impact assessments should include both the injection and post-injection periods. This is important to demonstrate that the CO_2 plume has stabilized and that the reservoir pressures have returned to pre-injection levels. Post-injection assessments of CO_2 leakage are important because buoyancy will continue move the CO_2 along leakage pathways even after the reservoir pressure has relaxed to its pre-injection levels. Conclusions in this study were based only on the injection period.

References

Birkholzer, J.T, J.P. Nicot, C.M. Oldenburg, Q. Zhou, S. Kraemer, and K. Bandilla. 2011. Brine flow up a well caused by pressure perturbation from geologic carbon sequestration: Static and dynamic evaluations. International Journal of Greenhouse Gas Control (5): 850-861.

Keating E, D Bacon, S Carroll, and K Mansoor. 2016a. *Aquifer Impact Model (AIM) Tool User's Manual*. NRAP-TRS- III-XXX-2016, U.S. Department of Energy, National Energy Technology Laboratory, Morgantown, WV.

Keating E, D Bacon, S Carroll, K Mansoor, Y Sun, L Zheng, D Harp, and Z Dai. 2016b. "Applicability of aquifer impact models to support decisions at CO_2 sequestration sites." *International Journal of Greenhouse Gas Control* 52:319-330. 10.1016/j.ijggc.2016.07.001.

King S. 2016. *Reservoir Reduced-Order Model – Generator (RROM-Gen) Tool User's Manual*. NRAP-TRS-III-0XX-2016, U.S. Department of Energy, National Energy Technology Laboratory, Morgantown, WV.

Last GV, CJ Murray, and Y Bott. 2016. "Derivation of groundwater threshold values for analysis of impacts predicted at potential carbon sequestration sites." *International Journal of Greenhouse Gas Control* 49:138-148. http://dx.doi.org/10.1016/j.ijggc.2016.03.004.

Nicot, J.P., C.M. Oldenburg, S.L. Bryant, and S.D. Hovorka. 2009. Pressure perturbations from geologic carbon sequestration: Area-of-review boundaries and borehole leakage driving forces. Energy Procedia (1): 47-54.

Oldenburg, C.M., A. Cihan, Q. Zhou, S. Fairweather, and L. H. Sprangler. 2014. Delineating area of review in a system with pre-injection relative overpressure. Energy Procedia (63): 3715-3722.

Pan LH, SW Webb, and CM Oldenburg. 2011. "Analytical solution for two-phase flow in a wellbore using the drift-flux model." *Advances in Water Resources* 34(12):1656-1665. 10.1016/j.advwatres.2011.08.009.

Pawar RJ, GS Bromhal, SP Chu, RM Dilmore, CM Oldenburg, PH Stauffer, YQ Zhang, and GD Guthrie. 2016. "The National Risk Assessment Partnership's integrated assessment model for carbon storage: A tool to support decision making amidst uncertainty." *International Journal of Greenhouse Gas Control* 52:175-189. 10.1016/j.ijggc.2016.06.015.

Stauffer P, S Chu, C Tauxe, and R Pawar. 2016. *NRAP Integrated Assessment Model-Carbon Storage (NRAP-IAM-CS) Tool User's Manual, Version: 2016.11-1.1*. NRAP-TRS-III-010-2016, U.S. Department of Energy, National Energy Technology Laboratory, Morgantown, WV.

U. S. Environmental Protection Agency. 2012. Draft Underground Injection Control (UIC) Program Class VI Well Testing and Monitoring Guidance. EPA 816-D-10-009.