# An Assessment of the National Risk Assessment Program's $CO_2$ Sequestration Leakage Modeling Tools
## Subtask 6.1 – NRAP Assessment
## Topical Report

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CARBONSAFE ILLINOIS EAST SUB-BASIN

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## Executive Summary

The CarbonSAFE East Sub-Basin project team explored and assessed the carbon sequestration site characterization National Risk Assessment Partnership (NRAP) Toolset, developed by the National Energy Technology Laboratory, Lawrence Berkeley National Laboratory, Lawrence Livermore National Laboratory, Los Alamos National Laboratory, and Pacific Northwest National Laboratory (PNNL) for the NRAP. We ran the Integrated Assessment Model (IAM) tool using inputs derived from verified regional geologic data. We investigated $CO_2$ and brine leakage rates, and total $CO_2$ and brine leaked, from a hypothetical cemented injection well borehole to the nearest underground source of drinking water (USDW), identified as the St. Peter Sandstone, in a hypothetical monitoring well. The distance of the monitoring well from the injection well was varied to identify leakage variations with increasing distance from the injection well and to establish an area of review (AOR) for the project, and the effect of high and low wellbore cement permeability on model results was compared.

## CarbonSAFE Introduction and Study Site

The proposed CarbonSAFE East Sub-Basin project site (map) lies near the eastern edge of the Illinois Basin, in Vigo County, Indiana. The injection reservoir, the Mt. Simon Sandstone, is an excellent target for large-scale carbon storage, due to its depth, large lateral extent, formation seals, and petrophysical characteristics. Data used to develop the reservoir simulation models and dataset used as inputs for the NRAP Toolset were compiled from several previous studies within the region, including the US DOE FutureGen initiative, the US DOE's Regional Carbon Sequestration Partnership program via the Midwest Geological Sequestration Consortium (MGSC), and other DOE-funded projects evaluating Cambrian-Ordovician strata and the Mississippian Cypress Sandstone.

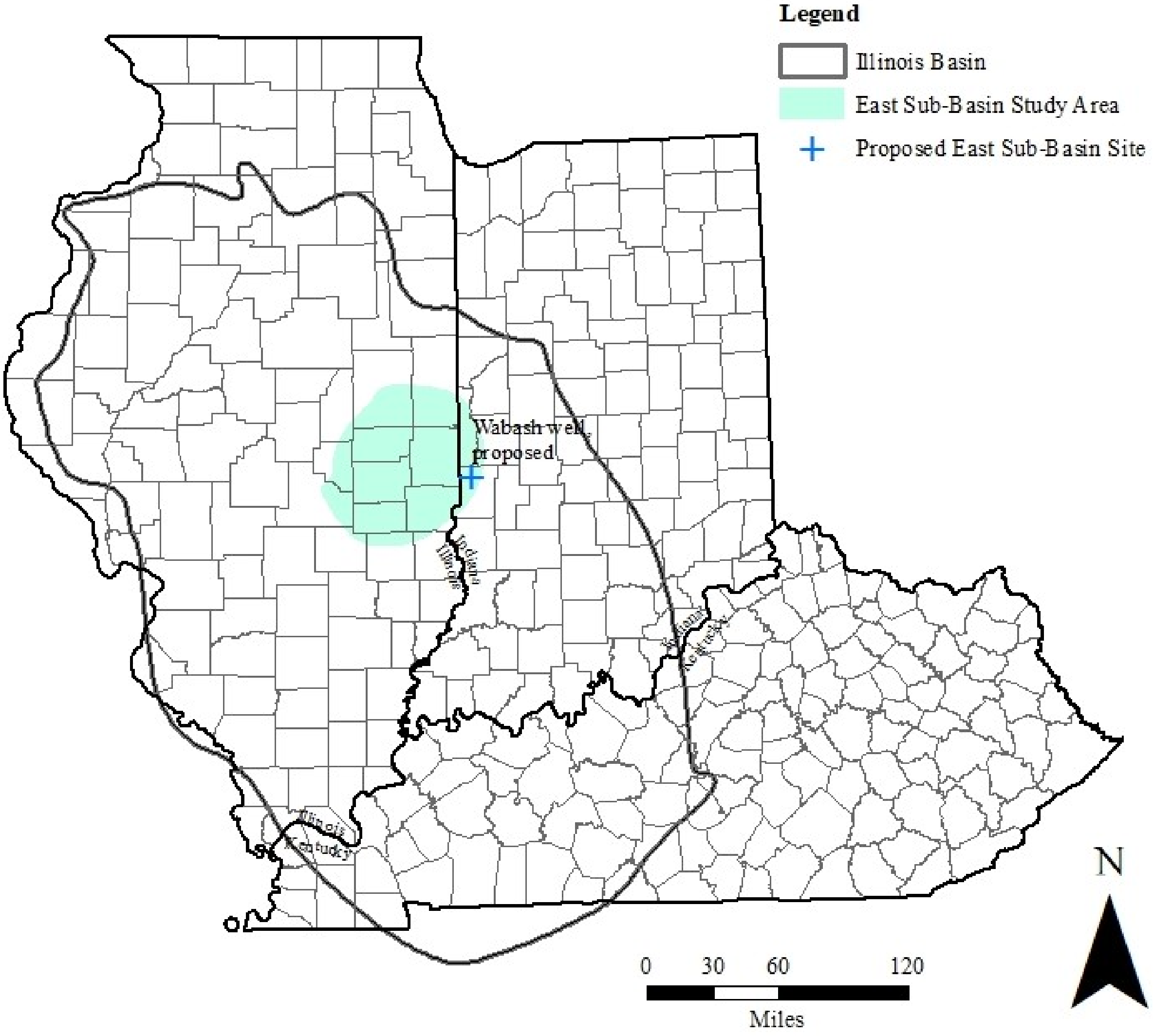

*Figure 1. The CarbonSAFE East Sub-Basin study area and the proposed East Sub-Basin site within the Illinois Basin.*

## NRAP Toolset

The National Risk Assessment Partnership (NRAP) project is a multi-laboratory effort that leverages broad technical capabilities across the DOE complex to develop the science-based methodologies and tools needed to assess risk at $CO_2$ storage sites. NRAP is led by the National Energy Technology Laboratory (NETL), with support from four other national laboratories: Los Alamos National Laboratory (LANL), Lawrence Berkeley National Laboratory (LBNL), Lawrence Livermore National Laboratory (LLNL), and Pacific Northwest National Laboratory (PNNL).

Phase I of NRAP was focused on risk assessments associated with large-scale $CO_2$ storage and quantifying uncertainties associated with those assessments. A key product of NRAP's Phase I efforts was the release of ten science-based computational tools, collectively referred to as the NRAP Toolset, to assess environmental risk performance of geologic $CO_2$ storage sites. The individual tools and their applications are:

### *Integrated Assessment Model*

The NRAP Integrated Assessment Model-Carbon Storage (NRAP-IAM-CS) tool simulates long-term full system behavior (from storage reservoir to aquifer/atmosphere). This tool provides results that can be used to compute risk profiles (time-lapse probability of leakage and groundwater impacts) and quantitative estimates of long-term containment effectiveness, in the context of system uncertainty (Stauffer et al., 2016).

### *Aquifer Impact Model*

The Aquifer Impact Model (AIM) tool gives a rapid probabilistic estimation of aquifer volume impacted by a potential leak of injected $CO_2$ or saline water pushed out of the $CO_2$ storage reservoir. This tool distinguishes between $CO_2$ and saline water leaks, and is used to determine impacted groundwater relative to select regulatory or detection threshold criteria (Keating et al., 2016).

### *Designs for Risk Evaluation and Management*

The Designs for Risk Evaluation and Management (DREAM) tool evaluates and selects the optimal monitoring design for a geologic carbon storage (GCS) site, estimating earliest time to detection and probability of leakage detection given site- and technology-specific constraints (Yonkofski et al., 2016).

### *Multiple Source Leakage Reduced-order model*

The Multiple Source Leakage Reduced-order model (MSLR) rapidly predicts the probability that the concentration in an atmospheric plume of $CO_2$ will exceed a defined critical concentration, given known leakage rates from one or more sources (Zang & Oldenburg, 2016).

### *NRAP Seal Reduced-Order model*

The NRAP Seal Reduced-Order model (NSealR) estimates migration of brine and supercritical $CO_2$ through an imperfect (fractured or perforated) seal barrier above the injection horizon using stochastically defined parameters and Monte Carlo analyses, useful for estimating containment effectiveness (Lindner, 2016).

### *Reservoir Evaluation and Visualization*

The Reservoir Evaluation & Visualization (REV) tool distills key information from raw numerical reservoir simulations on reservoir pressure change and $CO_2$ plumes sizes over time, helping to assess the portion of the site that may be subject to regulation of monitoring and site care (King, 2016a).

### *Reservoir Reduced-Order Model- Generator*

The Reservoir Reduced-Order Model- Generator (RROM-Gen) tool generates reservoir look-up table reduced-order models (ROMs) from established reservoir simulations; they can be incorporated into the NRAP Integrated Assessment Model-Carbon Storage (NRAP-IAM-CS) for site-specific risk assessment (King, 2016b).

### *Well Leakage Analysis Tool*

The Well Leakage Analysis Tool (WLAT) allows rapid evaluation of leakage risk from existing wells at $CO_2$ storage sites. It models potential migration of brine and/or $CO_2$ from the storage reservoir as a function of well disposition and reservoir conditions (Huerta & Vasylkivska, 2016).

### *Ground Motion Prediction – Induced Seismicity*

The Ground Motion Prediction applications to potential Induced Seismicity (GMPIS) tool estimates shaking intensity at the surface that could result from potential induced earthquakes at $CO_2$ storage sites, providing useful information during the project planning and permitting stages (Bradley et al., 2016).

### *Short-Term Seismic Forecasting*

The Short-Term Seismic Forecasting (STSF) tool performs a probabilistic analysis that considers the site's previously recorded seismic history and new injection data to forecast expected seismicity rate over the next few days (Bachmann, 2016).

## CarbonSAFE East Sub-Basin NRAP Toolset Application

The NRAP tool evaluated within the CarbonSAFE East Sub-Basin project was NRAP-IAM-CS for data availability and applicability of the model to the site. The model components within NRAP-IAM-CS 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 geologically-sequestered $CO_2$. 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 component models within NRAP-IAM-CS.

NRAP-IAM-CS incorporates several NRAP tools into one package. $CO_2$ and brine leakage estimates were generated using models that are also incorporated into the WLAT tool. WLAT is a collection of reduced-physics models and ROMs that provide the means to estimate the rate of $CO_2$ and brine leakage for different types of wells under a variety of conditions. Within the NRAP-IAM-CS, two options are present for wellbore leakage models: Open Wellbore and Cemented Wellbore models. While the Open Wellbore was tested, this model generates leakage rates that are outside the range used to develop the Aquifer Impact Model; therefore, the simulations cannot be used to predict groundwater impacts and thus, are not considered within this report. Only results from the Cemented Wellbore model are presented in the following sections.

### *Simulation Conditions*

ISGS personnel evaluated the NRAP-IAM-CS tool by assessing the impact of a) increasing monitoring distance from the injector, and b) variable wellbore permeability of a leaking legacy well on the amount of $CO_2$ and brine leaked from the storage reservoir into the overlying aquifer.

The RROM-Gen tool used pressure and saturation data from a reservoir model, completed as part of the overall study, to generate lookup tables for $CO_2$ saturation and reservoir pressure as input for the NRAP-IAM-CS tool. Other NRAP-IAM-CS model inputs were compiled using regional geological and geochemical data for the injection zone and USDW (Table 1). Finally, the NRAP-IAM-CS tool was used to model leakage of $CO_2$ and brine from the target Mt. Simon reservoir into the St. Peter Sandstone, which was applied as the proximal USDW.

Ten total simulations, each consisting of a single realization, were run with a hypothetical leaking cemented wellbore. The well was placed at 0.0, 0.5, 1.0, 1.5, and 2.0 km away from the injection well, and the permeability of the cement in the leaking wellbore was manually varied between a high and low value ($2.0 \times 10^{-14}$ $m^2$ and $2.0 \times 10^{-16}$ $m^2$, or 20 mD to 0.2 mD).

A second set of simulations were completed using the built-in wellbore permeability distributions of the NRAP-IAM-CS tool. Again, a high and low set of permeability distributions were used in the simulations, which involved a total of 2,500 realizations for each simulation. Distances of 0.5, 1.0 1.5 and 2.0 km well spacing between the injector and leaking well were simulated, producing 8 separate simulations.

Table 1. NRAP-IAM-CS tool input parameters

| **Injection Zone** | | |
|---|---|---|
| Attribute | Value | Units |
| Elevation of top | -2213 | Meters |
| Elevation of bottom | -2217 | Meters |

| | | |
|---|---:|---:|
| Initial pressure | 23.03 | MPa |
| Thickness | 4.07 | Meters |
| Salinity | 230000 | ppm |
| Molality | 5.32 | - |
| Temperature | 56.71 | Celsius |

**USDW**

| | | |
|---|---:|---:|
| Elevation of top | -827.9 | Meters |
| Elevation of bottom | -837.6 | Meters |
| Thickness | 9.75 | Meters |
| Mean permeability | $4.441 \times 10^{-14}$ | Meters$^2$ |
| Mean porosity | 0.15 | - |
| Initial pressure | 10.04 | MPa |
| Salinity | 28000 | ppm |
| Molality | 0.65 | - |
| Temperature | 31.45 | Celsius |

**Legacy Wells, Manual Permeability Entry**

| | | |
|---|---:|---:|
| Location | 0.0, 0.5, 1.0, 1.5, 2.0 | Kilometers |
| High Permeability Wellbore Cement | $2.05 \times 10^{-14}$ | Meters$^2$ |
| Low Permeability Wellbore Cement | $2.05 \times 10^{-16}$ | Meters$^2$ |

**Legacy Wells, Built-in Permeability Distributions**

| | | |
|---|---:|---:|
| Location | 0.5, 1.0, 1.5, 2.0 | Kilometers |
| High Permeability Wellbore Cement | Min: $9.336 \times 10^{-23}$<br>Max: $3.001 \times 10^{-11}$<br>Mean: $1.569 \times 10^{-14}$ | Meters$^2$ |
| Low Permeability Wellbore Cement | Min: $9.034 \times 10^{-25}$<br>Max: $1.773 \times 10^{-13}$<br>Mean: $6.131 \times 10^{-16}$ | Meters$^2$ |

**Numerical Model Outputs**

| | | |
|---|---:|---:|
| Pressure | | MPa |
| Saturation | | decimal |

## Results

The results are divided into the two groups based on how permeability was assigned to the leaking cemented wellbore: 1) manual permeability entry, where the wellbore cement was manually assigned a single high or low permeability value, and 2) built-in permeability distribution, where the wellbore cement permeability was selected from two built-in distributions of permeability values collected for the FutureGen project. The resulting $CO_2$ leakage rate, total leaked $CO_2$, brine leakage rate, and total leaked brine were analyzed across the cement permeability values and well distances.

*Manually permeability entry*

The results for the ten different simulations using a manually-entered value for permeability are summarized in Figure 2, comparing the differences in $CO_2$ leakage rate, total amount of $CO_2$ leaked, brine leakage rate and total amount of brine leaked.

*$CO_2$ leakage*

The NRAP-IAM-CS simulation indicated that $CO_2$ never occurred at the hypothetical monitoring well collocated with the injection well (0.0 km distance), while the well located 0.5 km away showed an initially large $CO_2$ leakage rate, which decreased to 0 by 4 years into the simulation (Figure 2a). The $CO_2$ leakage rate at the hypothetical wells placed 1.0 km, 1.5 km, and 2.0 km from the injection well showed somewhat similar behavior. The leakage rate at these three wells first spiked dramatically, then tapered. In the case of the well 1 km from the injection well, the leakage rate decreased to 0 by 15 years into the simulation. The leakage rates simulated at the two wells located 1.5 km and 2.0 km from the injection well decreased to a non-zero minimum, then began to increase for the remainder of the simulation duration. As anticipated, the initial leakage spike in the monitoring wells occurred later in the observation period with increased distance from the injection well. The cumulative leaked $CO_2$ (Figure 2b) accurately reflects the simulated leakage rates over time.

The response of leakage rates, and therefore the total leaked $CO_2$, to the change in cement permeability was unexpected: leakage rates were larger (roughly double) when the cement permeability was 0.2 mD than when the cement permeability was 20 mD.

*Figure 2. $CO_2$ and leakage into the USDW at five hypothetical monitoring wells located 0.0, 0.5, 1.0, 1.5, and 2.0 km from the injection well.*

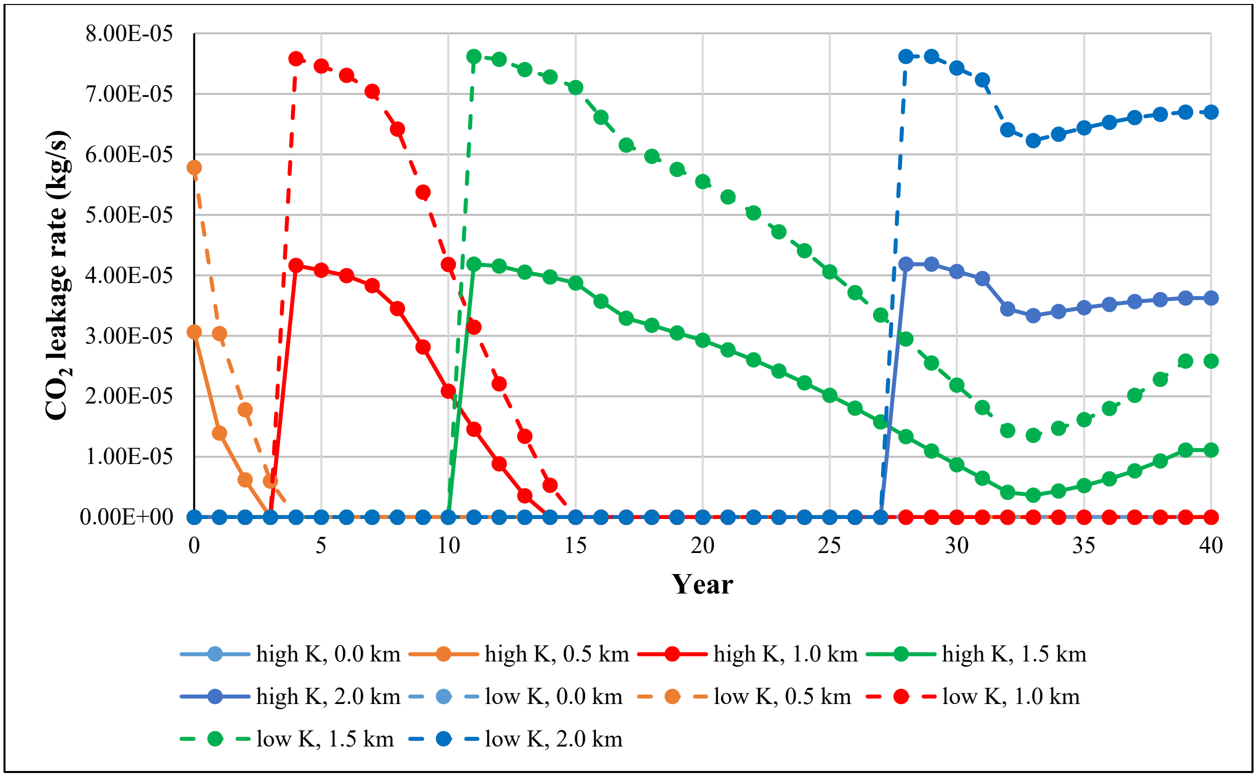

*Figure 2a. CO$_2$ leakage rates into the USDW using manually entered permeability.*

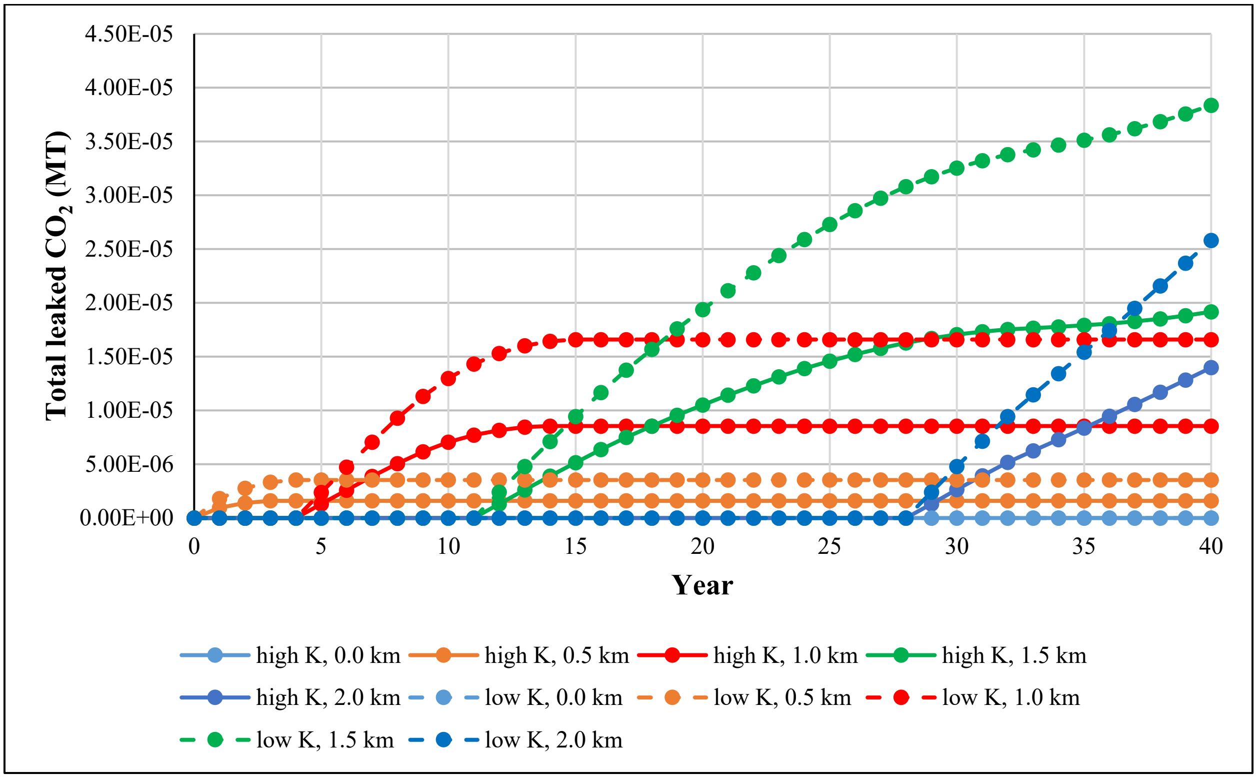

*Figure 2b. Total CO$_2$ leakage into the USDW using manually entered permeability.*

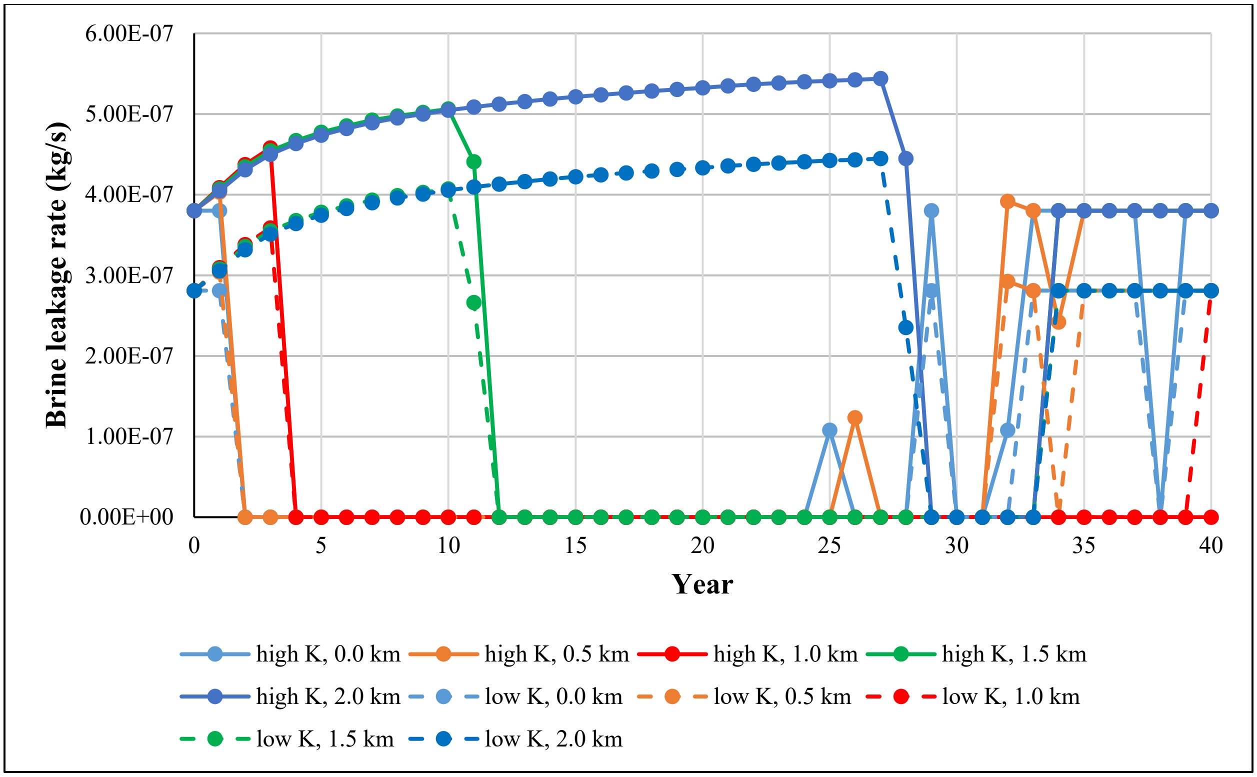

*Figure 2c. Brine leakage rates into the USDW using manually entered permeability.*

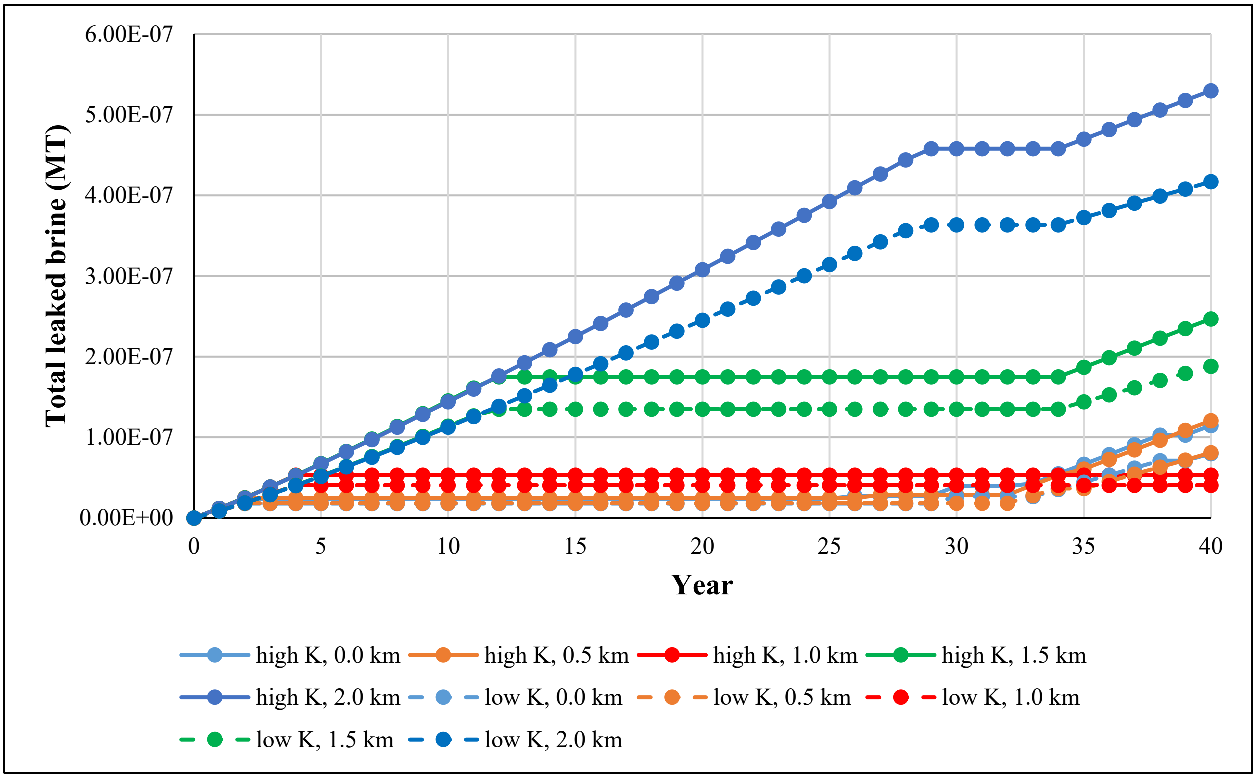

*Figure 2d. Total brine leakage into the USDW using manually entered permeability.*

### *Brine leakage*

The brine leakage rates at all five hypothetical monitoring well distances followed a similar pattern (Figure 2c). Brine leakage was present at all distances as soon as $CO_2$ injection began. Then the brine leakage rate decreased to zero when the $CO_2$ plume reached the leaking well. Thus, the amount of brine leaked increased with distance between the leaking and injector well. However, there were some instances where brine leakage appeared after the $CO_2$ leakage had begun. More surprisingly, wells with higher permeability resulted in higher rates of brine leakage, the expected result, but opposite of the trends observed for $CO_2$ leakage.

### *Built-in permeability distributions*

The results of all 2,500 realizations for each of the eight simulations are shown in Figure 3 while Figure 4 compares the average results of the eight different simulations. In both figures, comparisons are made between differences in $CO_2$ leakage rate, total amount of $CO_2$ leaked, brine leakage rate and total amount of brine leaked.

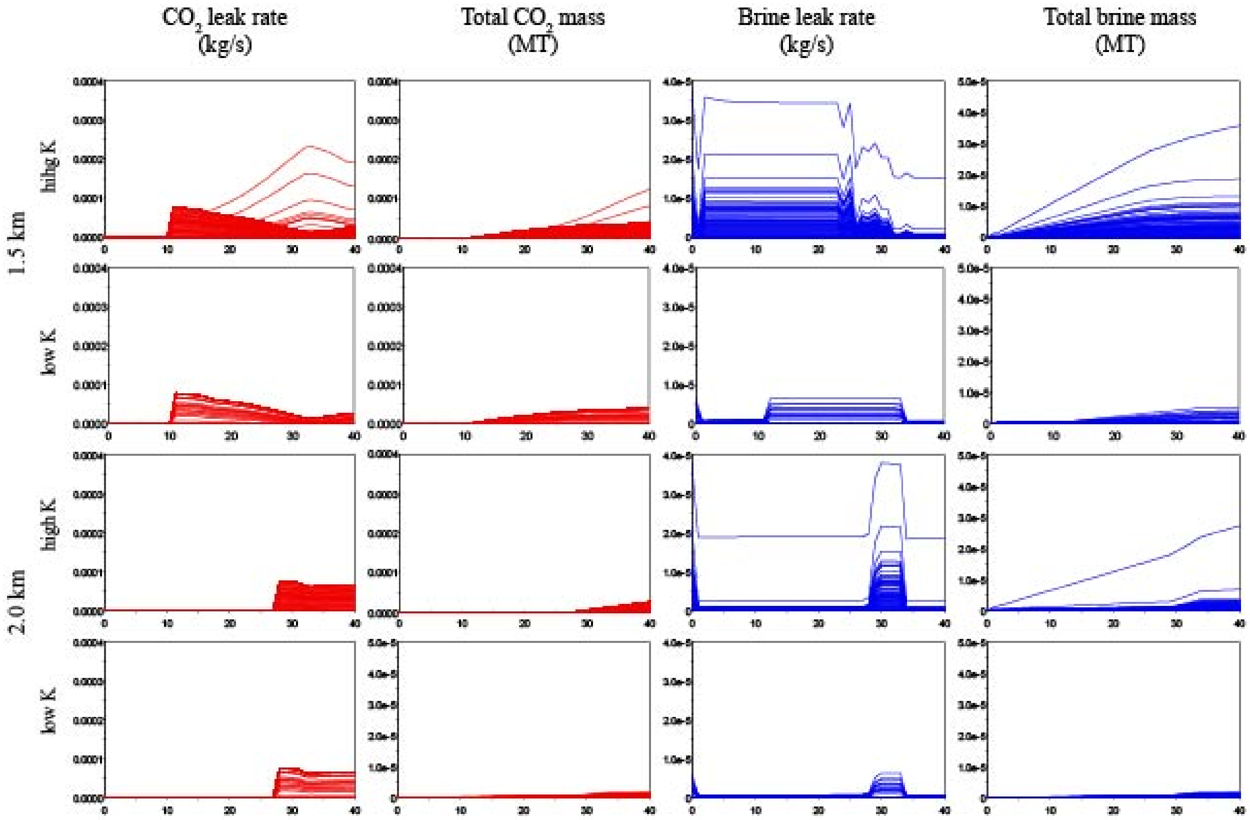

*Figure 3a. Leakage of $CO_2$ and brine from all 2500 realizations for simulations with spacing between the injector and legacy well of 0.5 km and 1.0 km and employing the high and low built-in wellbore cement permeability distributions.*

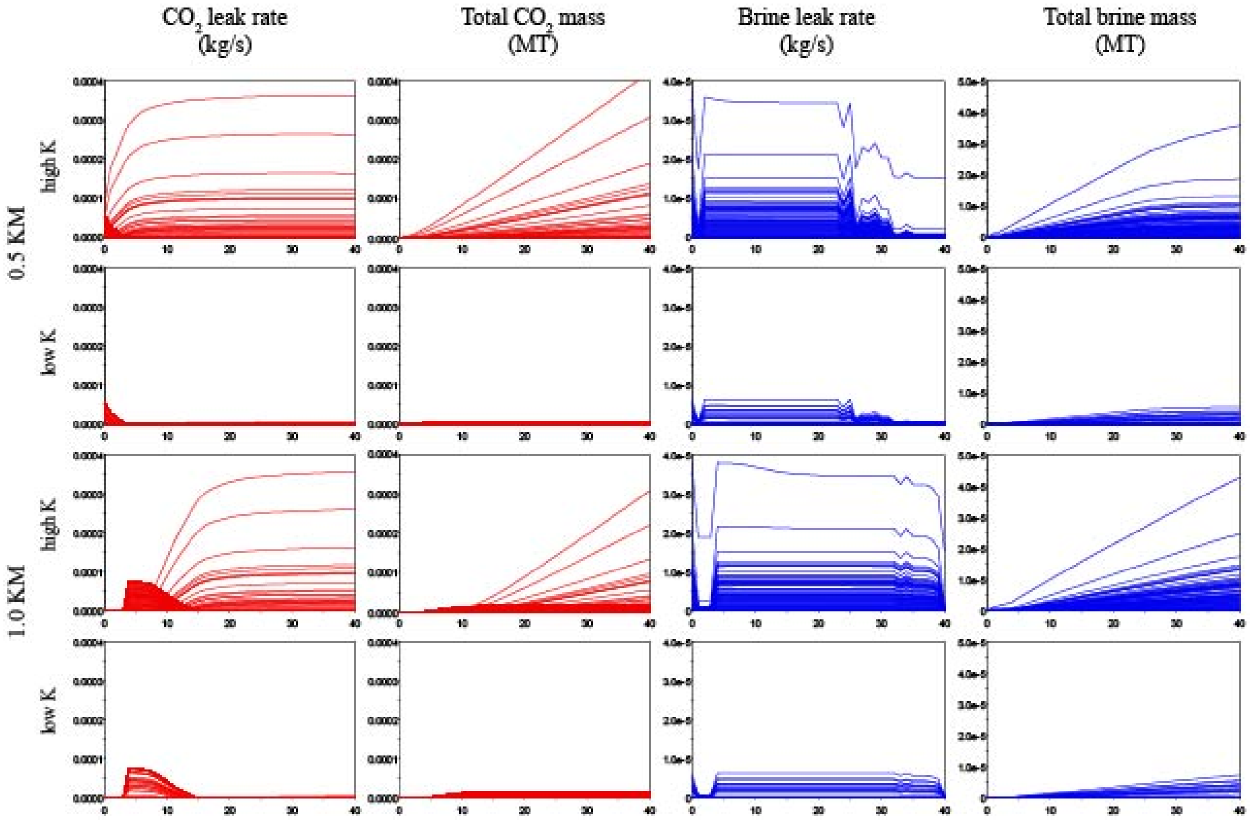

*Figure 3b. Leakage of $CO_2$ and brine from all 2500 realizations for simulations with spacing between the injector and legacy well of 1.5 km and 2.0 km and employing the high and low built-in wellbore cement permeability distributions.*

### *$CO_2$ leakage*

Like the simulations using the manual entry for permeability, the built-in permeability distributions resulted in a rapid increase in $CO_2$ leakage, then a drop-off. A delay before the initial spike in $CO_2$ leakage occurred in proportion to the distance of the leaking well from the injector. Also, like the previous simulations, $CO_2$ leakage occurred for a shorter period of time for wells closer to the injection than those farther away.

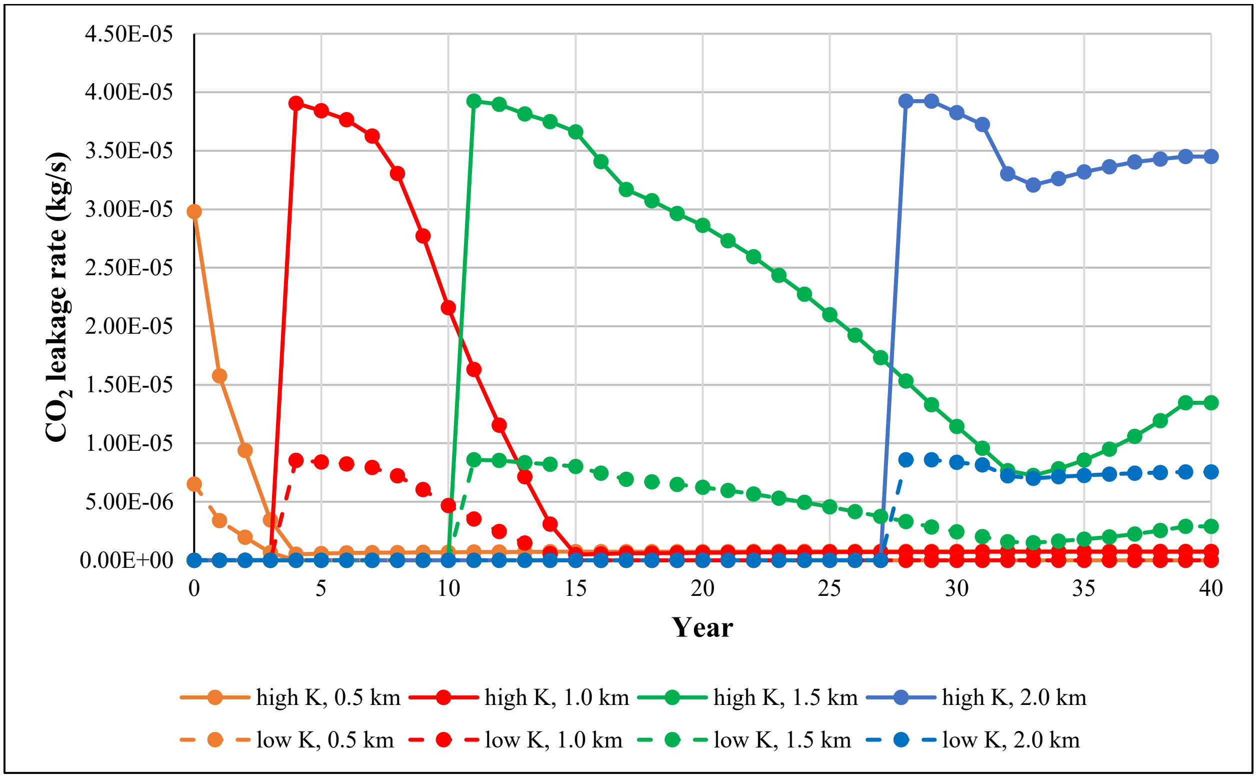

*Figure 4a. Average of $CO_2$ leakage rates across all simulation realizations into the USDW using built-in permeability distributions.*

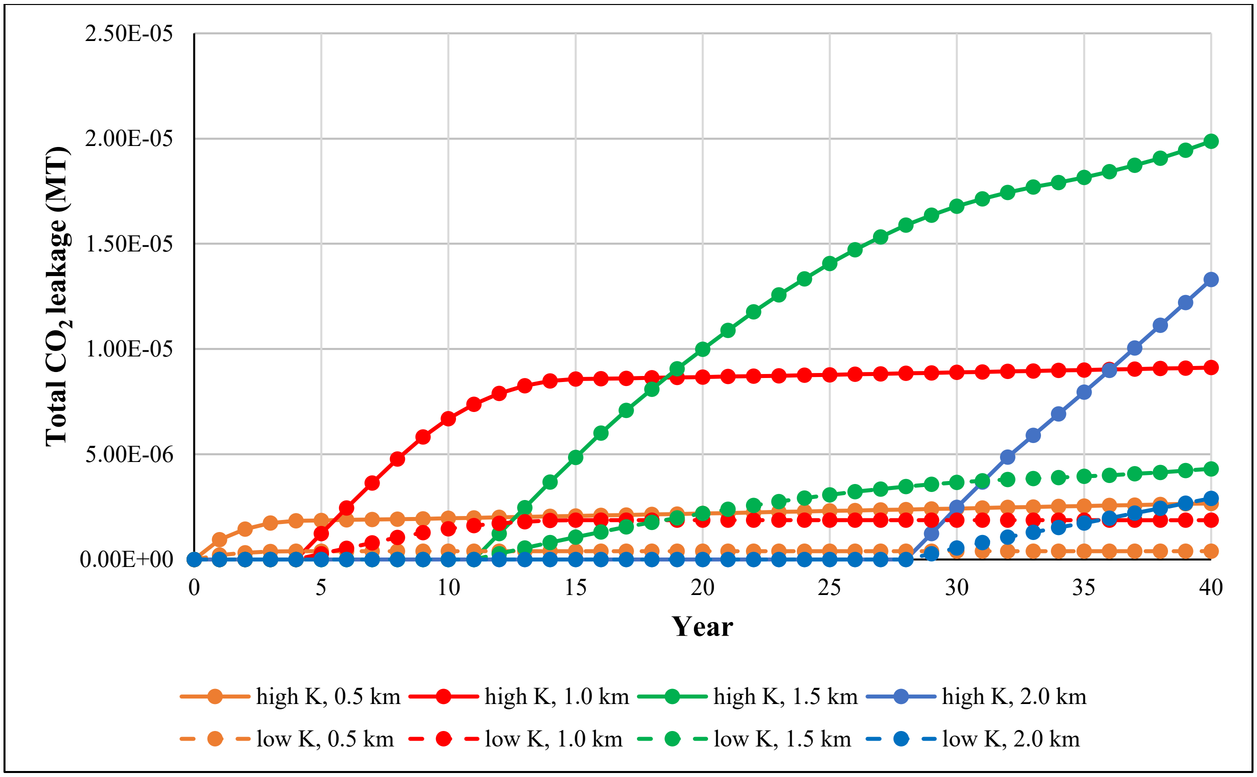

*Figure 4b. Average of total $CO_2$ leakage across all simulation realizations into the USDW using built-in permeability distributions.*

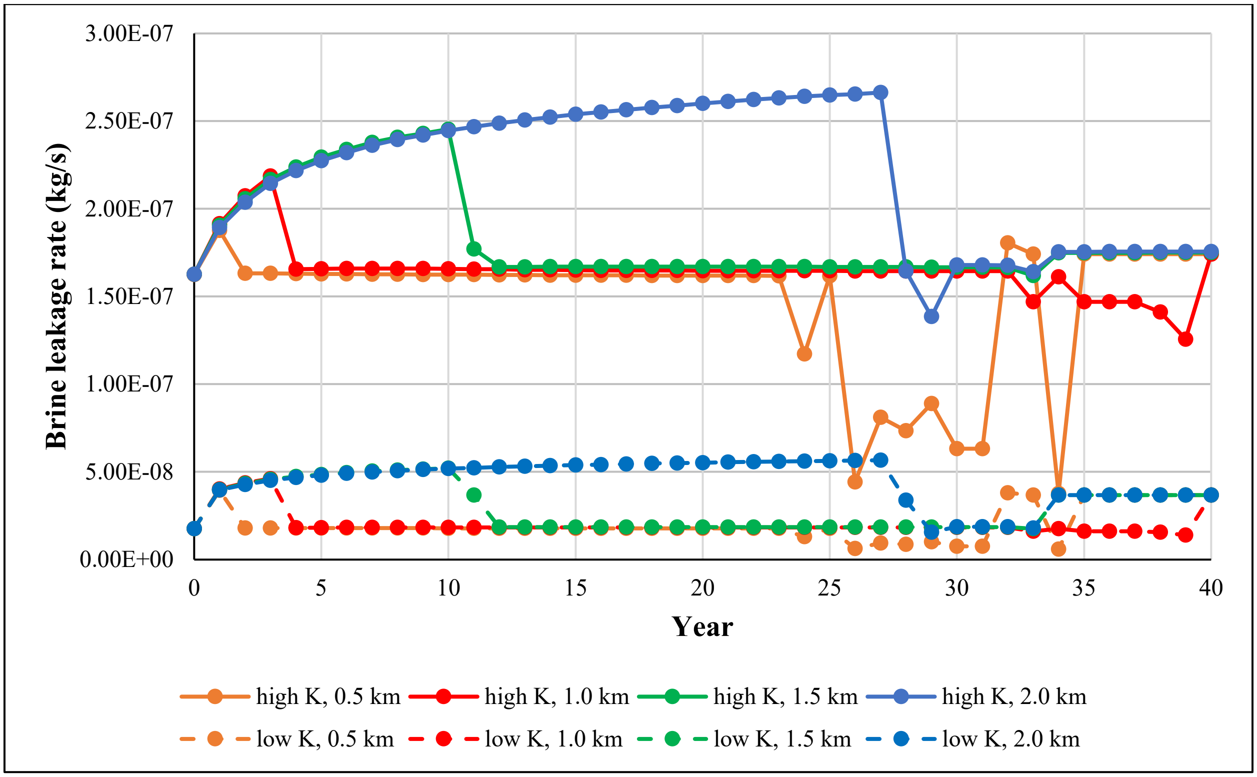

*Figure 4c. Average of brine leakage rates across all simulation realizations into the USDW using built-in permeability distributions.*

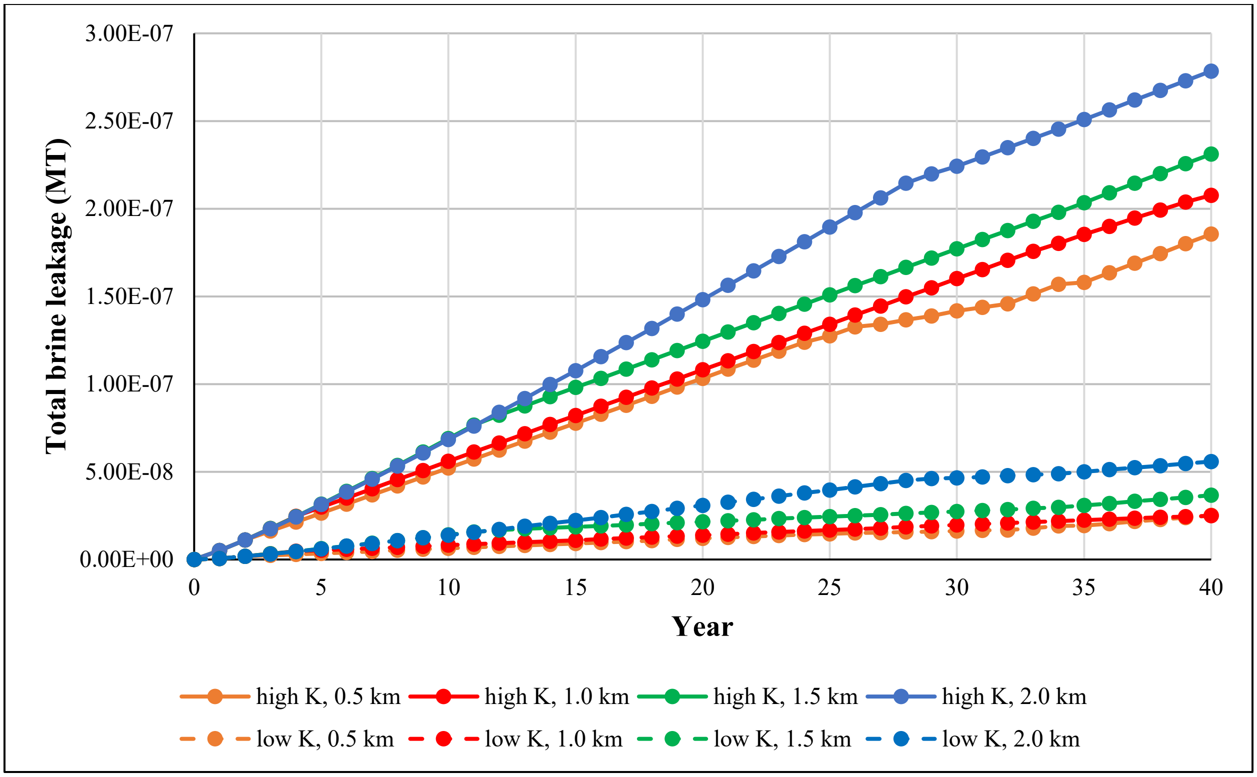

*Figure 4d. Average of total brine leakage across all simulation realizations into the USDW using built-in permeability distributions.*

Unlike the simulations which used manually entered permeability values, the average of all realizations using the built-in permeability values showed that wells with higher permeability had higher rates of $CO_2$ leakage, and as a result, projected larger amounts of $CO_2$ leaked, while lower permeability had consistently lower rates of $CO_2$ leakage. However, plotting the total amount of $CO_2$ leaked against the wellbore cement permeability for each realization does not, in all cases, reveal a straightforward relationship (Figure 5). Instead, as permeability increases past a cutoff value, the mass of $CO_2$ leaked is constant until reaching a second inflection value where the mass of $CO_2$ leaked decreases to zero. Above permeability of $1 \times 10^{-13}$ $m^2$, the mass of $CO_2$ increases rapidly. .

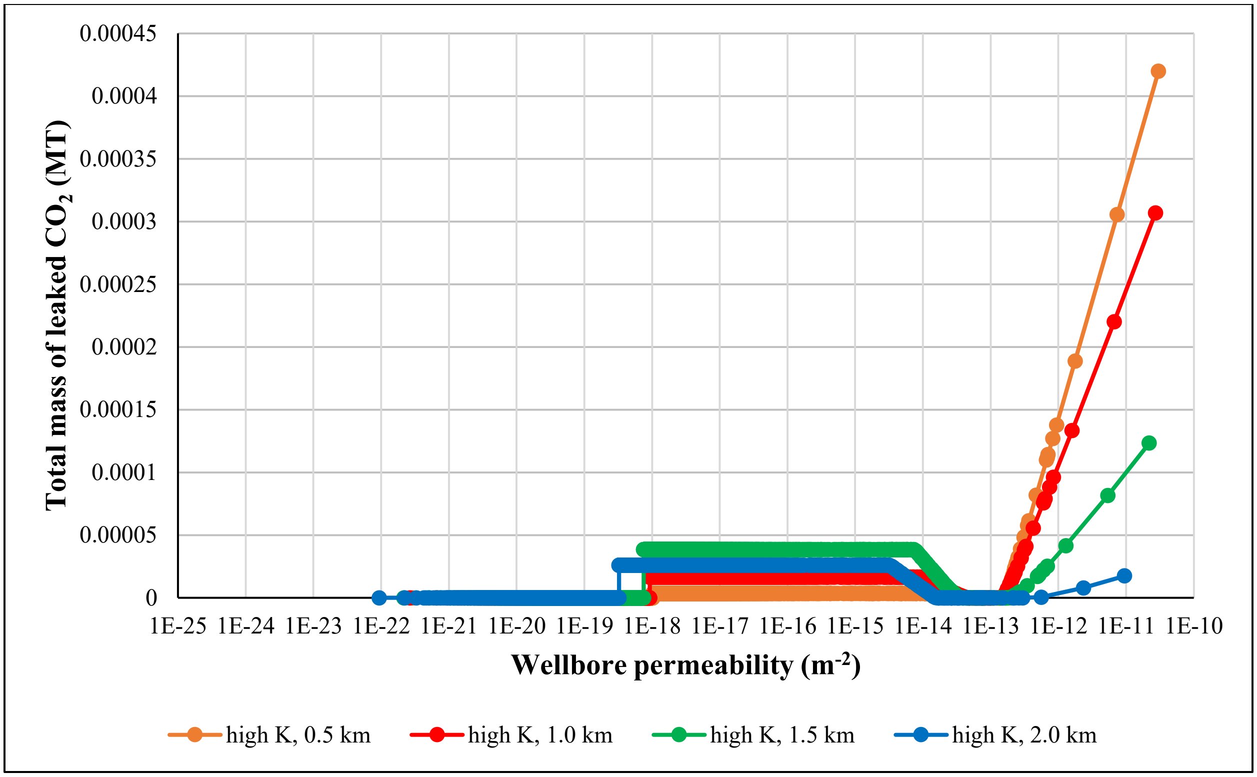

*Figure 5a. Total leaked CO₂ vs. wellbore permeability for all scenarios using the built-in high permeability distribution.*

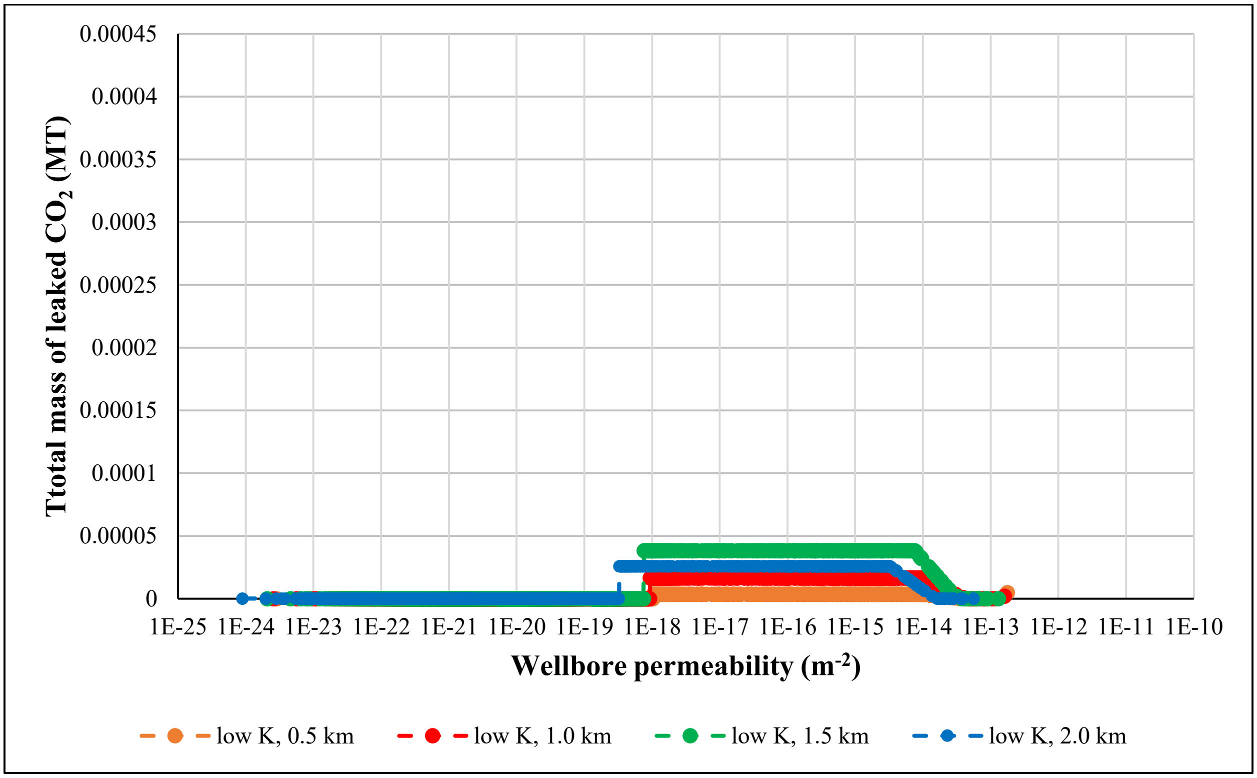

*Figure 5b. Total leaked CO₂ vs. wellbore permeability for all scenarios using the built-in low permeability distribution.*

*Brine leakage*

Like the initial simulations, brine leakage tended to increase with distance between the leaking and injection well. The difference with the multiple realization simulations is that brine leakage tended to not drop to zero once $CO_2$ leakage began, but decreased to a lower rate. As with $CO_2$ leakage, the trend of higher brine leakage occurs for wells with higher permeability values.

## Conclusions

The CarbonSAFE East Sub-Basin NRAP review successfully applied our reservoir simulation model data to the RROM-Gen tool and used that output to run the NRAP-IAM-CS tool. Simulations were successful, but some results were problematic. Overall, the NRAP-IAM-CS tool has considerable conceptual merit, but needs additional testing to improve it for public release. Further testing of the tool by comparison with other simulation software is encouraged.

*Issues and recommendations*

- The IAM tool requires output from a reservoir simulator, and therefore is not yet the quick-look tool it is intended to be. If the IAM tool contained a built-in simple reservoir simulation model, then the entire process of site characterization could take place within the tool, without requiring external reservoir model simulations.
- The open well bore simulation option generates leakage rates that are greater than those used to develop the AIM. This should be mentioned in the user's guide, or the option to use this ROM with IAM-CS should be disabled.
- Simulations run to test variable wellbore cement permeabilities, using directly input cement permeability (as compared to using built-in distributions), indicated $CO_2$ leakage rates were higher for low permeability values than for high permeability values.
  This trend was not observed for brine leakage however, nor did this occur when using built-in distributions of permeability. This behavior was unknown to PNNL, and surprising for both PNNL and ISGS personnel. A bug report has been filed with the tool developer so that this issue can be addressed in an update to the NRAP-IAM-CS tool.
- Simulated leaking wells within 1 km of the injection well showed zero leakage within a 15 year observation period while wells further than 1 km from the injection well demonstrated continuous leakage for the entire forty year simulation. One suggestion was the $CO_2$/pressure front had passed the near sites and was still moving past the far wells.
- A number of variables currently cannot be changed, such as the permeability of the aquifer. Currently, the aquifer permeability used is from the Edwards aquifer.
- The RROMGEN tool, designed to average the reservoir simulation data to fit a coarser grid and produce a lookup table compatible for the NRAP-IAM-CS tool, takes six to ten hours to complete a run for a dataset that is not unusually large for reservoir simulations.
- A significant number of the permeability values assigned to wellbore cement within the built-in distributions are unlikely: a cement with an effective permeability equal to or greater than $1.0 \times 10^{-16}$ $m^2$ (~0.1 mD) would be analogous to a micro annulus, or a gap in cement around the casing, extending the total depth between the storage reservoir and the overlying aquifer, which in this case would be 1385 m (4544 ft.).

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