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Application of quantitative risk assessment to address stakeholder questions in geologic carbon storage

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Abstract

Ambitious international greenhouse gas emissions reduction targets demand a rapid transformation to a low-carbon economy. This transformation includes the accelerated adoption of carbon dioxide (CO_2) capture and storage (CCS) technology. However, as with any large-scale engineering enterprise, the widespread commercial-scale deployment of geologic carbon storage (GCS) raises important questions about technology and cost-effectiveness, safety, environmental risk, and long-term liability. Effectively assessing and managing risks and liability associated with GCS projects is a key technical need throughout the project life cycle- from site selection and permitting to monitoring design, operational risk management, and post-operational site closure. This presentation highlights recent advancements in tools for quantitative risk assessment, being developed by the National Risk Assessment Partnership (NRAP). NRAP is a multi-year, multi-national laboratory research collaboration sponsored by the U.S. Department of Energy's Office of Fossil Energy and Carbon Management. Our focus will be on these tools' applications in addressing critical stakeholder questions related to:

- Supporting permitting to ensure secure and environmentally protective storage,
- Designing effective and efficient monitoring plans,
- Evaluating the effectiveness of remedial actions and risk management alternatives, and
- Informing liability assessment and investment decisions.

This paper will detail the key functionality of NRAP's Open-Source Integrated Assessment Model (NRAP-Open-IAM), a computational framework for assessing leakage risk and containment assurance. This model features streamlined workflows for calculating leakage risk profiles, delineating risk-based area of review, and assessing contingency plans and post-injection site care requirements. ORION is an open-source, observation-based ensemble forecasting toolkit to help operators assess the seismic hazard at a carbon storage site. The State of Stress Analysis

Tool (SOSAT), designed to assess subsurface stress conditions and evaluate geomechanical risk resulting from CO_2 injection in an area of interest will also be presented. We will also introduce a prototype model to evaluate storage project costs and liability associated with risk management. The Technoeconomic and Liability Evaluation for Storage (TALES) model uses results from forecasts of leakage and induced seismicity risk to estimate the lifecycle cost of managing risk. Finally, a preliminary example of how the NRAP Risk-based Adaptive Monitoring Plan (RAMP) tool can be used to design efficient and effective site monitoring plans and estimate the detectability of fluid leakage will be provided. The relevance of these tools for addressing key stakeholder questions amidst uncertainty will be emphasized.

Keywords: quantitative risk assessment, decision support, leakage risk assessment, induced seismicity risk assessment, liability

Nomenclature

AoR	Area of Review
CCS	Carbon capture and storage
DOE	Department of Energy
GCS	Geologic carbon storage
LANL	Los Alamos National Laboratory
LBNL	Lawrence Berkeley National Laboratory
LLNL	Lawrence Livermore National Laboratory
NETL	National Energy Technology Laboratory
NRAP	National Risk Assessment Partnership
IAM	Integrated Assessment Model
ORION	Operational Forecasting of Induced Seismicity Toolkit
PISC	Post-Injection Site Care
PNNL	Pacific Northwest National Laboratory
RAMP	Risk-Adaptive Monitoring Planning Tool
SOSAT	State of Stress Analysis Tool
TALES	Techno-economic and liability for Storage Model

1. Introduction

Broad commercial-scale deployment of carbon capture and storage (CCS) technology requires safe and effective implementation of geologic carbon storage of carbon dioxide (CO_2). [1, 2. Meeting this need requires the translation of scientific and engineering knowledge from research, field demonstration, and analogous industrial experience into tools and protocols to promote risk communication and support effective risk-based decision-making.

2. The NRAP Phase III Toolset

The U.S. DOE's National Risk Assessment Partnership (NRAP) is a longstanding research collaboration between five contributing U.S. Department of Energy national laboratories – sponsored by the DOE's Office of Fossil Energy and Carbon Management's Carbon Transport and Storage Program – that is focused on developing and demonstrating methods and computational tools to assess and manage subsurface environmental risks associated with GCS, amidst uncertainty.

NRAP is developing open-source, computational tools to support risk assessment and decision support related to containment assurance and leakage risk, assessing and managing subsurface stress, analysis of how seismic hazard

evolves at a site in response to CO_2 injection, evaluating the effectiveness of monitoring designs, estimating requirements for remedial responses to address potential impacts and lifecycle costs of storage projects that account for the cost of managing risk. **Table 1** provides a summary of the set of NRAP Phase III computational tools and their release status; **Figure 1** illustrates the relationship between the current and forthcoming Phase III NRAP computational tools and functionality within a carbon storage risk management workflow. This is followed by a detailed description of released and forthcoming NRAP tools.

1. NRAP Phase III Tools and brief functionality description.

NRAP Phase III Tool	Brief Description	Release Status	Reference
NRAP Open-Source Integrated Assessment Model (NRAP-Open-IAM)	An open-source platform to simulate long-term, full-system behavior (reservoir to aquifer/atmosphere) of GCS sites and support decision-making amidst uncertainties.	β v1.2.0; 8/30/2024	[3,4]
State of Stress Analysis Tool (SOSAT)	SOSAT is an online tool designed to quantify uncertainties in the initial state of stress and assess geomechanical risks (unintentional fracturing and fault reactivation) associated with injection operations.	V2.0.0 11/2024	[5]
Operational Forecasting of Induced Seismicity (ORION Toolkit)	Rapid seismic hazard assessment that uses field data (microseismic, well pressure, flow rate) to calibrate field or basin models and identify conditions requiring operator intervention.	V1.0.0; 3/2024	[6]
Risk-based Adaptive Monitoring Planning (RAMP) Tool	RAMP is an open-source software product that enables users to design, assess, and optimize a geologic carbon storage site monitoring plan with combinations of monitoring technologies, sensor configurations, and schedules.	α version mid-2025	forthcoming
Techno-economic and Liability Evaluation for Storage (TALES) Model	The TALES model represents a comprehensive engineering economic model for calculating revenues and costs for all aspects of a saline storage project, including financial and remedial costs.	α v0.5 internal testing	forthcoming

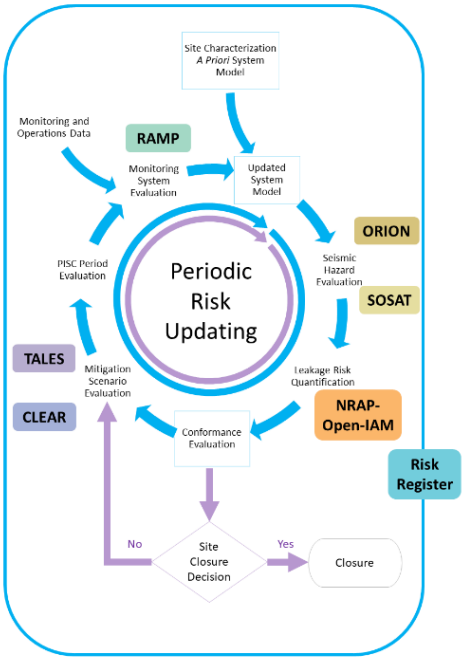

Figure 1. Conceptual Simplified schematic of geologic carbon storage project risk management illustrating the integration of NRAP computational tools (modified from [7])

NRAP Open-Source Integrated Assessment Model (NRAP-Open-IAM)

NRAP-Open-IAM is an open-source software that quantifies containment effectiveness and leakage risks at storage sites in the context of system uncertainties and variability [3,4]. NRAP-Open-IAM represents the next generation in a line of systems-based computational models developed for quantitative GCS risk assessment. The model couples a set of reduced-order and analytical models of various system components, such as potential leakage pathways and receptors of concern, including groundwater resources and the atmosphere. This framework supports stochastic simulations for risk-performance evaluation and a basic graphical user interface to support scenario development, data input simulation definition, and basic post-processing and interpretations. The NRAP-Open-IAM tool can be downloaded from ...

The Operational Forecasting of Induced Seismicity (ORION) Toolkit

ORION is an open-source, observation-based ensemble forecasting toolkit geared towards helping operators understand the seismic hazard (i.e., probabilistic assessment of the magnitude and frequency of potential induced seismic events) at a geologic carbon storage site [6]. ORION analyzes how seismic hazards evolve during injection of an earthquake exceeding a specific threshold is observed, it suggests possible mitigation strategies. Through its ensemble modelling approach, ORION leverages the benefits of statistical-, physics-, and machine learning-based forecasting methodologies, while reducing the impact of each model's respective limitations. ORION will then provide a spatial and temporal ensemble forecast of seismicity defined as the probability of exceedance of a given earthquake magnitude over a forecast period. Additionally, ORION will provide statistically derived probability distributions of expected earthquake magnitudes. Finally, ORION can be used to evaluate potential effectiveness of proposed operational management strategies (e.g. reduce injection volumes at specific wells) based on the level of hazard [9]. ORION was developed jointly through two DOE Office of Fossil Energy and Carbon Management-sponsored initiatives: the National Risk Assessment Partnership (NRAP) and the Science-informed Machine Learning to Accelerate Real-Time Decisions in Subsurface Applications (SMART) Initiative. The ORION tool can

be downloaded from: https://edx.netl.doe.gov/dataset/orion-operational-forecasting-of-induced-seismicity.

State of Stress Analysis Tool (SOSAT)
SOSAT is software designed to comprehensively assess subsurface stress conditions and calculate the probability of geomechanical risks at carbon storage sites, building stakeholder confidence in managing risk and empowering operators and regulators to formulate effective execution plans [5,8,9]. SOSAT applies a Bayesian approach to quantify uncertainties in the initial stress state and changes in stress that arise from fluid injection. Within an area of interest, SOSAT uses available field measurements and data including well logs, well test data (e.g., leakoff and minifrac tests), regional geological insights, and constraints imposed by the presence of faults and fractures. to constrain the initial conditions referred to as the state of stress. These data are specified using probability distributions for the key observational parameters. Based on the uncertainty of each parameter, SOSAT generates millions of realizations of the uncertain parameters to determine the probability of fault activation and unintentional hydraulic fracturing resulting from the pore pressure increase associated with CO_2 injection. Unlike Monte Carlo approaches that treat the three principal stresses as independent stochastic variables, SOSAT accounts for covariance between the principal stress components and computes the joint probability for the principal stresses. SOSAT outputs can also be used to generate random samples of the posterior stress distribution for use in other analyses, such as applying initial conditions to numerical geomechanical models. The cloud-hosted SOSAT tool can be accessed at htttps://sosat.pnnl.gov/.

Risk-based Adaptive Monitoring Planning (RAMP) Tool
The RAMP tool is an open-source software product that enables users to design and assess the effectiveness of a geologic carbon storage monitoring plan. The tool allows consideration of plans with combinations of multiple monitoring technologies, sensor configurations, and monitoring intervals to select an optimal site monitoring plan. Monitoring technologies that can be considered in the RAMP tool include downhole pressure, fluid geochemical sampling, and indirect geophysical methods: seismic, gravity, and electricalelectromagnetic. Two primary objectives drive the conceptual design and capabilities of RAMP: reduce risk and improve confidence in storage performance. RAMP builds on previously developed optimization functionality [10, 11] to establish a modular design that is risk-based and adaptive with time, enables consideration of trade-offs between different monitoring scenarios, and considers the value of information of new monitoring data. In future versions the RAMP tool will be coupled with both the NRAP-Open-IAM and TALES tools to enable workflows in which monitoring data can be used for parameter and forecast updating, adapt monitoring designs and estimate project costs. The RAMP tool is currently under development a prototype version will be available for public testing in late 2025.

Technoeconomic and Liability Evaluation for Storage (TALES)
The TALES tool, currently under development, is a comprehensive engineering economic model for calculating revenues and costs for all aspects of a CO_2 saline storage project, including financing costs. The liability term in the TALES title refers to the liability associated with potential adverse events that may occur at a CO_2 saline storage project. The focus of TALES, as with other NRAP tools, is on two potential adverse events: leakage of fluid out of the storage formation into an underground source of drinking water or induced seismic incidents. Liability is further defined as the cost of responding to an adverse event. In a typical workflow, TALES first calculates the revenues, costs and financial performance for a storage project assuming there are no adverse events. This is referred to as the baseline scenario. TALES then calculates the revenues, costs and financial performance of additional scenarios. These additional scenarios involve the operator implementing remedial response actions to address specific adverse events. TALES calculates the revenues, costs and financial performance for each of these additional scenarios. The results for the scenarios involving remedial responses are compared with the baseline scenario to determine how significant each adverse event might be and whether the saline storage project could suffer one of these adverse events, implement a remedial response and remain financially viable. This product was developed in collaboration between NRAP and the SMART Initiative for Carbon Storage.

Other Emerging NRAP tools and functionality

A recently developed NRAP Risk register tool supports risk management and decision making by providing a structured framework for creating a risk register and risk matrices (semi-quantitative representations of likelihood and consequences) that consider both subsurface technical and project risks. The tool includes a user-friendly interface designed to streamline the creation, ranking, and management of project risks. Output from this tool enables operators to form risk management plans in support site selection, permitting, and other geologic carbon storage project decisions. The cloud-hosted NRAP risk register tool can be accessed online at: https://nrap-risk-register.pnnl.gov/

NRAP has developed a prototype application linking elements of NRAP-Open-IAM with the of SOSAT to enable basin-scale IAM application assesses well leakage risk at a basin, given multiple GCS sites. This application allows users to use a modified analytical model to estimate pressure responses across the basin from multiple commercial-scale operations, incorporate injection and legacy wells at any location in the basin, perform a leakage risk evaluation at the basin scale, use available information about pore pressure changes in response to large-scale injection together with available information on initial stress state and fault orientation to estimate risk of fracturing caprock and activating faults in the basin as a result of new injection operations.

NRAP is developing new functionality to estimate the effectiveness of engineering interventions to reduce reservoir driving force for out-of-zone fluid migration or to manage impactful leakage to a groundwater aquifer- information useful in evaluating the effectiveness of proposed emergency remedial responses, and in estimating the life cycle cost of managing risk. The first of these is the Carbon Capture, Utilization, and Storage Leakage Evaluation and Remediation (CLEAR module; internal α testing) that is designed to estimate remedial action (and cost) associated with addressing hypothetical impact to underground sources of drinking water. The model draws estimates for CO_2 and/or brine plume distribution over time in the impacted aquifer from leakage risk calculations performed in NRAP-Open-IAM and estimates how those plumes respond to pump and treat or monitoring natural attenuation remedial responses. A second model, the Reservoir Remediation Module (Remed-Res; internal α testing) estimates the effectiveness of brine production to reduce pressure in the storage interval and control CO_2 plume migration. Estimate pressure mitigation effect of brine production scenarios.

Testing and Application of NRAP Tools and Methods

The NRAP toolset is intended to serve as a resource to support carbon storage deployment, with testing and use of these tools supported through stakeholder engagement, developing recommended practices for risk assessment and management, and demonstrating the applicability of NRAP tools and methods to support stakeholder risk-related decision. Current areas of focus include:

- Demonstrating the value of NRAP tools within an industry-standard risk management framework (e.g., bowtie method) to promote integration of quantitative risk assessment into industry risk management workflows.
- Promoting safe reuse of existing subsurface infrastructure by addressing risk-based decisions relative to Class II to Class VI well transition.
- Enabling integrated analysis of long-term risk and liability/financial risk to inform GCS investment and insurance decisions.
- Developing risk-based, adaptive monitoring designs to promote efficient and effective monitoring during and post injection.
- Extending the application of NRAP methods and tools to inform decision making for broad deployment of commercial-scale storage projects across a geologic basin.

3. Summary

The U.S. DOE's National Risk Assessment Partnership is deveoping and deploying open-source tools and recommended practices to directly support the DOE's Office of Fossil Energy and Carbon Management's goal to enable safe and secure commercial GCS deployment. The NRAP products are intended to support stakeholder decision making, amidst uncertainty, for site selection, injection operation design, and risk management at both the site and basin scales. NRAP will continue engage with industry and regulatory stakeholders to test and improve the NRAP tools and risk management workflows to ensure their utility for real-world applications.

4. Disclaimer

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